MITei
MIT Energy Initiative

# INSIGHTS INTO FUTURE MOBILITY

A report from the Mobility of the Future study

**Full report can be found at: energy.mit.edu/insightsintofuturemobility**

This report should be cited as:
MIT Energy Initiative. 2019. *Insights into Future Mobility*. Cambridge, MA: MIT Energy Initiative.
http://energy.mit.edu/insightsintofuturemobility

# INSIGHTS INTO FUTURE MOBILITY

A report from the Mobility of the Future study

*November 2019*

# Study Participants

## Faculty Chair

**WILLIAM H. GREEN**
Hoyt C. Hottel Professor in Chemical Engineering, MIT

## Lead Investigators

**ROBERT C. ARMSTRONG**
Director, MIT Energy Initiative; Chevron Professor of Chemical Engineering, MIT

**MOSHE BEN-AKIVA**
Edmund K. Turner Professor of Civil and Environmental Engineering; Director, Intelligent Transportation Systems Lab, MIT

**JOHN HEYWOOD**
Sun Jae Professor of Mechanical Engineering, Emeritus, MIT

**CHRISTOPHER KNITTEL**
George P. Shultz Professor of Applied Economics, Sloan School of Management, MIT

**SERGEY PALTSEV**
Deputy Director, Joint Program on the Science and Policy of Global Change, MIT

**BRIAN REIMER**
Research Scientist, AgeLab, MIT

**CHINTAN VAISHNAV**
Senior Lecturer, Sloan School of Management, MIT

**JINHUA ZHAO**
Edward and Joyce Linde Associate Professor of City and Transportation Planning;
Director, JTL Urban Mobility Lab, MIT

## Executive Director

**RANDALL FIELD**
Executive Director, Mobility of the Future,
MIT Energy Initiative

## Coordinating Authors

**EYTAN GROSS**
Project Engineer, Mobility of the Future study,
MIT Energy Initiative
SM, Transportation ('18),
Intelligent Transportation Systems Lab, MIT

**JOANNA MOODY**
Research Program Manager, Mobility Systems Center, MIT Energy Initiative
PhD, Transportation ('19),
JTL Urban Mobility Lab, MIT

## Contributing Authors

**EMIL DIMANCHEV**
Research Associate, Center for Energy and Environmental Policy Research, MIT

**EMRE GENÇER**
Research Scientist, MIT Energy Initiative

**ABBAS GHANDI**
Research Scientist, Joint Program on the Science and Policy of Global Change, MIT

**I-YUN LISA HSIEH**
PhD Candidate, Chemical Engineering, Green Research Group, MIT

**IAN MILLER**
Research Associate, MIT Energy Initiative

**JENNIFER MORRIS**
Research Scientist, Joint Program on the Science and Policy of Global Change, MIT

**ELIZABETH MURPHY**
SM, Technology and Policy ('18), MIT

**ASHLEY NUNES**
Research Scientist, AgeLab, MIT

**JIMI B. OKE**
Postdoctoral Associate, Intelligent Transportation Systems Lab, MIT; Assistant Professor, Civil and Environmental Engineering, University of Massachusetts Amherst

**RAKESH SRIDHAR**
SM, Transportation ('19), and SM, Technology and Policy ('19), MIT

**DUSTIN WEIGL**
SM, Transportation ('19), and SM, Technology and Policy ('19), MIT

---

## Research Advisors

**ARUN AKKINEPALLY**
Research Scientist, Intelligent Transportation Systems Lab, MIT

**CARLOS LIMA AZEVEDO**
Associate Professor, Transport Division, Department of Management Engineering, Technical University of Denmark

**KAKALI BASAK**
Senior Software Development Project Manager, Singapore-MIT Alliance for Research and Technology

**Y.-H. HENRY CHEN**
Research Scientist, Joint Program on the Science and Policy of Global Change, MIT

**JOSEPH COUGHLIN**
Director, AgeLab, MIT

**JOSEPH FERREIRA**
Professor, Department of Urban Studies and Planning, MIT

**DAVID R. KEITH**
Assistant Professor of System Dynamics, MIT Sloan School of Management

**PAUL KISHIMOTO**
Postdoctoral Research Scholar, International Institute for Applied Systems Analysis

**RAVI SESHADRI**
Principal Research Scientist, Singapore-MIT Alliance for Research and Technology

**RAYMOND SPETH**
Associate Director, Laboratory for Aviation and the Environment, MIT

**P. CHRISTOPHER ZEGRAS**
Associate Professor of Transportation and Urban Planning, MIT

## Students and Research Assistants

**CHAEWON AHN**
PhD Candidate, Urban Studies and Planning, MIT

**SIYU CHEN**
PhD Candidate, Transportation, Intelligent Transportation Systems Lab, MIT

**SHARLENE CHIU**
SB, Computer Science ('19), MIT

**DONGHYUN MICHAEL CHOI**
MEng, Electrical Engineering and Computer Science ('17), MIT

**JUNGWOO CHUN**
PhD Candidate, Urban Studies and Planning, MIT

**HANS HAN**
BS, Economics ('18), Wellesley College

**YAFEI HAN**
PhD, Transportation ('19), Intelligent Transportation Systems Lab, MIT

**KRISTEN HERNANDEZ**
Research Assistant, AgeLab, MIT

**SEAN HUA**
MEng, Electrical Engineering and Computer Science ('17), MIT

**JINTAI LI**
SM, Transportation ('19), and Master in City Planning ('19), JTL Urban Mobility Lab, MIT

**YOUSSEF ABOUTALEB MEDHAT**
PhD Candidate, Transportation, Intelligent Transportation Systems Lab, MIT

**MAHSA NAMI**
SM, Technology and Policy ('17), MIT

**XUENAN NI**
SM, Transportation ('19), and Master in City Planning ('19), JTL Urban Mobility Lab, MIT

**AKSHAY PADMANABHA**
MEng, Electrical Engineering and Computer Science ('17), MIT

**HAOANG SUN**
Intern, MIT Energy Initiative; Undergraduate student, Mathematics, Northeastern University

**IVEEL TSOGSUREN**
MEng, Electrical Engineering and Computer Science ('18), MIT

**SHENHAO WANG**
PhD, Computer and Urban Science ('20), JTL Urban Mobility Lab, MIT

**YUEHAN WANG**
Master's student, Real Estate Development and City Planning, MIT

**YIFEI XIE**
PhD Candidate, Transportation, Intelligent Transportation Systems Lab, MIT

**JIN JASMINE ZHOU**
Master in Statistics ('17), Columbia University

# Contents

# Foreword and Acknowledgments

This report is the culmination of a three-year study to examine how the complex interactions between advanced drivetrain options, alternative fuels, refueling infrastructure, consumer choice, vehicle automation, and government policy may shape the future for personal mobility. The MIT Energy Initiative (MITEI) undertook this study in the context of its mission to explore and create solutions that will efficiently meet global energy needs while minimizing environmental impacts and mitigating climate change. The study is part of MIT's Plan for Action on Climate Change.

The study's focus on the movement of people via ground transportation in part reflects a recognition that this is the segment that is likely to be most strongly and rapidly affected by fast-moving developments in advanced powertrains, alternative fuels, and environmental policies. This study is designed to serve as a balanced, fact-based, and analysis-driven guide for a diverse set of stakeholders in the transportation sector, including public and private entities. Our study applies a multi-disciplinary approach using economic modeling, data analytics, consumer research, agent-based simulation, technology and policy analytics, systems analysis, and more to identify the forces that are re-shaping the transportation sector and to gain a better understanding of potential futures of personal mobility.

The MIT Energy Initiative gratefully acknowledges the 10 consortium members whose generous sponsorship made this research possible: Alfa, Aramco, BP, Chevron, Equinor, ExxonMobil, Ferrovial, General Motors, Shell, and the Toyota Mobility Foundation. We also thank Bosch for its contribution to the project. Representatives from all of these companies engaged with the MITEI team in extensive discussions, providing valuable critique and perspective that helped us sharpen our analysis and improve this report. We also acknowledge Niklas Anzinger and Dalia Research, who provided participant recruitment and implementation of our international survey. Some of the analysis in this report uses historic data on consumption of refined oil for transportation in the U.S. and Europe from the Mobility Model database developed by the International Energy Agency © OECD/IEA 2017; the resulting analysis has been prepared by MIT and does not necessarily reflect the views of the International Energy Agency.

We also thank Professor Robert Armstrong, Director of MITEI, for supporting this study and for his active participation throughout the study and for his review of this report. We also appreciate Joanna Moody, Research Program Manager for the MITEI Mobility Systems Center, for providing exceptional contributions both as an author and in the integration and completion of this report. We thank Eytan Gross, Project Engineer for Mobility of the Future, for providing vital contributions in coordinating and developing this report. A special thanks to the MITEI events team, specifically to Carolyn Sinnes and Debi Kedian, for their patience, dedication, and organization. Thanks also to MITEI communications team members Jennifer Schlick, Digital Project Manager; Emily Dahl, Director of Communications; and Kathryn Luu, Communications Specialist. Additional thanks to Antje Danielson, MITEI Director of Education, and Charles Fine, Professor and Co-Director of the International Motor Vehicle Program at the MIT Sloan School of Management. Finally, we thank Marika Tatsutani for editing the report with great skill and dedication.

---

*This report represents the findings of the study researchers who are solely responsible for its content, including any errors. The consortium members are not responsible for the findings contained in the report, and their opinions and views may differ from those expressed herein.*

# Executive Summary

Personal mobility is a central and highly valued feature of human society—indeed, mobility is essential for the productive functioning of economies and the ability of individuals to access the opportunities they need to thrive. Therefore, the benefits of the technologies and systems that have evolved to enable personal mobility on a large scale are difficult to overstate. However, even as mobility options proliferate, expanding accessibility for many, there is growing concern regarding the long-term sustainability of our transportation systems, which have a substantial physical footprint, require enormous public and private investment, consume significant energy resources, are a major contributor of anthropogenic greenhouse gas emissions and local air pollutants, and impose many other negative externalities. While these issues apply to all modes, private vehicles are the most ripe for disruption.

A few simple statistics serve to underscore this point. In 2015, the number of passenger vehicles in use worldwide totaled roughly one billion (International Organization of Motor Vehicle Manufacturers [OICA] 2015). Collectively, these vehicles consumed roughly 400 billion gallons of fuel (U.S. Energy Information Administration [EIA] 2016). Global spending on the automotive industry is about $2 trillion per year (OICA 2019b), and this figure does not include the large public expenditures needed to support road networks and other vehicle-related infrastructure. Light-duty vehicle (LDV) travel generated more than 3 billion metric tons of carbon dioxide emissions per year, accounting for almost 40% of total transportation sector emissions (Sims, et al. 2014). Cars and other personal transport vehicles also remained a major source of airborne pollutant emissions that contribute to poor air quality and substantial public health damages, particularly in densely populated urban areas (Anenberg, et al. 2019). Travel time delays due to congestion on the world's roads impose massive economic and social costs (INRIX Research 2019). Road safety remains a critical global issue, with an estimated 1.35 million deaths as a result of auto-related crashes each year (World Health Organization [WHO] 2018).

As populations increase and incomes rise, global demand for personal mobility is expected to grow, adding an urgent dimension to the daunting policy challenges implicit in these figures. This is especially true in emerging economies that currently have relatively low levels of vehicle ownership. More than half a billion passenger vehicles could be added to the global fleet by mid-century. In the U.S. alone, LDV travel is expected to increase by roughly 50% in the same timeframe to reach nearly 5 trillion miles per year (National Petroleum Council [NPC] 2012). Projected increases in number of vehicles and vehicle miles traveled raise important questions about resource use, climate and pollution impacts, system capacity, and safety.

Concurrently, and partly in response to these pressures, personal mobility itself is changing. As mobility technologies and services, consumer preferences and behaviors, and transportation policies co-evolve over the coming decades, there is great uncertainty about both the pace of continued change and which mobility options will be adopted. A few things, however, are certain: as the world's population grows and becomes wealthier, the demand for personal mobility, convenience, and flexibility will increase. As the world urbanizes, mobility solutions will need to become more compatible with the density of activities concentrated in cities. As the world responds to environmental concerns, powertrains and fuels must evolve to become more sustainable. And as disruptive technologies and business models develop, some conventional lifestyles regarding car ownership, shopping, and commuting may yield to the shared economy, e-commerce, and telecommuting. The forces involved are complex and sometimes in conflict, but they have the potential to shape a mobility landscape that looks very different from today's.

We undertook this study to explore some of the major factors that will affect the evolution of personal mobility leading up to 2050 and beyond. Our aim was to provide information that will help stakeholders anticipate and navigate some of the disruptions and changes that lie ahead. We used a scenario-based approach to explore how different factors—from consumer preferences to powertrain technologies—will play a role in shaping the future of personal mobility. Our scenarios were designed to address questions at different levels of granularity, ranging from global and national markets down to individual mobility choices in different cities.

Two points are important to emphasize at the outset. First, we did not attempt to explore or consider all aspects of personal mobility; rather, we focused on personal motorized vehicles. Although we looked at interactions between vehicle use and other travel modes, we did not investigate how these other mobility options themselves might change. Second, this study does not attempt to predict the future, nor does it offer a normative vision of what the future of mobility should be. Instead, we used historical trends, data-driven models, and scenarios to explore the potential impacts of, and tradeoffs involved in, the near- and medium-term evolution of technology, behavior, and policy.

This report is organized into five main areas of inquiry, each of which focuses on a particular aspect or set of influences on the future landscape for personal mobility:

- The potential impact of climate change policies on global fleet composition, fuel consumption, fuel prices, and economic output (Chapter 2).
- The outlook for vehicle ownership and travel, with a focus on the world's two largest LDV markets—the U.S. and China (Chapter 3).
- Characteristics of alternative vehicle powertrains and fuels that could affect their future market share (Chapter 4).
- Infrastructure considerations for charging and fueling, particularly as they affect future demand for electric and hydrogen fuel cell vehicles (Chapter 5).
- The future of personal mobility in urban areas, with a focus on the potentially disruptive role of autonomous vehicles and ride-hailing services (Chapter 6).

The remainder of this summary highlights our main findings in each of these areas.

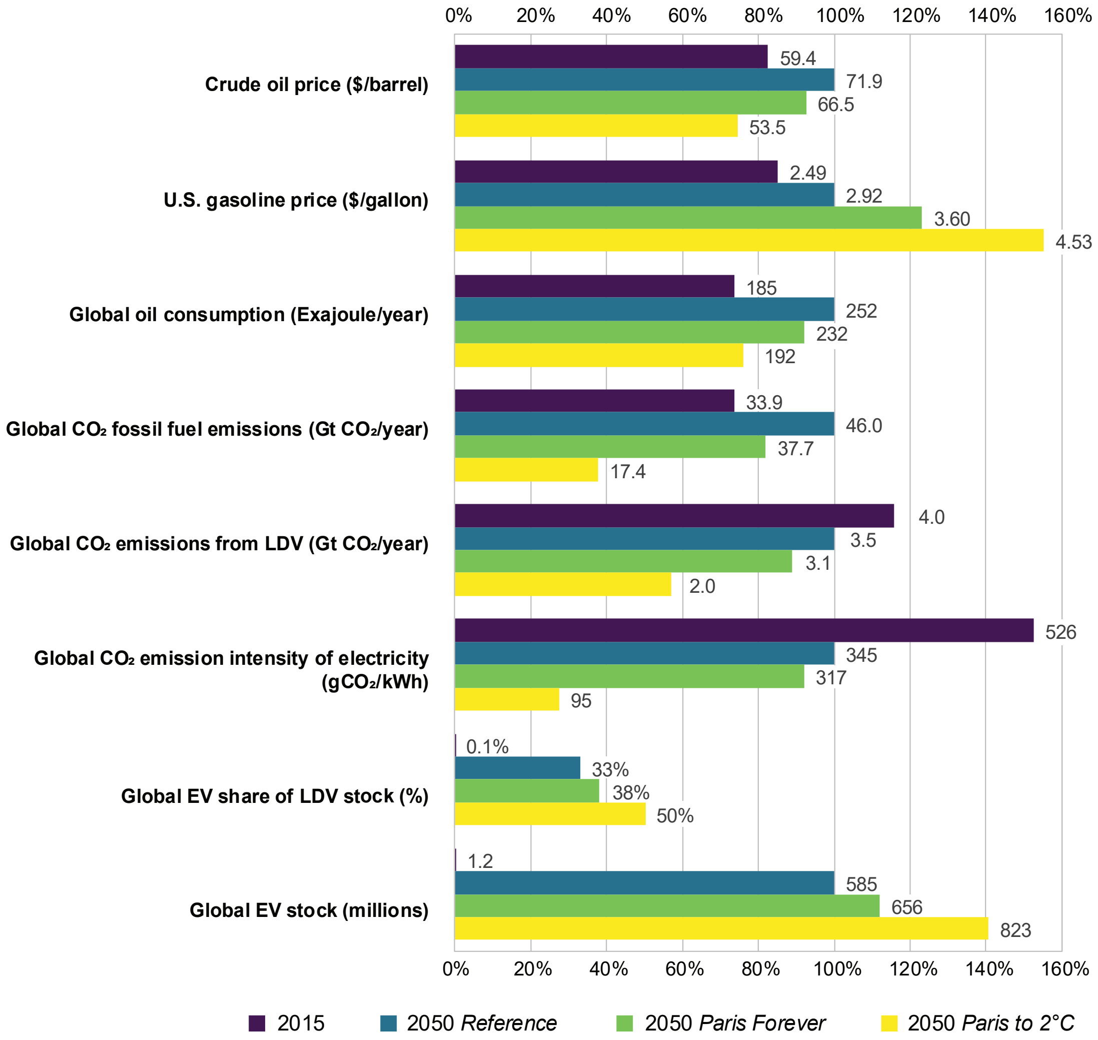
## THE IMPACT OF CLIMATE POLICIES

Using MIT's global Emissions Prediction and Policy Analysis (EPPA) Model,[1] we explore the impact of climate policies on the LDV market. We modeled three scenarios: (1) a *Reference* scenario that assumes no additional policies are enacted to mitigate greenhouse gas emissions and that excludes commitments associated with the Paris Agreement, (2) a *Paris Forever* scenario that assumes commitments made to date under the Paris Agreement on global climate change are fully implemented by 2030 and maintained thereafter with no further policy actions, and (3) a *Paris to 2°C* scenario that assumes all countries fulfill their Paris commitments to the year 2030 and thereafter greenhouse gas emissions are priced

---

[1] https://globalchange.mit.edu/research/research-tools/eppa

**Figure ES-1: Global policy impacts in 2050**



Note: Global oil consumption includes all sectors of the economy; global carbon dioxide ($CO_2$) fossil emissions includes $CO_2$ emissions from use of fossil fuels and from industrial processes; electric vehicles (EVs) includes both battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs).

worldwide at the level needed to limit global average warming to 2°C—a widely cited target for international climate policy.

Findings from the modeling analysis with respect to eight metrics of interest—including oil prices (to consumers and producers), carbon dioxide emissions, and fleet share of electric vehicles—are presented in Figure ES-1, alongside actual values for 2015. With the exception of the last item, all metrics are scaled relative to the 2050 *Reference* scenario.

Several points from the figure are worth highlighting:

- Absent further policy action, global carbon dioxide emissions in 2050 are expected to exceed 2015 emissions by more than 35%. Implementing the Paris commitments will limit this increase, but emissions in 2050 are 11% higher in absolute terms than in 2015. Achieving the 2°C target requires far more aggressive policy actions—sufficient to reduce global emissions by more than 60% relative to the 2050 *Reference* case.

- The electric vehicle share of the LDV fleet grows substantially by 2050 in all scenarios. But it is significantly larger in the most aggressive climate policy case (50% of the global vehicle fleet in the *Paris to 2°C* case compared to 33% in the *Reference* case).
- In the *Paris to 2°C* scenario, global emissions from LDVs in 2050 are cut by half compared to 2015 emissions and by more than 40% compared to the *Reference* case. In contrast, current Paris commitments, by themselves, produce only an 11% reduction in LDV emissions relative to the *Reference* case. Note that our model projects lower vehicle emissions in 2050 compared to 2015 even with no further policy action (i.e., in the *Reference* case), because gains in fuel economy and a growing market share of electric vehicles offset projected increases in fleet size and vehicle kilometers traveled.
- In the *Paris to 2°C* scenario, the global carbon intensity of electricity production is projected to decline more dramatically (more than 80%) by mid-century than carbon emissions from LDVs, reflecting the fact that mitigation options are more abundant and less expensive in the power sector compared to the transportation sector.
- Global oil consumption in 2050 is higher than it was in 2015 in all scenarios, but future oil consumption is reduced by approximately 25% (compared to the *Reference* projection for 2050) in the aggressive climate policy case. Only one fifth of this reduction is due to LDV electrification. The other contributors are improved fuel efficiency (for heavy- and light-duty vehicles), fewer vehicle miles traveled, and reduced industrial use of oil.

Overall, our scenarios suggest that, if coupled with decarbonization of the electricity supply, electrification of LDVs can be one important contributor to climate change mitigation. Although 2050 carbon dioxide emissions from LDVs are reduced by 43% in the *Paris to 2°C* scenario relative to the *Reference* scenario, that reduction represents only 5% of the total difference in global carbon dioxide emissions between the scenarios. This reflects the fact that LDVs currently comprise a smaller share of global total emissions than electricity production (12% versus 38% in 2015), as well as the previously noted fact that decarbonizing electricity production is generally less expensive than decarbonizing vehicle travel. Since the economics of decarbonization favor greater reductions in the electricity sector, the LDV share of total emissions in the *Paris to 2°C* scenario is actually higher than the share in the *Reference* scenario (in 2050).

Regardless of the penetration of electric vehicles in the LDV fleet, global decarbonization will come with significant macro-economic costs. Depending on the policy scenario, we estimate that the reduction in global economic output across all sectors in 2050 as a result of climate policies ranges from about 1.1% to 3.3% relative to the *Reference* scenario. This represents a substantial amount of money ($1–$3 trillion in 2050), an impact equal to the loss of one to two years of global economic growth. While this number may seem daunting to some, to others it may appear a small price to pay for the economic benefits of carbon mitigation efforts, which could include avoided damages from climate change-related temperature rise and natural disasters, avoided adaptation costs, and ancillary benefits, such as public health improvements from other pollutant reductions as a result of switching to less carbon-intensive energy sources. While growth of the global economy is slower in the climate scenarios than the *Reference* scenario due to impacts on overall economic activity, our projections show the global economy expanding from 2015 to 2050 by more than 140% in all scenarios.

## THE OUTLOOK FOR VEHICLE OWNERSHIP AND TRAVEL IN THE U.S. AND CHINA

The report focuses on the world's two largest auto markets, the U.S. and China, which together accounted for 27.3% of global passenger vehicles in use in 2015 and 43.8% of global passenger vehicle sales in 2017 (OICA 2019a). We explore various drivers of LDV ownership and use, including demographics, economics, policy, and consumer preferences.

For the U.S., we analyzed trends in population, household size, and socio-economic factors to estimate future demand for vehicles and vehicle travel. We also analyze whether there are generational differences in preferences toward car ownership and use. Additionally, we measured the value of the car as a symbol of social status and personal image—"car pride"—and its relation with car ownership in Houston and New York City.

- In the U.S., the LDV stock and the number of vehicle miles traveled are projected to increase by approximately 30% over the next three decades. These increases are mostly driven by population growth, as reflected in number of households, and—to a lesser extent—by income growth. However, we do not attempt to account for potentially disruptive developments, such as the wide-scale adoption of mobility services enabled by autonomous vehicles. Such services could put downward pressure on the size of the private vehicle fleet, but we do not expect that they will reduce growth in vehicle miles traveled.
- After controlling for socio-economic factors, we do not find a significant difference in preferences for vehicle ownership or travel between millennials and previous generations.
- Regarding car pride, or the attribution of social status and personal image to owning and using a car, we find that individuals who ascribe more symbolic value to their car have a much higher likelihood of car ownership, even after controlling for other socio-demographic characteristics. In fact, our analysis indicates that the effect of car pride on car ownership is as strong as the effect of income on car ownership.
- Together, these findings with respect to car pride and generational preferences suggest that consumer perceptions and behaviors are likely to reinforce the status quo for personal vehicle ownership and use unless they are changed by socio-economic circumstances or policies that proactively shape new social norms.

In the case of China, now the largest market for new vehicle sales, we looked at how cities form transportation policies and the potential impact some of these local-level policies might have on the future size of the country's vehicle stock.

- In contrast to the U.S., China is experiencing rapid growth in vehicle ownership, tied mostly to rising incomes. This growth is expected to persist for several decades and accounts for much of the projected increase in the size of the global LDV fleet by 2050. Furthermore, China is a world leader in the adoption of battery electric vehicles, with significant national-level policies promoting their manufacture and sale.
- China's cities are diverse in their urbanization and motorization patterns, leading to different local challenges and policy priorities. Primarily in response to crippling congestion and local air pollution, China's cities have adopted a variety of car ownership and usage restrictions.
- These city-level policies could have national-level impacts on the private vehicle fleet. Continuing the restrictions on car ownership that have already been adopted in six major Chinese cities could reduce the size of the country's overall fleet in 2030 by as much as 4% (or 12 million vehicles) relative to the no-restriction scenario. If a recent national ban on the proliferation of these policies is retracted and these policies are adopted in 64 of China's largest cities, the projected reduction in national fleet size is 10%, or roughly 32 million fewer vehicles by 2030 relative to the no-restriction scenario.
- Finally, in an examination of car pride across a variety of countries across the globe, we find that car pride is generally higher in developing countries (the U.S. is an exception among developed countries). Therefore, current projections may *understate* expected growth in car ownership in countries with rising incomes and a rapidly growing middle class.

## ALTERNATIVE VEHICLE POWERTRAINS AND FUELS

The report provides a detailed review of alternatives to internal combustion engine vehicles, including hybrid gasoline electric, plug-in hybrid electric, battery electric, and hydrogen fuel cell electric vehicles. For each type of powertrain and fuel, we examined costs relative to a comparably sized conventional vehicle; vehicle emissions characteristics and associated emissions control technology costs; and full lifecycle carbon dioxide emissions, taking into account emissions associated with vehicle manufacture and fuel production and distribution, as well as vehicle use.

- The current manufacturing cost gap between battery electric vehicles and internal combustion engine vehicles is on the order of $10,000 per vehicle for similarly sized models with ranges of more than 200 miles, presenting a major barrier to electric vehicle adoption. Though battery costs have declined substantially, predictions about future price declines must be approached with caution as they often fail to account for the cost of the raw materials used to make batteries. Based on a careful analysis of the cost structure of the battery supply chain—from materials extraction and synthesis to battery cell and pack production—we estimate that the price of lithium-ion battery packs is likely to drop by almost 50% between 2018 and 2030, reaching $124 per kilowatt-hour. Battery price projections beyond 2030 are highly uncertain and are likely to be disrupted by the development and commercialization of new battery chemistries.
- Our cost analysis indicates that a mid-sized battery electric vehicle with a range of 200-plus miles will likely remain upwards of $5,000 more expensive to manufacture than a similar internal combustion vehicle through 2030. This suggests that market forces alone will not support substantial uptake of electric vehicles through 2030 because cost differences with incumbent internal combustion engine vehicles will persist.
- Although the manufacturing cost differential between electric and conventional vehicles is expected to persist well beyond 2030, lower operating costs help to offset the higher purchase price of battery electric vehicles. In most markets, these vehicles have lower operating costs than a conventional gasoline vehicle. However, this operating cost advantage is highly dependent on the price of electricity (at home and at charging stations), local gasoline prices, vehicle maintenance costs, battery life, and ambient temperature, which can handicap electric-vehicle efficiency.

  In plausible scenarios without government subsidies, the total cost of ownership for battery electric and conventional vehicles is likely to reach parity in many countries with high gasoline taxes before the mid-2020s and in the U.S. around 2030 as battery prices decline. However, some consumers tend to value upfront costs much more than future savings; consequently, internal combustion engine vehicles may continue to be perceived as the more affordable powertrain well beyond these dates. Nevertheless, cost parity alone cannot be expected to drive widespread adoption of any new powertrain. Other factors besides total cost of ownership will likely shape the adoption of new vehicle technologies, including consumer familiarity and the availability and convenience of charging and fueling infrastructure.
- If electric vehicles are deployed on a large scale, there will be new business opportunities and needs for developing cost-effective methods for recycling batteries on an industrial scale.
- For similar-sized vehicles in the U.S. today, per-mile lifecycle (including vehicle and battery production) greenhouse gas emissions for battery electric vehicles run on the present U.S.-average grid electricity are approximately 55% of the emissions from conventional internal combustion engine vehicles. Per-mile greenhouse gas emissions for hybrid, plug-in hybrid, and fuel cell electric vehicles (run on hydrogen generated by steam methane reforming) are all approximately 72%–73% of emissions from conventional vehicles. These

lifecycle emissions are dependent on battery size and life, fuel cell life, fuel economy, and many other factors.

- Lifecycle emissions for all vehicles are highly sensitive to the methods used to produce and distribute the fuels (or electricity) on which they operate. This means that a battery electric vehicle operating on green electricity will have much lower greenhouse gas emissions than a gasoline-powered hybrid vehicle, whereas a battery electric vehicle operating on carbon-intensive electricity (as in most of China and in some parts of the U.S.) will have higher emissions than a gasoline-powered hybrid vehicle. Likewise, the method used to produce hydrogen—whether steam methane reforming, with or without carbon capture, or electrolysis using current average electricity versus a "greener" electricity mix—can have a substantial impact on the lifecycle emissions of fuel cell vehicles.
- Due mainly to projected reductions in U.S. grid carbon intensity and increases in fuel economy, lifecycle greenhouse gas emissions from all types of vehicles are projected to decline over the next three decades (to 2050): by 30%–47% for battery electric vehicles, by 20%–40% for internal combustion engine vehicles, and by 25%–40% for hybrid electric vehicles. But if the grid carbon intensity declines dramatically and/or low-carbon production methods for hydrogen are developed and deployed, the carbon intensity of battery electric and fuel cell electric vehicles could be further reduced.

## INFRASTRUCTURE FOR FUELING AND CHARGING

The buildout of infrastructure for fueling or charging will affect patterns and rates of adoption for alternative vehicle technologies. In the U.S. today, roughly 85% of plug-in electric vehicle charging is done at home. Increased availability of public charging stations could help expand the potential market for these vehicles to individuals who do not have the option to charge at home and to ameliorate concerns about vehicle driving range and charging convenience when away from home. We used a system dynamics model to explore the co-evolution of electric vehicle deployment and charging infrastructure. We also examined consumers' sensitivity to the availability of home charging and to charging rates at public stations.

- Charging speed and proximity of charging stations to other common destinations have more influence on electric vehicle adoption than the total number of public charging stations.
- Home charging, at low power, is the primary way owners of battery electric vehicles power their vehicles as of 2019. Long term, this could be a constraint on electric-vehicle penetration since many U.S. households do not have the space or power capacity needed for home charging. Where available, workplace charging can be a partial substitute for home charging, but this option is also limited by space, power capacity, and costs.
- The proliferation of public "fast" (Level 3) charging stations is important for wider adoption of electric vehicles. Our modeling suggests that modestly accelerating improvements in charging rates at public stations could increase the number of new battery electric vehicles sold in 2050 in the U.S., as faster charging speeds help alleviate car buyers' anxiety about vehicle range and charging convenience.
- For the electric vehicle market to mature, continuation of government-initiated policy incentives (for vehicles and for charging infrastructure) would be necessary.

While the existing electricity generation and transmission infrastructure can handle the charging needs of current and near-term numbers of plug-in electric vehicles, large-scale deployment of electric vehicles in the LDV fleet would require significant investments to upgrade and reinforce the power distribution system. Our analysis does not account for these costs nor does it tackle the question of who will pay for them.

Hydrogen is another important candidate for decarbonizing transportation. The potential use of hydrogen for LDVs is closely coupled with other sectors of the economy. Hydrogen can be a major contributor in overcoming many of the challenges of reaching net-zero emissions by providing (1) large-scale energy storage required to support electric power systems with high penetration of renewables, (2) low-carbon fuels for long-haul freight, (3) decarbonization of major industrial processes including steelmaking and fertilizer production, and (4) decarbonization of building heating systems. Given hydrogen's potential role in decarbonizing multiple economic sectors, there is an opportunity to develop a massive hydrogen production, storage, distribution, and utilization ecosystem. And this future ecosystem could benefit hydrogen fuel cell LDVs by lowering costs and increasing availability of hydrogen.

While hydrogen fuel cell LDVs are often the most discussed application for a nascent hydrogen ecosystem, passenger vehicle travel is also the application that requires the largest distribution network, and the vehicle market itself is more sensitive to capital costs than fuel costs. The more economic and pragmatic strategy for building out a hydrogen ecosystem might be to start with applications that have large fuel demands that could be met with a smaller number of fueling stations, e.g., vehicle fleets and heavy-duty trucking. However, the time for deploying alternative fuel vehicles is already upon us. In the world as it exists today, even in California with its strong pro-hydrogen policies, fuel cell LDVs are at a disadvantage relative to electric vehicles because public charging stations are more abundant than hydrogen fueling stations and early adopters of electric vehicles can charge at home while adopters of fuel cell vehicles cannot. In California there are currently more than 17 times as many public Level 3 charging stations as there are hydrogen fueling stations. Nevertheless, fuel cell electric vehicles have a clear advantage over battery electric vehicles in terms of fueling time and vehicle range for their owners.

Both battery electric and fuel cell electric vehicles have a potential role to play in large-scale transportation decarbonization and in efforts to reduce air pollution. Both need continuing support to overcome cost and convenience barriers, but of the two, battery electric vehicles face the path of lower resistance during the transition away from internal combustion engines within the LDV fleet. The evolution toward zero-carbon ground transportation solutions may well include hydrogen for long-haul and high-mileage applications (both heavy- and light-duty) that require fast fueling, while short-haul and low-mileage applications will more likely be captured by battery electric vehicles.

## VEHICLE AUTOMATION AND THE FUTURE OF PERSONAL MOBILITY IN URBAN AREAS

According to United Nations projections, as much as 68% of the world's population will live in urban areas by mid-century—up from 55% currently (2018). In absolute numbers this means that city populations will grow by tens of millions more people each year, with much of the increase concentrated in cities in the developing world. Mobility is just one of the many challenges that rapidly growing urban areas can expect to face, but it is a critical one—especially in light of the extreme levels of traffic congestion and growing concerns regarding air quality that already exist in many large cities around the world.

At the same time, new business models, including the proliferation of on-demand, for-hire vehicle services and new technologies such as autonomous vehicles (AVs), promise to change the landscape of urban mobility. However, there is significant uncertainty regarding how these new technologies and services will evolve and interact with incumbent mobility systems in different urban environments. In our analysis, we characterized different types of cities and then modeled transportation scenarios to explore the impacts of introducing autonomous mobility on-demand services in select city types. We also examined regulatory and technological challenges for the deployment of AVs and analyzed public perceptions of AV technology using results from a global survey of mobility.

- Autonomous vehicles are not nearly as close to widespread deployment as some companies and the media have claimed. Significant improvement is still needed before the technology reaches maturity, particularly with regard to correctly identifying objects, driving under difficult weather conditions, and negotiating complex mixed-use urban streets. While the frequency of AV disengagements—incidents when a human safety driver must take over for the autonomous driving system—has improved substantially in the past five years, recent data show roughly one disengagement for every thousand miles traveled.
- A remote intervention system is required when there is no "safety driver" in the car to address these disengagements. In other words, AVs are likely to need human assistance given the likelihood and severity of certain "edge cases" that are not well handled by automated systems. A control center to support a fleet of AVs has the potential to provide a backstop for the AV, but the economics of this approach are only viable if each operator is responsible for monitoring multiple vehicles at the same time. This suggests that the profitability of commercial business models adds further uncertainty to prospects for widespread autonomous mobility on-demand deployment, in addition to the technological barriers.
- Both the U.S. and Chinese governments have encouraged testing for AVs. But before these vehicles can become a mainstream transportation option, new regulations will be needed to address issues such as vehicle-to-operator ratios, sensor requirements (pertaining to both quantity and quality), communication network requirements for vehicle monitoring, liability, and sharing of data on autonomous vehicle disengagement and accidents.
- Public perceptions of AV technology and safety are likely to affect how, where, and when the technology is adopted. Our analysis of international survey data suggests that optimistic public perceptions and predictions of AV safety may create a market for early adoption among individuals who are young, male, highly educated, high-income, urban, and car consuming, and among residents of developing countries where road safety is a major issue. The rest of the population remains more skeptical of the potential for AVs to offer a safe, alternative mode of transportation.
- Once AV technology becomes mature, our analysis suggests that unregulated low-cost, door-to-door mobility services will likely compete with other modes of transportation, increasing energy consumption and vehicle travel. In the two city types we examined that are typical of auto-dependent cities in the U.S., a much larger fraction of mass transit trips switched to automated on-demand services relative to the fraction of car trips that made the switch to an automated service. These mode shifts were far smaller in our prototype city that is representative of extremely dense, wealthy, international hubs with extensive mass transit networks.
- Average travel time on the road network can be expected to increase due to congestion when a low-cost, on-demand mobility service is introduced. The magnitude of this increase depends on the type of city.
- Though some have argued that automated mobility on-demand services could replace mass transit altogether, in reality this would create a congestion disaster in large, dense cities. The physical constraints of road capacity simply do not enable autonomous, on-demand vehicles (even with high utilization) to offer a substantial improvement over the passenger capacity provided by well-developed urban mass transit networks.

- A more promising scenario might be one in which automated on-demand services, using vehicles in various sizes, complement mass transit, especially in providing service to and from stations and in areas that are under-served by mass transit. An integrated first/last-mile solution, in which AVs support the mass transit network, could reduce both congestion and emissions by providing a viable alternative to car trips.

## LOOKING FORWARD

Current trends in population and income, coupled with growing concern about the negative externalities of current mobility systems, point to a substantial and complicated set of technological and policy challenges in the decades ahead. Clearly, one of the central imperatives will be to develop and deploy more environmentally sustainable mobility options while also satisfying consumer requirements with respect to cost, convenience, flexibility, and preference.

The findings of this study indicate the potential to reduce carbon emissions through continued improvements in vehicle fuel economy coupled with large-scale deployment of electric vehicles and concerted efforts to decarbonize the electricity grid. In the longer term, the development of a hydrogen production and fueling system, perhaps initially for applications other than the LDV market, offers opportunities to expand the role of fuel cell electric vehicles. These findings are based on research conducted by transportation engineers, mechanical engineers, chemical engineers, economists, policy experts, planners, computer scientists, and others, working with several detailed models, survey data, interviews with government officials, and other data sources.

The outlook for autonomous vehicle technology and new on-demand mobility services is less clear. Autonomous vehicle technology is not as close to maturity as is sometimes portrayed, and significant regulatory issues must still be addressed. New mobility services, on the other hand, are already here but their impact on congestion and energy use seems more likely to be negative rather than positive. Integrating mass transit systems with on-demand mobility services using autonomous vehicles, especially if the autonomous vehicles are also low- or zero-emission, may hold promise for advancing multiple objectives, but significant technological and policy progress is needed to make this a reality.

Further research is needed to explore the role of other forms of personal mobility beyond light-duty vehicles, such as public and non-motorized transport, and to develop a fuller picture of options for responding to the complex mobility challenges that lie ahead. But through careful consideration of the multifaceted impacts of new technologies, policies, and markets, such as those undertaken in this study, we can anticipate and shape a future of mobility that works better for people and for our planet.

## REFERENCES

Anenberg, Susan, Joshua Miller, Daven Henze, and Ray Minjares. 2019. *A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015*. Washington, D.C.: The International Council on Clean Transportation. https://theicct.org/publications/health-impacts-transport-emissions-2010-2015

INRIX Research. 2019. "Global Traffic Scorecard." http://inrix.com/scorecard/

International Organization of Motor Vehicle Manufacturers (OICA). 2019a. "World Motor Vehicle Sales: By Country and Type 2005–2018." http://www.oica.net/category/sales-statistics/

———. 2019b. "Economic Contributions." Accessed August 9, 2019. http://www.oica.net/category/economic-contributions/facts-and-figures/

———. 2015. "World Vehicles in Use: By Country and Type 2005–2015." http://www.oica.net/category/vehicles-in-use/

National Petroleum Council (NPC). 2012. *Advancing Technology for America's Transportation Future*. Washington, D.C.: NPC. https://www.npc.org/reports/trans.html

Sims, Ralph, Roberto Schaeffer, Felix Creutzig, Xochitl Cruz-Nuñez, Marcio D'Agosto, Delia Dimitriu, Maria Josefina Figueroa Meza, Lew Fulton, Shigeki Kobayashi, Oliver Lah, Alan McKinnon, Peter Newman, Minggao Ouyang, James Jay Schauer, Daniel Sperling, and Geetam Tiwari. 2014. "Transport." In *Climate Change 2014: Mitigation of Climate Change. Contributions of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Ottomar Edenhofer, et al., 599–670. Cambridge, United Kingdom: Cambridge University Press.

U.S. Energy Information Administration (EIA). 2016. "Chapter 8: Transportation Sector Energy Consumption." In *International Energy Outlook 2016*, 127–137. Washington, D.C.: EIA. https://www.eia.gov/outlooks/archive/ieo16/transportation.php

United Nations, Department of Economic and Social Affairs, Population Division. 2018. *World Urbanization Prospects: The 2018 Revision*. https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

World Health Organization (WHO). 2018. *Global Status Report on Road Safety 2018*. Geneva, Switzerland: WHO. https://www.who.int/violence_injury_prevention/road_safety_status/2018/en/

## Chapter 1

# Introduction

Personal mobility is a highly valued good. In many places around the globe, individuals already rely on light-duty vehicle (LDV) ownership to increase their mobility, and use LDVs to travel thousands of kilometers per year. As incomes rise and vehicles become more affordable throughout the world, LDV ownership and use is projected to grow significantly, expanding mobility and access to opportunities for hundreds of millions of people.

Along with its benefits, personal mobility has significant costs. Around the world, transportation is a significant share of household consumption—a share that increases as households become wealthier (World Bank 2019). In the U.S., households spent an average of around $9,700 on transportation in 2017, making it the second largest household expenditure category after housing (U.S. Bureau of Transportation Statistics 2018). These costs are currently dominated by personal vehicles, with U.S. consumers collectively spending almost $1.1 trillion on personal vehicles in 2017 (U.S. Bureau of Transportation Statistics 2018). Because LDVs are such a big segment of the economy, automotive imports and exports are treated in a special way in trade negotiations (Canis, Villarreal, and Jones 2017). Most LDVs are powered by fuels made from petroleum, and much of the petroleum is imported from distant lands, raising additional "balance of trade" concerns. Therefore, the future of the LDV market is not just about mobility; it is also about economic growth, trade policy, and national security.

In addition to their monetary costs, LDVs powered by petroleum-based fuels also come with many societal burdens. Increased motorization has led to significant congestion in urban areas and a global epidemic of road traffic injuries and deaths. Pollutant emissions from automobiles have been implicated as major causes of urban air pollution and related health problems in cities as diverse as Los Angeles, Paris, Mexico City, New Delhi, and Beijing. LDVs also account for about 12% of global greenhouse gas emissions (Partnership on Sustainable Low Carbon Transport 2018). Decarbonizing this sector to meet the Paris Climate Agreement target of limiting the average increase in the world's temperature to no more than 2°C will be both technologically and economically challenging. Emissions and fuel economy regulations have led to the introduction of much less polluting and more fuel-efficient vehicles, but these gains are partially offset by increased numbers of vehicles and resulting congestion in urban centers. Achieving efficient personal mobility also requires significant public investment in infrastructure and involves multiple related land-use decisions.

Because of the great importance of personal mobility to the wellbeing of individual citizens and to the economy as a whole, and given its large societal costs, governments at every level (national, regional, and local) regulate, tax, subsidize, mandate, and/or operate various aspects of the transportation system. Although personal mobility is largely controlled by individual decisions and economic factors, government actions—now and in the future—can significantly favor or disfavor certain mobility options. The current regulatory and policy situation is very complicated, and it is hard to know how policies will change in coming years.

The future of personal mobility will be shaped by technologies, markets, business models, consumer preferences, and policies. It will have wide-ranging consequences—not only in terms of mobility and accessibility, but also in terms of congestion, road safety, air pollution, and greenhouse gas emissions. Only through careful consideration of the interplay among these factors—together with rigorous analysis of the costs, benefits, and impacts of different futures—can we begin to understand where we are headed and how we might shape a future of mobility that is better for people and for our planet.

There are a variety of ways to provide personal mobility while reducing societal costs. Some of these would involve substantial changes in vehicle powertrains and fueling and charging infrastructure; indeed, it appears a large change in the transportation system will ultimately be needed to slow climate change and meet the goals of the Paris Agreement. Because the current transportation system, which relies on internal combustion engine vehicles, is so highly developed and relatively inexpensive, with large capital assets already in place, there are substantial obstacles to any major change. For this study, we assessed several proposed changes in LDV technology, to try to quantify the potential long-term benefits and costs of each change, while also analyzing short-term barriers to making the change.

In the short term, an effective way to provide the benefits of affordable personal mobility while reducing associated societal harms is for governments to force continual improvements in LDV fuel economy (by some combination of taxes, subsidies, and mandates such as fuel economy standards), while also strictly enforcing pollutant and fuel quality standards. Automobile manufacturers have demonstrated they can achieve significant progress in emissions control and energy efficiency at modest cost, first by downsizing engines and then by pursuing hybridization and electrification. These energy efficiency improvements can help moderate the impact of increased demand for mobility.

However, to significantly cut global emissions from the LDV sector to meet climate goals, additional technology changes will be required in the medium term (i.e., before 2050). At present, the two most plausible technology options for drastically cutting greenhouse gas emissions of LDVs involve converting much of the fleet to either (1) battery electric vehicles or (2) hydrogen fuel cell electric vehicles. Both options appear capable of providing an acceptable solution for most consumers in the long term, when they will be perhaps only slightly more expensive and slightly less convenient than petroleum-based vehicles. Currently, however, both technologies are much more expensive than existing LDVs, and both face several substantial challenges in terms of consumer acceptance, for reasons that include limited driving range, limited availability of fueling and charging infrastructure, and lack of familiarity. These challenges constrain each technology's potential to supplant LDVs powered by petroleum-based fuels in the near term. Technology advances, including manufacturing-cost reductions, are needed to make battery electric and hydrogen fuel cell vehicles economically viable. It seems plausible that these technological improvements will occur over the next 10 to 30 years. However, it also seems unlikely that technological advances alone will overcome all the barriers these alternatives face on a timescale consistent with achieving the Paris Agreement targets. Therefore, some government action is likely to be required to induce large-scale change, perhaps through mandates, carbon taxes, and increased support for research and development. This report considers a range of scenarios to try to assess the timescales, challenges, and costs associated with these plausible future transitions.

In addition to developing new powertrains, significant efforts are underway to make vehicles drive autonomously and to shift the business model for mobility away from the current dominant paradigm of private car ownership by providing shared mobility services. If developed together, autonomous vehicle technology and new business models have the potential to provide motorized mobility to many people who cannot currently access it, either because they cannot drive or because they cannot afford a car. This would have large societal benefits. Autonomous vehicles may also liberate a large amount of time now spent driving, improve road safety, and reduce the need for parking, thereby freeing up valuable real estate in urban areas, with potentially huge economic value.

However, new approaches to providing mobility also have their own challenges; for example, they might exacerbate congestion problems in some urban areas, particularly if they attract riders away from mass transit. On-demand mobility services such as taxis, Uber, and Didi provide a valuable service, but the cost per mile is often much higher than private car ownership, primarily because of labor costs. This calls into question the longevity of on-demand business models without significant subsidies. In the future, autonomous vehicles may be able to reduce costs per mile, perhaps substantially, but they currently require significant human oversight, which makes the economics less attractive. This report highlights some of the key issues that need to be overcome before these new mobility modalities can have a larger positive impact.

Vehicle technologies and business models provide options, but humans will ultimately decide which options will be allowed (by government policies) and which options will be widely adopted (by consumer choices). It is unlikely that any mobility option would be widely deployed in a given locale if it were considered to be unacceptable by a large portion of the population for any reason, whether prompted by economic, environmental, national security, land use, or safety considerations. But people will differ in what they consider unacceptable. Because mobility has such broad implications in such a variety of places, and because mobility affects everyone, it is impossible to comprehensively cover all the issues involved. For this study, we had to be selective in our focus. As part of our consideration of how different policy and technology scenarios are likely to affect the future of personal mobility, we report on current measurements of human transportation behavior, on current policies, on current technology options, and on how people currently value different transportation options.

## REPORT OUTLINE

This report includes five main chapters: Global Economic and Policy Modeling, Vehicle Demand, Powertrains and Fuels, Fueling and Charging Infrastructure, and Urban Mobility and Autonomous Vehicles. In each of these chapters, we provide a general description of the methodologies used as well as a discussion of important results. The Conclusion chapter summarizes key findings from the study, limitations of our approach, and opportunities for future research. The Afterword complements the data-driven analyses in this report with a series of thought pieces that provide a diverse set of perspectives on the future of mobility.

### Global Economic and Policy Modeling (Chapter 2)

In this chapter, we examine how various climate policies could impact the size and powertrain composition of the global LDV fleet, as well as the quantity of vehicle fuels consumed. Our climate policy scenarios range from a scenario where no Paris Agreement pledges are implemented, to a scenario that limits global average temperature rise to 2°C above pre-industrial levels. This chapter also examines potential outcomes from accelerated government support for electric and hydrogen fuel cell vehicles within the transportation sector and for renewable energy within the electricity sector. Results include projections regarding LDV fleet composition, fuel prices, electricity production, oil consumption, and $CO_2$ emissions to 2050 across scenarios. We also discuss implications for macroeconomic indicators and government revenues.

### Vehicle Demand (Chapter 3)

The Vehicle Demand chapter takes a closer look at vehicle markets in the U.S. and China. For the U.S., we analyze how growth in population and number of households together with socio-economic factors could increase future demand for vehicle ownership and vehicle miles traveled. We also explore whether the millennial generation might differ from previous generations in terms of consumer demand for LDVs.

For China, we start by analyzing the policy decision-making process at the local level: who the key players are, what motivates decisions, and how decisions are made. In addition, we cluster 287 of China's largest cities into four distinct clusters based on various attributes. We then construct a vehicle ownership model for these Chinese city clusters, applying different potential policy measures and observing their effects on the size of China's LDV fleet.

In the last part of this chapter, we present selected results from our survey of individuals in two large U.S. cities, New York City and Houston, and our global survey of close to 42,000 individuals across 51 countries. In particular, we look at "car pride," a measure of the value—in terms of social status and personal image—that people derive from owning and using their cars. At the individual level, we explore how car pride drives greater car ownership. We also show how car pride can help explain why demand for vehicles varies between countries, especially when comparing countries whose residents have similar purchasing power.

### Powertrains and Fuels (Chapter 4)

This chapter takes a comprehensive look at vehicle powertrains and fuels, including their state of technological development and relative emissions and costs.

This chapter starts with an overview of the current status of various powertrains, including internal combustion engine vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles. We then discuss recent developments and new challenges for these technologies.

We also present a lifecycle analysis of the above powertrains and fuels, comparing the emissions created by similar-sized sedans and examining sensitivity to key factors. We consider how the efficiency of various powertrains might continue to improve and how their energy sources may decarbonize, which together will reduce lifecycle emissions for the various powertrain options.

We also present an analysis of future battery prices, based on technological improvements and productivity enhancements. These battery cost projections, plus the other costs associated with buying and operating a vehicle, are examined to enable cross comparisons and sensitivity analyses of the total cost of ownership for battery electric vehicles relative to internal combustion engine vehicles.

### Fueling and Charging Infrastructure (Chapter 5)

This chapter examines the important relationship between the adoption of alternative fuel vehicles and the development of the infrastructure required to fuel and charge those vehicles. It begins with an overview of the infrastructure used for fueling and charging, including current availability and characteristics. We then present results of our analysis of the co-evolution of the vehicle fleet and fueling and charging infrastructure. Finally, we analyze the outlook for a battery swapping business model by comparing it to other strategies for battery electric vehicle charging in the specific case of a taxi fleet operation.

### Urban Mobility and Autonomous Vehicles (Chapter 6)

This chapter looks at transportation behavior in the urban environment, with an emphasis on how vehicle automation may impact existing systems.

We begin by characterizing different types of cities around the world and then examine how different transportation scenarios would play out within three of these city types. Using detailed simulations, we explore the impacts of introducing a low-cost, autonomous, door-to-door mobility service on congestion, demand for other travel modes, vehicle miles traveled, energy consumption, and other metrics. Evaluating the performance of different transportation policies in various cities provides insights about how the negative impacts of introducing new on-demand services can be mitigated by adopting complementary policies in different types of cities.

Finally, we assess current regulatory and technological challenges to the deployment of autonomous vehicles. We also identify various factors hindering widespread autonomous vehicle deployment. Using results from our global mobility survey, we analyze public perceptions of autonomous vehicle safety and identify the segments of the population that are likely to be more willing to adopt this technology.

## REFERENCES

Canis, Bill, M. Angeles Villarreal, and Vivian C. Jones. 2017. *NAFTA and Motor Vehicle Trade*. Washington, D.C.: Congressional Research Service. https://fas.org/sgp/crs/row/R44907.pdf

Partnership on Sustainable Low Carbon Transport (SLoCaT). 2018. *Transport and Climate Change Global Status Report 2018*. http://slocat.net/tcc-gsr

U.S. Bureau of Transportation Statistics. 2018. "Chapter 6 – Household Spending on Transportation." In *Transportation Economic Trends 2018*. Washington, D.C.: Department of Transportation. https://www.bts.gov/browse-statistical-products-and-data/transportation-economic-trends/tet-2018-chapter-6-household. Last updated December 28, 2018.

World Bank. 2019. "Global Consumption Database: Transport." http://datatopics.worldbank.org/consumption/sector/Transport

## Chapter 2

# Global Economic and Policy Modeling

To consider the potential impacts of global decarbonization on trends in the light-duty vehicle (LDV) fleet from 2020 to 2050, we model three policy scenarios: a reference scenario that assumes no additional policy action to mitigate climate change, and two scenarios that assume different levels of international effort to reduce global greenhouse gas emissions. In all scenarios, we used an enhanced version of the MIT Economic Projection and Policy Analysis (EPPA) model (Chen, et al. 2016; Ghandi and Paltsev 2019) to explore changes in LDV fleet composition, fuel consumption, electricity production, carbon dioxide ($CO_2$) emissions, and macroeconomic impacts (including the cost of avoided $CO_2$ emissions). EPPA is a multi-sector multi-region computable general equilibrium (CGE) model that is used for projecting the macroeconomic, energy, and emission implications of different climate policy scenarios. The EPPA model provides economy-wide coverage of the world, disaggregated into 18 regions, and solves at five-year increments. The model represents households at an aggregate level and generates estimates of LDV fleet composition—that is, relative stocks of internal combustion engine vehicles (ICEVs) versus electric vehicles (EVs)[1]—based on empirical relationships between income growth and demand for mobility (see Appendix A.1 for more details).

We begin this chapter with a brief description of each scenario. Section 2.2 presents results for the global and regional impacts of global climate change mitigation on ICEV and EV stocks, $CO_2$ emissions, and fuel consumption and prices. We also discuss macroeconomic impacts and implications for government revenues. Section 2.3 considers key sensitivities surrounding the penetration of EVs in the LDV fleet. We then summarize our findings in Section 2.4.

## 2.1 SCENARIOS OF ECONOMIC AND POLICY DEVELOPMENT

This section begins by summarizing key assumptions for the three policy scenarios modeled: (1) the *Reference* scenario; (2) a *Paris Forever* scenario, which assumes implementation of commitments under the Paris Agreement by 2030 and continuation of those policies thereafter, but no additional policy action; and (3) a *Paris to 2°C* scenario, which assumes policy action beyond current Paris commitments to ensure that the increase in Earth's average surface temperature (relative to pre-industrial levels) does not exceed 2°C. Later sections describe key results of the modeling analysis for each scenario.

### 2.1.1 *Reference* Scenario Assumptions

Our *Reference* scenario assumes continued strengthening of fuel efficiency standards for LDVs, as well as expanded use of renewables for power generation.[2] It does not include mitigation pledges made by countries in their submissions for the Paris Agreement (United Nations 2015). The key drivers of change in future demand for mobility are population growth and growth in economic activity, as measured by gross domestic product (GDP). For population growth, we adopt a central estimate from the United Nations (2017), which projects that the world population will

---

[1] Note that the EV category in our analysis includes plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

[2] We include in the model regional mandates for renewables based on International Energy Agency projections up to 2040 and keep them at that level thereafter (2017, appendix tables).

increase from 7.8 billion in 2020 to 9.8 billion in 2050. The fastest growth is expected to occur in Africa, the Middle East, and Australia and New Zealand, where the model assumes average annual population growth rates of 2.1%, 1.2%, and 1%, respectively, over the 2020–2050 timeframe. Some countries, such as Japan, Russia, China, and South Korea, are projected to experience negative population growth over this period.

For near-term GDP growth, we rely on forecasts from the International Monetary Fund (2018), and then follow assumptions about long-term productivity growth from Reilly, et al. (2018). This results in an assumed world GDP average annual growth rate of about 2.6% for the 2020–2050 study period. We assume slower growth in developed countries than in developing countries. For example, average annual GDP growth between 2020 and 2050 is modeled at 1.7% in Europe and Japan and about 2% in the U.S., while GDP for China, India, Africa, and East Asia is assumed to grow at an average annual rate of about 4%–4.5% during that period. Global economic growth slows from about 2.9% in 2020 to about 2.35% in 2050.

The average fuel efficiency of the LDV fleet varies by region, with Europe, Japan, and the U.S. having the most fuel-efficient ICEV fleets—averaging 24–26 miles per gallon—in 2015. To model future gains in LDV fuel efficiency, we assume that fuel efficiency standards increase in all regions by 1%–2% per year. In the U.S. and Europe, standards are assumed to increase by 1.4% per year, in China by 1.3% per year, and in India by 1.1% per year. In most developing countries, the assumed increase is faster (close to 2% per year), bringing fleet efficiency in these countries closer to that of developed countries. For the U.S., our assumptions are driven by the assessments of the U.S. Energy Information Administration (2018). For other regions, we rely on a study by Karplus, et al. (2015).

### 2.1.2 *Paris Forever* Scenario Assumptions

Our *Paris Forever* scenario assumes that the country-level commitments pledged under the Paris Agreement are met by 2030 and retained thereafter. Appendix A.2 describes how we modeled the implementation of nationally determined contributions under the Paris Agreement. While we assume the same population growth in all scenarios, GDP growth is affected by economic and climate policies and is different across policy scenarios. For the *Paris Forever* scenario we explore additional cases that assume lower global costs for EV technology and higher demand for private transportation in China.

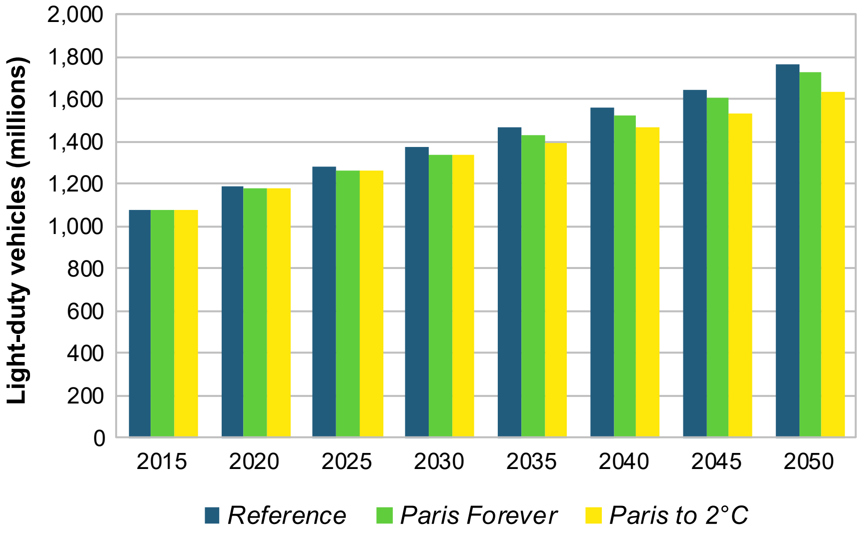
### 2.1.3 *Paris to 2°C* Scenario Assumptions

Our *Paris to 2°C* scenario assumes the same mitigation efforts as the *Paris Forever* scenario up to 2030, with implementation of more aggressive policy action thereafter to reach the global emissions trajectory needed to limit global average surface temperature warming to 2°C. We assume mitigation is achieved through global economy-wide carbon pricing after 2030, with emission profiles from Sokolov, et al. (2017). For this scenario, we consider additional cases that assume lower EV costs and higher levels of support for the deployment of renewable energy. We also test a case in which fuel cell electric vehicles running on hydrogen comprise 5% of the LDV fleet in the U.S.

## 2.2 GLOBAL AND REGIONAL IMPLICATIONS

This section summarizes key findings from the EPPA modeling analysis. Results for LDV fleet size, powertrain mix, $CO_2$ emissions, fuel use and prices, carbon intensity of electricity generation, and macroeconomic impacts are compared across our three scenarios for the 2020–2050 period.

**Figure 2.1: Global LDV stock**



### 2.2.1 LDV Stock

In all scenarios, growth in economic activity and population drive a substantial increase in the global stock of LDVs[3]—from approximately 1.1 billion vehicles in 2015[4] to an estimated 1.65–1.75 billion vehicles in 2050 (Figure 2.1). In the *Reference* scenario, the global stock of LDVs is close to 1.4 billion vehicles in 2030 and about 1.75 billion vehicles in 2050. The implementation of climate change mitigation policies in the *Paris Forever* and *Paris to 2°C* scenarios affects fuel prices, vehicle efficiency, income levels of consumers, and consumers' demand for transportation. As a result, the global stock of LDVs in 2030 is about 30 million vehicles fewer in both the *Paris* scenarios compared to the *Reference* scenario. After 2030, the more aggressive carbon constraints in the *Paris to 2°C* scenario have a further dampening impact on LDV fleet growth worldwide. Our modeling results for 2050 show 40 million fewer vehicles globally in the *Paris Forever* scenario compared to the *Reference* scenario. The corresponding reduction in the *Paris to 2°C* scenario is about 125 million vehicles.

In all scenarios, the LDV stock grows in all regions. Figure 2.2 shows results for regional LDV stocks in the *Paris Forever* scenario (Appendix A.1 provides more detail about which countries are included in different EPPA regions). Europe (EUR), the U.S. (USA), and China (CHN) are the regions with the largest LDV fleets in 2015.[5] These regions continue to have the largest fleets over the study period; in 2050, their combined share of the global LDV fleet is more than 50%. However, there are differences in the rate of fleet growth between regions. For Europe and the U.S., the model predicts a 22% increase in number of LDVs between 2015 and 2050; in China, by contrast, projected fleet growth over this period is approximately 100%. As a result, the model projects about 320 million vehicles in Europe, about 300 million vehicles in the U.S., and approximately 275 million vehicles in China in 2050 under the *Paris Forever* scenario.

Some regions experience even faster fleet growth than China, but they start from a smaller base. In India (IND), the LDV fleet is projected to grow 230% by mid-century, from about 30 million vehicles in 2015 to close to 100 million vehicles in 2050. Projected fleet growth in the rest of

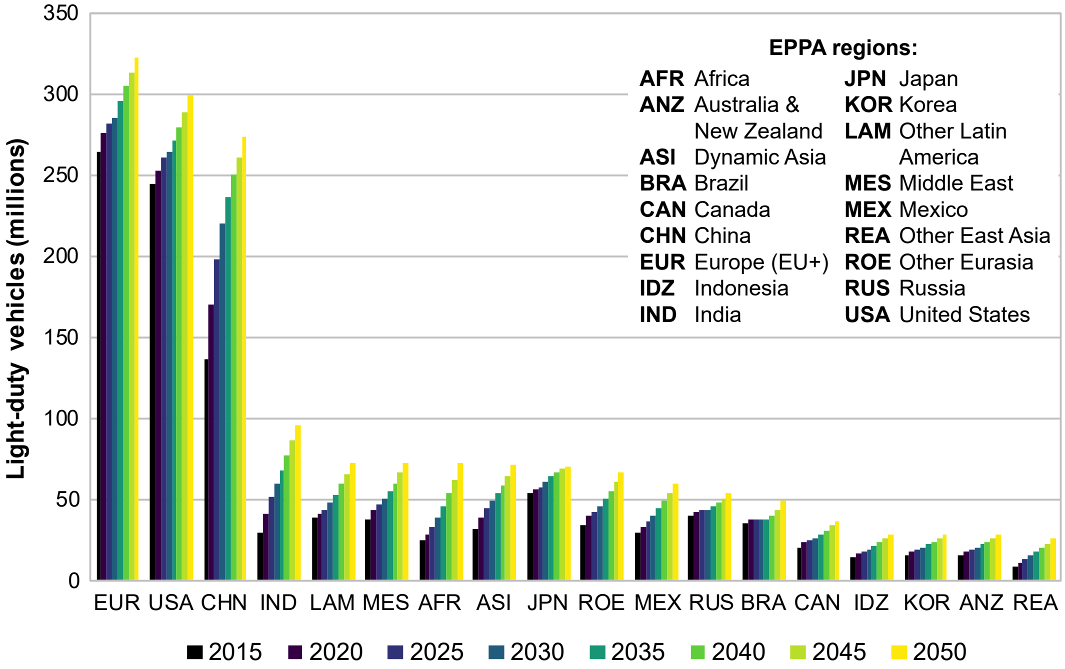
---

[3] We use the terms "vehicle fleet" and "vehicle stock" interchangeably.

[4] Different sources report different historic data for number of vehicles. For a discussion about how our modeled results compare to historic LDV data from different sources, see Ghandi and Paltsev (2019).

[5] See Ghandi and Paltsev (2019) for a discussion of historic data.

**Figure 2.2: Regional LDV stock in the *Paris Forever* scenario**



East Asia (REA) is 210%, from about 8.5 million vehicles to 26 million vehicles; in Africa (AFR), the fleet grows 190%, from 25 million to 72 million LDVs.

### 2.2.2 EV Stock

The global stock of EVs is likewise projected to grow significantly and at a much faster rate than the global LDV stock: from about 1 million EVs in 2015 to 585–825 million EVs in 2050 depending on the scenario modeled (Figure 2.3). The EV total includes plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs). Under our base cost assumptions, fuel cell electric vehicles (FCEVs) are too expensive to enter the market without explicit support (we test a sensitivity case, discussed in Section 2.3.4 of this chapter, which includes hydrogen cars). In the *Reference* scenario, the EV share of the global LDV fleet is projected to grow to 33% by 2050; in the *Paris Forever* and *Paris to 2°C* scenarios, with more aggressive climate policies, the EV share grows to 38% and 50%, respectively.

We project that, over time, battery cost improvements[6] and rising gasoline prices will shift the composition of the global EV fleet toward BEVs and away from PHEVs. The ratio of BEVs to PHEVs in the global EV fleet changed from 1.4–to–1 in 2015 to 1.6–to–1 in 2017. This change was influenced by China, which is pushing BEV technology development for numerous reasons. Conversely, in the U.S. and Europe, the ratio of BEVs to PHEVs has stayed roughly the same. Figure 2.4 shows our projections for the global composition of EVs in the *Paris Forever* scenario. While the model captures the 1.4–to–1 ratio of BEVs to PHEVs in 2015, it projects that the stock of PHEVs in the early years of the study period (i.e., from 2020 to 2050) grows at roughly the same rate as the stock of BEVs. Thereafter, BEV deployment accelerates and the ratio of BEVs to PHEVs increases over time. In 2050, the ratio is about 20–to–1 and BEVs comprise about 95% of the global EV market. At that point, our modeling analysis projects a global stock of approximately 625 million BEVs and 30 million PHEVs.

---

[6] Assumed battery pack cost drops from about $200/kWh in 2020 to about $130/kWh in 2030 (see Figure 7 in Ghandi and Paltsev 2019), which is consistent with the projections shown in Section 4.3.

**Figure 2.3: Global EV stock**

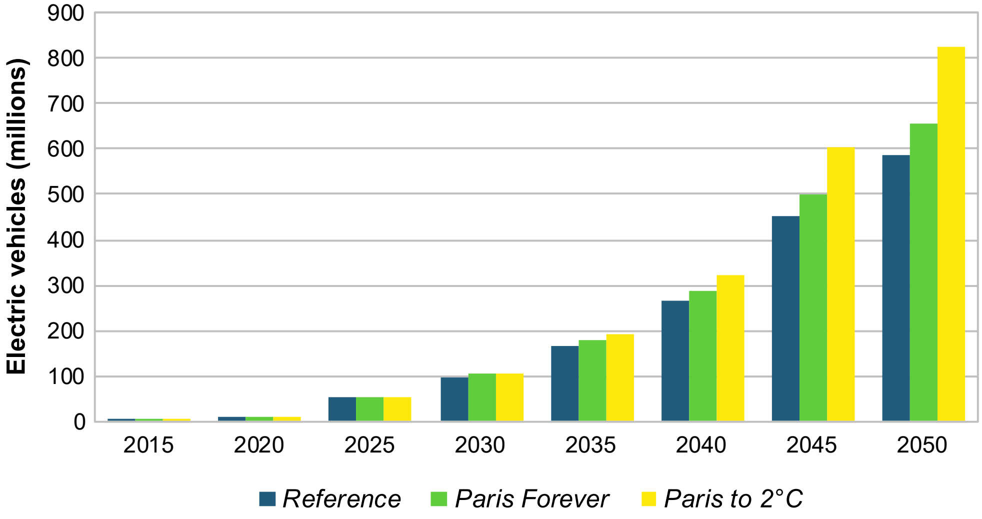


**Figure 2.4: Composition of the global EV stock (numbers of BEVs vs. PHEVs) in the *Paris Forever* scenario**

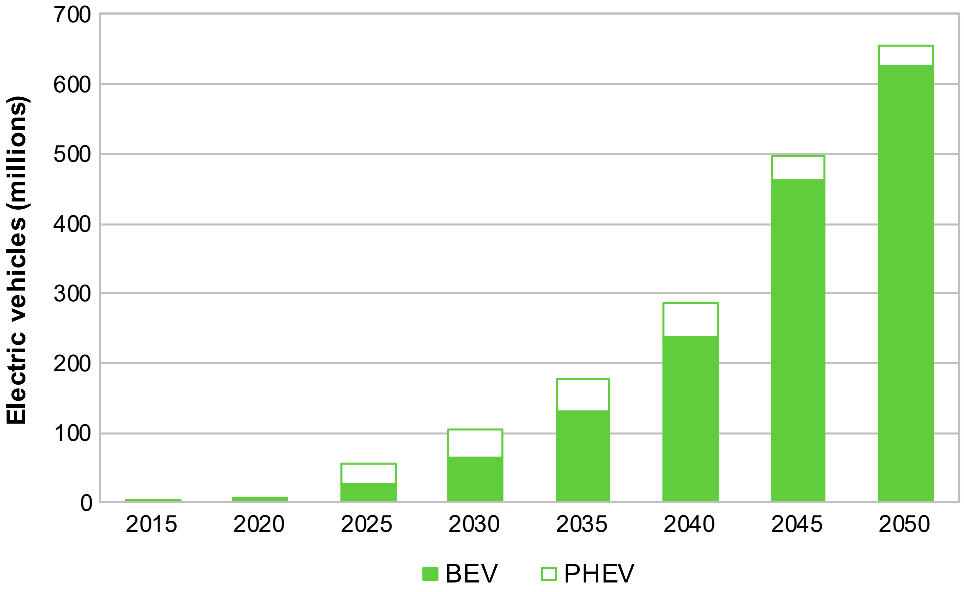


Figure 2.5 shows our projections for the total EV stock by region in the *Paris Forever* scenario. While the U.S., Europe, and China keep their leadership positions in terms of the size of their EV fleets (with more than 100 million EVs by 2050 in each of these regions), the number of EVs grows in all world regions. By 2050, India (IND), Brazil (BRA), Rest of Eurasia (ROE), Dynamic Asia (ASI), and Japan (JPN) have substantial EV fleets. However, the U.S., Europe, and China together still account for more than half of the global EV stock in 2050.

### 2.2.3 $CO_2$ Emissions

Projected global $CO_2$ emissions[7] from use of fossil fuels and from industrial processes are presented in Figure 2.6 in gigatonnes of carbon dioxide (Gt $CO_2$). In the *Reference* scenario, global emissions grow

---

[7] The EPPA model tracks emissions of all greenhouse gases since they all affect the Earth's climate. In this report we focus on $CO_2$ trajectories.

**Figure 2.5: EV stock by region in the *Paris Forever* scenario**

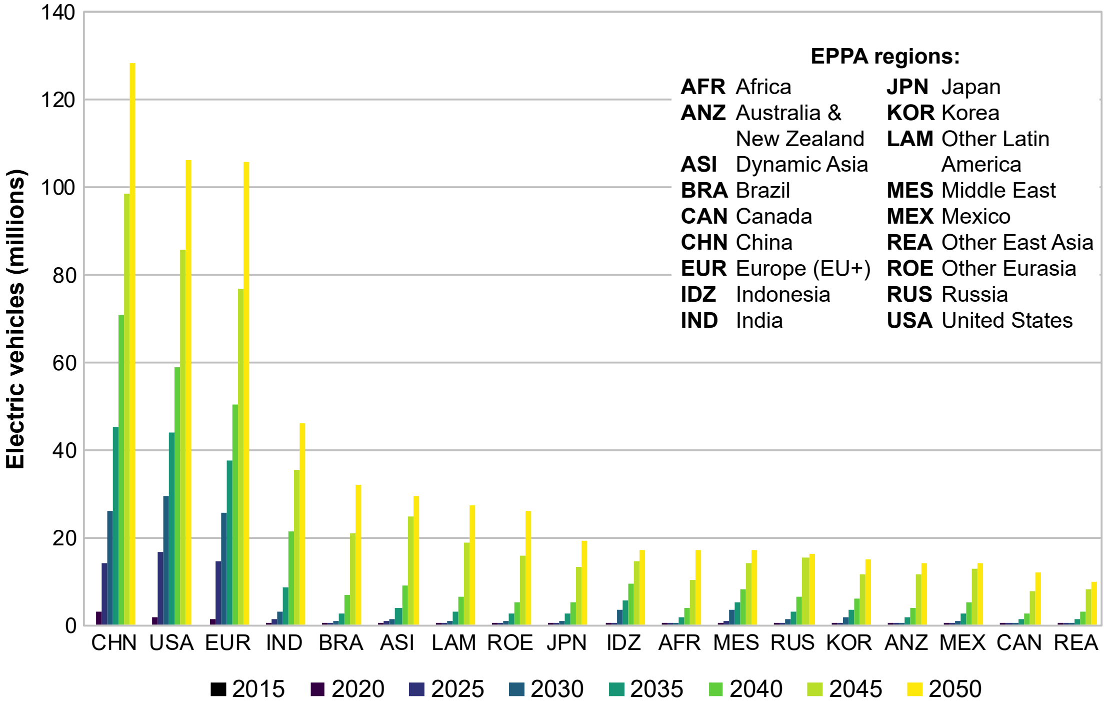
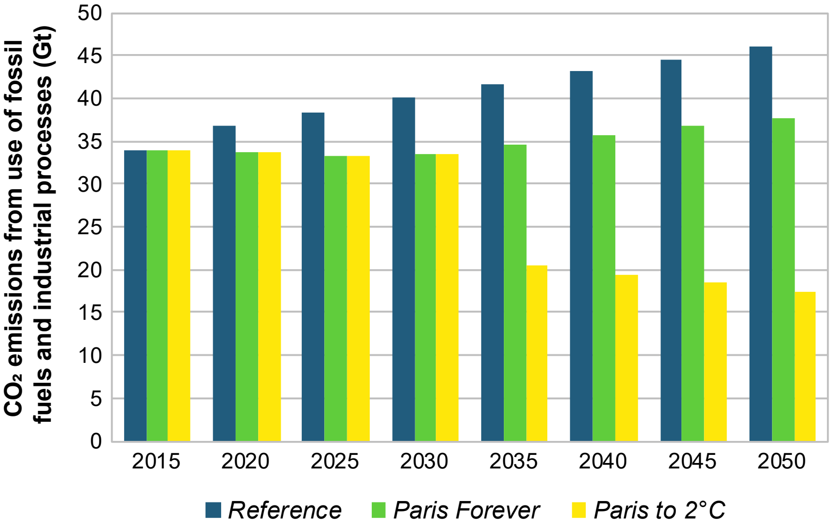


**Figure 2.6: Global $CO_2$ emissions in different scenarios**



from about 34 Gt $CO_2$ in 2015 to about 46 Gt $CO_2$ in 2050, a 36% increase. In the *Paris Forever* scenario, global emissions are roughly stable up to 2030. After that, global emissions begin rising again due to the adoption of carbon intensity targets by China and India, which allow for continued growth in emissions with growing GDP, combined with a lack of hard emissions constraints in some less developed countries. In this scenario, global emissions grow by about 10% from 2015 to 2050, though they are lower (by about 18%) than they would be in the *Reference* scenario.

In the *Paris to 2°C* scenario, we assume that countries intensify their climate change mitigation efforts after meeting their pledged nationally determined contributions under the Paris

Agreement through 2030. Specifically, we assume that countries implement the additional emissions reductions needed to achieve the overarching goal of the Paris Agreement, which is to limit the increase in global average temperature to less than 2°C. This constraint implies a sharp decline in emissions between 2030 and 2035 to put the world on a trajectory that is consistent with meeting the 2°C goal.

Our modeling for the *Paris Forever* scenario assumes no emissions trading, which means that each region has its own carbon price. EPPA results for projected carbon prices under this policy scenario are shown for the U.S., Europe, and China in Figure 2.7. The figure shows roughly stable carbon prices in these regions from 2030 to 2050 at about \$70–\$80 per metric ton $CO_2$ ($tCO_2$) in the U.S., \$90–\$100/$tCO_2$ in Europe, and about \$20–\$35/$tCO_2$ in China. All monetary values are reported in real terms in 2015 U.S. dollars.

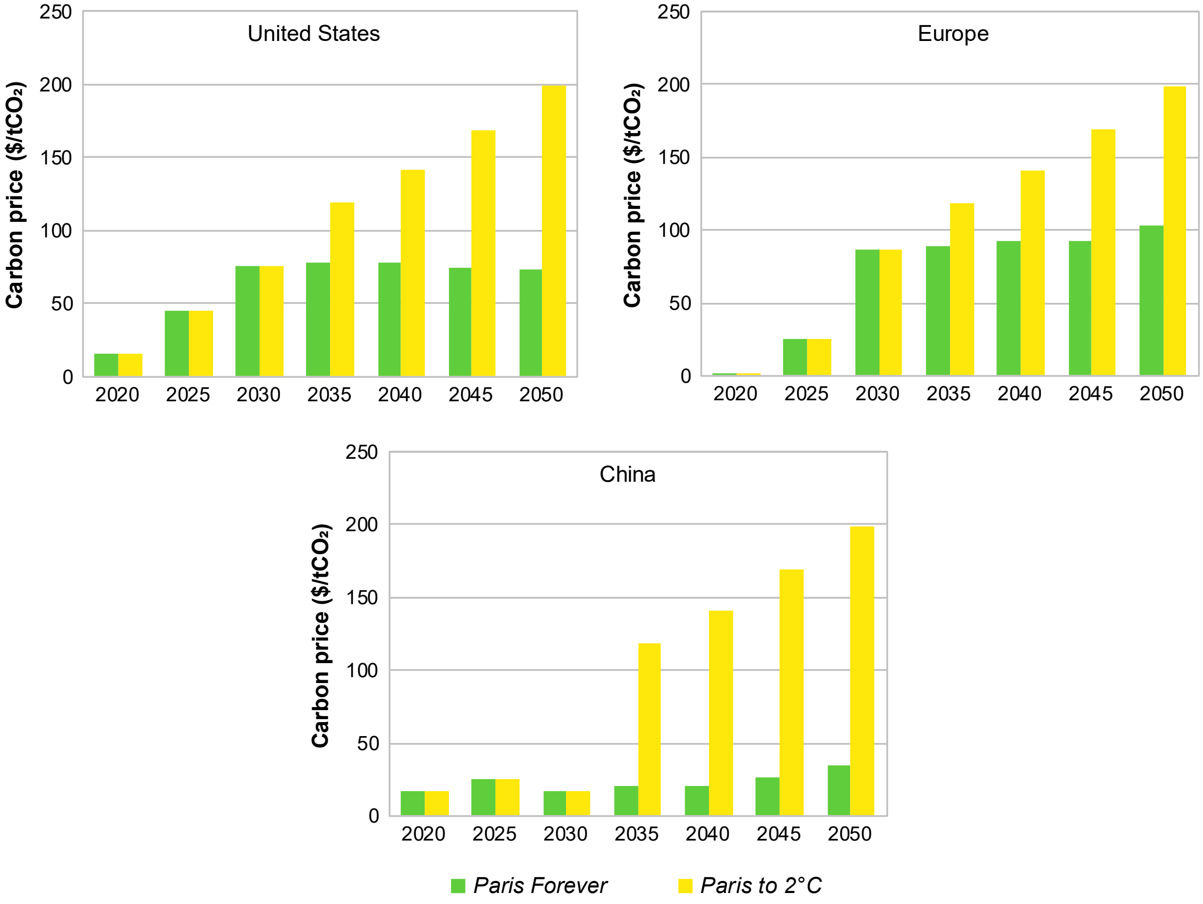
Our modeling for the *Paris to 2°C* scenario assumes that global emissions trading is introduced after 2030. In this scenario, the global carbon price increases from about \$120/$tCO_2$ in 2035 to about \$200/$tCO_2$ in 2050. The projected change in carbon prices between 2030 and 2035 depends on the stringency of country-level commitments under the Paris Agreement up to 2030. Regions that undertake more ambitious mitigation efforts, such as Europe and the U.S., see only a gradual increase in the carbon price as they transition from their Paris nationally determined contributions to a global carbon price that is consistent with the 2°C emissions trajectory. For China, however, the carbon price jumps dramatically, from \$17/$tCO_2$ in 2030 to \$119/$tCO_2$ in 2035. The model projects similarly sharp carbon price transitions in other countries that pursue less aggressive mitigation policies under the Paris Agreement. In the *Paris to 2°C* scenario, global $CO_2$ emissions in 2050 are 62% lower than in the *Reference* scenario and 54% lower than in the *Paris Forever* scenario.

More aggressive climate policies and correspondingly higher carbon prices drive the increase in EV adoption shown in Figure 2.3, which in turn affects emissions from private transportation. The full emissions impact of expanded EV deployment depends on the carbon intensity of electricity production.

In our *Reference* scenario, the global carbon intensity of electricity production starts at approximately 525 grams $CO_2$ per kilowatt hour ($gCO_2/kWh$) in 2015 and falls to 345 $gCO_2/kWh$ by 2050. With more aggressive policies to decarbonize the electricity sector, carbon intensity falls more substantially in the two policy scenarios: to 317 $gCO_2/kWh$ in 2050 under the *Paris Forever* scenario, and to 95 $gCO_2/kWh$ in 2050 under the *Paris to 2°C* scenario. In percentage terms, the carbon intensity of electricity production is reduced by 35%, 40%, and 80% between 2015 and 2050 across the three scenarios considered. This translates to an average annual rate of decline in carbon intensity of about 1.2% per year under the *Reference* scenario, 1.4% per year under the *Paris Forever* scenario, and 4.8% per year under the *Paris to 2°C* scenario.

The speed and extent of projected electric sector decarbonization varies across regions. China is projected to achieve carbon intensity reductions faster than the U.S. in all scenarios. Comparing 2050 to 2015 in the *Reference* and *Paris Forever* scenarios, China reduces the carbon intensity of its electric sector by about 50% while the U.S. achieves a 36% reduction. In the *Paris to 2°C* scenario, China reduces electric sector carbon intensity by about 97% compared to a 50% reduction for the U.S. Because China starts with a far more carbon-intensive power mix in 2015 (790 $gCO_2/kWh$ for China compared to 420 $gCO_2/kWh$ for the U.S.), it still ends up with higher carbon intensity in 2050 in both the *Reference* and *Paris Forever* scenarios (around 400 $gCO_2/kWh$ in China versus around 270 $gCO_2/kWh$ in the U.S.). Under the *Paris to 2°C* scenario, however, China achieves lower carbon intensity than the U.S. by 2050: 26 $gCO_2/kWh$ in China versus 215 $gCO_2/kWh$ in the U.S. This is because adding zero- and low-carbon generation is cheaper in China than in the U.S. By mid-century, China is projected to have a nearly

**Figure 2.7: Carbon prices in the U.S., Europe, and China in different scenarios**



carbon-free generation mix of coal with carbon capture and storage, renewables, nuclear, and hydropower. Meanwhile, the U.S. continues to use inexpensive natural gas.

### 2.2.4 Fuel Use and Prices

Projections of future oil consumption and oil prices are sensitive to a host of factors, including trends in demand for personal mobility and preferred modes for delivering mobility. In 2015, LDVs accounted for almost a quarter of global oil consumption (International Energy Agency 2017). Modeling results for our *Paris Forever* scenario show a 7% reduction in global oil use in 2030 and an 8% reduction in 2050 relative to the *Reference* scenario (Figure 2.8). The *Paris to 2°C* scenario results in a more substantial 25% reduction in global oil consumption (equal to more than 60 exajoules of oil) by 2050 compared to the *Reference* scenario. However, only about one-fifth of this reduction is due to the electrification of the LDV fleet. Other contributors include improved fuel efficiency (for both heavy- and light-duty vehicles), fewer vehicle miles traveled, and reduced use of oil in the industrial sector.

Policies to reduce carbon emissions—consistent with nationally determined contributions pledged under the Paris Agreement and (in the case of our *2°C* scenario) a global carbon price after 2030—will increase the price consumers pay for carbon-emitting fuels, including petroleum-based fuels, relative to the *Reference* scenario (Table 2.1). At the same time, carbon constraints, by reducing demand for oil, reduce the prices received by oil producers. Figure 2.9 shows the trajectory of projected crude oil prices for producers in our modeling scenarios. In 2030, the difference between crude oil prices in the *Reference* scenario and both *Paris* scenarios is about

Figure 2.8: Global oil use in different scenarios

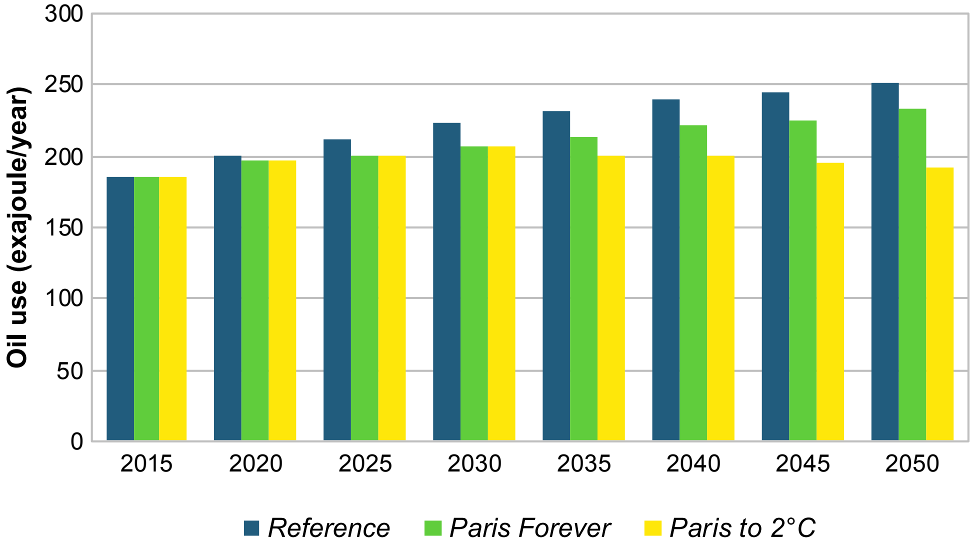
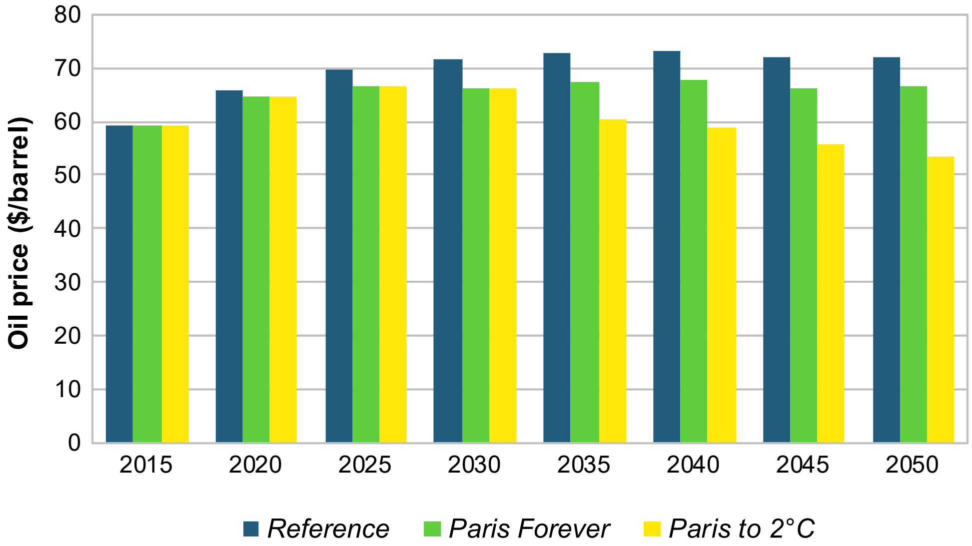


Figure 2.9: Crude oil prices to producers in different scenarios



$5/barrel (producers receive $71/barrel in the *Reference* scenario compared to $66/barrel in the *Paris* scenarios). In 2050, the price reduction to producers under carbon constraints is larger: At that point producers receive $72/barrel in the *Reference* scenario compared to $67/barrel in the *Paris Forever* scenario and $54/barrel in the *Paris to 2°C* scenario.

Crude oil is traded globally and the EPPA model treats crude oil as a homogenous product that has the same price in all regions of the world. Prices for refined oil products such as gasoline and diesel include regional taxes, tariffs, and trade margins; therefore, they differ by region. Table 2.1 shows projected consumer prices for gasoline in the U.S. and China for the three scenarios. Policies to limit carbon emissions increase oil prices for consumers relative to the *Reference* scenario. In our analysis, carbon prices are added on top of any existing fuel taxes. In 2050, the modeled gasoline price to U.S. consumers ranges from $2.92/gallon in the *Reference* scenario to $4.53/gallon in the *Paris to 2°C* scenario. In China the corresponding price range is from $5.32/gallon in the *Reference* scenario to $7.72/gallon in the *Paris to 2°C* scenario.

**Table 2.1: Gasoline prices ($/gallon) in the U.S. and China under different scenarios**

| | U.S. | | | China | | |
|---|---|---|---|---|---|---|
| **Year** | ***Reference*** | ***Paris Forever*** | ***Paris to 2°C*** | ***Reference*** | ***Paris Forever*** | ***Paris to 2°C*** |
| 2015 | 2.49 | 2.49 | 2.49 | 4.52 | 4.52 | 4.52 |
| 2020 | 2.72 | 2.86 | 2.86 | 4.94 | 5.30 | 5.30 |
| 2025 | 2.84 | 3.27 | 3.27 | 5.18 | 5.61 | 5.61 |
| 2030 | 2.91 | 3.62 | 3.62 | 5.30 | 5.43 | 5.43 |
| 2035 | 2.96 | 3.68 | 3.92 | 5.39 | 5.56 | 7.03 |
| 2040 | 2.96 | 3.70 | 4.10 | 5.39 | 5.55 | 7.25 |
| 2045 | 2.92 | 3.61 | 4.28 | 5.33 | 5.59 | 7.43 |
| 2050 | 2.92 | 3.60 | 4.53 | 5.32 | 5.78 | 7.72 |

### 2.2.5 Macroeconomic Implications

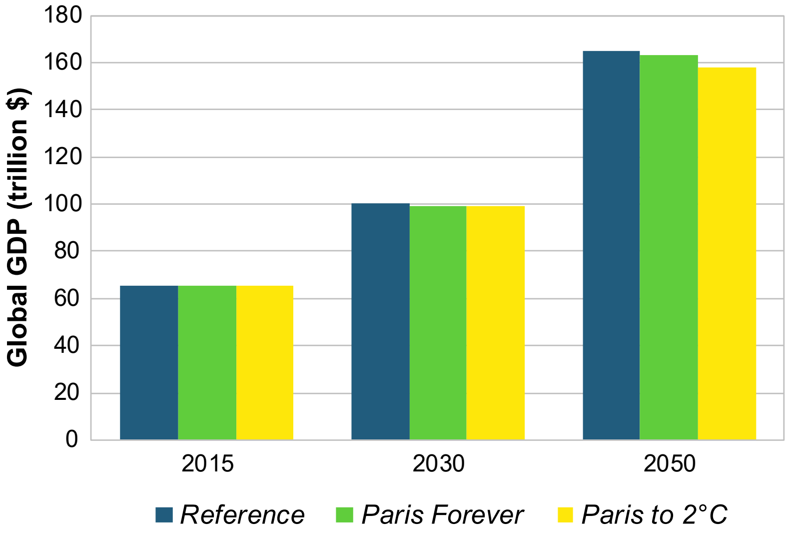
We estimate that the macroeconomic costs of our modeled climate policies range from a 1.1% to 3.3% reduction in global GDP in 2050, relative to the *Reference* scenario. While this represents a substantial amount of money ($1–$3 trillion), the cost is equal to one to two years of economic growth. While growth of the global economy is slower in the climate scenarios than the *Reference* scenario due to impacts on overall economic activity, including global oil consumption and the size of the passenger vehicle fleet, our projections in Figure 2.10 show the global economy expanding from 2015 to 2050 by more than 140% in all scenarios.

Importantly, these calculations do not consider benefits from mitigating climate change and reducing air pollution. Estimating such benefits is challenging, as the impacts of climate change span a large number of economic sectors and ecosystem services are difficult to convert to monetary values; in addition, impacts vary strongly by region (Monier, et al. 2018). While there are several reports (Intergovernmental Panel on Climate Change 2014; The World Bank 2012) that find potentially devastating impacts of climate change such as the inundation of coastal cities; increasing risks for food production that could potentially lead to higher malnutrition rates; many dry regions becoming dryer and wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased intensity of tropical cyclones; and irreversible loss of biodiversity, there is a wide uncertainty about the magnitude of damages. Therefore, our analysis reports only the costs of achieving emission mitigation targets.

### 2.2.6 Implications for Government Revenue

Many countries use tax incentives to support initial EV deployment. As EVs achieve greater market penetration, these incentives become increasingly costly for governments; thus, many countries can be expected to remove preferential EV tax treatments and other EV supports after an initial period of time. The expiration of government incentives will affect the relative costs of EVs versus ICEVs from the consumer's perspective. Government support for EVs can take many forms: tax credits to lower the upfront cost of vehicles; reductions in vehicle registration fees; vehicle or infrastructure rebates, loans, special low-cost charging rates, parking cost and toll reductions; and high-occupancy-vehicle lane exemptions. Zero-emission vehicle mandates or new fuel efficiency standards favor EVs over ICEVs. Our analysis does not attempt to explicitly account for monetary flows related to different forms of government support for EVs—instead, we rely on a simplified representation based on relative costs of vehicles and their penetration rates. We assume a gradual decrease in the cost of battery packs (Ghandi and Paltsev 2019) and a gradual reduction in government support to EVs, with a full phase-out of government support by 2025.

**Figure 2.10: Global GDP in different scenarios, without accounting for climate damages**



Another policy that has implications for the relative cost of different types of LDVs is a fuel tax. Fuel taxes are an important source of government revenue in many countries. Substituting ICEVs with EVs leads to a reduction in fuel tax revenues. Table 2.2 presents the results of an illustrative calculation of the potential revenue impacts from reduced fuel tax collections for selected regions in the *Paris Forever* scenario. Fuel taxes are much higher in Europe ($3.50/gallon) than in the U.S. (less than $0.50/gallon) in 2018. China, India, and Mexico also have substantial fuel taxes at approximately $1.50–$2.00 per gallon. Foregone tax revenue due to a smaller ICEV fleet and reduced fuel use by ICEVs varies by region. For example, in the U.S. foregone fuel tax revenues (federal and state combined) may reach $7 billion by 2030 and $29 billion by 2050. In Europe, foregone tax revenues are larger, reaching about $43 billion in 2030 and $215 billion in 2050.

In the *Paris to 2°C* scenario, potential revenue losses from reduced fuel tax collections are larger in all countries by 2050 when compared to the *Paris Forever* scenario. For example, by 2050, the revenue differential between these two scenarios could reach $32 billion in the U.S., $218 billion in Europe, $181 billion in China, and $66 billion in India.

These losses, however, are unlikely to materialize because governments will likely anticipate them and make adjustments in tax policy accordingly. Facing reduced fuel tax collections, governments will likely consider alternative tax approaches to maintain their revenue streams. For example, they could impose new taxes based on vehicle travel. Another approach would be to tax carbon as an alternative source of revenue (Yuan, et al. 2017). Other taxes can also be adjusted. The exact implications of alternative tax schemes depend on the specifics of tax design. Our policy scenarios assume that governments collect carbon-related revenues based on the carbon content of fossil fuels, and then redistribute these revenues in a lump sum fashion.[8]

[8] Lump sum distribution means that all collected taxes are returned to a representative agent in the corresponding region in each time period and other tax rates are unaffected. Different distribution schemes assume changes in other types of taxes and would lead to different results. We assume a lump sum distribution because this is the scheme most commonly assumed in the economic literature on the basis that it minimizes distortions of other taxes.

**Table 2.2: Potential fuel tax revenue reduction due to EV penetration for *Paris Forever* scenario**

| | | Annual loss of government tax revenue due to reductions in oil consumption for private transport (billion $) | | | Reduction in tax revenue relative to total government expenditure (%) | | |
|---|---|---|---|---|---|---|---|
| **EPPA region** | **Gasoline tax in 2018 ($/gallon)** | **2020** | **2030** | **2050** | **2020** | **2030** | **2050** |
| **United States** | 0.47 | 0.34 | 7.05 | 29.05 | 0.01 | 0.22 | 0.59 |
| **Europe (EU+)** | 3.50 | 1.84 | 43.22 | 215.07 | 0.05 | 0.90 | 3.13 |
| **China** | 1.88 | 2.33 | 24.51 | 142.21 | 0.19 | 1.27 | 3.98 |
| **India** | 1.92 | 0.05 | 2.60 | 52.29 | 0.02 | 0.49 | 4.76 |

## 2.3 SENSITIVITY ANALYSIS

Many factors might affect the pace of EV deployment and its implications for climate-related goals. To explore a wider range of future outcomes, we developed a sensitivity analysis to test the impacts of different assumptions about (1) LDV growth in China, (2) accelerated government support for EV deployment, (3) increased investment in renewable energy, and (4) mandates for fuel cell vehicle market share. We also examined prospects for the deployment of hydrogen cars.

### 2.3.1 Higher Demand for Private Transportation in China

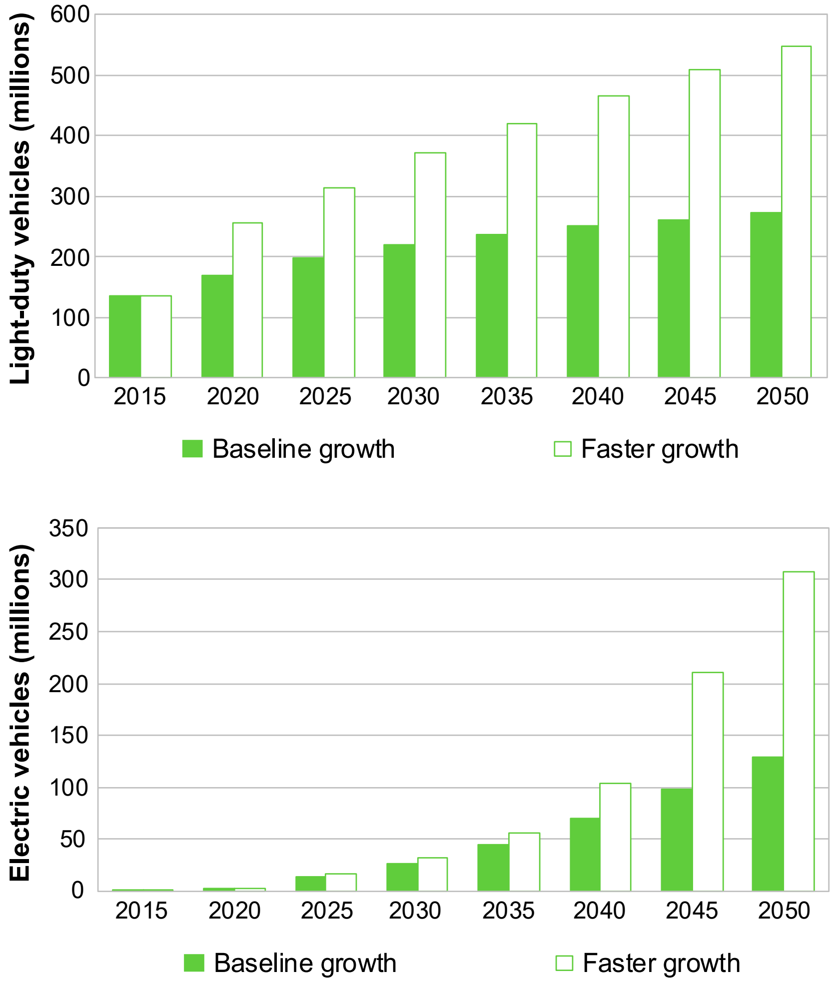
China's LDV fleet is the fastest growing in the world. Over the decade from 2005 to 2015, China's LDV fleet grew at an average rate about 10 times faster than in the rest of the world (Ghandi and Paltsev 2019). Car ownership in China is likely to continue expanding rapidly for some time, but more recently there have been some indications of slowing growth. A forecasted reduction in China's economic growth in the upcoming years (IMF 2018) together with measures to reduce congestion and local air pollution may serve to dampen LDV fleet growth. It is too early to tell if a decline in the growth of car sales in China in 2018 and 2019 is indicative of a new trend or if it is a temporary phenomenon. Chapter 3 of this report explores different aspects of future vehicle ownership in China. Here we examine how different assumptions regarding the income elasticity of demand for private transportation in China affects LDV deployment in China. Higher income elasticity means a larger increase in vehicle ownership for the same level of income growth.

As described earlier, China's LDV fleet is projected to grow to about 220 million vehicles in 2030 and 275 million vehicles in 2050 in the *Paris Forever* scenario with our baseline assumption for income elasticity. EVs constitute nearly half (47%) of China's LDV fleet in 2050 in this scenario. Figure 2.11 illustrates the results when the same scenario is modeled with a higher income elasticity assumption.[9] In this case, China's LDV stock reaches more than 370 million vehicles in 2030 and grows further, to about 550 million vehicles, in 2050. China's projected EV fleet is also larger in this case, with 33 million EVs in 2030 (versus 26 million in the baseline case) and about 308 million EVs in 2050 (versus 129 million in the baseline case). Based on these results, EVs also account for a larger share of China's overall LDV fleet in 2050: 56% instead of 47% in the baseline case. Nonetheless, a larger LDV fleet results in higher $CO_2$ emissions from China's transportation sector. In fact, under the higher income elasticity assumption, modeled transportation emissions for China more than double compared to the baseline case.

---

[9] In the base setting we use elasticities from Kishimoto (2018). We double the elasticity in the higher income elasticity case based on results from more detailed modeling of the LDV fleet in China (see Section 3.3).

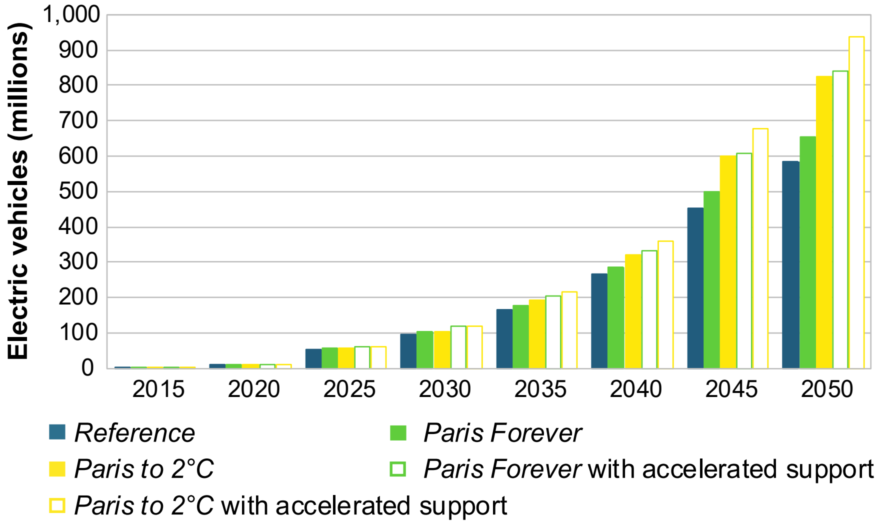
**Figure 2.11: LDVs and EVs in China in the *Paris Forever* scenario**



## 2.3.2 Accelerated Support for EV Deployment

As we have already noted, numerous forms of government support can lower the relative cost of owning an EV and accelerate the penetration of EVs. We tested the case where all countries increase public support for EV deployment, thereby reducing EV costs by about 15% compared to the base case. As shown in Figure 2.12, the global EV fleet expands more rapidly in the *Paris Forever* scenario with accelerated support, reaching about 824 million vehicles in 2050, a 28% increase compared to the same scenario with baseline support. In the *Paris to 2°C* scenario, the global EV fleet in 2050 is larger by about 15% with accelerated support compared to the baseline setting, reaching about 940 million vehicles in 2050. Increased public support has a larger impact on projected EV fleet size under the *Paris Forever* scenario than under the more aggressive *Paris to 2°C* scenario. This is because stricter carbon constraints in the *Paris to 2°C* scenario result in higher gasoline prices, and so EVs require less support. These estimates should be treated as illustrative since they depend on the exact design of the policy mechanisms used to support EVs. While we did not explicitly model different support mechanisms, our calculations show that policies to lower the relative cost of EVs are important to accelerate EV deployment.

**Figure 2.12: Global EV stock with accelerated support**



### 2.3.3 Accelerated Support for Renewable Electricity Generation Technologies

EV deployment will have different implications for $CO_2$ emissions depending on the carbon intensity of the generating mix used to produce electricity for these vehicles. When powered by a generation mix that relies heavily on coal, EVs do not provide substantial $CO_2$ benefits relative to ICEVs (Chapter 4, which discusses vehicle powertrains, provides more detail on this topic). As noted in our discussion of the *Paris to 2°C* scenario, the imposition of a uniform carbon price in all regions of the world after 2030 leads to different carbon intensities of electricity production in different countries due to country-specific differences in fuel costs, technology costs, and other inputs. While the average carbon intensity of the global electricity generating mix in 2050 is 95 $gCO_2$/kWh in the *Paris to 2°C* scenario, China ends up with lower carbon intensity than the U.S. (26 $gCO_2$/kWh in China versus 215 $gCO_2$/kWh in the U.S. in 2050). This result is driven by a global carbon price that supports a switch from coal to low-carbon generation in China, whereas natural gas in the U.S. remains competitive at that carbon price for a long time.

To model the effect of policies that provide additional support for renewable power, we assume a lower cost for wind and solar generation relative to natural gas in all regions of the world compared to the baseline setting.[10] In this case, the global average carbon intensity of electricity production in 2050 drops to 25 $gCO_2$/kWh in the *Paris to 2°C* scenario, while China's carbon intensity falls to 3 $gCO_2$/kWh and carbon intensity in the U.S. is 34 $gCO_2$/kWh. With low-carbon power generation, EV deployment makes a larger contribution to $CO_2$ reductions. Thus, in the U.S., accelerated support for renewable power generation produces an 83% reduction of grid carbon intensity and a corresponding 10% reduction in the projected carbon intensity of the overall LDV fleet in 2050.

---

[10] The EPPA model recognizes that at low penetration of intermittent technologies in power generation, such as wind and solar, the existing dispatchable generation capacity can compensate for the intermittent power generators. At higher penetrations of intermittent power generation technologies, the EPPA baseline model represents the increased cost on the electricity power system by assuming that all intermittent power generation capacity above 25%-30% of total generation requires 1-for-1 backup with a dispatchable technology such as gas turbines. In the accelerated renewable electricity case in EPPA, we assume that intermittency issues are fully resolved and there is no requirement for backup for intermittent power generation technologies.

### 2.3.4 Hydrogen Cars

While EVs currently dominate the market for lower-emission vehicles, hydrogen-based vehicles offer another pathway to decarbonizing personal transportation (Chapter 4 provides more detail about hydrogen and other powertrain technologies). One option involves vehicles powered by fuel cells that generate electricity from hydrogen and oxygen. Fuel cell electric vehicles (FCEVs) are more expensive than ICEVs and they rely on infrastructure that needs substantial development. Numerous studies have examined the costs and challenges of transitioning to a hydrogen-based transportation system, including the cost of fuels, infrastructure, and vehicles (Simbeck and Chang 2002; Study Task Force of the Hydrogen Council 2017). To explore the potential role of FCEVs for purposes of our analysis, we applied several simplifying assumptions. For example, we assumed that the total cost of ownership for an FCEV is twice as high as the cost of ownership for a comparable ICEV and we further assumed that hydrogen would be produced in a manner that produces no $CO_2$ emissions (for example, through water electrolysis using zero-carbon electricity, or through steam methane reforming or biomass gasification with carbon capture).

We consider a case where FCEVs account for a mandated 5% share of the LDV fleet in the U.S. by mid-century. This results in the addition of 17 million FCEVs but does not substantially affect the overall size of the LDV fleet in the U.S. in 2050. The global LDV fleet is about 292 million vehicles with or without the imposition of an FCEV requirement in the U.S. With this requirement, FCEVs replace about 9 million BEVs, 0.4 million PHEVs, and about 8 million ICEVs in the U.S. fleet in 2050 (Figure 2.13).

Introducing a 5% FCEV mandate in the U.S. by mid-century reduces domestic oil consumption by about 0.9%. In 2050, the projected cost of such a mandate amounts to a 0.11% reduction in U.S. macroeconomic consumption relative to the case without a FCEV requirement. The average cost per metric ton of avoided $CO_2$ emissions in 2050 is also higher in the case with FCEVs: \$122/t$CO_2$ compared to \$105/t$CO_2$ without the FCEV mandate. Our illustrative calculations show that hydrogen has potential, but is currently a more expensive option for reducing LDV carbon emissions. Substantial progress toward lowering the cost of fuel cell vehicles, while also lowering the cost of hydrogen production and fueling infrastructure, is needed to realize this technology's potential.

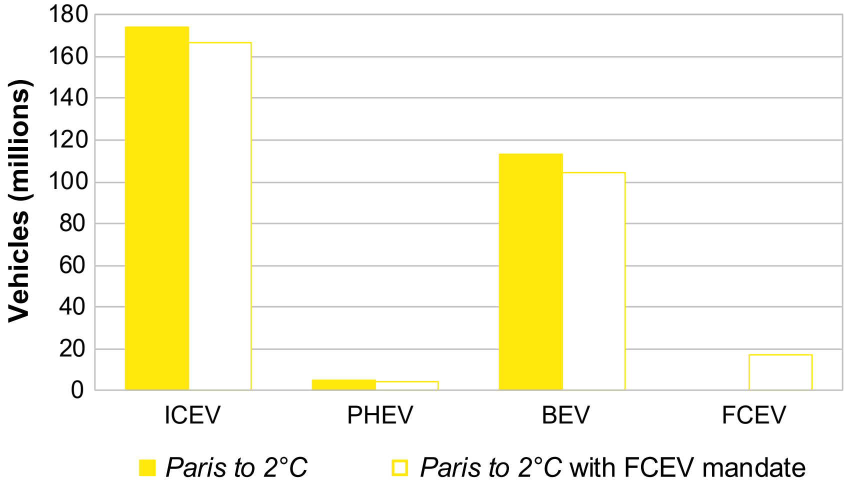
## 2.4 CONCLUSION

Meeting the ambitious climate change mitigation targets adopted by 195 nations under the Paris Agreement (United Nations 2015) will require substantial greenhouse gas emissions reductions across all sectors of the global economy, including personal transportation. A realistic path to decarbonizing light-duty vehicle travel will require strategies that combine the objective of reducing emissions with those of improving personal mobility and supporting economic growth. Our modeling analysis is designed to find the pathways that maximize welfare subject to the specific emissions, resource, and budget constraints of different countries and regions.

The results of this analysis envision a substantial electrification of private transportation. We project that the global EV fleet will grow from approximately 3 million vehicles in 2017, to about 95–105 million EVs by 2030, and 585–823 million EVs by 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall LDV fleet by 2050 in different scenarios, with the stricter carbon constraints implied in the *Paris to 2°C* scenario leading to the largest EV share. Our modeling suggests that EV uptake will vary across regions. China, the U.S., and Europe remain the largest markets in our study timeframe, but the EV presence is projected to grow in all regions.

Figure 2.14 summarizes the impact of our modeled climate scenarios on several major output measures in 2050, relative to a 2015 baseline. EVs play a role in reducing oil use, but a more substantial reduction in oil consumption comes

**Figure 2.13: ICEVs, PHEVs, BEVs, and FCEVs in the U.S. in 2050 under the *Paris to 2°C* scenario, with and without an FCEV mandate**



from economy-wide carbon pricing. Absent more aggressive efforts to reduce carbon emissions, global oil consumption is not radically reduced in the next several decades because of increased demand from other sectors, such as for heavy-duty transport and non-fuel uses. The figure indicates that global oil consumption does decline—by roughly 25% compared to the reference case—in the *Paris to 2°C* scenario, but only about one fifth of this reduction is due to light-duty vehicle electrification.

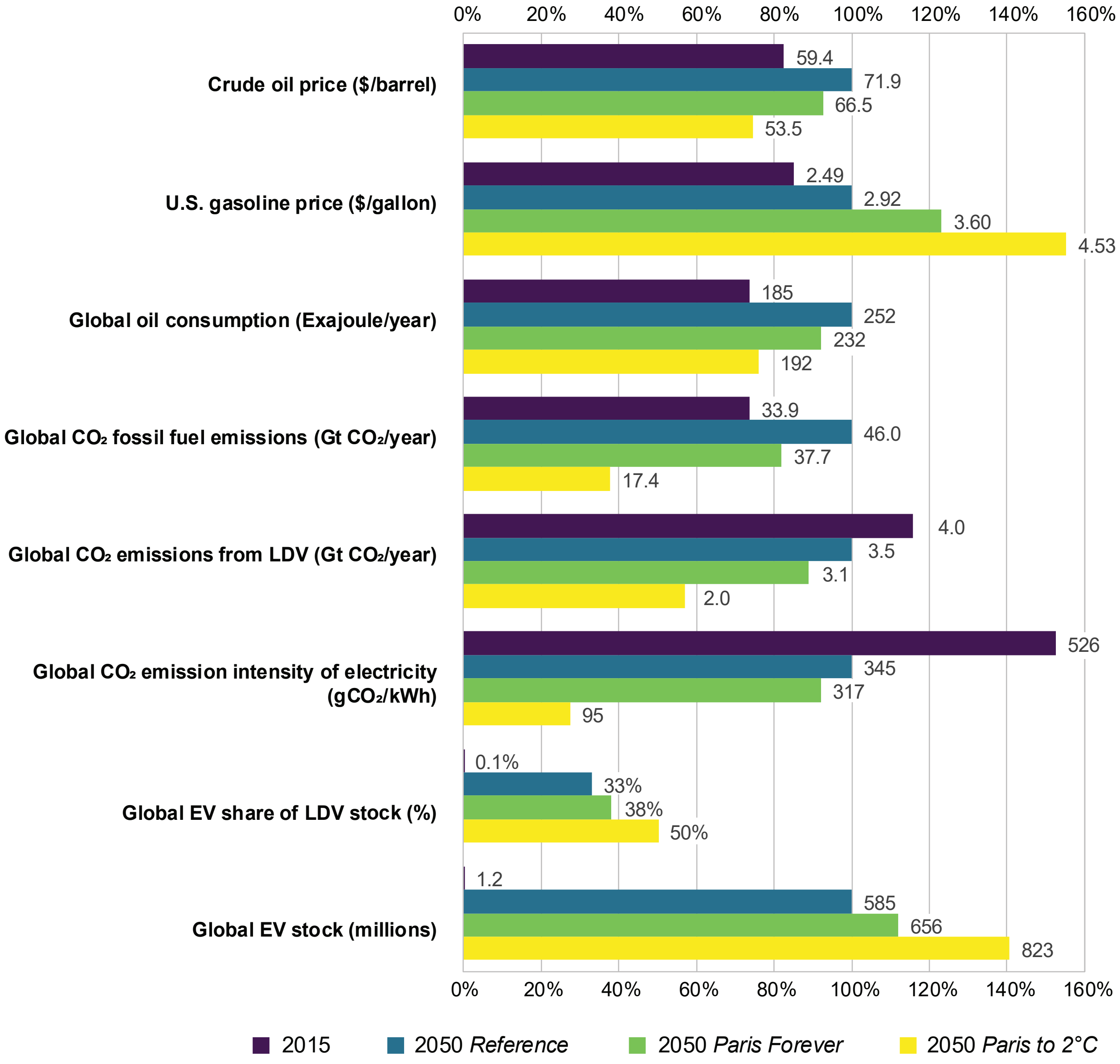
In the *Paris to 2°C* scenario, global energy-related $CO_2$ emissions in 2050 are 62% lower than in the *Reference* scenario. Although 2050 $CO_2$ emissions from LDVs are 43% lower in the *Paris to 2°C* scenario than in the *Reference* scenario, this reduction in LDV emissions accounts for only 5% of the total difference in emissions, from all sources, between the scenarios. This reflects two realities: First, as a share of global carbon emissions, LDVs are a smaller contributor (12% of total emissions in 2015) than electricity generation (38% of total emissions). Second, decarbonizing the electricity sector is generally less expensive than decarbonizing transportation. Since the economics of decarbonization favor greater reductions in the electricity sector, the LDV share of total carbon emissions in the *Paris to 2°C* scenario in 2050 is actually higher than the LDV share of total carbon emissions in the *Reference* scenario.

The very substantial emissions reductions demanded by the *Paris to 2°C* scenario require a confluence of many factors, including electrification of about 50% of the LDV fleet and significant decarbonization of electricity production (sufficient to achieve a 72% reduction in the carbon intensity of the global power mix).

We estimate that the macroeconomic costs of the climate policies considered here range from a GDP loss of about 1.1% to 3.3% in 2050, relative to the *Reference* scenario. While growth of the global economy is slower in the climate scenarios, the world can still prosper under climate policy; under our *Paris to 2°C* scenario, the global economy expands by more than 140% from 2015 to 2050. Our calculations do not account for the benefits (or avoided costs) of mitigating climate change, which could also be very substantial.

We project that EVs will constitute a substantial share of the light-duty fleet by mid-century, regardless of climate policy. However, carbon policies will affect the speed of penetration and ultimate number of EVs on the road over the next few decades. The climate impacts of EV deployment depend on progress toward decarbonizing the electric grid. Accordingly, policies to support EVs should go hand-in-hand with policies to support low-carbon electricity generation. Hydrogen-based FCEVs offer another pathway for decarbonization, but their potential

Figure 2.14: Major impacts of modeled climate scenarios in 2050



within the mid-century timeframe depends on substantial cost reductions in terms of both vehicles and fuel production and distribution infrastructure.

Overall, we find that EVs, along with more efficient ICEVs, represent a viable opportunity among a set of options for reducing global carbon emissions at a manageable cost. Support for further research and development to advance these and other low-carbon transportation options will allow for the attainment of more ambitious decarbonization targets. The ultimate goal of mitigating climate change requires actions from all economic sectors, and efforts to address the contribution from personal transportation should be part of an integrated policy response to maximize human welfare, manage climate risks, and secure a foundation for sustainable economic growth and development in the future.

## 2.5 REFERENCES

Chen, Y.-H. Henry, Sergey Paltsev, John M. Reilly, Jennifer F. Morris, and Mustafa H. Babiker. 2016. "Long-Term Economic Modeling for Climate Change Assessment." *Economic Modeling* 52, part B: 867-883. https://doi.org/10.1016/j.econmod.2015.10.023

Ghandi, Abbas, and Sergey Paltsev. 2019. *Representing a Deployment of Light-Duty Internal Combustion and Electric Vehicles in Economy-Wide Models*. Technical Note 17. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/17199

Study Task Force of the Hydrogen Council. 2017. *Hydrogen Scaling-Up: A Sustainable Pathway for the Global Energy Transition*. Belgium: Hydrogen Council. http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

Intergovernmental Panel on Climate Change (IPCC). 2014. *AR5 Synthesis Report: Climate Change 2014*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Core Writing Team, Rajendra K. Pachauri and Leo A. Meyer. Geneva, Switzerland: IPCC. https://www.ipcc.ch/report/ar5/syr/

International Energy Agency (IEA). 2017. *World Energy Outlook 2017*. Paris, France: IEA. https://www.iea.org/weo2017/

International Monetary Fund (IMF). 2018. *World Economic Outlook 2018*. Washington, D.C.: IMF. https://www.imf.org/en/Publications/WEO/Issues/2018/09/24/world-economic-outlook-october-2018

Karplus, Valerie J., Paul N. Kishimoto, and Sergey Paltsev. 2015. "The Global Energy, $CO_2$ Emissions, and Economic Impact of Vehicle Fuel Economy Standards." *Journal of Transport Economics and Policy* 49, no. 4: 517-538. https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Reprint_15-34.pdf

Kishimoto, Paul N. 2018. *Transport Demand in China: Methods for Estimation, Projection, and Policy Assessment*. Ph.D. dissertation. Cambridge, MA: Massachusetts Institute of Technology. http://globalchange.mit.edu/publication/17175

Reilly, John M., Ronald Prinn, Y.-H. Henry Chen, Andrei Sokolov, Xiang Gao, Adam Schlosser, Jennifer F. Morris, Sergey Paltsev, and Henry Jacoby. 2018. *2018 Food, Water, Energy, and Climate Outlook*. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publications/signature/2018-food-water-energy-climate-outlook

Monier, Erwan, Sergey Paltsev, Andrei Sokolov, Y.-H. Henry Chen, Xiang Gao, Qudsia Ejaz, Evan Couzo, C. Adam Schlosser, Stephanie Dutkiewicz, Charles Fant, Jeffrey Scott, David Kicklighter, Jennifer Morris, Henry Jacoby, Ronald Prinn, and Martin Haigh. 2018. "Toward a Consistent Modeling Framework to Assess Multi-Sectoral Climate Impacts." *Nature Communications* 9, no. 660. https://www.nature.com/articles/s41467-018-02984-9

Simbeck, Dale, and Elaine Chang. 2002. *Hydrogen Supply: Cost Estimate for Hydrogen Pathways - Scoping Analysis*. NREL/SR-540-32525. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy03osti/32525.pdf

Sokolov, Andrei, Sergey Paltsev, Y.-H. Henry Chen, Martin Haigh, Ronald Prinn, and Erwan Monier. 2017. *Climate Stabilization at 2°C and Net Zero Carbon Emissions*. Report 309. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/16629

World Bank. 2012. *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided*. Washington, D.C.: World Bank. http://documents.worldbank.org/curated/en/865571468149107611/Turn-down-the-heat-why-a-4-C-warmer-world-must-be-avoided

United Nations. 2015. *Paris Agreement*. Paris, France: United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations, Department of Economic and Social Affairs, Population Division. 2017. *World Population Prospects: The 2017 Revision*, Key Findings and Advance Tables. ESA/P/WP/248. https://population.un.org/wpp/Publications/Files/WPP2017_KeyFindings.pdf

U.S. Energy Information Administration (EIA). 2018. *Annual Energy Outlook 2018*. Washington, D.C.: U.S. Department of Energy. https://www.eia.gov/outlooks/archive/aeo18/

Yuan, Mei, Gilbert E. Metcalf, John M. Reilly, and Sergey Paltsev. 2017. *The Revenue Implications of a Carbon Tax*. Report 316. Cambridge, MA: Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/16742

## Chapter 3

# Vehicle Demand

Worldwide, demand for personal cars is on the rise. As global incomes grow, so does demand for new car purchases and the number of personal vehicle miles traveled. While some mature auto markets—such as the U.S. market—have seen their growth slow as they reach saturation, markets in China and other developing countries have significant room for continued growth. This chapter explores how local socio-demographic characteristics, urban conditions, vehicle restriction policies, and attitudes might impact future demand for personal vehicles in both mature and developing markets. We focus on the two largest vehicle markets in the world—the U.S. and China.

Section 3.1 delves into the U.S. auto market, exploring whether new generations of Americans have different preferences when it comes to car ownership and use. We also identify key socio-economic drivers of future demand. In Sections 3.2 and 3.3, we turn our attention to the vehicle market in China. Section 3.2 explores the transportation policymaking process at the city level in China, demonstrating that different types of Chinese cities have adopted various types of transportation policies in response to their different local conditions. In particular, we model the factors that have driven some Chinese cities to adopt comprehensive car ownership and usage restrictions. Section 3.3 presents projections of the future vehicle stock in China and explores the potential impact of widespread adoption of car ownership restriction policies in cities on the number of vehicles purchased nationally. Finally, Section 3.4 illustrates how individuals' attitudes, particularly "car pride," influence car ownership and use for individuals in two cities in the U.S. and in an international sample of 51 countries.

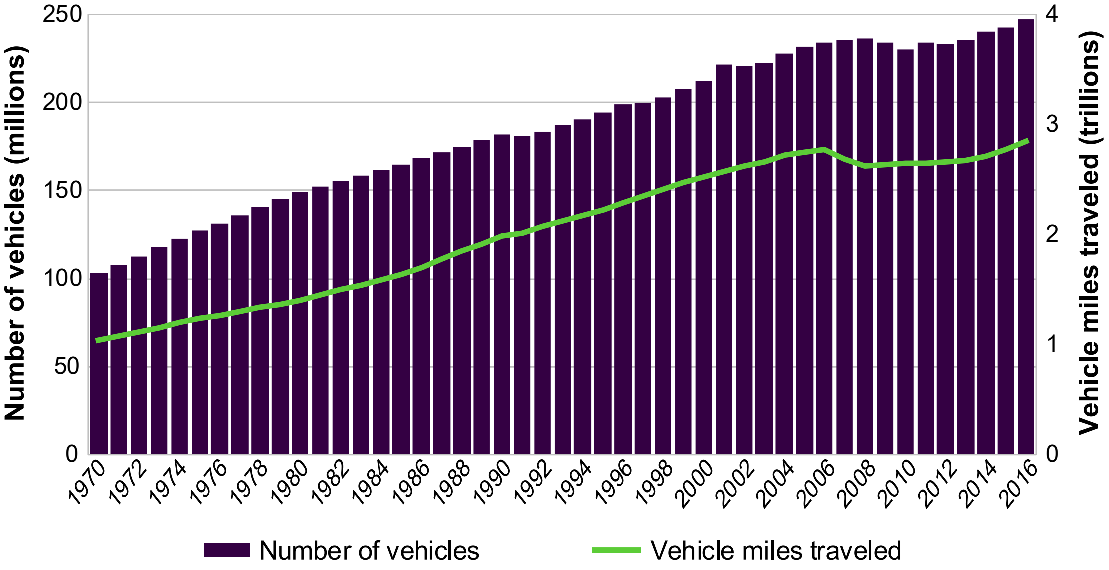
## 3.1 VEHICLE OWNERSHIP AND USAGE PATTERNS IN THE UNITED STATES

This section explores how the forces of market growth and consumer choice may influence mobility demand in the future. We begin by looking at trends in U.S. population size and number of households. Then we address the role of consumer choice and examine how consumer preferences and socio-economic factors may influence future vehicle ownership and use. We conclude with a discussion about how the combined forces of market size and consumer choice could influence future demand for personal mobility. In this section, we focus on the impacts of household preferences and socio-economic factors. We do not consider the impact of technological changes, such as the advent of ride-hailing services and vehicle automation, which may change the landscape of vehicle ownership. These technologies and their impacts are discussed in Chapter 6.

### 3.1.1 Current Vehicle Ownership and Vehicle Travel in the U.S.

In 2016, levels of vehicle ownership and vehicle miles traveled (VMT) in the U.S. reached a new peak (Figure 3.1). Demand for mobility, as expressed by either of these two variables, has grown decade after decade despite temporary pauses, most notably during the Great Recession of 2007–2009. This rising demand has been driven by two forces: (1) the growing size of the market as the U.S. population has increased, and (2) changes in individual consumer choices such as whether to own a vehicle and if so, how many vehicles to own. Therefore, projections of future demand need to account for changes in these key drivers.

**Figure 3.1: Historical vehicle ownership and VMT in the U.S.**



Note: Vehicle ownership has been linearly interpolated between 1970, 1975, 1980, 1985, and 1990 using data from the U.S. Bureau of Transportation Statistics (BTS) (2019). Vehicle totals for the years prior to 2007 include vehicles defined by BTS as "passenger cars and other 2-axle 4-tire vehicles"; figures for the years from 2007 onward combine vehicles defined by BTS as "light duty vehicle, long wheel base" and "light duty vehicle, short wheel base." These categories are slightly different, so post-2007 data are not directly comparable to prior data.

The level of motorization, expressed as the ratio of vehicles to people, illustrates how individual vehicle ownership in the U.S. has evolved over time (Figure 3.2). This ratio grew steadily throughout the 20th century and peaked at 0.79 vehicles per person in 2006, just before the Great Recession. In 2014, in the wake of the subsequent economic recovery, the level of motorization began to rise again, though as of 2016, it remained 3% lower than it was in 2006 (U.S. Bureau of Transportation Statistics 2019; U.S. Census Bureau 2018a). This raises a question as to whether the ratio of vehicles to people in the U.S. is reaching saturation. Whether this is the case depends on a wide number of factors that influence household purchasing decisions, including household preferences and how they might change by generation.

### 3.1.2 Household Preferences: Are Millennials Different?

When it comes to household preferences, a pertinent question is whether the millennial generation, and subsequent cohorts, display fundamentally different tastes for vehicle ownership and usage than previous generations. Future demand for vehicles and fuels will be largely driven by the purchasing habits of millennials, which we define as the generation born between 1980 and 1994 (Table 3.1), and subsequent generations. In 2015, millennials surpassed baby boomers as the largest U.S. adult population cohort. As baby boomers and other generations grow older, the influence of younger generations of consumers will dominate (Fry 2018). This generational shift is also reflected in vehicle sales data (Figure 3.3). In 2016, millennials represented the second largest group of car buyers after baby boomers (Kurylko 2017).

**Figure 3.2: Level of motorization and VMT per person in the U.S., 1990–2016**

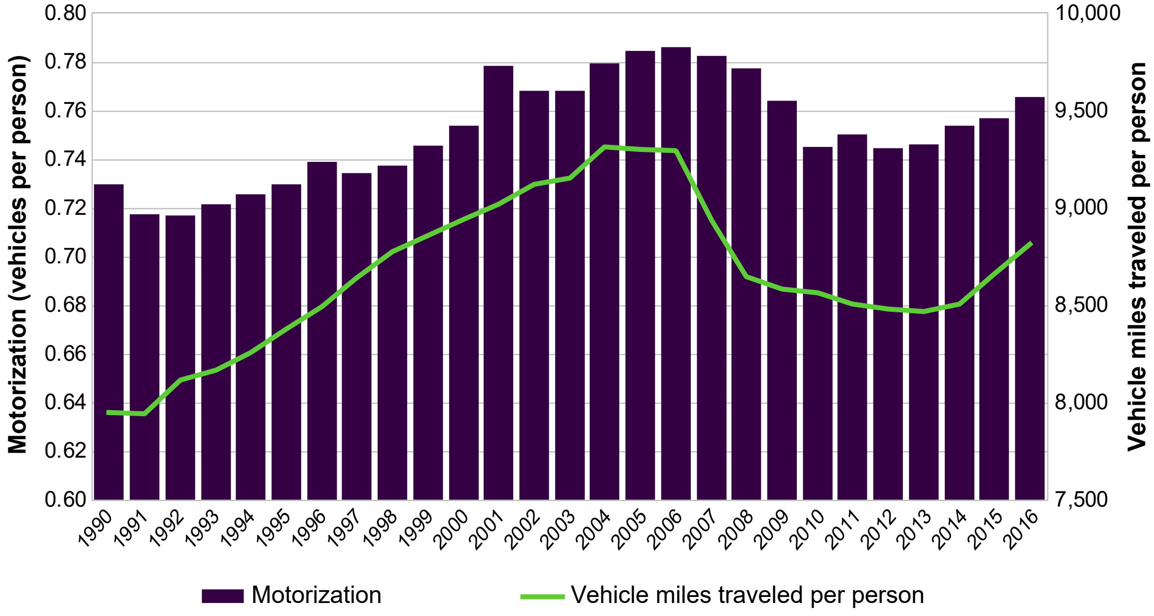


**Table 3.1: Definitions of American generations used in this report**

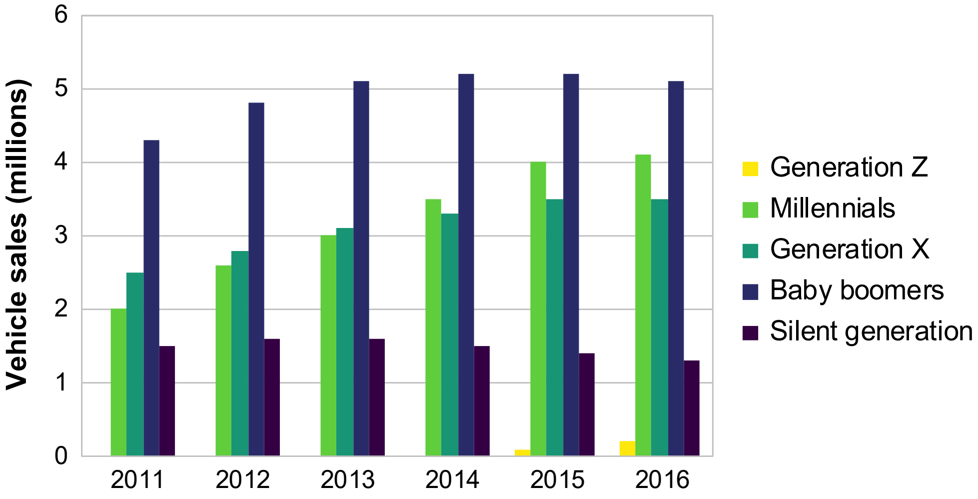
| Generation | Birth years |
|---|---|
| Generation Z | 1995–2015 |
| Millennials | 1980–1994 |
| Generation X | 1965–1979 |
| Baby boomers | 1946–1964 |
| Silent generation | 1928–1945 |
| Greatest generation | 1901–1927 |

There has been considerable speculation about the possibility that the transportation preferences of millennials differ in fundamental ways from those of previous generations. Claims abound that millennials are the “go nowhere generation,” meaning that they are more risk averse and economically static (Buchholz 2012), or the “cheapest generation” (Thompson 2012), meaning that they are uninterested in making large investments in cars or houses. There is clear evidence that millennials are acquiring their driver’s licenses at an increasingly later age (Sivak and Schoettle 2012). The share of American 19-year-olds with a driver’s license declined from 87.3% in 1982 to 69.5% in 2010. Studies have also shown a recent decline in average vehicle miles traveled by young people (Dutzik, Inglis, and Baxandall 2014).

Differences in socio-economic characteristics relative to previous generations could provide an alternative explanation for the observed behavior of millennials with respect to vehicle ownership and miles traveled (Atkinson 2018; Martin 2014; Nielsen Company 2014). Our analysis of household data from the U.S. Department of Transportation’s National Household Travel Survey (NHTS) shows that millennials are more likely to earn lower incomes, live in urban areas, form smaller households, and have fewer children than households of previous generations (Murphy 2018). To control for age, this comparison included only households in the same age range as the current age range for millennials.

To isolate the impact of consumer preferences, we compare millennials with previous generations on an apples-to-apples basis by controlling for socio-economic factors that may influence mobility demand. For purposes of this analysis, we develop linear econometric models for household vehicle ownership and VMT. Each model explains the variable of interest (vehicle ownership or miles traveled) using socio-economic variables and the generation that the household falls into. We assign generations on the basis of the age of the oldest household member. We consider 13 socio-economic control variables: income, household

Figure 3.3: U.S. Vehicle sales by population cohort



Note: Data from Kurylko (2017).

size, household compositions,[1] location (urban or rural),[2] state, education, survey year, age, sex, race, family life cycle, marital status, and number of children. Since all relevant socio-economic variables are controlled for, any differences between generations indicate a difference in preferences (captured by the coefficient reported in Figure 3.4). The models use nationally representative household-level data from NHTS surveys from 1990, 1995, 2001, 2009, and 2017.[3] Detailed explanations of the equations for the regression models and robustness checks on the results can be found in Knittel and Murphy (2019).

### *The impact of generational preferences on vehicle ownership*

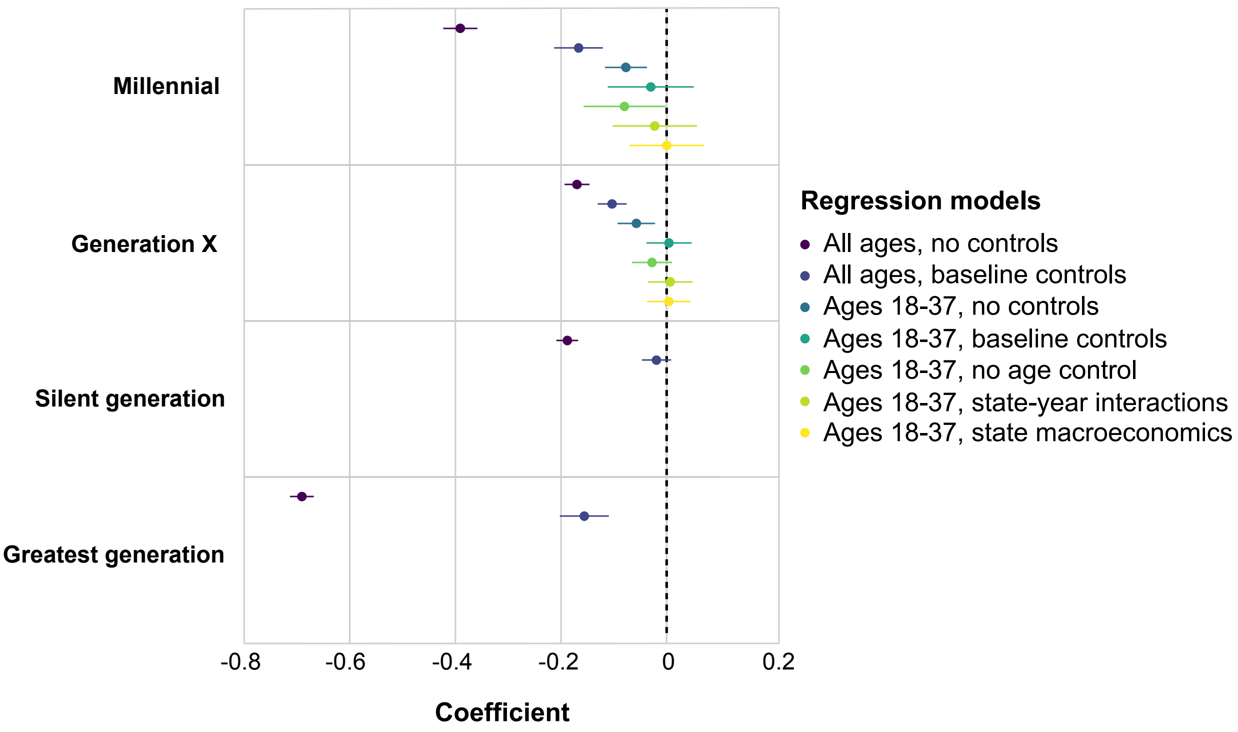
The results from our statistical analysis (displayed in Figure 3.4) show that millennials do not differ in significant ways from other generations in their vehicle ownership preferences. The x-axis in Figure 3.4 shows the magnitude of the coefficient measuring the impact that generation has on vehicle ownership (a negative value indicates that an average member of the specified generation owns fewer vehicles than an average baby boomer). Each dot refers to results from a different model formulation. The dark purple, dark blue, and dark teal dots show the impact of generation without controlling for relevant socio-economic variables (an oranges-to-apples comparison). Specifically, the dark purple dot indicates that, on average, millennials own 0.4 fewer vehicles per household than baby boomers. These results confirm the general notion that millennials own fewer vehicles than baby boomers. In contrast, the light teal dots show the impact of generation on vehicle ownership once all relevant socio-economic factors have been controlled for (an apples-to-apples comparison). Baseline controls refer to the control variables mentioned above. Additionally, this model further controls for age by using only data for households where the head of household is between the ages of 18 and 37 (the current age range of millennials).

[1] The NHTS data contain household composition indicators. These indicate whether the household has 1 or 2 working adults as well as whether the household has (1) no children, (2) a youngest child between 0 and 5 years old, (3) a youngest child between 6 and 15 years old, or (4) a youngest child between 16 and 21 years old.

[2] Urban status follows the U.S. Census definition, which considers urban areas with more than 2,500 residents.

[3] The 2017 survey spans April 2016 through April 2017. We refer to it as the '2017 survey' throughout this report.

**Figure 3.4: Vehicle count regression coefficients by generation relative to baby boomers**



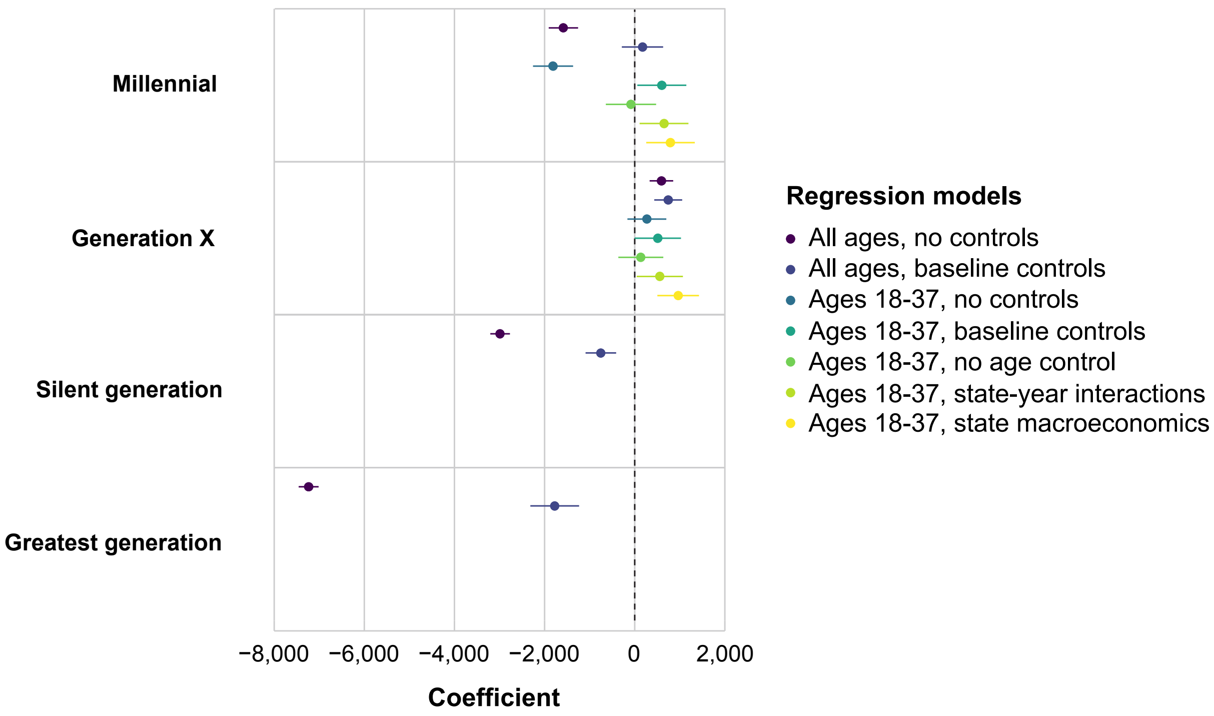
The lines in Figure 3.4 display the 95% confidence interval around the coefficients. As illustrated, the coefficient for the impact of generation is not significantly different from zero. The remaining green, yellow-green, and yellow dots show that these results are robust to alternative model specifications where these alternative specifications include, respectively: (1) omitting age as a control variable, while still only using data for 18–37 year-olds; (2) including state–year interactions to capture effects specific to a given state in a given year; and (3) including state-level macroeconomic data. We validated these findings by repeating the analysis using data from the U.S. Census and the American Community Survey (ACS). A decomposition analysis further confirms that lower vehicle ownership among millennials is due primarily to this generation's distinct socio-economic characteristics (Knittel and Murphy 2019).

### *The impact of generational preferences on VMT*

Differences in VMT across generations also do not appear to be significantly affected by any differences in preferences. Figure 3.5 displays our regression results for VMT. Differences in VMT between millennials and baby boomers based on oranges-to-apples comparisons (dark purple and dark teal dots) disappear when we control for relevant socio-economic factors. Some of our models suggest that millennials even prefer to drive *more* than baby boomers (light teal, yellow-green, and yellow dots) but this result is not robust to alternative model assumptions (as shown by the green dot) (see Knittel and Murphy 2019).

Overall, our analysis indicates that there are no substantial differences in generational preferences—either in terms of vehicle ownership or VMT—after controlling for socio-economic factors. This suggests that changes in generational preference are unlikely to be a determining factor for projecting mobility demand to 2050 compared to other socio-economic and market drivers. Therefore, we turn next to assessing those key market forces that could substantially influence future demand.

Figure 3.5: VMT regression coefficients by generation relative to baby boomers



### 3.1.3 Predicting Key Drivers of Mobility Demand to 2050

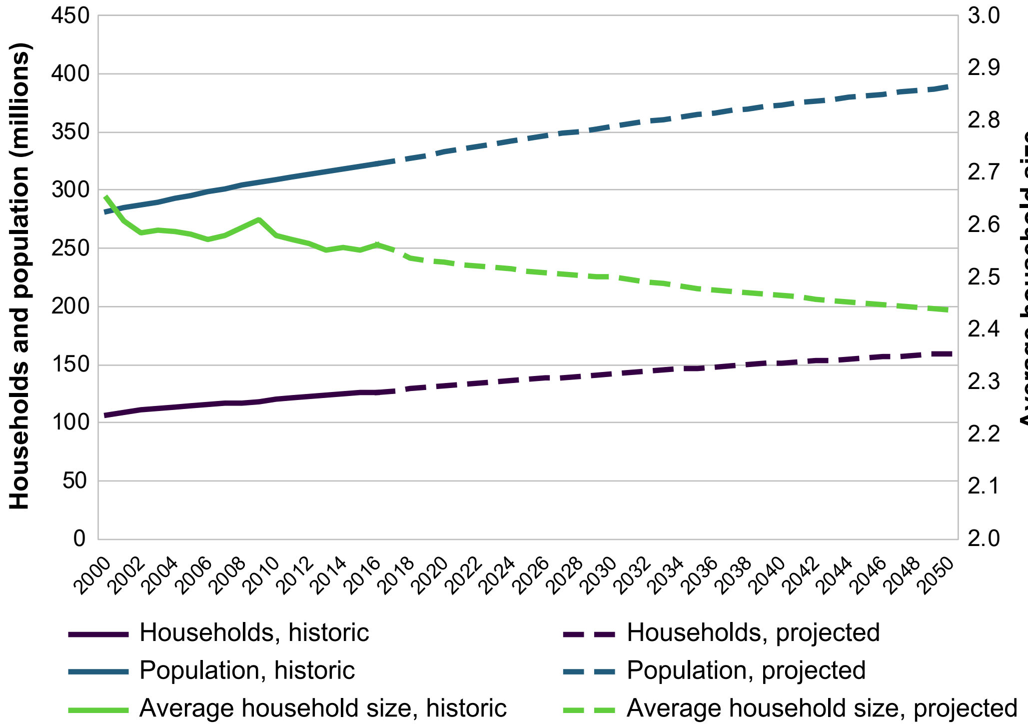
Here we explore how key drivers of mobility demand will evolve in the future. We begin by predicting how the number of households and their characteristics will develop to 2050. We then examine how these and other socio-economic factors will predict changes in mobility demand in the U.S. over the next three decades.

*U.S. population and household growth*

Growth in the size of the U.S. adult population and the number of U.S. households is the first main driver of increased demand for vehicles. The U.S. Census Bureau projects that the national population will grow by 20% from 2017 to 2050 (2017). Trends in vehicle ownership are also influenced by the future number of households. As it is typical for members of the same household to share vehicles, vehicle purchasing decisions are best studied at the household level. The number of U.S. households grew faster than the population itself in the 2000–2017 period (U.S. Census Bureau 2018b), in part because of growth in the number of single-parent households and a decline in the number of children per household (Pew Research Center 2015). Between 2000 and 2017, the size of the average U.S. household declined 4%, from 2.65 people per household, on average, to 2.55 people per household.

To shed light on household formation, we use the headship rate metric: the number of people in a certain age range who serve as heads of households compared to the total number of people in the same age range in the entire U.S. population. The evolution of headship rates over time differs by age group. For example, the headship rate for young adults between the ages of 25 and 34 declined 4% from 2000 to 2017 according to our analysis, indicating that people in this age group have become less likely to form households. In contrast, the headship rate among those 75 years and older increased by almost 4% over the same time period, which indicates a rise in single-person households in this older age group.

**Figure 3.6: Projections for U.S. population, number of households, and household size**



The number of households in the U.S. can be estimated from projections for headship rates and population. We construct future projections for headship rates differentiated by age by extending historical trends using linear regressions. We assume the trends continue until 2030, after which headship rates are assumed to stay constant. Combining these projections with U.S. Census Bureau projections of population by age allows us to estimate the total number of U.S. households. Figure 3.6 displays the results of this calculation alongside the historical trend. The figure also displays our estimates of future average household size (right axis). Based on this analysis, we project that the number of households in the U.S. will increase 25% from 2017 to 2050.

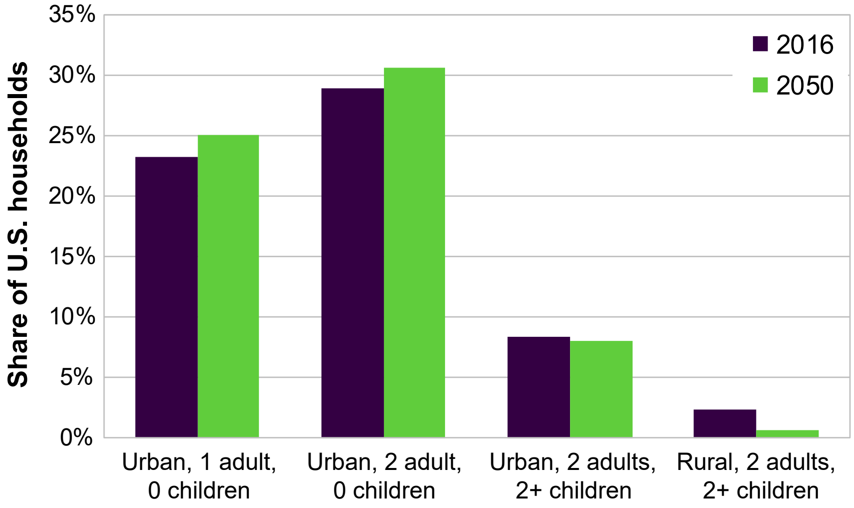
Predicted growth in the number of households suggests that the market for personal vehicles in the U.S. will continue to expand. But whether demand for additional vehicles materializes will depend on a second set of factors: how individual households make vehicle purchasing decisions, and, with regard to VMT, how individual household demand for miles driven changes in the future.

### *Changes in American household characteristics*

We project that average household income in the U.S. will grow by 54% in real terms from 2017 to 2050. This projection is based on GDP results from the EPPA model, combined with the household projections presented above. For purposes of our vehicle ownership and use projections, we assume that this growth is equally distributed among households. The share of urban dwellers is projected to grow from 80% in 2017 to 89% in 2050 (United Nations 2018). In contrast, we project that average household size will decline over this time period by about 5% (from an average of 2.6 persons per household to 2.5 persons per household) based on the projections we previously presented. The average number of children per household is also projected to decrease by 16% from 2016 to 2050, based on U.S. Census projections and our household projections. The number of adults per household is projected to decline 1.6% in the same time period.

These socio-economic shifts will change the prevalence of different household types. Figure 3.7 displays our projections for the changing

Figure 3.7: Prevalence of selected U.S. household types, 2016 and 2050



prevalence of a small selection of American households. We estimate shares of household types using an optimization method that keeps the distribution of household types as close as possible to the 2017 distribution while matching average household socio-economic characteristics with the projections presented in the previous paragraph (more details are provided in Appendix B). As illustrated by Figure 3.7, we project that smaller, urban households will become somewhat more common, while large, rural households will become somewhat less common.

### *Socio-economic drivers of mobility demand*

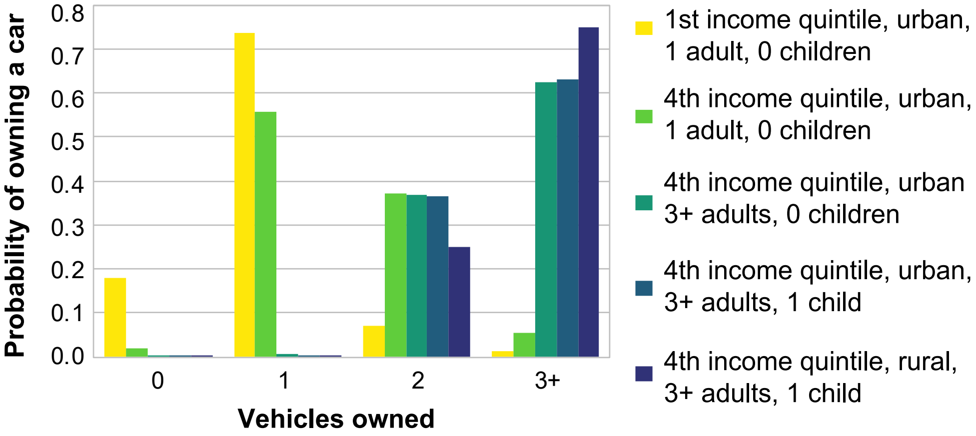
We turn next to socio-economic variables as predictors of future mobility demand. Here we develop econometric models to explore the ability of such factors to predict the probability that a household owns a given number of vehicles, as well as to predict annual household VMT. Modeling the relationship between socio-economic factors and mobility demand allows us to project demand for different types of households. We then estimate total vehicle ownership and usage by combining these models with projections for the changing prevalence of different household types (discussed above).

Four variables are likely to have a significant impact on future demand for vehicles and VMT: household income, number of adults, number of children, and urban status (that is, whether the household resides in an urban area). To estimate the impact of these variables on vehicle ownership, we fit a nested series of binary logistic regressions to historical data from the NHTS (more details on the methodology can be found in Appendix B). We also use a linear regression to model household VMT as a function of these variables.

Figure 3.8 displays our estimates for the current impact of each socio-economic variable on the probability of vehicle ownership. The figure shows five types of U.S. households, each distinguished by a colored bar. The sum of the probabilities for each type of household is 100%. At one extreme, a household in the first income quintile (corresponding to $5,000–$30,000 annual income), living in an urban area, and with only one adult member, is more than 70% likely to own one vehicle. In contrast, an otherwise similar household in the fourth income quintile (corresponding to $88,500–$137,500 annual income) is considerably more likely to own two vehicles. This finding illustrates the impact of income on demand for vehicle ownership.

Household size also increases the probability of owning more vehicles, as shown by the green bars. Number of children has a small but statistically significant impact on the probability of vehicle ownership for different households. The impact

**Figure 3.8: Impact of household socio-economic characteristics on current (and future) vehicle ownership**



of children on the probability of vehicle ownership appears small, in part due to the categories shown in Figure 3.7. Children make a smaller difference for households with three or more adults because such households are already likely to own more vehicles. The presence of children has a larger impact on vehicle ownership for one-adult households (not illustrated). Finally, the probability of ownership is higher for rural households, as illustrated by the purple bars. All four variables are statistically significant predictors of vehicle ownership at the 99% confidence level.

We can use these estimated coefficients along with our projections for changes in household number and characteristics to predict future demand for mobility in the U.S.

### 3.1.4 Future Demand for Mobility in the U.S.

We estimate future demand for vehicles and VMT by applying our household-level models across all household types while also accounting for the changing prevalence of different household types in the future. The models have been calibrated to reproduce 2016 demand. Our projections for future vehicle ownership are presented in Figure 3.9. This figure assumes that the number of non-household vehicles (commercial and government-owned fleets), which currently represent 10% of all light-duty vehicles in the U.S., grows at the same rate as the number of household vehicles estimated by our model. With these assumptions, total light-duty fleet size is projected to grow to 319 million vehicles by 2050. This amounts to an increase of 28% compared to 2017, or an average growth rate of 0.7% per year, which is less than half the long-term average rate of growth—of 1.9% per year—experienced between 1970 and 2017. Average levels of motorization rise more slowly, increasing 7% over the study period, from 0.77 vehicles per person in 2017 to 0.82 vehicles per person in 2050 (this translates to an average growth rate of 0.2% per year).

The impact of individual demographic and socio-economic factors is displayed in Figure 3.10. Future growth in demand is mainly driven by an increase in the number of households. By comparison, income plays a relatively smaller role. Decreasing household size and increasing urbanization slightly reduce overall demand. These factors have less of an impact than income, largely because they are not projected to change as much as income between 2017 and 2050.

#### *Vehicle miles traveled in the U.S.*

Next, we explore the impact of socio-economic factors on VMT. We estimate VMT based on household characteristics with regard to income, number of adults, number of children, and urban status using a similar method as described previously—the main exception is that we apply a linear regression (more details can be found in Appendix B).

**Figure 3.9: Projected vehicles and motorization in the U.S.**

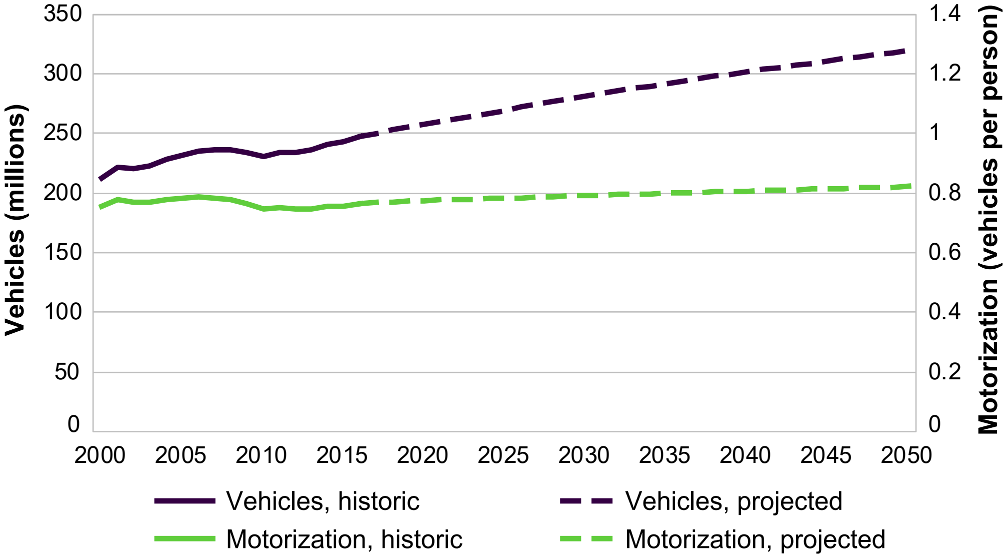
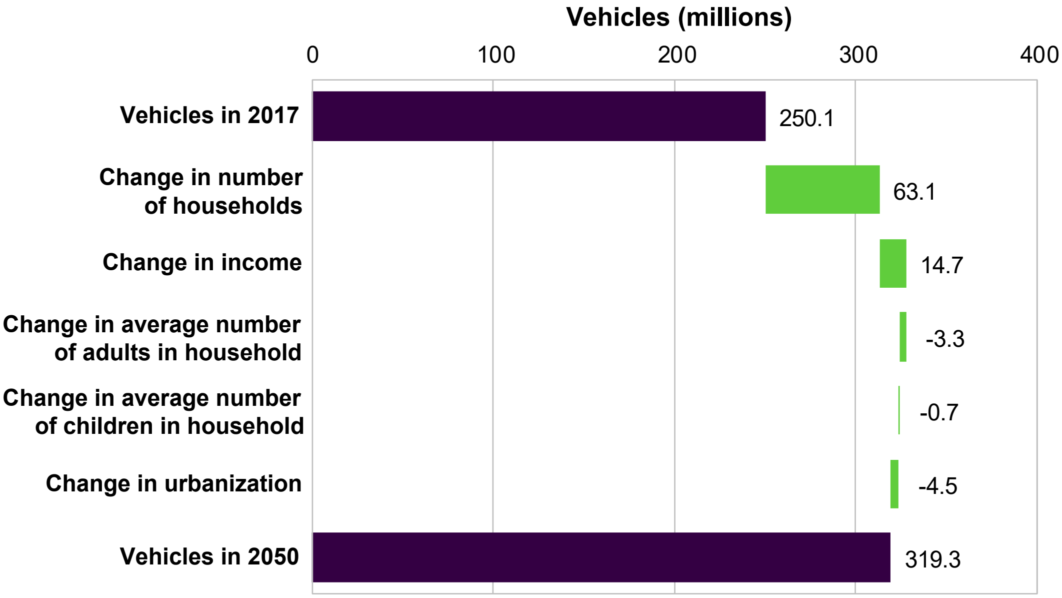


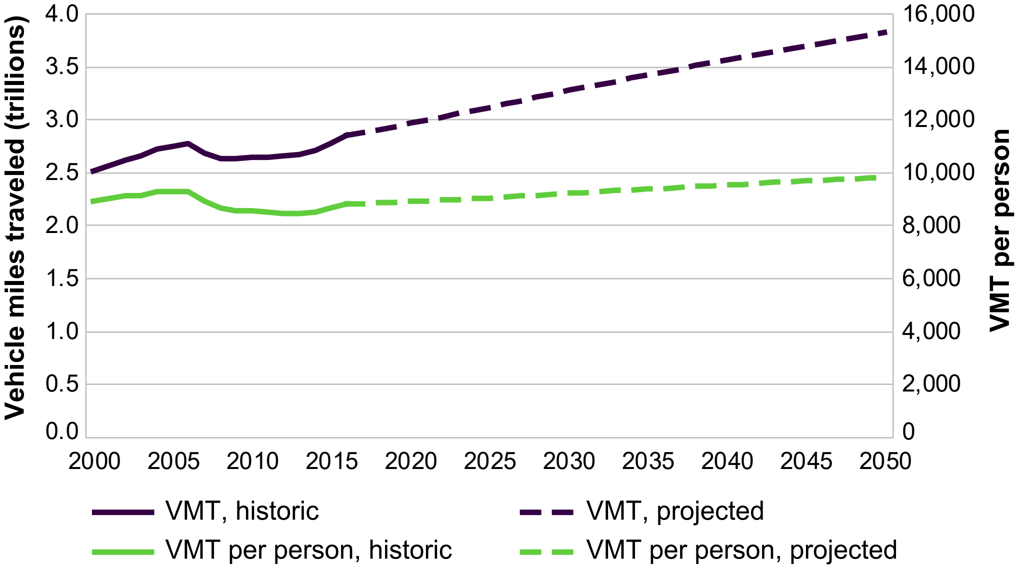
**Figure 3.10: Impact of individual factors on household vehicle demand growth**



As illustrated in Figure 3.11, this approach yields projected VMT growth of 33% over the 2017–2050 period, or an average annual growth rate of 0.9%. By contrast, the historical average annual growth rate for the period 1971–2016 was 2.2%. Similar to our projections for vehicle ownership, VMT growth is driven primarily by an increase in the number of households together with rising household income. VMT per person grows more slowly than total VMT, by 11% between 2017 and 2050, or 0.3% per year, on average.

Since VMT grows faster than the number of vehicles, we project that VMT per vehicle will rise by 4% from 2017 to 2050. This can partially be explained by our finding that VMT is more

**Figure 3.11: Projections for future VMT in the U.S.**



sensitive than vehicle ownership to future income growth. Thus, rising incomes are projected to have a greater impact with respect to increased driving than increased vehicle ownership.

Individual factors that drive projected VMT growth are shown in Figure 3.12. The main factor is an increase in the number of households. Among socio-economic characteristics, household income is the dominant driver of growth out to 2050.

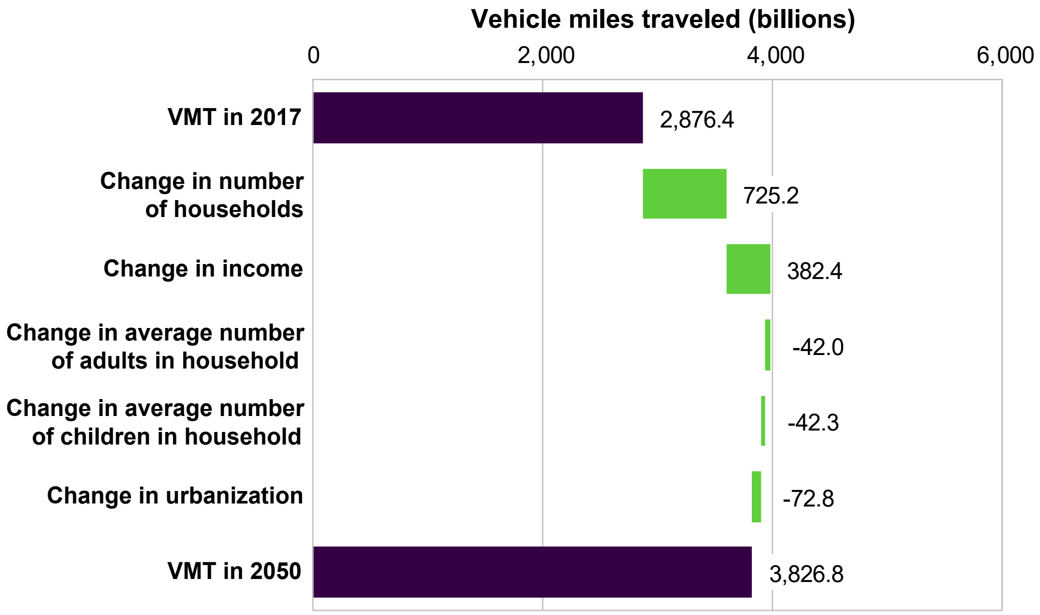
### 3.1.5 Summary

In the U.S., socio-economic factors such as household income, household size, and urbanization have a greater impact on vehicle ownership and VMT than generational preferences. Therefore, future demand for mobility will likely be influenced by demographic trends and by the changing socio-economic characteristics of American households.
In particular, an increase in the number of households in the U.S. is projected to sustain demand for both vehicles and VMT, overwhelming the demand-slowing effects of shrinking household size and urbanization. We also project that the overall ratio of vehicles to people will grow only slightly, which may indicate that vehicle ownership in the U.S. is approaching saturation.

It is worth noting that our projections omit crucial variables that may influence future demand for mobility such as the rising prevalence of the mobility-on-demand business model and the advent of autonomous vehicles. These disruptions to the auto industry will have implications for the costs of mobility and the paradigm of vehicle ownership. Our projections for fleet size are particularly sensitive to the influence of mobility-on-demand services, which may reduce car ownership. However, the relationship between mobility-on-demand and VMT is less clear. Regardless of nascent auto industry disruptions, Americans will likely continue to show relatively high demand for mobility (as reflected in VMT).

The results presented in this section shed some light on what the future may look like absent significant disruptions to the automotive industry. Should consumer behavior remain similar to what we observe in the early 21st century, the U.S. may see continued, albeit slower, growth in number of vehicles and VMT. Rising demand for mobility poses a challenge for policymakers and regulators seeking to minimize the externalities of transportation, including climate change, air pollution, and road congestion.

Figure 3.12: Impact of individual factors on VMT demand growth



## 3.2 MANAGING MOBILITY DEMAND IN CHINA

While growth in vehicle demand in the U.S. is slowed, China's vehicle market is booming, particularly in cities (Sun, et al. 2015). Continuing motorization, accompanied by trends of urbanization and sprawl, is putting pressure on China's cities in the form of congestion and air pollution, posing challenges for city governments.

China is often seen as having a top-down, command-and-control political structure, with policy largely dictated by the national government. In recent years, however, transportation policymaking in China has been decentralized, with municipal/city governments being allowed to enact innovative policies that better respond to local conditions. This has led to heterogeneity in municipal-level transport policies that underscores the diversity of urban challenges and mobility issues facing different Chinese cities. This section explores how Chinese city governments are responding to these challenges by formulating and implementing new, innovative urban transportation policies. We find that the complex and nuanced adoption of transportation policies across Chinese cities is at least partially evidence-based and responsive to local conditions.

We adopt a robust, mixed-methods approach that combines qualitative understanding of the policymaking process and existing transportation policies with quantitative modeling. Our analysis attempts to answer several questions, starting with: *What prompts local governments in China to adopt transportation policies?*

To explore how transportation policy is formulated in Chinese megacities, we conducted in-depth, semi-structured interviews with government officials, academics, and transportation professionals in Beijing and Shanghai. The interviews were designed to identify important actors in the transportation policymaking process within these cities and gain insight into key contributors and obstacles to effective and efficient policymaking. The results suggest that most transportation policymaking is reactive as local governments attempt to respond to local problems. To further probe the relationship between transportation policies and local conditions, we explored whether the types of policies adopted by different Chinese cities reflect variation in their levels of urbanization and motorization. Finally, given that car ownership and usage restrictions could have a large impact on the automotive market in China, we modeled the uptake of these large-scale policies by cities over time to understand what prompts their adoption.

### 3.2.1 Transportation Policy Formulation in Chinese Megacities

#### *Data and methods*

Transcripts from our interviews with municipal officials, academics, and transportation professionals in Beijing and Shanghai were coded in three steps using the "grounded theory" approach developed by Corbin and Strauss (2008). The goal of this method is to identify key words (actors and themes) that appear across multiple responses, connect these words to specific instances of policy implementation, and then organize them chronologically in a processual model. Using this three-step method, we identified underlying contributors and obstacles to effective and efficient policymaking and mapped how they fit into the overall process by which authorities in Chinese megacities arrive at policy decisions (Chun, Moody, and Zhao 2019).

#### *Contributors to transportation policymaking*

1. *Learning from other cities:* There is substantial evidence that government officials in Shanghai and Beijing learn from the implementation of transportation policies in other cities, both domestic and foreign. Government officials in both cities were also aware that their new transportation policies might serve as examples for other Chinese cities. These findings corroborate an existing literature that identifies Beijing and Shanghai as past and current trendsetters in innovative transportation policymaking in China (Li 2007).

2. *Public opinion:* While the general public is not directly involved in formulating policy in China (Li, Ng, and Skitmore 2012; Li and de Jong 2017), our interviews show that city officials pay significant attention to public perception. Public outcry helps draw attention to local problems and is often the impetus for policy formulation. Interviewees (in Shanghai particularly) also suggested that the government actively collects information about public reactions to draft policies before implementing them.

3. *Transportation informatization:* This term refers to newly developed information technologies (such as customized station videos, mobile phone applications, and other computer software) that provide disaggregated data to system users and operators in near real-time. These data can be used to disseminate information to the public and to more accurately formulate and target transportation policies. Interview participants from both cities expressed confidence that new information platforms will facilitate more data-driven transportation policy decisions in the future.

#### *Obstacles to transportation policymaking*

1. *Lack of cross-departmental communication and coordination:* Interview responses suggest that departments within the same city government are often reluctant to share information, even when certain policy outcomes rely heavily on cross-departmental correspondence.

2. *Public complaint:* While general public support can facilitate a transportation policy decision, specific public complaints can inhibit policy adoption. Thus, depending on the policy and the city, public opinion can both help and hinder decision-making with respect to transportation policies.

3. *Unilateral decision-making:* Officials in both cities noted that one or two individuals in top leadership positions in the city government (such as the mayor) usually make final policy decisions. These decisions may not always reflect the detailed recommendations or findings of research reports prepared by technical staff.

4. *Lack of adaptiveness:* Many interviewees suggested that the current transportation policy decision-making process is inefficient because it lacks the capacity to adapt to ever-changing local contexts. In certain cases, initial policy recommendations are made on the basis of research findings that become outdated before the policy is actually implemented.

#### *The transportation policymaking process in Chinese megacities*

In addition to identifying key contributors and obstacles to decision-making, we also sought to clarify the process by which information flows among actors in city government before they arrive at policy decisions. Figure 3.13 illustrates connections between each of the contributors and obstacles identified above and relevant actors and information flows within the decision-making process.

We find that transportation policies at the city level are responsive to local transportation problems or strong demand from the general public. Once a problem is identified, the transportation committee in each city tasks its respective research center to analyze the problem, formulate possible policy responses, and produce recommendations. These recommendations may lead to direct policy adoption by the city transportation committee; alternatively, recommendations may be submitted to the city government leadership for a final decision.

### 3.2.2 Transportation Policy Profiles of Different Chinese Cities

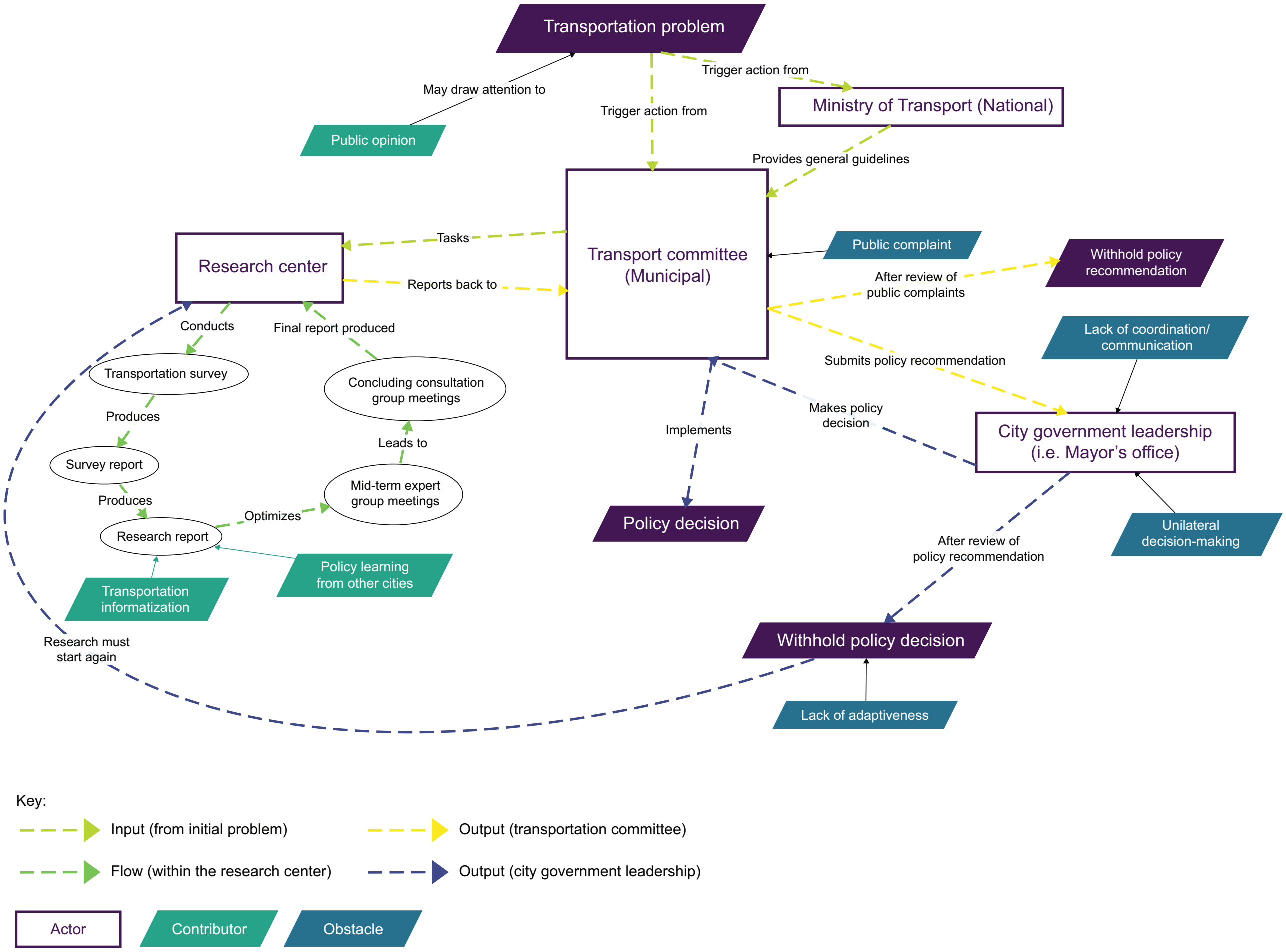
Chinese megacities, such as Beijing and Shanghai, are piloting innovative transportation policies and are often seen as trendsetters for other Chinese cities. However, the experiences of China's largest and wealthiest cities may not apply to other cities with different urban forms and travel patterns. Therefore, we adopt a mixed methods approach (Teddlie and Tashakkori 2013) to explore whether transportation policies generally reflect the unique land use and transportation conditions of the cities that adopt them. First, we cluster all 287 official Chinese cities into four clusters based on similarities in their urbanization and motorization trends over the past 14 years. Next, we collect qualitative information on 20 different categories of transportation policy for 42 representative cities. We then compare the types of transportation policies adopted by the representative cities for each cluster. This approach allows us to contextualize the policy profiles of Chinese cities that face different urbanization and motorization challenges (Moody, et al. 2019).

#### *Chinese city clusters*

Cities in China are often classified into three tiers based on some combination of GDP, population, and level of political administration. Politically, Beijing, Shanghai, and a few other megacities are often included in the first tier, provincial capitals are considered the second tier, and all other cities are grouped into a third tier (Li 2007). While a simple classification of this sort may be useful for some political and administrative purposes, a more nuanced classification that accounts for additional features—such as city density, infrastructure, and mobility patterns—may be more suited to analyzing city-level transportation policies.

Using panel data for 287 Chinese cities from 2001 to 2014, we conduct a time-series clustering method on eight variables: four indicators related to urbanization (total urban population, GDP per

**Figure 3.13: Processual model for transportation policymaking in Chinese megacities (such as Beijing and Shanghai)**



capita, urban density, and road area per capita) and four indicators related to motorization (number of automobiles, taxis, buses, and subway lines per capita[4]). Based on 14-year trends in our eight variables (Figure 3.14), we classified Chinese cities probabilistically into four clusters:

1. Large, dense, wealthy megacities with heavy rail (23 cities, including Shanghai, Beijing, Guangzhou, Shenzhen, Tianjin, and Hangzhou);
2. Low-density, wealthy cities with auto-oriented mobility patterns (41 cities, including the cities of Haikou and Sanya in Hainan Province);
3. Low-density, medium-wealth cities with moderate mobility (134 cities); and
4. High-density, low-income cities with lower mobility levels (89 cities).

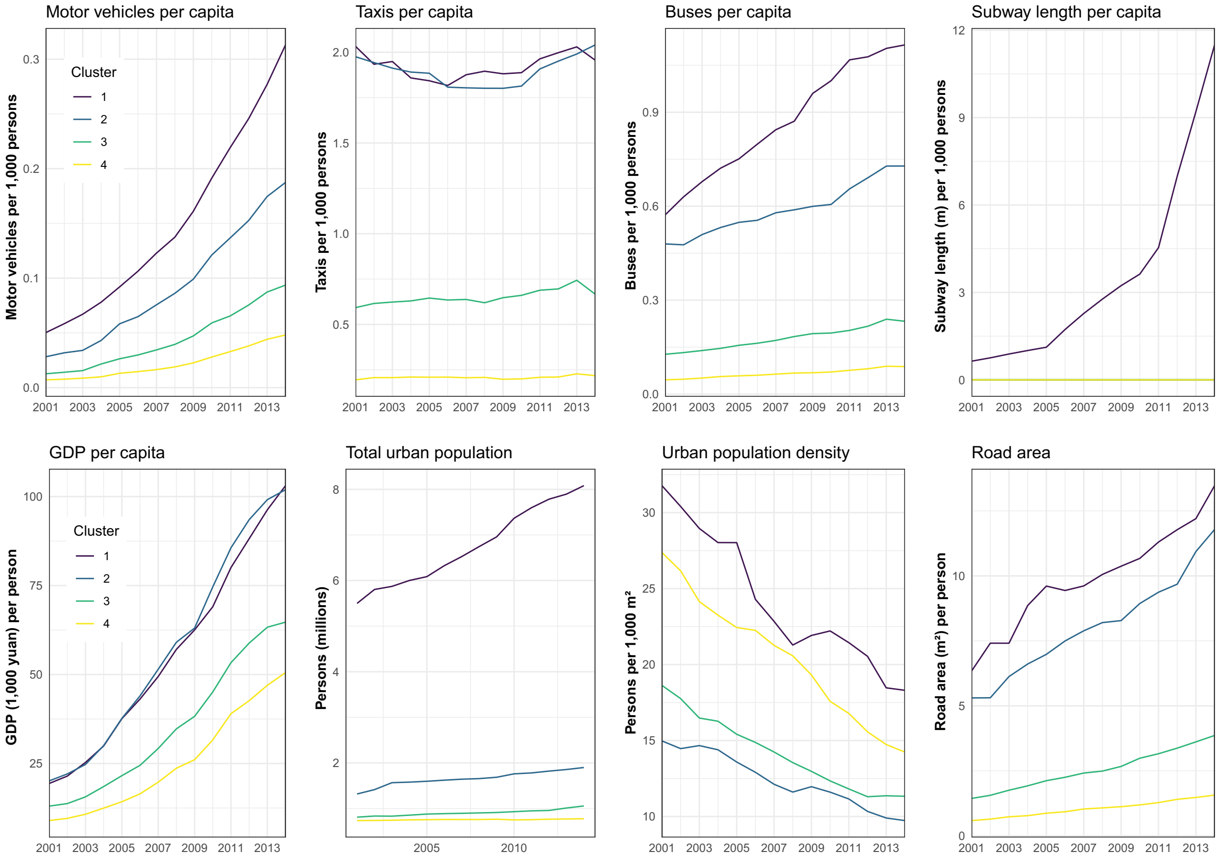
Table 3.2 summarizes the four clusters based on each of the eight indicators used in the clustering analysis in the most recent year for which data are available (2014).

By accounting not only for each city's size and wealth, but also for key variables such as urban density, infrastructure, and motorization, this

---

[4] Note that we used total registered population as the denominator instead of total urban population because the automobile numbers reported in the statistical yearbooks refer to the automobiles owned by the total registered population. Likewise, the total registered population is used as the denominator for the bus number per capita and taxi number per capita. Subway lines per capita are calculated by dividing by total urban population.

**Figure 3.14: Average time series trajectories of the eight urbanization and motorization indicators used in our clustering analysis for Chinese cities**



clustering method provides a classification of Chinese cities that is more nuanced than the traditional three-tier structure. In fact, Cluster 1 includes most traditional Tier 1 and Tier 2 cities, while Clusters 2, 3, and 4 identify distinct patterns among medium and small Chinese cities that traditionally have all been considered Tier 3. By examining the temporal dimension and by specifically analyzing urbanization and motorization indicators, our clustering exercise indicates that variation among cities in Clusters 2, 3, and 4 is as important as variation between these cities and the largest and wealthiest megacities, such as Beijing and Shanghai.

### *Policy profiles across city clusters*

To compare transportation policy priorities within each city cluster and across clusters, we collected qualitative policy information for 42 cities from each city's 2017 *Report on the Work of the Government* (政府工作报告), an official transcript of the oral report given by the mayor to the national government. We conducted a keyword search on each city government report and extracted all information regarding transportation policies. Text segments for each city were manually categorized, labeled, and condensed into 20 policy types. The cities were then categorized according to the results of the clustering analysis and their policy profiles were compared within and across clusters (Moody, et al. 2019).

While significant variations exist between cities, we find clear patterns in the types of transportation policies adopted within city clusters and clear differences across clusters (Table 3.3). We find that wealthy megacities (Cluster 1) are leveraging their existing urban rail systems with multimodal integration and transit-oriented development, while more car-oriented wealthy

**Table 3.2: Average values ± standard deviations for eight urbanization and motorization indicators across four Chinese city clusters (2014)**

| | Indicator (unit) | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|---|
| Urbanization | Total urban population (million) | **8.08** ± 5.58 | 1.97 ± 1.34 | 1.04 ± 0.60 | 0.80 ± 0.40 |
| | GDP per capita (1,000 Yuan/p) | 103.07 ± 33.22 | **100.63** ± 55.89 | 66.43 ± 27.16 | **49.70** ± 27.60 |
| | Urban density (p/1,000 m$^2$) | 18.31 ± 14.91 | **9.91** ± 4.01 | 10.85 ± 4.48 | **14.76** ± 7.35 |
| | Road area (m$^2$) per capita | 13.47 ± 14.72 | **11.82** ± 8.38 | 3.98 ± 1.96 | **1.60** ± 0.78 |
| Motorization | Automobiles[a] per 1,000 p | 0.31 ± 0.20 | **0.19** ± 0.09 | 0.09 ± 0.04 | **0.05** ± 0.02 |
| | Taxis per 1,000 p | 1.96 ± 1.34 | **2.01** ± 1.19 | 0.70 ± 0.54 | **0.22** ± 0.13 |
| | Buses per 1,000 p | 1.11 ± 0.85 | 0.73 ± 0.44 | 0.24 ± 0.14 | 0.09 ± 0.05 |
| | Subway lines (m) per 1,000 p | **11.49** ± 8.95 | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.00 ± 0.00 |

Note: **Bolded** indicators are key differentiators between clusters; m = meters; p = people.

[a] The dataset includes information on five major categories of motor vehicles: total automobiles, motorcycles, tractors, trailers, and others. Among the five categories, automobiles and motorcycles account for 90% of the total number of vehicles. For this analysis, we considered only total number of automobiles, including passenger automobiles, freight automobiles, and other types of automobiles.

**Table 3.3: Combined results of the mixed methods approach to identifying transportation policy profiles for Chinese city clusters**

| | Key features in terms of urbanization and motorization | Transportation policy priorities |
|---|---|---|
| **Cluster 1** | Large, dense, wealthy megacities with passenger rail | • Expanding existing urban rail<br>• Improving and expanding bus services<br>• Improving multimodal connectivity through transfer hubs, including non-motorized forms of transport<br>• Connecting land use and transport planning with transit-oriented development<br>• Continued investment in urban expressways |
| **Cluster 2** | Low-density, wealthy cities with auto-oriented mobility patterns | • Developing new urban rail<br>• Improving and expanding bus services<br>• Public transport discounts (to develop PT mode share) |
| **Cluster 3** | Low-density, medium-wealth cities with moderate mobility | • No urban rail development, so focus is on improving and expanding bus services<br>• Particular emphasis on clean energy (electric) buses<br>• Significant ongoing investment in additional parking spaces as well as urban and rural roads |
| **Cluster 4** | High-density, low-wealth cities with lower mobility levels | • Focused on road development to connect the urban core to rural areas on the periphery<br>• Prioritizing interconnection with other cities in the region (via road, rail, and air) |

cities (Cluster 2) are building urban rail and discounting public transport. Sprawling, medium-wealth cities (Cluster 3) are opting for electric buses. The poorest dense cities with low mobility levels (Cluster 4) have focused on road building to connect the urban core to rural areas. Together, these patterns suggest that the types of transportation policies being adopted by different Chinese cities are at least partially reflective of local trends in urbanization and motorization.

### 3.2.3 Drivers of Comprehensive Car Restriction Policy Adoption in Chinese Cities

As China's cities continue to urbanize and motorize, many city governments are implementing restrictions on car usage or ownership. In this study, we consider the adoption of "comprehensive" car restriction policies. By "comprehensive" we mean those policies that are citywide, in effect year-round, and apply to most types of vehicles. These comprehensive car restriction policies include car usage restrictions (often based on the last digit of the car's license plate[5]) and ownership restrictions (that ration the number of new license plates sold in a city and allocating these license plates through lottery or auction). Here we investigate what prompts cities to adopt comprehensive car ownership and usage restrictions, which is important for anticipating future trends in the world's largest automobile market. In Section 3.3, we dive deeper into understanding the cumulative impact of car ownership restrictions on China's car market.

### *Investigation of policy documents*

To explore the adoption of car restriction policies in China, we began by compiling a database of these policies and their main features, by year, over the period 2001–2014, for each of China's 287 cities. We downloaded and collated the policy documents for each large-scale car ownership and usage restriction implemented in any city in any year since 2001. For each policy, we noted the national and/or local laws and regulations cited in support of the legitimacy of the policy, as well as the local government's objectives in implementing the policy. We found that 44% of all car restriction policies cited precedents in national laws related to transportation and road safety; in addition, 30% cited national laws related to preventing air pollution. In addition, local regulations concerning pollution mitigation were cited most often (in 51% of cases). Regarding policy objectives, authorities referenced improving air quality or addressing local pollution in approximately 84% of the car restriction policies adopted, and an additional 28% of policies were justified on the basis of the related objective of improving public health. Only approximately 21% of the policy documents we examined referred to mitigating transportation congestion or improving travel efficiency as the primary policy purpose. Thus, we find that the primary reason given by local governments for adopting car restriction policies is to improve air quality and, secondarily, to mitigate congestion (Wang, Moody, and Zhao 2019). We next sought to test empirically whether city-level adoption of comprehensive car restriction policies is indeed a response to local air quality problems and numbers of vehicles on the road.

### *Quantitative adoption model*

To complement the information collected from policy documents, we compiled a dataset of economic, socio-demographic, transportation, and urbanization indicators for all 287 Chinese municipalities over the period 2001–2014 by using the China Premium Database from CEIC, a data company. We refined and cross-validated the information in the CEIC database to corresponding city and provincial yearbooks, paying particular attention to any outliers or missing data points. In addition, we integrated a subway-length variable into our database using information from the website of China Association of Metros. Finally, we collected air pollution index (API) values for all cities from the official website of China's Ministry of Ecology and Environment. Both the mean and maximum API values in a given year were recorded for each city.

For each city-year, we used as the dependent variable a binary indicator of whether or not the city had adopted a comprehensive car ownership and usage restriction policy. Duration models were used to assess the statistical significance and predictive accuracy of 14 indicators measuring economic growth, population, air pollution, car ownership, urban density, and local transportation conditions in predicting the adoption of comprehensive car restriction policies (Cox 1972; Han and Hausman 1990). Our model results suggest that cities with a higher number of motor vehicles per capita and higher mean and maximum API are significantly more likely to adopt car restriction policies in a given year. These results

---

[5] For instance, cars can be prohibited from driving on certain days based on whether their license plate number ends on an odd or even digit. This study excludes more selective and intermittent car usage restrictions such as policies that limit driving only in some areas of the city, during certain times of day (such as rush hour), on particular days (such as high-pollution days or during special events), or that limit only certain types of cars (such as high emitters).

demonstrate empirically that car restriction policies are adopted in response to local problems such as air pollution and traffic congestion, as opposed to general economic and land use indicators (such as total population, GDP, and urban densities) or to the presence of alternative modes of transportation (such as bus and taxi). We further find that the number of motor vehicles per capita and poor air quality remain positively and significantly predictive of the adoption of car restriction policies, across different provinces and cities (Wang, Moody, and Zhao 2019).

Taken together, these findings lead us to conclude that the adoption of comprehensive car ownership and usage restrictions in Chinese cities primarily responds to air pollution concerns and secondarily to mobility concerns. The fact that this result is consistent with the purposes stated in official policy documents lends confidence in our findings.

### 3.2.4 Summary

Transportation policymaking in China occurs primarily at the municipal level, rather than at the national level. This decentralized approach to policymaking across a diverse array of cities makes it more difficult to systematically understand trends in Chinese transportation policy and assess the potential impacts of these trends on future car consumption in an important developing market.

Our findings suggest that transportation policies in Chinese cities are developed and implemented in response to local conditions. Interviews in Beijing and Shanghai reveal that the policymaking process is often reactive rather than proactive. These Chinese megacities continue to pilot innovative transportation and mobility policies; however, we demonstrate that these policies may not fit the unique circumstances of China's smaller cities. Instead, we provide a framework for facilitating policy learning by clustering Chinese cities that are similar in urban form, travel patterns, and policy profiles (see Table 3.3).

Finally, we find that Chinese cities are adopting comprehensive car ownership and usage restrictions to address air pollution and growing vehicle demand. This suggests that as the country continues to urbanize, the economy continues to develop, and as more people buy cars, China's large, auto-oriented (Cluster 2) cities may be driven to follow the innovative (Cluster 1) megacities in adopting stringent car ownership and usage restrictions.

## 3.3 CHINA'S VEHICLE MARKET

Between 2005 and 2015, sales of passenger vehicles grew faster in China than in any other country in the world. In 2008, China overtook the U.S. as the largest auto market (International Organization of Motor Vehicle Manufacturers 2019). Despite this recent growth, car ownership in China—on a per-capita basis—is just passing the level of motorization seen in the U.S. in the 1920s (Davis, Diegel, and Boundy 2014). This suggests that car ownership in China is nowhere near the saturation point and that there is room for additional growth in the future. As the Chinese economy continues to expand and more people can afford to purchase a car, China is expected to remain a primary growth market for automobiles.

At the same time, China's megacities have been adopting policies to restrict growth in car ownership through the allocation of license plates for new internal combustion engine vehicles by lottery, auction, or both (Table 3.4). In the coming years, additional cities in China could reach congestion and air pollution levels that might prompt them to adopt car ownership restrictions (Section 3.2). While targeted at local problems, widespread adoption of these restrictions could have national implications for China's private vehicle market.

Given this dynamic context, this section explores how rising purchasing power may shape China's private car market from now to 2030. First, we develop a model that projects economically driven demand at the national level absent any city-level

**Table 3.4: Municipal car ownership restriction policies adopted by August 2019**

| City/province | Adoption year | Allocation mechanism |
|---|---|---|
| Shanghai | 1994 | Auction |
| Beijing | 2010 | Lottery |
| Guangzhou | 2012 | Lottery and auction |
| Shenzhen | 2014 | Lottery and auction |
| Tianjin | 2014 | Lottery and auction |
| Hangzhou | 2014 | Lottery and auction |
| Hainan | 2018 | Lottery and auction |

Note: The cities of Guiyang and Shijiazhuang adopted less stringent restrictions on car sales in 2011 and 2013, respectively. Guiyang's policy uses a lottery to allocate a special kind of license plate to enter specific districts that have serious congestion (generally, in the inner city). Shijiazhuang's policy does not allow households to purchase a third car.

car ownership restrictions. Then we use scenario analysis to explore the potential impact of car restrictions on the country's future vehicle stock.

### 3.3.1 Growth in China's Private Car Stock and Vehicle Sales

Car purchasing power—the combination of per-capita income and car price—has been shown to be more strongly predictive of car ownership than income alone (Huo and Wang 2012). This holds especially true for developing economies like China, where car prices are falling as the automotive industry is expanding. For this reason, we build a model that projects private car stock and sales based on the evolution of car purchasing power following the method outlined in Hsieh, Kishimoto, and Green (2018). We employ Monte Carlo simulation, conditioned on historical data,[6] to capture key uncertainties in these economically driven projections (particularly, the parameter of the Gompertz function that represents the saturation level of number of cars per household for high incomes[7]). We calculate average car prices that account for growth in electric vehicle sales required to meet the government target of 40% of vehicle sales by 2030.

Our model shows a range of possible estimates for the future stock of private cars[8] in China, with a mean predicted value of 319 million vehicles (first decile of 225 million; ninth decile of 422 million) in 2030 (Figure 3.15). By comparison, the Global Economic and Policy model with high elasticity to income, as described in Chapter 2, projects that China's fleet will reach roughly 370 million vehicles in the *Paris Forever* scenario in the same time frame. Car sales consist of "new-growth purchases" (or first-time purchases associated with rising income) and "replacement purchases" (for scrapped cars); the split between these two segments determines the maturity level of the auto market. As depicted in Figure 3.16, while current car sales in China are mainly driven by new-growth purchases, replacement purchases will dominate car sales from about 2025 onward, indicating market maturity. Table 3.5 summarizes the expected size

---

[6] Data came from the China Urban Household Survey provided by the National Bureau of Statistics of China. We use data only from 2008, 2009, and 2010 to avoid using data from years (after 2011) in which multiple cities had adopted license plate quota systems. This way, we avoid historic effects of government intervention on the relationship between car purchasing power and vehicle ownership in our no-car-ownership-restriction counterfactual model.

[7] Updates in model inputs from the model presented in Hsieh, Kishimoto, and Green (2018) are summarized in Hsieh, et al. (2019).

[8] Currently, private cars account for about 88% of all vehicles in China.

**Figure 3.15: Private vehicle stock, outcomes from Monte Carlo simulation, 2010–2030**

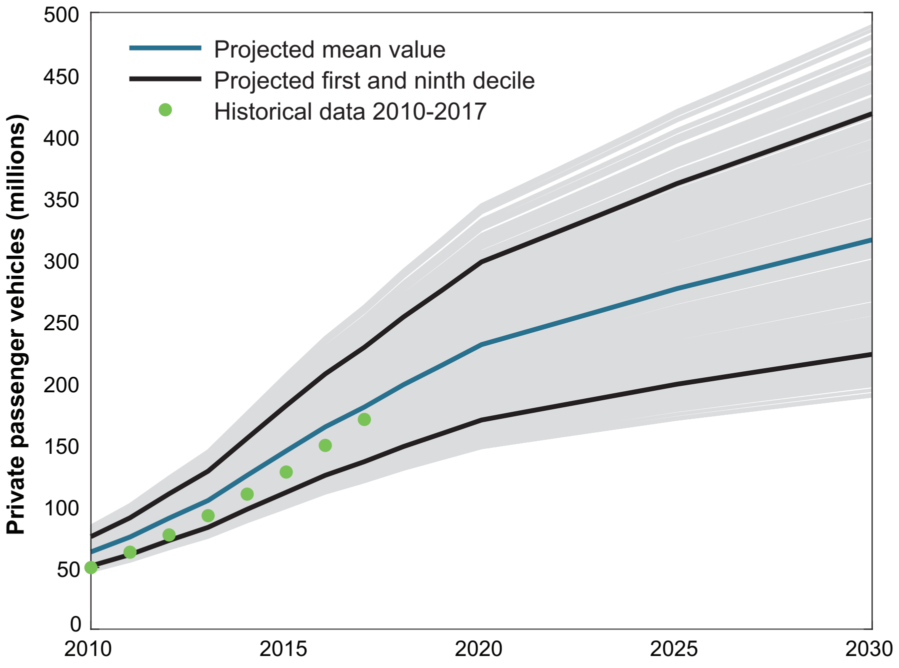


**Figure 3.16: Possible outcomes for private car sales and replacement purchase share of total car sales in China, with first decile, mean, and ninth decile indicated by lines**

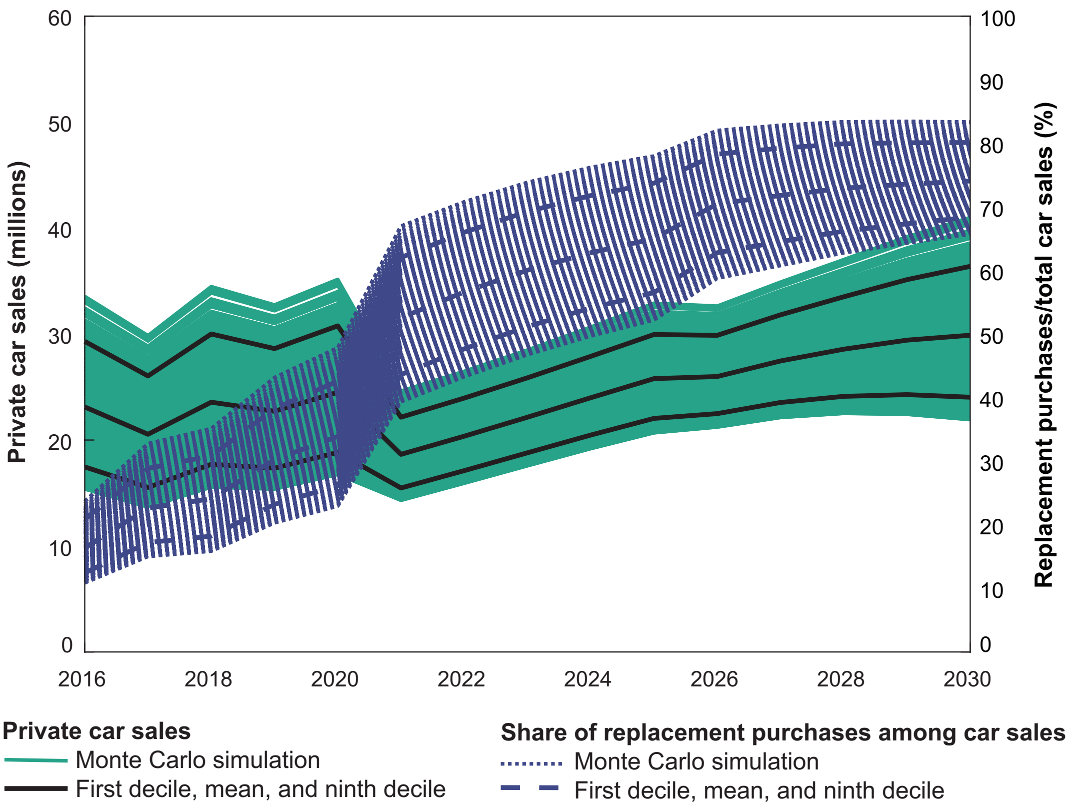


**Table 3.5: Private vehicle stock and sales projections (in the form of expected value ± standard deviation) from national model**

| | 2025 | 2030 |
|---|---|---|
| Car ownership (private cars per 1,000 people) | 195 ± 43 | 223 ± 52 |
| Car stock (million) | 276.1 ± 61.2 | 315.7 ± 73.4 |
| Car sales (million) | 25.8 ± 3.0 | 29.9 ± 4.7 |
| Replacement sales (as % of total sales) | 65.0 ± 6.4 | 74.1 ± 4.4 |

of the private car fleet, car sales, and share of replacement purchases, together with modeled standard deviations.

Based on results from a sensitivity analysis of this national model, we find affordability is the main controlling factor for the number of vehicles in China from 2019 to around 2030; subsequently, as China's economy and car market become more mature, ownership will be more tied to demographics (and, conversely, less affected by economic factors) (Hsieh, Kishimoto, and Green 2018).

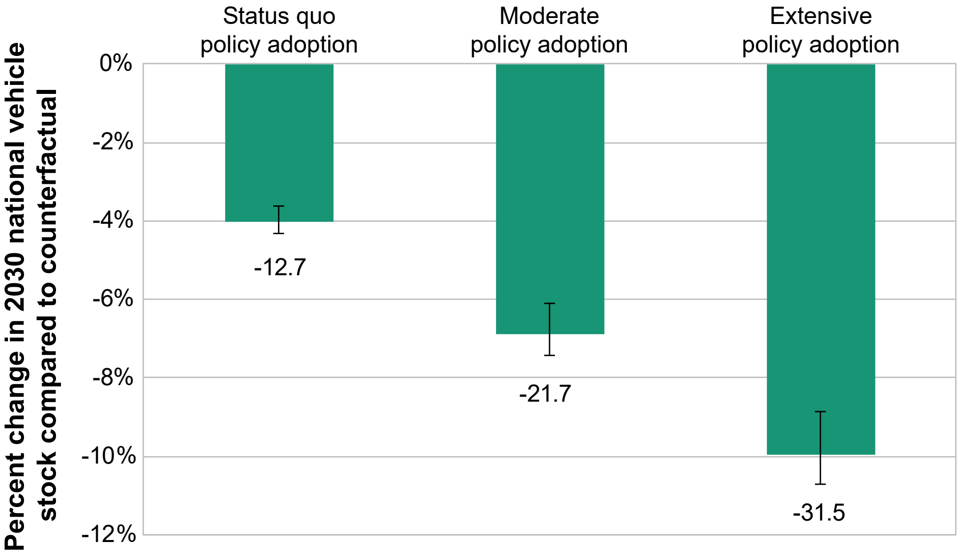
In the near term, when first-time car purchases still represent a larger share of car sales in China, both national and local governments have a significant opportunity to shape consumers' demand for vehicles, including their type, size, fuel economy, and emissions performance. By conditioning consumers' first experience of vehicle ownership, there is also an opportunity to affect future vehicle replacement decisions and additional purchases. From 2025 onward, replacement purchases account for an increasingly larger share of total vehicle sales as the market saturates. Replacement sales are not currently controlled under vehicle licensing policies in Chinese cities, and previous research in other car markets suggests that owners who already have a vehicle are likely to select a replacement that is similar, or even to upgrade to a larger or more powerful model (Knittel 2011; Sivak and Schoettle 2014). This suggests that additional government interventions must be implemented swiftly if they are to have a substantial influence on China's car market.

### 3.3.2 The Potential Impact of Car Restriction Policies

Our national-level projections for private car stock and car sales in China are based on expected growth in car purchasing power (a combination of per-capita income and car price). They do not account for municipal restrictions on car ownership. However, given that six Chinese megacities, along with the island province of Hainan, have adopted such policies (Table 3.4), there is reason to believe that additional Chinese cities may adopt similar restrictions to address growing air pollution and congestion (as discussed in Section 3.2 of this chapter). While targeted at local problems, widespread adoption of these restrictions could have national implications on China's private vehicle market. In fact, fearing the impact of additional city-level ownership restriction on China's domestic car manufacturing industry, China's national government announced a new policy to temporarily stop local governments from implementing new restrictions on car purchases for 2019-2020 (National Development and Reform Commission 2019).

Here we adopt a scenario-based approach to explore the potential impact of widespread car ownership restriction policies among China's cities on the national vehicle stock. Recognizing that China's largest cities account for most current and near-term growth in car ownership and are most likely to adopt restrictions, we disaggregate our national-level fleet model developed in Section 3.3.1 using the four city clusters identified in Section 3.2. We then apply scenarios that explore the potential impact of additional car ownership restrictions among certain cities. Detailed discussion of these methods can be found in Hsieh, et al. (2019).

**Figure 3.17: Percent change in projected 2030 stock of personal vehicles nationwide by scenario compared to the no-car-ownership-restriction counterfactual**



Note: All results are relative to 2030 vehicle stock in the no-car-ownership-restriction counterfactual model: mean = 315.7 million, first decile = 222.8 million, and ninth decile = 418.0 million. Labels give absolute reduction in millions of vehicles for the mean projection. Error bars indicate values calculated from the first and ninth deciles of the counterfactual model.

### *Scenario definitions*

We construct plausible scenarios that explore the impact on the national vehicle fleet if different numbers (and types) of cities adopt car ownership restriction policies. We begin by defining three potential levels of policy adoption:

1. *Status quo policy adoption:* The 6 cities[9] that have adopted policies by 2016 maintain the policies to 2030; no additional cities adopt restriction policies.
2. *Moderate policy adoption:* All Cluster 1 cities (n = 23) adopt a car restriction policy in 2020.
3. *Extensive policy adoption:* All Cluster 1 cities (n = 23) and all Cluster 2 cities (n = 41) adopt a car restriction policy in 2020.

For all scenarios, we assume that city policies cap new-purchase vehicle sales at 25%[10] of overall demand based on car purchasing power. We then compare projections for vehicle stock under each scenario with projections based on growth in purchasing power absent any municipal-level restriction (Figure 3.17). This allows us to quantify the potential impact of car ownership restrictions adopted by Chinese cities.[11] We find that maintaining current restrictions in six of China's largest megacities (the status quo scenario) reduces the projected stock of vehicles nationally in 2030 by around 4% compared to the mean no-restriction counterfactual.

Extensive adoption of car restriction policies in all Cluster 1 and Cluster 2 cities by 2020 could produce a larger reduction in the projected 2030

---

[9] These six cities are a subset of Cluster 1 (see Section 3.2).

[10] The cap is derived from the average ratio of the actual number of vehicles sold via quota to economically driven projections for new-purchase vehicles for 2016 and 2017 in the six cities that currently have car restriction policies.

[11] We use the mean value of the Monte Carlo simulations for the no-car-ownership-restriction model. All scenarios are constructed relative to this baseline model. While uncertainty exists when projecting vehicle stock and sales for any given scenario, systematic errors are removed when comparing across scenarios.

vehicle stock—of around 10%. While significant, the national impact of even our most aggressive scenario, in which 64 of China's largest cities adopt car ownership restriction policies, is constrained by the fact that much of the economically driven growth in new-purchase vehicle sales (and therefore total vehicle stock) comes from Cluster 3 and Cluster 4 cities, which are less likely to adopt car restriction policies in the near- to medium-term future.

### 3.3.3 Summary

In recent years, China's personal vehicle market has experienced rapid growth driven by increasing household car purchasing power. While the country's stock of personal vehicles is expected to continue to grow through 2030, growth beyond 2030 is likely to slow. As the Chinese car market continues to mature, replacement purchases rather than first-time purchases will begin to dominate vehicle sales.

With worsening congestion and local air pollution in China's cities, however, municipal governments are likely to continue experimenting with aggressive transportation policies. In particular, China's largest megacities have begun to adopt policies that restrict car ownership, typically by capping the number of new-purchase vehicles by using auctions or lotteries to distribute a limited number of license plates. Using scenario analysis, we show that these policies can have a significant cumulative impact on China's personal vehicle market by 2030. We find that the policies already in place could reduce the country's stock of personal vehicles by 4% by 2030 compared with a no-restriction scenario; further, we find that widespread adoption of policies that restrict car ownership in 64 of China's largest cities could reduce the national vehicle stock by as much as 10%. This suggests that China's national ban on the proliferation of these policies may be responding to real concerns over the impact of these city-level restrictions on economic growth.

## 3.4 CAR PRIDE

People's attitudes toward different modes of transportation affect their travel behavior. Attitudes influence short-term decisions (such as when to travel and what mode to use) and long-term decisions (such as whether or not to own a vehicle and what type of vehicle to purchase, as well as intentions to adopt new technologies and services in the future). Cars, in particular, not only fulfill instrumental transportation functions, they also hold significant symbolic and affective meaning for their owners and users (Gärling and Loukopoulos 2008; Steg 2004; Steg, Vlek, and Slotegraaf 2001; Dittmar 1992). Thus, decisions about car ownership do not merely reflect rational economic choices—often they are as much about aesthetic, emotional, and sensory values people associate with cars, such as freedom and independence, social status and prestige, and excitement (Sheller 2004). However, such attitudes are notoriously difficult to measure and are often overlooked in transportation modeling (Urry 2004; Sheller 2004).

One important attitudinal factor is "car pride": the attribution of social status and personal image to driving and using a car (Moody 2019; Zhao and Zhao 2018). This section develops robust measures of car pride using purpose-built survey scales to explore the role of car pride in determining patterns of car ownership across cities and countries.

### 3.4.1 Surveys

Here we describe the data we collected and the analysis we used to measure car pride and its relationship to car consumption at the city level, in the U.S.—which is widely regarded as having a strong pro-car culture—and at the country level internationally (Moody 2019).

*City-level data collection: The U.S. city survey*

At the city level, purpose-built surveys were deployed that collected socio-demographic information about respondents, information about their current car ownership and commuting behavior, and their attitudes and preferences with regard to different travel modes, technologies, and services in two U.S. cities: New York City and Houston. Qualtrics, a private survey company, recruited survey participants and implemented the survey in early 2016. Quotas were applied to the respondent pool to ensure that the composition of the sample was representative of each metropolitan area population in terms of age, gender, and income level.

### *Country-level data collection: The international mobility survey*

In addition, Dalia Research administered a 20-question survey via mobile phone to nearly 42,000 participants in 51 countries during the two-month period from December 2016 through January 2017. Sample respondents were recruited through a variety of ad-exchanges, demand-side platforms (DSPs), apps, and mobile websites. Each participant was pre-screened to ensure data quality—this involved dynamically profiling each participant based on responses to a series of consistency and attention checks and then generating unique user trust scores based on this active and passive information. Only high-quality, verified users were asked to complete the survey for research purposes. Survey respondents were rewarded in the form of virtual currencies, prepaid credits, access to premium content, and other rewards, depending on the specific recruitment channel.

The final sample size for this international survey was 41,932 respondents. Within-country sample sizes vary from around 1,000 participants for larger countries to 500 participants for smaller countries (the smallest sample size, for Hong Kong, was approximately 200). Quotas were applied to ensure that the survey sample was reasonably representative of mobile phone users in each of the countries surveyed with respect to age and gender.

## 3.4.2 Measuring Car Pride across Cities and Countries

### *The polytomous car pride scale*

Our U.S. city surveys contained 12 statements designed to measure the degree to which respondents attribute social status and personal image to driving and using a car. Responses were coded on a 7-point scale from "strongly disagree" (-3) to "strongly agree" (+3). To fully capture the construct of car pride, survey questions related both driving and owning a car to two facets of pride that are well established in the social psychology literature. Alpha or hubristic pride refers to an individual's subjective feelings of superiority in relation to others (for example, "Driving a car makes me feel superior to those who don't"), whereas beta or authentic pride refers to genuine feelings of self-esteem and self-worth (for example, "driving a car positively affects my perception of myself") (Tracy and Robins 2007a; 2007b).

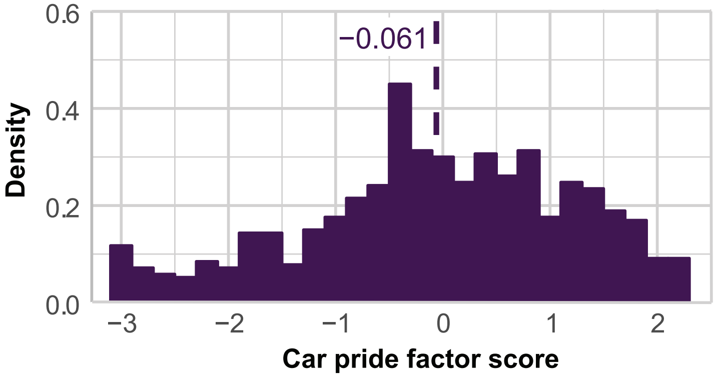
Using confirmatory factor analysis (CFA), we establish the validity and reliability of our 12-item measure of car pride in each of the U.S. cities surveyed (Moody and Zhao 2019). We find that respondents in New York City have lower average car pride ($\mu_{NYC} = -0.061$) than respondents in Houston ($\mu_{HOU} = 0.099$) and that this difference is statistically significant based on a two-tailed t-test: $t = -2.41$, $p = .016$ (Figure 3.18).

### *The dichotomous car pride scale*

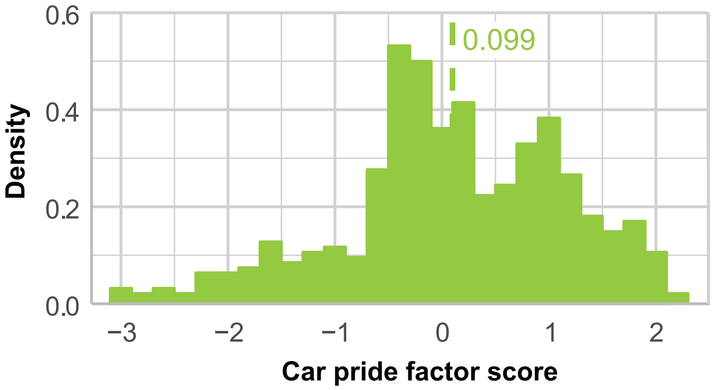
A binary version of the car pride scale was developed for use in the international mobility survey. Respondents were asked whether they agree (1) or disagree (0) with nine statements that relate owning and using a car to social status and personal image. Multilevel confirmatory factor analysis, which accounts for the hierarchical structure of the data (with individuals nested within countries), was applied to establish the reliability and validity of this binary car pride measure (Moody 2019). From this analysis, we derive a measure of car pride for individuals and for countries (Figure 3.19).

**Figure 3.18: Distributions of car pride scores across individuals in the two U.S. cities surveyed**

**(a) New York City**



**(b) Houston**



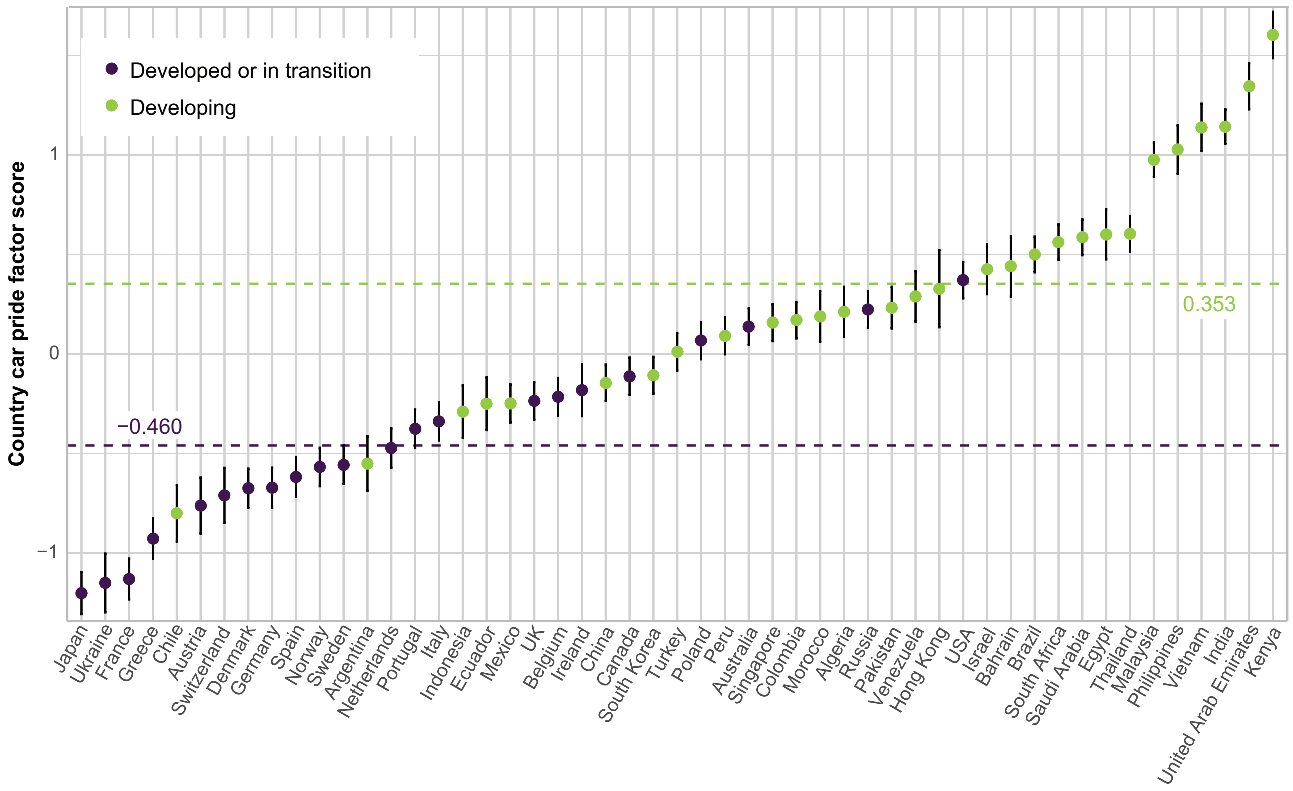
Note: Car pride factor scores are standardized around a mean of zero across all individuals in the New York City and Houston samples. City averages are given by dashed lines. Figure adapted from Moody (2019).

The results of this analysis indicate significant variability in car pride among individuals within countries. Further, we find that, in any given country, there are many more individuals with extremely high car pride than individuals with extremely low car pride. Applying multivariate, multilevel modeling techniques, we find that individuals with higher household income, who live in larger towns or cities, and who are younger, male, highly educated, and employed full-time, have higher car pride across our international sample.

We also see patterns in levels of car pride across countries (Figure 3.19), with developing countries generally exhibiting higher car pride than developed countries.

Equipped with car pride scores for our U.S. city samples and our international sample, we then explored how this important attitudinal variable affects car ownership.

**Figure 3.19: Mean car pride scores by country**



Note: Mean car pride scores for countries are given by dots colored according to whether they are a developed (purple) or developing (green) country according to the United Nations' classification. Black bars represent standard errors. Figure adapted from Moody (2019).

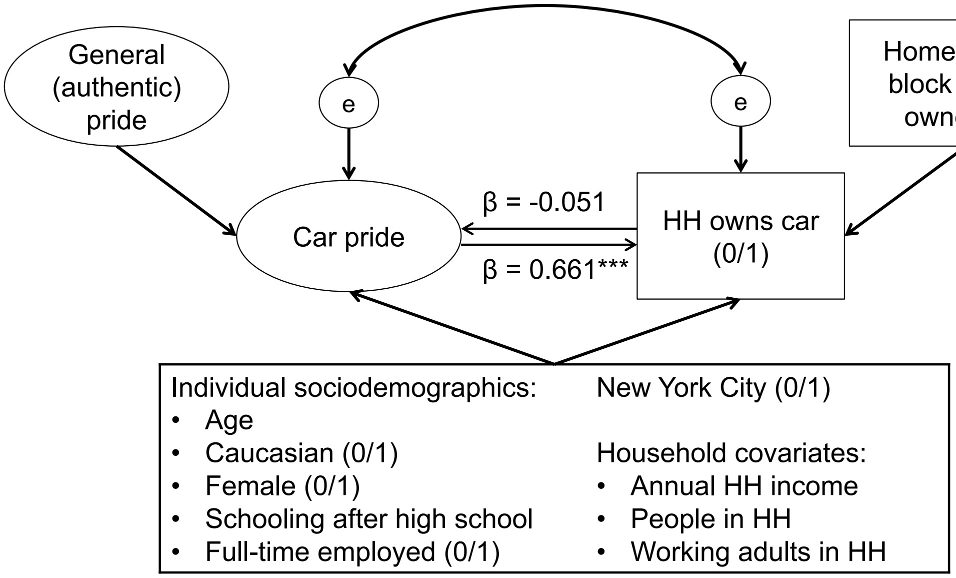
## 3.4.3 Understanding the Relationship between Car Pride and Car Ownership

*Findings for U.S. cities*

It is often assumed that attitudes play an important role in determining people's travel behavior following the "theory of planned behavior" (Ajzen 2005). Conversely, however, there is also reason to think that behavior can have a significant influence on attitudes (in other words, that the interaction between attitudes and behavior works in both directions) (Kroesen, Handy, and Chorus 2017). For instance, we might expect that higher levels of car pride among commuters in New York City and Houston is predictive of higher levels of car ownership; conversely, we might also expect that car ownership is predictive of higher levels of car pride, since ownership reinforces attitudes. Understanding the bidirectional relationships between attitudes and behavior has important implications for planning and policy and can be helpful in determining whether interventions should target attitudes, such as car pride (e.g., through informational campaigns and marketing), or the behavior itself (e.g., through restrictions or fees on car ownership and usage).

We empirically examined the bidirectional relationship between car pride and household car ownership using the structural equation model with instrumental variables diagrammed in Figure 3.20. We find that car pride is positively and significantly predictive of household car ownership. In fact, we find that an individual's car pride (attitude) is a stronger predictor of household car ownership (behavior) than the individual and household socio-demographic characteristics captured in our survey, including income. Considering the opposite path from

**Figure 3.20: Relative strengths of the bidirectional relationship between car pride and car ownership among U.S. commuters**



Note: HH = household; β = standardized coefficient; statistical significance of two-tailed t-test against unstandardized regression coefficient b = 0: *=10%, **=5%, and ***=1% level. Figure adapted from Moody and Zhao (2019).

car ownership to car pride, we find it is not significantly different from zero. Thus, comparing the relative magnitudes of the bidirectional relationship, we conclude that car pride influences car ownership much more strongly than the reverse (behavior reinforcing attitude) among commuters in New York City and Houston.

*Country-level findings*

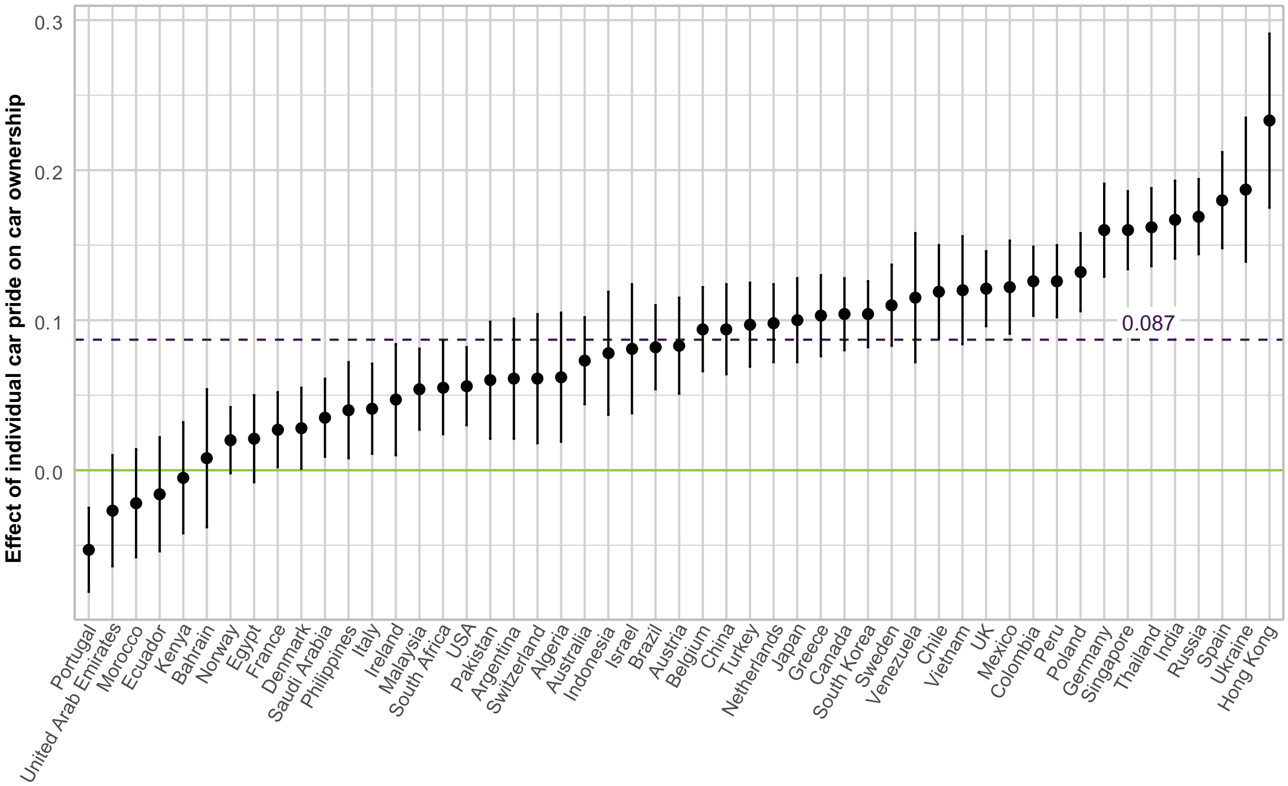
Using our international sample, we estimate a multilevel structural equation model to measure the direct path from car pride to car ownership at the individual level, while controlling for sample representativeness of all socio-demographic characteristics (Moody 2019). We find that car pride is positively and significantly predictive of car ownership across individuals. On average, we find that a one-unit increment in an individual's car pride score (equivalent to moving from the mean to the 76th percentile) predicts a 4% increment in the probability of owning a car. This suggests that car pride is predictive of car ownership in addition to the individual socio-demographic factors often included in car-ownership prediction models.

Estimating the relationship between individual car pride and car ownership by country rather than as a global average, we find that the relationship is positive and statistically significant for almost all countries in the sample (Figure 3.21). We also find that the relationship is stronger than the global average in many countries. For example, in India, a one-unit increment in an individual's car pride predicts a 7% increment in the likelihood of owning a vehicle. Even without accounting for car pride, developing countries are projected to have the highest rates of growth in car ownership and usage in the near future—trends that imply continued growth in greenhouse gas emissions and energy consumption from the global transportation sector. The relationship between individual car pride and likelihood of car ownership, together with current patterns of car pride across countries, will likely only exacerbate this trend.

### 3.4.4 Summary

Our analysis of the relationship between car pride and car ownership suggests that traditional transportation models may fail to capture the full

**Figure 3.21: Variation in the association of individual car pride with car ownership (0/1) across countries**



Note: The dashed line is the average (or fixed) effect of 0.087. Error bars show the mean probit regression coefficient plus or minus one standard deviation based on 50 draws from the estimated Bayesian posterior distribution. Figure adapted from Moody (2019).

picture of consumers' travel-related decisions if they do not include measures of attitudes and preferences, such as car pride. Without robust measures of individual attitudes and preferences that can be aggregated and compared across cities and countries, we lose important insight into the social and cultural factors that influence the consumption of different transportation modes, technologies, and services.

The relationship between car pride and car ownership is bidirectional, but survey results from U.S. cities suggest that car pride influences car ownership much more than car ownership influences car pride. At the international level, we find higher levels of car pride in developing countries than in developed countries. This result means that current projections may *understate* expected growth in car ownership (and associated environmental consequences) in those countries.

## 3.5 CONCLUSION

Many factors contribute to current and projected future demand for vehicle ownership and VMT, including demographics, policy, and attitudes. Household income and population remain the two main drivers of projected growth in vehicle ownership and VMT over the coming decades. As the global population grows and as more people become wealthy enough to afford vehicle travel, the global demand for mobility is expected to grow. This chapter has examined how policies and attitudes may interact with population- and income-driven trends in mobility demand in both developed and developing auto markets.

In China, in particular, we find that government policies can significantly impact vehicle ownership. For example, city-level restrictions on car ownership may reduce the country's total vehicle stock by about 10% by 2030, even if such policies are only implemented in China's 64 largest cities. An important finding is that car-related policymaking in these Chinese cities is primarily motivated by current problems of air quality and congestion, not future concerns such as climate change. How widely and how quickly such policies are likely to be adopted in China is difficult to predict, but we can anticipate that cities experiencing similar problems are more likely to follow the policy examples set by Beijing, Shanghai, and other large cities.

Attitudes regarding mobility can differ across people and places. Although anecdotal evidence has been cited to suggest that millennials in the U.S. are less interested in car ownership, our econometric analysis concludes that this generation's appetite for cars and car travel is very similar to that of older generations after accounting for relevant socio-economic factors, including income and urbanization. In our examination of attitudes across 51 countries, we found that car pride is generally higher in developing countries, with the U.S. being the exception among developed countries. As developing countries become wealthier, the growth of the middle class in these countries will likely yield higher vehicle ownership, if unconstrained by policy.

## 3.6 REFERENCES

Ajzen, Icek. 2005. *Attitudes, Personality, and Behavior*, 2nd edition. New York, NY: Open University Press.

Atkinson, Andrew. 2018. "Millennials All Over the World Are Worse Off Than Gen Xers Were at Their Age." *Money*, February 19. http://money.com/money/5165475/millenials-poorer-generation-x/

Buchholz, Todd, and Victoria Buchholz. 2012. "The Go-Nowhere Generation." *The New York Times*, March 10. https://www.nytimes.com/2012/03/11/opinion/sunday/the-go-nowhere-generation.html

Chun, Jungwoo, Joanna Moody, and Jinhua Zhao. 2019. "Transportation Policymaking in Beijing and Shanghai: Contributors, Obstacles, and Process." *Case Studies on Transport Policy*. https://doi.org/10.1016/j.cstp.2019.09.003

Corbin, Juliet, and Anselm Strauss. 2008. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. Thousand Oaks, CA: Sage Publications, Inc.

Cox, David R. 1972. "Regression Models and Life-Tables." *Journal of the Royal Statistical Society: Series B (Methodological)* 34, no. 2: 187–220. http://www.biecek.pl/statystykaMedyczna/cox.pdf

Davis, Stacy C., Susan W. Diegel, and Robert G. Boundy. 2014. *Transportation Energy Data Book*, 33rd edition. Oak Ridge, Tennessee: Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/pub50854.pdf

Dittmar, Helga. 1992. *The Social Psychology of Material Possessions: To Have Is to Be*. Havester Wheatsheaf, UK: St. Martin's Press.

Dutzik, Tony, Jeff Inglis, and Phineas Baxandall. 2014. *Millennials in Motion: Changing Travel Habits of Young Americans and the Implications for Public Policy*. Denver, CO: U.S. PIRG Education Fund. https://uspirg.org/sites/pirg/files/reports/Millennials%20in%20Motion%20USPIRG.pdf

Fry, Richard. 2018. "Millennials Projected to Overtake Baby Boomers as America's Largest Generation." *Pew Research Center FactTank*, March 1. http://www.pewresearch.org/fact-tank/2016/04/25/millennials-overtake-baby-boomers/

Gärling, Tommy, and Peter Loukopoulos. 2008. "Economic and Psychological Determinants of Car Ownership and Use." In *The Cambridge Handbook of Psychology and Economic Behavior*, edited by Alan Lewis, 383–405. Cambridge, UK: Cambridge University Press.

Han, Aaron, and Jerry A. Hausman. 1990. "Flexible Parametric Estimation of Duration and Competing Risk Models." *Journal of Applied Econometrics* 5, no. 1: 1–28. https://doi.org/10.1002/jae.3950050102

Hsieh, I-Yun (Lisa), Paul N. Kishimoto, and William H. Green. 2018. “Incorporating Multiple Uncertainties into Projections of Chinese Private Car Sales and Stock.” *Transportation Research Record: Journal of the Transportation Research Board* 2672, no. 47: 182–193. http://doi.org/10.1177/0361198118791361

Hsieh, I-Yun (Lisa), Joanna C. Moody, William Green, and Jinhua Zhao. 2019. “Potential Impact of China’s Municipal Car Ownership Restrictions on Future Vehicle Stock.” [working paper].

Huo, Hong, and Michael Wang. 2012. “Modeling Future Vehicle Sales and Stock in China.” *Energy Policy* 43 (April): 17–29. https://doi.org/10.1016/j.enpol.2011.09.063

International Organization of Motor Vehicle Manufacturers (OICA). 2019. “World Motor Vehicle Sales: By Country and Type 2005–2018.” http://www.oica.net/category/sales-statistics/

Knittel, Christopher R. 2011. “Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector.” *American Economic Review* 101, no. 7 (Dec): 3368–3399. https://doi.org/10.1257/aer.101.7.3368

Knittel, Christopher R. and Elizabeth Murphy. 2019. *Generational Trends in Vehicle Ownership and Use: Are Millennials Any Different?* Working Paper 25674. Cambridge, MA: National Bureau of Economic Research. http://www.nber.org/papers/w25674.pdf

Kroesen, Maarten, Susan Handy, and Caspar Chorus. 2017. “Do Attitudes Cause Behavior or Vice Versa? An Alternative Conceptualization of the Attitude-Behavior Relationship in Travel Behavior Modeling.” *Transportation Research Part A: Policy and Practice* 101 (July): 190–202. https://doi.org/10.1016/j.tra.2017.05.013

Kurylko, Diana T. 2017. “The Millennials Are Coming: Slow to Recover from Recession, but Fast Becoming a Major Buyer Segment.” *Automotive News*, February 17. https://www.autonews.com/article/20170227/RETAIL/302279963/the-millennials-are-coming

Li, Cheng. 2007. “The Leadership of China’s Four Major Cities: A Study of Municipal Party Standing Committees.” *China Leadership Monitor*, no. 21: 1–19. http://media.hoover.org/sites/default/files/documents/CLM21CL.pdf

Li, Huifeng, and Martin de Jong. 2017. “Citizen Participation in China’s Eco-City Development. Will ‘New-Type Urbanization’ Generate a Breakthrough in Realizing It?” *Journal of Cleaner Production* 162 (Sept): 1085–1094. https://doi.org/10.1016/j.jclepro.2017.06.121

Li, Terry Hongyang, Shiu Tong Thomas Ng, and Martin Skitmore. 2012. “Public Participation in Infrastructure and Construction Projects in China: From an EIA-Based to a Whole-Cycle Process.” *Habitat International* 36, no. 1: 47–56. https://doi.org/10.1016/j.habitatint.2011.05.006

Martin, Steven P., Nan Marie Astone, and H. Elizabeth Peters. 2014. *Fewer Marriages, More Divergence: Marriage Projections for Millennials to Age 40*. Washington, D.C.: Urban Institute. https://www.urban.org/research/publication/fewer-marriages-more-divergence-marriage-projections-millennials-age-40

Moody, Joanna C. 2019. *Measuring Car Pride and Its Implications for Car Ownership and Use across Individuals, Cities, and Countries*. Ph.D. dissertation. Cambridge, MA: Massachusetts Institute of Technology.

Moody, Joanna C., and Jinhua Zhao. 2019. “Car Pride and Its Bidirectional Relations with Car Ownership: Case Studies in New York City and Houston.” *Transportation Research Part A: Policy and Practice* 124 (June): 334–353. https://doi.org/10.1016/j.tra.2019.04.005

Moody, Joanna C., Jungwoo Chun, Shenhao Wang, Xuenan Ni, and Jinhua Zhao. 2019. “Transportation Policy Profiles of Chinese City Clusters: A Mixed Methods Approach.” *Transportation Research Interdisciplinary Perspectives* 2 (Dec). https://doi.org/10.1016/j.trip.2019.100053

Murphy, Elizabeth. 2018. *Will Millennials Save the Planet? Generational Trends in Vehicle Ownership and Use*. S.M. thesis. Cambridge, MA: Massachusetts Institute of Technology.

National Development and Reform Commission (中华人民共和国国家发展和改革委员会). 2019. 推动重点消费品更新升级 畅通资源循环利用实施方案(2019-2020年) [*Notice of the National Development and Reform Commission, the Ministry of Ecology and Environment, and the Ministry of Commerce on Issuing the Implementation Plan for Promoting the Upgrading of Key Consumer Goods and the Recycling of Resources (2019-2020)*].

Nielsen Company. 2014. “Millennials Prefer Cities to Suburbs, Subways to Driveways.” *Nielsen Newswire*, March 4. https://www.nielsen.com/us/en/insights/news/2014/millennials-prefer-cities-to-suburbs-subways-to-driveways.html

Pew Research Center. 2015. *Parenting in America: Outlook, Worries, Aspirations Are Strongly Linked to Financial Situation*. http://www.pewresearch.org/wp-content/uploads/sites/3/2015/12/2015-12-17_parenting-in-america_FINAL.pdf

Sheller, Mimi. 2004. “Automotive Emotions: Feeling the Car.” *Theory, Culture & Society* 21, no. 4–5 (Oct): 221–242. https://doi.org/10.1177/0263276404046068

Sivak, Michael, and Brandon Schoettle. 2012. “Update: Percentage of Young Persons with a Driver’s License Continues to Drop.” *Traffic Injury Prevention* 13, no. 4: 341. https://doi.org/10.1080/15389588.2012.696755

———. 2014. *What Do Current Owners of Hybrids and Non-Hybrids Think about Hybrids?* Technical Report UMTRI-2014-25. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Steg, Linda. 2004. "Car Use: Lust and Must. Instrumental, Symbolic, and Affective Motives for Car Use." *Transportation Research Part A: Policy and Practice* 39, no. 2–3: 147–162. https://doi.org/10.1016/j.tra.2004.07.001

Steg, Linda, Charles Vlek, and Goos Slotegraaf. 2001. "Instrumental-Reasoned and Symbolic-Affective Motives for Using a Motor Car." *Transportation Research Part F: Traffic Psychology and Behaviour* 4, no. 3 (Sept): 151–169. https://doi.org/10.1016/S1369-8478(01)00020-1

Sun, Bindong, Tinglin Zhang, Zhou He, and Rui Wang. 2015. "Urban Spatial Structure and Motorization in China" *Journal of Regional Science*. https://doi.org/10.1111/jors.12237

Teddlie, Charles, and Abbas Tashakkori. 2013. "Chapter 4. Mixed Methods Research: Contemporary Issues in an Emerging Field." In *Strategies of Qualitative Inquiry*, 4th edition, edited by Norman K. Denzin and Yvonna S. Lincoln, 135–168. Thousand Oaks, CA: Sage Publications, Inc.

Thompson, Derek, and Jordan Weissman. 2012. "The Cheapest Generation: Why Millennials Aren't Buying Cars or Houses, and What That Means for the Economy." *The Atlantic*, September. https://www.theatlantic.com/magazine/archive/2012/09/the-cheapest-generation/309060/

Tracy, Jessica L., and Richard W. Robins. 2007a. "Emerging Insights into the Nature and Function of Pride." *Current Directions in Psychological Science* 16, no. 3 (June): 147–150. https://doi.org/10.1111/j.1467-8721.2007.00493.x

———. 2007b. "The Psychological Structure of Pride: A Tale of Two Facets." *Journal of Personality and Social Psychology* 92, no. 3: 537–547. http://dx.doi.org/10.1037/0022-3514.92.3.506

United Nations, Department of Economic and Social Affairs. 2018. *World Urbanization Prospects: The 2018 Revision*. https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

U.S. Bureau of Transportation Statistics. 2019. "Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances." https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances

U.S. Census Bureau. 2017. "2017 National Population Projections Datasets." https://census.gov/data/datasets/2017/demo/popproj/2017-popproj.html

———. 2018a. "Population and Housing Unit Estimates." https://www.census.gov/programs-surveys/popest/data/data-sets.2017.html

———. 2018b. HINC-03. "People in Households – Households, by Total Money Income, Age, Race and Hispanic Origin of Householder." https://www.census.gov/data/tables/time-series/demo/income-poverty/cps-hinc/hinc-03.2000.html

Urry, John. 2004. "The 'System' of Automobility." *Theory, Culture, & Society* 21, no. 4–5 (Oct): 25–39. https://doi.org/10.1177/0263276404046059

Wang, Shenhao, Joanna C. Moody, and Jinhua Zhao. 2019. "What Prompts the Adoption of Car Restriction Policies among Chinese Cities?" [working paper].

Zhao, Zhan, and Jinhua Zhao. 2018. "Car Pride and Its Behavioral Implications: An Exploration in Shanghai." *Transportation*. https://doi.org/10.1007/s11116-018-9917-0

## Chapter 4

# Powertrains and Fuels

In 2017, transportation accounted for roughly 28% of energy consumption—both globally and in the U.S.—and roughly 23% and 28% of global and U.S. greenhouse gas emissions, respectively (International Energy Agency [IEA] 2018; U.S. Energy Information Administration [EIA] 2018; U.S. Environmental Protection Agency [EPA] 2019). Of all the energy consumed worldwide for transportation, passenger travel via light-duty vehicles accounts for the largest share and consumes more energy than the sum of all modes of freight transport (U.S. EIA 2016). Therefore, improving the sustainability of passenger light-duty vehicles can have a meaningful impact on the transportation sector as a whole.

A wide range of options exists for reducing the energy consumption and carbon footprint of light-duty vehicles. These include improving the efficiency of powertrains that run on petroleum-based fuels, reducing the carbon intensity of fuels, and using alternative fuel powertrain technologies, such as electric and fuel cell systems. Each powertrain option has different costs, as described in Section 4.1, and different greenhouse gas emissions, as described in Section 4.2. Given growing interest in the potential for electric powertrains to play a major role in the passenger light-duty vehicle fleet, Section 4.3 examines the outlook for battery development over the next decade, and Section 4.4 examines the total cost (including purchase and operating costs) of owning hybrid and battery electric vehicles compared to conventional internal combustion engine vehicles.

## 4.1 OVERVIEW OF POWERTRAIN TECHNOLOGIES AND COSTS

The present-day automobile industry has more powertrain options than ever before. Conventional gasoline- and diesel-powered vehicles are no longer the only options for car buyers; alternatives such as hybrid, plug-in hybrid, battery electric, and fuel cell vehicles are becoming increasingly popular due to improving costs, supportive government policies, and growing public concerns about the environment. From an environmental perspective, the adoption of these technologies could deliver global and local benefits with the reduction of both greenhouse gas and air pollutant emissions. While many factors can impact future demand for alternative vehicle propulsion systems, including government policy, this chapter focuses on market characteristics, such as affordability, functionality, and convenience for consumers. We conduct a techno-economic analysis of several vehicle propulsion systems that are expected to coexist in the market over the next several decades. These systems are categorized into two groups: (1) internal combustion engine propulsion, used in gasoline, diesel, and hybrid vehicles, and (2) electric propulsion used in plug-in hybrid, battery electric, and fuel cell vehicles.

### *Internal combustion engine (ICE) propulsion*

ICEs have been the leading propulsion system used in automobiles for more than 100 years. The two types of ICEs that are currently in commercial production include spark ignition (SI) gasoline engines and compression ignition (CI) diesel engines. SI and CI engines differ in how they introduce and ignite fuels (U.S. Department of Energy 2013). Compared to SI gasoline engines, CI diesel engines have a higher compression ratio, which allows them to achieve higher thermal efficiency (a measure of the amount of work an engine delivers per unit of energy input). Furthermore, CI engines have lower throttle loses compared to SI engines, which contributes to their superior efficiency, especially at low load operation. A conventional hybrid electric vehicle (HEV) uses both an ICE and an electric motor to achieve better fuel efficiency than non-hybrid counterparts. Conventional HEVs cannot be charged by plugging into an external source of electricity.

#### *Electric propulsion*

As countries pursue policies to improve air quality, reduce dependence on imported petroleum, and mitigate climate change, global demand for electric vehicle propulsion systems is expected to increase. Plug-in hybrid electric vehicles (PHEVs) combine an ICE with an electric motor that is powered by a battery. In contrast to a conventional HEV, and as the term "plug-in hybrid" implies, the battery can be charged from an external source of electricity. PHEVs have various modes of operation: some run entirely on electric power when possible and the ICE turns on only when the battery is depleted to a minimum level, while others are designed for blended operation and use a combination of electricity and gasoline before the battery is depleted. Battery electric vehicles (BEVs) have a fully electric powertrain with a rechargeable battery and no ICE; these vehicles are becoming more competitive due to supportive policies (generally motivated by environmental concerns) and improvements in battery cost and performance. Fuel cell electric vehicles (FCEVs) also use electric propulsion—in this case from a small onboard battery that is continuously charged by fuel cells. Hydrogen fuel cells harness electrochemical energy generated by reacting oxygen from the air with hydrogen from a pressurized fuel tank; the only byproduct of the process is water.

### 4.1.1 Current Powertrain Costs

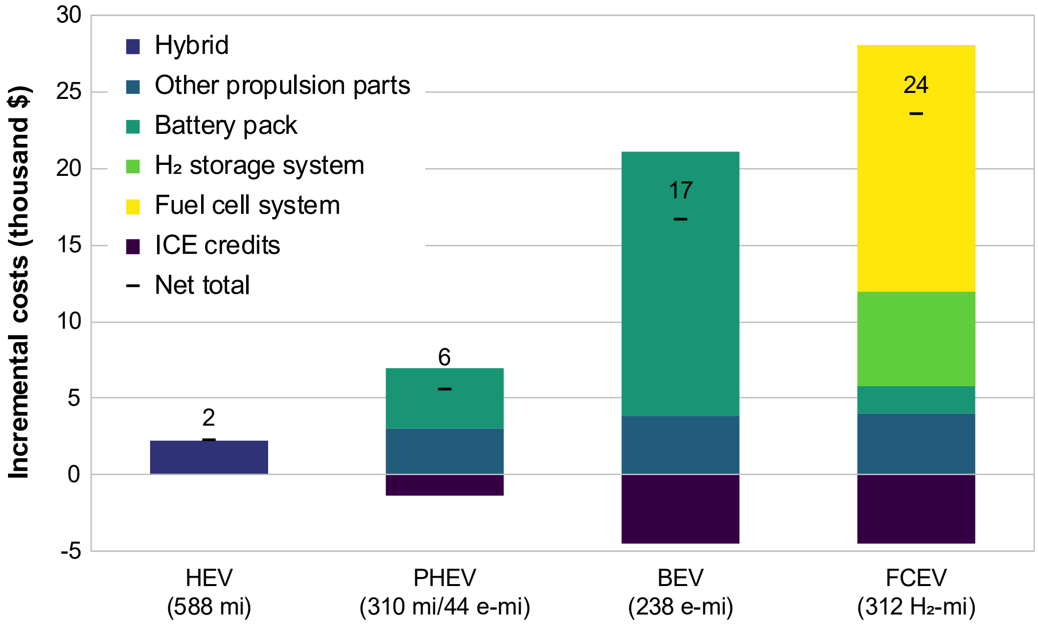
In this section, we estimate cost structures for alternative powertrains. Because costs of different propulsion systems vary with vehicle size, we select representative vehicle models with similar interior passenger and cargo volumes ranging from 99 cubic feet ($ft^3$) to 118 $ft^3$ (Table 4.1). These vehicle models, which range in size from a large subcompact to a mid-size car, were selected based on the availability of data regarding their underlying technology costs (Hummel, et al. 2017; German 2015; James, et al. 2017).

Figure 4.1 presents the incremental cost of different vehicle propulsion systems over the cost of a representative ICE system. The negative incremental costs shown in the figure (labeled ICE credits) represent cost savings associated with reducing the size of, or eliminating, the ICE powertrain. These credits are subtracted from the total incremental cost to yield net incremental cost, indicated by the black lines and numbers in Figure 4.1. Key assumptions for each of the powertrains included in our cost analysis are summarized in the following subsections.

**Table 4.1: Vehicle models used for the powertrain cost estimation**

| Propulsion system | Representative vehicle model | Passenger and cargo volume ($ft^3$) |
|---|---|---|
| ICEV | VW Golf | 109 |
| HEV | Toyota Prius | 118 |
| PHEV | Toyota Prius Prime | 111 |
| BEV | Chevy Bolt | 117 |
| FCEV | Toyota Mirai | 99 |

**Figure 4.1: Propulsion system cost breakdowns for vehicles with interior volumes of 99–118 $ft^3$**



Note: Costs are relative to a representative ICE powertrain with cost $4,500 and range of 383 miles; black lines and numbers indicate net incremental costs over a 2017 ICEV; values in parentheses for each drivetrain denote the total range (mi), all-electric range (e-mi) or hydrogen range ($H_2$-mi) for these vehicles.

### *Internal combustion engine vehicle (ICEV)*

For the representative ICEV, we use a 2017 model year VW Golf. Its ICE powertrain is made up of combustion engine parts ($1,700), combustion engine auxiliaries ($1,370), transmission ($600), exhaust system ($520), and engine control unit/ sensors ($310) (Hummel, et al. 2017). This yields a total propulsion system cost of $4,500. The VW Golf has a gasoline turbocharged engine using direct injection; the cost of the powertrain accounts for about 20% of the entire car price.

### *Hybrid electric vehicle (HEV)*

At the state of development for this technology in 2017, the incremental manufacturing cost for an HEV is estimated to be $2,000–$2,500 higher than a comparable ICEV. The hybrid cost differential has progressed downward as demonstrated by the Toyota Prius, for which incremental costs declined at a rate of 5% per year from 2000 to 2010 (German 2015). Figure 4.1 shows the average cost increment for an HEV relative to an ICEV powertrain.

### *Plug-in hybrid electric vehicle (PHEV)*

The battery pack of a PHEV is smaller than that of a BEV, but it still needs to provide a high level of power. PHEV batteries therefore have higher power density and thus higher cost per kilowatt-hour (kWh) of energy storage than BEV batteries. The cost premium for a PHEV battery was reported to be around $60–$70/kWh (compared to a BEV battery) in 2013 (National Research Council [NRC] 2013). Cost improvements were estimated to reduce this premium to about $35/kWh in 2016. Our calculations assume a PHEV battery pack price of around $324/kWh and a battery capacity of 8.8 kWh (Wolfram and Lutsey 2016; NRC 2013). This amounts to a battery pack cost of around $2,850, 20% less costly than its counterpart battery pack in a BEV (see below).

In addition to an electric motor and high-power battery, PHEVs are also equipped with a combustion engine—albeit a smaller and less costly combustion engine than would be found in a similar ICEV. In our calculations, we assume the

ICE in our PHEV vehicle is 35% less costly than its counterpart in a conventional ICEV (Wang, et al. 2012); PHEVs (unlike BEVs) also require an exhaust system.

*Battery electric vehicle (BEV)*

For the representative BEV, we use a 2017 model year Chevy Bolt. Its electric propulsion system is made up of an e-motor, including an integrated single-speed transmission ($800); other components of the e-drive module (besides the e-motor), such as motor housing, gear train, resolvers, etc. ($400); an invert ($700); and other parts[1] ($1,900) (Hummel, et al. 2017). Thus, the cost of an electric powertrain, excluding the cost of the battery pack, was estimated to be $3,800, 16% lower than the cost of a full ICE powertrain at $4,500. We use the market-average price for a battery pack in 2016 from Hsieh, et al. (2019): $289/kWh, which assumes lithium-ion nickel manganese cobalt chemistry matching the dominant battery technology for vehicle applications in model year 2017.

*Hydrogen fuel cell electric vehicle (FCEV)*

Powertrain costs for a FCEV include the cost of the fuel cell system and hydrogen storage system, as well as additional costs for a battery, electric motor, gear box, and so on. All of these costs together account for more than 50% of the current list price. For the 2017 model year Toyota Mirai, the manufacturing cost of the fuel cell system (including stack and balance-of-plant) is $16,078 (James, et al. 2017). This system provides 114 kilowatts (kW) of power at a unit fuel cell system cost of $141/kW; its hydrogen storage system is $6,168 (James, et al. 2017).

These cost breakdowns represent the current cost and performance of different drivetrain technologies. However all propulsion systems, including ICE and newer electric and fuel cell propulsion technologies, have room for cost and performance improvements, which we consider next.

### 4.1.2 Future Powertrain Efficiencies and Costs

*ICE propulsion*

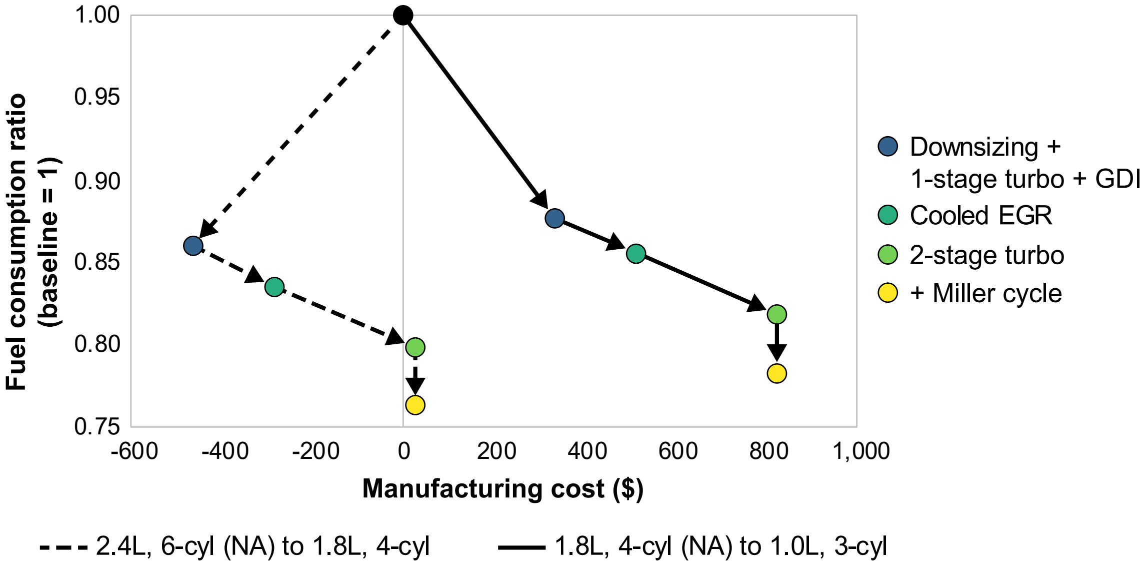
ICE technologies have become more efficient over recent decades. While substantial opportunities remain for additional efficiency improvement, there is debate about when future regulatory requirements for reduced criteria pollutant and carbon dioxide ($CO_2$) emissions might challenge the economic viability of ICE light-duty vehicles. Diesel vehicles, in particular, are challenged by tightening emissions standards for nitrogen oxides and particulate matter. Stringent fuel efficiency targets have encouraged the uptake of several technology advances: improvements to naturally aspirated engines, downsized turbocharged engines, and advanced transmissions (Isenstadt, et al. 2016). Other advances such as lightweight materials to enable reductions in vehicle mass, and tires with reduced rolling resistance can be applied across all propulsion systems, including ICEVs. Since the savings from downsizing an engine and reducing the number of engine cylinders often offset the incremental costs of turbocharging, integrating turbochargers with smaller engines is believed to be one of the most attractive pathways to address the growing demand for fuel-efficient cars. Turbochargers increase fuel economy and reduce greenhouse gas emissions by increasing the engine's power density—this allows for downsizing the engine while maintaining the same level of vehicle performance (Isenstadt, et al. 2016; Xia, Yang, and Isenstadt 2018).

A variety of advanced engine technologies have potential to succeed in vehicle markets around the world as emissions standards tighten. One example is variable compression ratio (VCR) technology which adjusts the compression level of an ICE under varying conditions of load and speed; while higher loads require lower compression ratios to prevent knock, lower loads can take advantage of higher compression ratios to deliver fuel efficiency benefits. Several engine concepts

---

[1] Other parts include thermal management ($250), a power distribution module ($328), inverter/converter ($697), DC/DC converter ($179), EV communication controller ($51), vehicle interface control module ($93), high voltage cable ($335), onboard charger ($598), and charging cord ($150) (Hummel, et al. 2017).

**Figure 4.2: Manufacturing cost and fuel consumption benefits of turbocharging and downsizing technologies**



Note: NA = naturally aspirated (baseline) engine; GDI = gasoline direct injection; EGR = exhaust gas recirculation.

that incorporate aspects of both gasoline SI and diesel combustion modes are also under active investigation and development. Besides gasoline and diesel, ICEs can run on alternative fuels, such as biofuels and natural gas.

A 2016 report from the International Council for Clean Transportation assessed technology developments and trends, including the costs and benefits of turbocharged, downsized gasoline engines (Isenstadt, et al. 2016). Several pathways and technology combinations may develop as turbocharged gasoline propulsion systems evolve in the future. Figure 4.2 shows the potential for achieving a roughly 15% reduction in fuel consumption by replacing a naturally-aspirated engine with a downsized turbocharged gasoline direct injection engine; a further 10% reduction is achievable with the addition of new technologies at an incremental cost of around $500 per vehicle. Figure 4.2 also shows that there are decreasing returns to downsizing: The cost and efficiency benefits of reducing the number of cylinders is greater when moving from a 6-cylinder to a 4-cylinder engine than it is when moving from a 4-cylinder to a 3-cylinder engine.

To further increase vehicle fuel economy, an ICE can be combined with an electric motor, resulting in a hybrid powertrain configuration. In conventional hybrid electric vehicles (HEVs), the ICE is the vehicle's sole energy source; the electric motor, which runs on electricity from the vehicle's battery, provides much of the normal power used in driving, while the ICE delivers additional power and runs at a relatively constant load to maximize efficiency. Each generation of the Toyota Prius, a leader in HEV market share, has delivered about a 10% efficiency improvement over the previous generation while reducing the incremental costs, relative to ICEV, by approximately 5% per year from 2000 to 2010 (German 2015). If the same rate of cost improvement can be sustained, the incremental manufacturing cost for a "full-function" hybrid system relative to a conventional ICE should fall to approximately $1,500 by 2025. However, significant uncertainties make it difficult to project how manufacturing costs for full-function hybrids will evolve; likewise, it is difficult to predict whether the development of more cost-effective "mild-hybrid" systems will play a major role in the future HEV market. Mild-hybrid systems, such as 48-volt systems, are believed to offer a better cost–benefit ratio than full-function hybrids: though they do not offer the same fuel efficiency benefit, their incremental cost is 50% less than that of a full-function hybrid (German 2015). Mild-hybrids have yet to achieve significant market share.

*Electric propulsion*

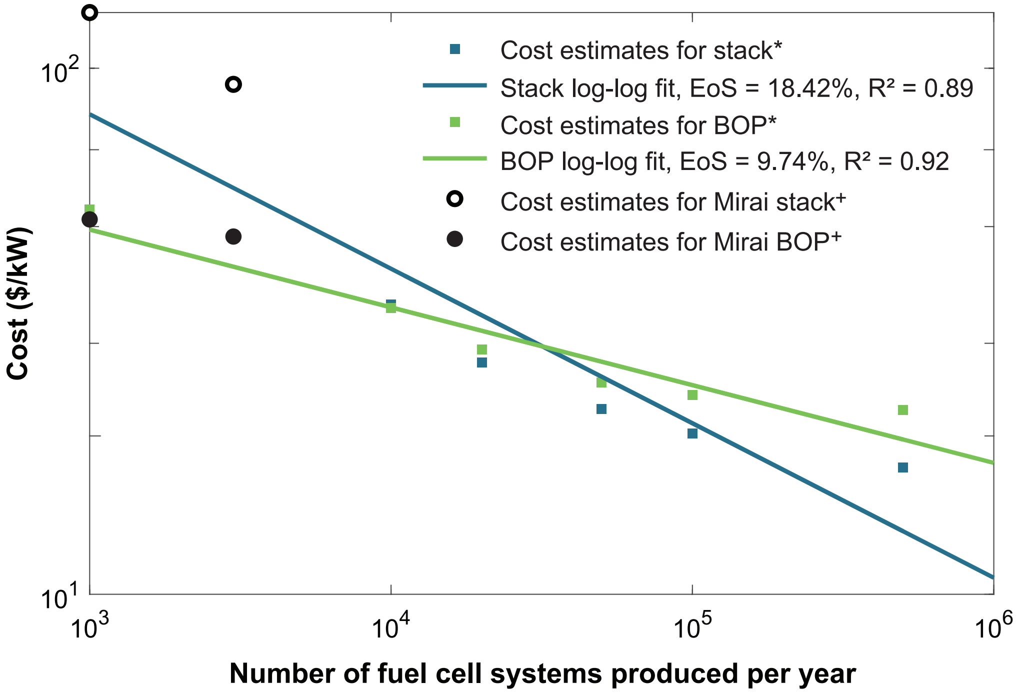
Just as with ICE propulsion systems, there is room for technological and cost improvements for electric propulsion systems (used by battery electric and fuel cell vehicles). Section 4.3 of this chapter provides a deep dive into potential battery chemistries and manufacturing cost reductions for battery electric vehicles, whereas Section 4.4 looks at the total cost of ownership differential between battery electric vehicles and current ICEV counterparts. In this section, we focus on potential prospects for the costs of fuel cell vehicles and leave discussion of the outlook for battery electric vehicles to later sections of this chapter.

Here we consider current and potential future costs of fuel cell systems. For purposes of cost analysis, fuel cell systems are often divided into two main components: the fuel cell stack itself and the supporting or auxiliary components needed to operate the stack as part of an integrated power system—these are collectively referred to as "balance-of-plant" (BOP). Within the fuel cell stack, many parts, such as membrane electrode assemblies and bipolar plates, are repeat components, meaning that a large number of these parts are needed for each system. This allows for economies of scale even when the number of fuel cell stacks being produced is relatively small. The same is not true for BOP components, such as air loops and sensor controllers. As a result, BOP production costs benefit less from mass-manufacturing effects. Based on published cost estimates for fuel cell technology (James, et al. 2017), we derive projected cost reductions as a function of annual production volumes, shown in Figure 4.3. Care should be taken, however, when using assumptions about economies of scale to make long-term cost projections, especially when the production rate is above 500,000 systems per year (the largest production scale for which cost data are available), at which point demand for essential materials (e.g., platinum) may create a practical limit on achieving further cost reductions through mass production. Figure 4.3 also provides information on current cost estimates for the best-selling FCEV: the Toyota Mirai. As annual production volumes double, we estimate that per-system stack costs will decline nearly twice as fast as BOP costs. The U.S. Department of Energy (DOE) targets a cost of $40/kW for an automotive fuel cell system (Satyapal 2016). Our estimates indicate that production levels would have to approach 500,000 systems per year to meet this cost target for FCEV technology.

### 4.1.3 Emission Control Technologies

Emission control technologies (ECTs) are used to reduce vehicle emissions, including both exhaust from the tailpipe and evaporative emissions from the fuel system, which contribute to ambient air pollution. Petroleum fuels (e.g., gasoline and diesel) are mixtures of hydrocarbons, meaning they consist of hydrogen and carbon. Under perfect combustion conditions, oxygen in the air unites with all the hydrogen and carbon in the fuel, resulting in exhaust that contains only water vapor and $CO_2$ while leaving the nitrogen in the air unaffected. In reality, the combustion process is not perfect and ICEs generate exhaust that contains a number of pollutants of concern. These include, in addition to $CO_2$, hydrocarbons (HC), nitrogen oxides ($NO_x$), carbon monoxide (CO), sulfur dioxide ($SO_2$), and particulate matter (PM). $CO_2$ is a concern because of its climate change impacts; the other pollutants are widely regulated because of their association with a variety of adverse public health and other impacts. For example, PM (especially fine PM) is a known contributor to excess mortality and morbidity

**Figure 4.3: Fuel cell system cost reductions as a function of annual production rates**



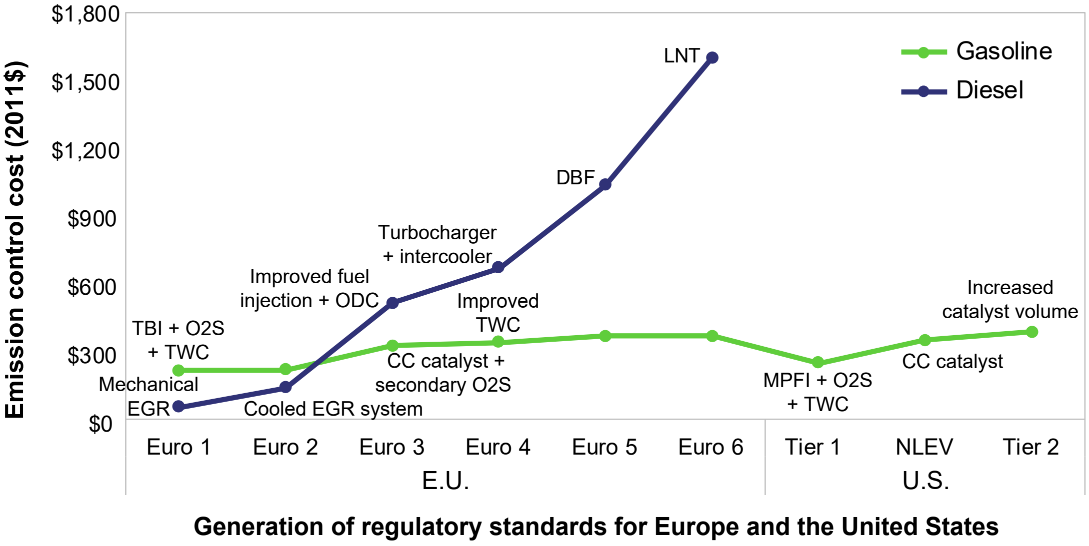
Note: EoS = economy of scale; BOP = balance-of-plant; *Cost estimates represent state-of-the-art technology in 2017; ⁺Toyota Mirai cost numbers are for reliable fuel cell technology at the time the vehicle was designed.

because of its impact on cardiovascular and respiratory health, CO is a toxic substance that lowers the oxygen-carrying capacity of the bloodstream, and $NO_x$ is a major contributor to the formation of ground-level ozone, which causes various health and environmental problems.

ECTs have been successfully applied to light-duty vehicles for decades and have improved over time to meet progressively more stringent emission standards. Because gasoline and diesel engines operate under different combustion conditions and have different emissions characteristics, they require different ECTs. The need to include ECTs adds to manufacturing costs for ICE vehicles. Figure 4.4 depicts the incremental cost of currently available ECTs for a 2.0-liter, inline 4-cylinder gasoline and diesel vehicle, as required to meet successive generations of European and U.S. emission standards; the major contributors to ECT cost at each level of regulation are indicated and briefly explained in the figure notes. Detailed cost estimates and technology descriptions can be found in two papers by Posada Sanchez, Bandivadekar, and German (2013a; 2013b). The U.S. EPA's Tier 3 standards, which were finalized in 2014, are being phased in from model years 2017 through 2025. They are expected to further reduce new-vehicle tailpipe and evaporative emissions at an estimated cost of $72 per vehicle (U.S. EPA 2014).

Figure 4.4 clearly indicates that cumulative emission-control costs for gasoline vehicles are much lower than for diesel vehicles. For gasoline vehicles, three-way catalyst technology has improved substantially and manufacturing costs have declined such that the incremental cost of meeting more stringent standards is small once the catalyst system is in place. Thus, ECT costs for gasoline cars are relatively modest. Diesel engines, on the other hand, because they operate under inherently lean combustion conditions (meaning a high ratio of air to fuel), require more complex

Figure 4.4: Cumulative cost of emission control technologies for 2.0-liter ICE gasoline and diesel vehicles



Source: adapted from Posada Sanchez, Bandivadekar and German (2012).

Note: NLEV = U.S. National Low-Emission Vehicle Standard; MPFI = multi-point fuel injection, a widely applied method of air–fuel control in current gasoline ICEVs; O2S = oxygen sensor, for air–fuel ratio feedback; TWC = three-way catalyst, designed to oxidize HC and CO into water and $CO_2$ when oxygen is present in the exhaust gas; CC catalyst = closed couple catalyst, designed for HC control during start-up; TBI = throttle body injection, a premixed fuel control technology that replaced carburetors around 1980 and was phased out in the 1990s; EGR = exhaust gas recirculation for in-cylinder $NO_x$ reduction; DPF = diesel particulate filter, a PM aftertreatment that uses a substrate to physically trap the solid fraction of PM, such as soot; LNT = lean $NO_x$ trap, an aftertreatment control that makes use of materials that can adsorb $NO_x$ during periods of lean combustion (note that LNT is economically viable for smaller engines, i.e., less than 2.0 liter displacement, while selective catalytic reduction or SCR, which makes use of ammonia to reduce exhaust $NO_x$ on a catalytic surface, is more viable for larger diesel cars, such as sport-utility vehicles or trucks).

engine-out and air–fuel management, and more sophisticated aftertreatment devices to achieve stringent emission limits.

## 4.2 LIFECYCLE ANALYSIS OF VEHICLES AND FUELS

To understand greenhouse gas emissions[2] from various powertrains, the full lifecycle of both the vehicle and its fuel must be considered. In terms of direct emissions, BEVs emit nothing and FCEVs emit only water, but perceptions and policies that consider only tailpipe emissions risk missing the larger picture. A complete environmental assessment must consider emissions at each stage of the vehicle and fuel lifecycle. For the vehicle, this includes emissions from the extraction and processing of materials required to make the car body, engine, battery, and other key components, as well as emissions from the vehicle manufacturing and assembly process itself. The fuel lifecycle includes emissions from the production, distribution, and use of fuel, where “fuel” in this context refers to an energy carrier for vehicle propulsion. This analysis focuses on three fuel options for light-duty vehicles: gasoline, electricity, and hydrogen.

---

[2] This section of the report is focused on greenhouse gas emissions. For conciseness, “emissions” is regularly used in this section to refer to “greenhouse gas emissions.” Although criteria pollutant emissions such as nitrogen oxides, particulate matter, and hydrocarbons have important impacts on the environment and human health, these pollutants are not part of this lifecycle analysis.

For gasoline, lifecycle emissions come from all stages of fuel production, distribution, and use. These stages include extracting and transporting crude oil, refining the crude oil into gasoline, distributing the gasoline to retail outlets, and combusting the gasoline in the car engine.

For electricity, a full accounting of emissions includes the construction and operation of the equipment used to generate the electricity, as well as any upstream emissions associated with the generation fuel source—such as coal, natural gas, oil, or uranium. Greenhouse gas emissions from electricity production vary widely depending on the fuel and generation technology used, from low-carbon technologies such as renewables and nuclear at one end of the spectrum to carbon-intensive generators such as conventional coal plants at the other.

Hydrogen can be produced by various pathways. The main production method in the U.S. and in many regions of the world at present is called steam methane reforming (SMR); it involves reacting high-temperature steam with methane in the presence of a catalyst to form hydrogen gas. This approach requires natural gas as a source of methane as well as energy for the fired reformer. The main production method in China currently is coal gasification, in which coal, oxygen, and water are reacted in a series of steps to generate hydrogen. These and other conversion processes for producing hydrogen from natural gas and coal generate $CO_2$, but these emissions can be mitigated by various carbon capture technologies. Another current pathway with potential for expanding hydrogen production in the future is electrolysis: using electricity to split water molecules into their constituent elements of hydrogen and oxygen. After hydrogen is produced, additional energy is required to compress and transport the hydrogen for use in vehicle applications. A fuel cell vehicle running on hydrogen generates no greenhouse gas emissions at the point of vehicle operation, but may have substantial indirect emissions depending on how the hydrogen was produced.

Figure 4.5 illustrates the various elements to be considered in a full lifecycle analysis of vehicles and fuels. It includes an "end-of-life" stage for vehicle recycling and disposal.

### 4.2.1 Methodology for Calculating Lifecycle Vehicle Emissions

Emissions per unit of distance traveled $\left(\frac{e}{d}\right)$ can be calculated for different types of vehicles using equation (1), which captures the fundamental structure of our lifecycle analysis:

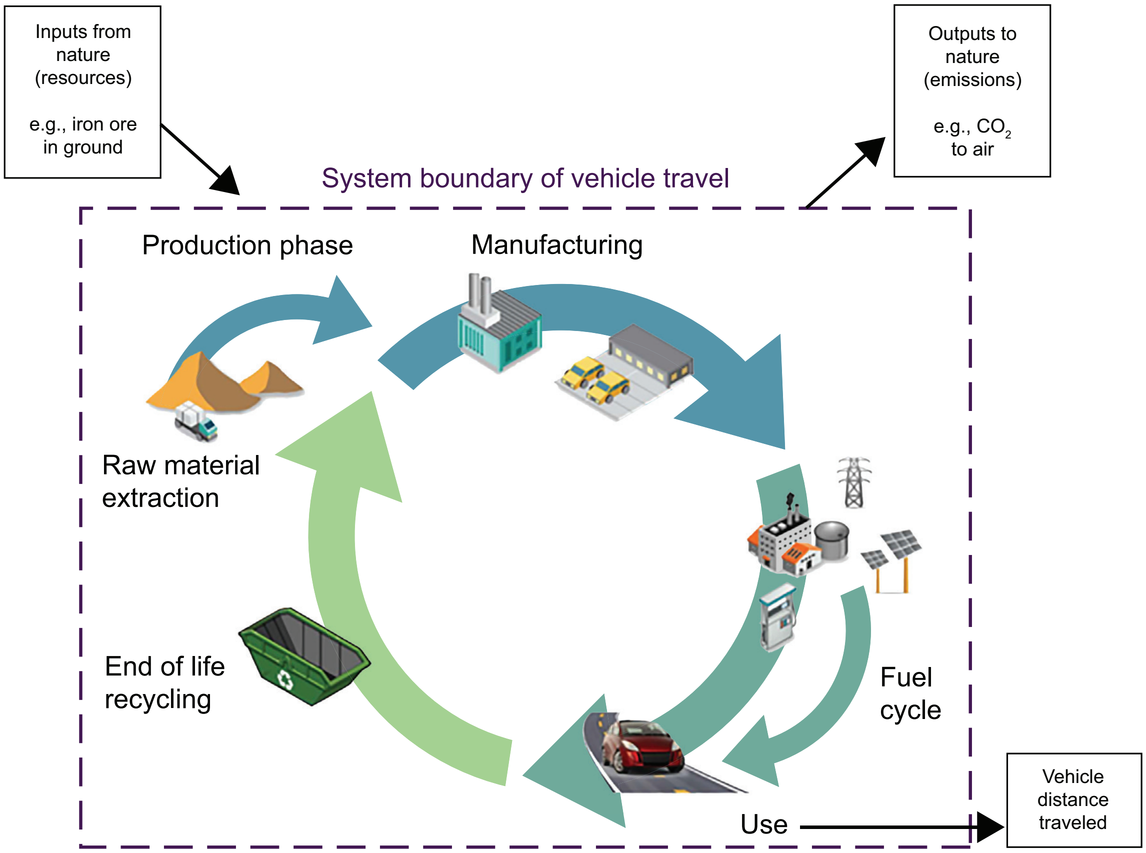
$$\frac{e}{d} = \frac{e_p + e_{EOL} + e_m}{d} + \frac{1}{MPG}\left(\frac{e_f}{E} + \frac{e_u}{E}\right)\frac{E}{G} \qquad (1)$$

where $e_p$ = emissions from vehicle manufacturing (in metric tons $CO_2$-equivalent or $CO_2e$);
$e_{EOL}$ = emissions from end-of-life disposal;
$e_m$ = emissions from vehicle maintenance;
$d$ = lifetime distance traveled or mileage (mi);
$MPG$ = miles per gallon gasoline-equivalent (mi/gal);
$\frac{e_f}{E}$ = emissions to produce fuel per unit of energy in fuel, in megajoules ($gCO_2e/MJ$); and
$\frac{e_u}{E}$ = emissions from using fuel per unit of energy in fuel ($gCO_2e/MJ$).

Since emissions from vehicle maintenance and end-of-life disposal are negligible compared to emissions from vehicle production and operation, we set $e_m$ and $e_{EOL}$ to zero for all powertrains (Klemola 2016). $\frac{E}{G}$ is the energy content of gasoline (lower heating value) and is equal to 33.7 kWh per gallon. By weight, around 80% of the material content of a typical passenger vehicle is recycled (Jody, et al. 2010). For this analysis, we count emissions from recycling (e.g., recycling aluminum parts instead of mining virgin bauxite) as part of vehicle production emissions.

Table 4.2 gives typical values for mid-size passenger vehicles with different drivetrains. The specific car models included in this analysis were chosen to facilitate apples-to-apples comparisons—that is, to minimize non-powertrain differences. We do this by choosing vehicles of similar size and make. The U.S. EPA defines mid-size vehicles as having an internal volume between 110–120 $ft^3$. Within this group, we

**Figure 4.5: Lifecycle of vehicles and fuels**



analyzed the Honda Clarity BEV (117 $ft^3$) because the Clarity also comes in PHEV (116 $ft^3$) and FCEV (113 $ft^3$) versions. For ICEVs, we analyzed the Toyota Camry (115 $ft^3$) because it is a top-selling mid-size sedan of comparable size to the Clarity, and because it also comes in an HEV (115 $ft^3$) version. Fuel economy, as expressed in miles per gallon (MPG), is the only input that is specific to the model of car being considered (Table 4.2). Note that the vehicle models used in this analysis are similar to, but not the same as, those used to estimate relative powertrain costs in Section 4.1.

We assume a nominal lifetime distance traveled of 180,000 miles for all powertrains. However, for certain powertrains, such as BEVs and FCEVs, component lifetimes for batteries and fuel cells could differ from vehicle lifetime. If certain components need to be replaced during the vehicle lifetime, this affects the emissions from vehicle production.

Other input values differ across types of powertrains for several reasons. Compared to an ICEV, manufacturing a BEV results in roughly 70% higher greenhouse gas emissions—due mainly (but not solely) to battery manufacture, which contributes roughly one-third of total BEV production emissions (Nealer, Reichmuth, and Anair 2015). Fuel production emissions are also typically higher for BEVs (and FCEVs) because, on average, generating and delivering a megajoule of electricity or hydrogen to a vehicle battery or fuel cell consumes much more energy than producing and delivering a megajoule of gasoline to the fuel tank of an ICEV. On the other hand, fuel-use emissions are zero for BEVs and FCEVs since these vehicles emit no tailpipe greenhouse gases during operation, whereas fuel-use emissions are high for ICEVs because these vehicles combust hydrocarbon fuels in their engines. Vehicle fuel economy as expressed in MPG is more than three times higher for BEVs than for ICEVs, primarily due

**Table 4.2: Typical values for variables that impact emissions per mile for 2018 mid-size sedans with different powertrains**

| Variable | | ICEV | HEV | PHEV | BEV | FCEV |
|---|---|---|---|---|---|---|
| $e_p$ | Emissions from vehicle manufacturing (metric tons $CO_2e$) | 8[a] | 10.4[a,b] | 12[a,b] | 13.6[a,b,c] | 12[a,b] |
| $d$ | Lifetime distance traveled, i.e. mileage (mi) | 180,000 | 180,000 | 180,000 | 180,000 | 180,000 |
| $MPG$ | Miles per gallon gasoline-equivalent (mi/gal) | 34[d]<br>(Camry) | 52[d]<br>(Camry) | 42[d], 110[d,*]<br>(Clarity) | 114[d]<br>(Clarity) | 68[d]<br>(Clarity) |
| $\frac{e_f}{E}$ | Emissions to produce fuel, per energy in fuel ($gCO_2e/MJ$) | 19[e] | 19[e] | 19[e], 121[f,*] | 121[f] | 113[g] |
| $\frac{e_u}{E}$ | Emissions from using fuel, per unit energy in fuel ($gCO_2e/MJ$) | 73 | 73 | 73, 0* | 0 | 0 |

Note: Emissions from vehicle manufacturing are from [a] Nealer, Reichmuth, and Anair (2015), [b] Heywood and MacKenzie (2015), and [c] Qiao, et al. (2017); BEV manufacturing emissions are based on BEVs with a range of ~265 miles and a lithium cobalt oxide battery with capacity of ~85 kWh; [d] MPG values (expressed in gasoline-equivalent terms) are from the U.S. EPA (2018); [e] emissions from fuel production are based on an MIT analysis of emissions from three representative crude oil compositions processed in 11 representative U.S. refinery configurations; [f] U.S. grid average for 2018 is based on the Economic Projection and Policy Analysis model described in Chapter 2; [g] hydrogen production emissions are based on an MIT analysis of steam methane reforming pathways (similar values have been reported in the literature, including Mehmeti, et al. [2018]). * First value for PHEV is for gasoline mode and second value is for electric mode.

to powertrain efficiency. For fundamental reasons including the thermodynamics of heat engines, electric motors are much more efficient in converting electrochemical energy to mechanical energy than internal combustion engines are at converting chemical energy into mechanical energy. To summarize: fuels for ICEVs can be produced more efficiently, in general, than fuels for BEVs and FCEVs, but BEVs and FCEVs *use* fuel much more efficiently than ICEVs.

Each of the nominal input values in Table 4.2 will influence the lifecycle emissions calculated by Equation 1. Lifecycle emissions across powertrains using these nominal values are presented in Section 4.2.2, while Section 4.2.3 looks at key sensitivities to these values. Section 4.2.4 then considers how relative emissions of different powertrains may evolve in the future.

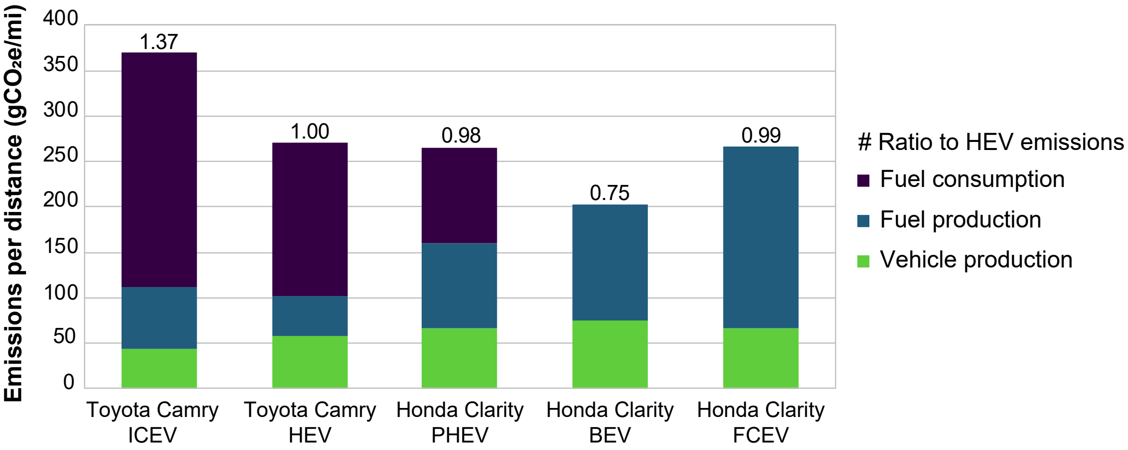
### 4.2.2 Current Emissions for Vehicles with Different Powertrains

Given representative values for each input shown in Table 4.2, we estimate emissions per mile for vehicles with different powertrains based on current parameters for electricity and hydrogen generation and transmission in the U.S. (Figure 4.6). Figure 4.6 shows that BEV emissions per mile are approximately 55% the emissions of comparable ICEVs. Increased emissions from battery and fuel production are more than offset by increased powertrain efficiency, such that total fuel-cycle emissions per mile are lower for BEVs. Second, hybrid vehicle emissions per mile fall between ICEV and BEV emissions. Finally, emissions per mile for hydrogen FCEVs are approximately the same as for hybrid vehicles.

### 4.2.3 Sensitivity Analysis of Current Emissions

Emissions are sensitive to multiple vehicle and fuel characteristics. Most inputs shown in Table 4.2 exhibit significant variability even for currently available car models. Table 4.3 lists important drivers of variability, while Table 4.4 and Table 4.5 show how such input variability can impact lifecycle emissions for BEVs and FCEVs, respectively. For this sensitivity analysis, we use HEV emissions as the baseline reference because, in any future scenario where government policies cause consequential reductions in greenhouse gas emissions, HEVs are the most relevant vehicle type to represent highly fuel-efficient gasoline-powered LDVs.

**Figure 4.6: Greenhouse gas emissions per mile for cars with different powertrains, U.S. 2018**



Note: Based on 180,000-mile life for all powertrains; U.S. 2018 average grid carbon intensity of 436 $gCO_2e/kWh$; gasoline production emissions of 19 $gCO_2e/MJ$; MPG values are 34 for ICEV, 52 for HEV, 42 gasoline and 110 electric for PHEV, 114 for BEV, 68 for FCEV (U.S. EPA 2018); 50/50 split of miles by gasoline and electric modes for PHEV; hydrogen production based on steam methane reforming with 13.6 $gCO_2e/gH_2$.

**Table 4.3: Important drivers of variability for different input variables and powertrains**

| Variable | | ICEV | BEV | FCEV |
|---|---|---|---|---|
| *MPG* | Miles per gallon gasoline-equivalent | City versus highway, aggressive driving | City versus highway, aggressive driving, ambient temperature | City versus highway, aggressive driving |
| $\frac{e_f}{E}$ | Emissions to produce fuel, per energy content of fuel | Oil source (e.g., tar sands versus conventional well) | Electricity generating source (e.g., coal versus solar power) | Hydrogen source (e.g., CG, SMR, SMR + CC, versus electrolysis) |
| $e_p$ | Emissions from vehicle production | Energy sources used to manufacture vehicle; production of battery or fuel cell replacement (if needed), potential "second-life" uses of batteries, battery size, and chemistry | | |
| $d$ | Lifetime distance traveled | Accidents, maintenance, policy | | |

Note: CG = coal gasification; SMR = steam methane reforming; CC = carbon capture.

### *Sensitivity of BEV-to-HEV emissions ratio*

Table 4.4 shows how changing certain input assumptions affects the ratio of per-mile BEV emissions to per-mile HEV emissions. The first takeaway from Table 4.4 is that BEV emissions per mile are highly sensitive to the carbon intensity of the power grid. In the U.S., in 2018, the carbon intensity of the power mix varies by roughly an order of magnitude across the 50 states. As a result, a BEV charged with the average electricity from the power grid in the state of Washington would generate roughly 70% less lifecycle greenhouse gas emissions than the same model BEV charged with average electricity from West Virginia's grid. If we compare two identical BEVs, one manufactured and charged with the U.S. grid-average energy mix and one manufactured and charged with China's grid-average energy mix, the U.S. BEV would generate roughly 25% less emissions than a similar sized HEV, while the China BEV would generate roughly 13% *more* emissions than a similar sized HEV. These comparisons provide just two examples of location sensitivity. Assessing the true emissions impact of a particular BEV requires knowledge of that vehicle's charging energy sources. Carbon intensity varies not only by region, but also by time. For example, in Texas, a BEV charged

Table 4.4: Sensitivity of BEV-to-HEV emissions ratio to MPG, lifetime mileage, battery replacement, and carbon intensity of the power grid

| Case | BEV/ HEV emissions ratio | | Assumptions |
|---|---|---|---|
| | # | % change | |
| **Base case:** U.S. average grid emission intensity | 0.75 | | U.S. average grid carbon intensity is 436 gCO$_2$e/kWh[a] |
| Higher MPG for BEV | 0.72 | -4 | Use fuel economy of Tesla Model 3 (123 MPG) instead of Clarity (114 MPG) |
| Lower lifetime mileage | 0.85 | +13 | Halve mileage from 180,000 to 90,000 miles |
| One entire battery replacement | 0.84 | +12 | Replace 85 kWh battery once during vehicle lifetime |
| Manufacture vehicles w/ average power of “greenest” state (Washington) | 0.71 | -5 | Washington state average grid carbon intensity is 101 gCO$_2$e/kWh[b] |
| Charge BEV w/ average power of “greenest” state (Washington) | 0.39 | -48 | Average grid carbon intensity is 101 gCO$_2$e/kWh[b] |
| Charge BEV w/ average power of “least green” state (West Virginia) | 1.30 | +72 | West Virginia average grid carbon intensity is 946 gCO$_2$e/kWh[c] |
| Use electricity from a much “greener” mix of power sources for both vehicle manufacturing and charging | 0.23 | -69 | Grid carbon intensity is 36 gCO$_2$e/kWh[d] |
| Use China average grid emission intensity for input electricity for both vehicle manufacturing and charging | 1.13 | +51 | Grid carbon intensity is 774 gCO$_2$e/kWh[a] |

Note: [a] from the Economic Projection and Policy Analysis (EPPA) model in Chapter 2; [b] U.S. EIA (2019b); [c] U.S. EIA (2019c); [d] based on Accelerated Support to Renewables case from Section 2.3.3; percent change in BEV/HEV emissions ratio is calculated relative to the base case.

at night will have a different emissions profile than a BEV charged during the day, because at night wind supplies a larger share of the power delivered to the Texas grid than during the day.

We also consider how vehicle and component lifetime might influence BEV emissions per mile. We find that these parameters do not influence the BEV-to-HEV emissions comparison as much as the charging power source, but they still have a significant impact. When it comes to vehicle lifetime mileage, Table 4.4 shows that halving the lifetime distance traveled of both the BEV and HEV from 180,000 to 90,000 miles increases BEV emissions from 75% to 85% of HEV emissions. This change is equivalent to halving the life of every component in every type of car: battery, body, seats, etc. If instead the vehicle lifetime mileage remains at 180,000 miles for both vehicles, but the BEV must replace its battery once in that time span (i.e., the battery life is only half the vehicle life), our sensitivity analysis suggests that BEV emissions per mile increase from 75% to 84% of HEV emissions per mile.[3]

---

[3] Data and analyses regarding battery life from the world’s two largest BEV manufacturers, BYD and Tesla, indicate that batteries for electric vehicles and electric buses are likely to last for more than 160,000 miles with less than 20% capacity degradation (Lambert 2018; Nørregaard, Johnsen, and Gravesen 2016). This suggests that battery replacement may not be necessary for a BEV with a lifetime mileage of 180,000 miles. However, other manufacturers may have higher degradation rates since battery life and performance are highly dependent on proprietary battery technologies and the battery management systems that control their operations. Battery life is also dependent on vehicle usage and charging patterns, as well as ambient conditions during usage and charging. Therefore, there is great uncertainty about EV battery performance in future decades. Note that battery degradation does not require that the entire battery pack be replaced. Individual battery cells or modules that have failed can be replaced, while good battery cells are retained. Our sensitivity analysis, which assumes replacement of the entire battery, represents a worst-case scenario.

**Table 4.5: Sensitivity of FCEV-to-HEV emissions ratio to vehicle lifetime mileage and hydrogen production method**

| Case | FCEV/ HEV emissions ratio | | Assumptions |
|---|---|---|---|
| | # | % change | |
| **Base case:** produce $H_2$ using conventional steam methane reforming (SMR) | 0.99 | | $H_2$ production with SMR has emissions of 13.6 $gCO_2e/gH_2$[a] |
| Lower vehicle lifetime mileage | 1.01 | +2 | Halve lifetime mileage from 180,000 to 90,000 miles |
| Produce $H_2$ using SMR with carbon capture (CC) | 0.56 | -43 | With CC, $H_2$ production emissions are reduced to 5.7 $gCO_2e/gH_2$[a] |
| Produce $H_2$ using coal gasification (CG) | 1.56 | +58 | With CG, $H_2$ production emissions increase to 24.2 $gCO_2e/gH_2$[b] |
| Produce $H_2$ using electrolysis with U.S. average electricity | 1.49 | +51 | U.S. average grid carbon intensity is 436 $gCO_2e/kWh$[c] |
| Produce $H_2$ using electrolysis with electricity from "greenest" state power mix (i.e., Washington state) | 0.62 | -37 | Washington state grid average carbon intensity is 101 $gCO_2e/kWh$[d] |
| Produce $H_2$ using electrolysis with 100% renewable electricity | 0.39 | -61 | Wind power carbon intensity is 12 $gCO_2e/kWh$[e] |
| Produce $H_2$ with electrolysis and manufacture all vehicles using a much greener power mix | 0.39 | -61 | Grid carbon intensity is 36 $gCO_2e/kWh$[f] |

Note: Electrolyzer efficiency is assumed to be 70% for all electrolysis cases; [a] this assumes 90% of the $CO_2$ generated in both the reforming part of the SMR process and in the combustion part of the process is captured, with remaining emissions coming mainly from upstream natural gas production and downstream hydrogen compression (Gençer and O'Sullivan 2019); [b] Mehmeti, et al. (2018); [c] from the Economic Projection and Policy Analysis (EPPA) model in Chapter 2; [d] U.S. EIA (2019b); [e] emissions are from upstream manufacturing of wind farm components, including turbines and foundations (Arvesen and Hertwich 2012); [f] based on Accelerated Government Support to Renewables case from Section 2.3.3.

While battery life can be shorter than vehicle life, it is also important to note that the total life of the battery can extend beyond its useful life as a vehicle battery. As noted in Section 4.3.4, which discusses battery recycling, companies are exploring businesses based on using retired EV batteries for stationary energy storage. If such applications are pursued at scale, battery manufacturing emissions would need to be amortized over both the vehicle lifetime and the second-use lifetime.

Compared to mileage and charging power source, the choice of a particular lithium-based battery chemistry is not as important a driver of BEV lifecycle emissions. A previous sensitivity analysis of seven alternative lithium-based battery chemistries found a maximum reduction in battery production emissions of approximately 40% relative to lithium cobalt oxide (Nealer, Reichmuth, and Anair 2015). This translates to a decrease in BEV production emissions of approximately 13% and a decrease in BEV lifecycle emissions per mile of approximately 5%.

### *Sensitivity of FCEV-to-HEV emissions ratio*

Similar to our sensitivity analysis for BEV emissions, Table 4.5 shows how different input assumptions change the ratio of FCEV emissions to HEV emissions.

As with BEVs, Table 4.5 shows that reducing the lifetime mileage of FCEVs yields a slightly less favorable comparison to HEVs, simply because higher emissions to manufacture the FCEV are amortized over fewer lifetime miles.

Just as BEV emissions depend on the grid electricity generation mix, FCEVs that use hydrogen from electrolysis are sensitive to the grid's carbon intensity. If the electricity used in electrolysis reflects the U.S. average power mix, FCEVs have lifecycle emissions that are 49% higher than HEV emissions. If wind power is used for electrolysis, FCEVs have emissions that are 61% lower than HEV emissions. The latter scenario is relevant because hydrogen production has been proposed as one way to effectively "store" excess power from wind and solar farms, which at some times and in some places is now being sold at negative prices (Martinez-Anido, Brinkman and Hodge 2016). A challenge of intermittent hydrogen production is that a lower capacity factor for the electrolyzer increases capital costs per kilogram of hydrogen produced. The use of wind power for electrolysis can reduce emissions from hydrogen production, but there are additional emissions related to other stages of the lifecycle, such as vehicle production. For this sensitivity analysis we assume that vehicle production emissions are based on the average electric grid even when hydrogen production uses 100% renewable electricity. As shown in Table 4.2, emissions to manufacture an FCEV are estimated at approximately 12 metric tons $CO_2$-equivalent ($CO_2e$) per vehicle; this translates to approximately 67 grams $CO_2e$ per mile ($gCO_2e/mi$), assuming lifetime vehicle mileage of 180,000 miles.

The abundance of coal in China and Southeast Asia could facilitate another hydrogen production pathway for FCEVs: coal gasification (CG). Lifecycle assessments have shown that CG emits significantly more greenhouse gases than SMR per unit of hydrogen produced (Mehmeti, et al. 2018). As a result, an FCEV using CG-hydrogen has roughly 57% higher lifecycle greenhouse gas emissions than the same model FCEV using SMR-hydrogen, as shown in Table 4.5. Coal gasification with carbon capture is another alternative hydrogen production pathway and would mitigate some of the emissions.

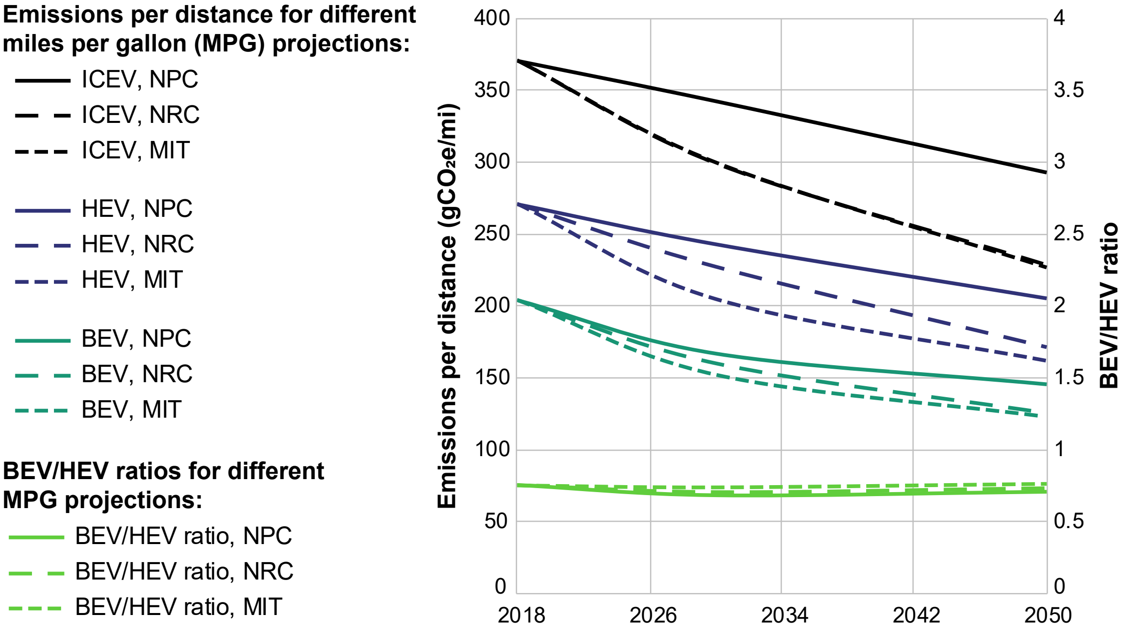
### 4.2.4 Projections of Future Emissions

Projecting future emissions from vehicle travel requires making assumptions about how the variables in equation (1) might change. Some variables are constrained by physics (e.g., powertrain efficiency cannot exceed 100%), but specific inputs are also highly influenced by unpredictable non-physical factors, such as policy conditions, business decisions, and consumer behavior. Given these uncertainties, it is important to explore the sensitivity of emissions projections to different assumptions.

Given the sensitivity of BEV emissions to grid carbon intensity and the likelihood that grid carbon intensity will keep declining, one might expect the environmental advantages of BEVs over HEVs to increase over time. Put another way, it seems reasonable to expect that the ratio of BEV-to-HEV emissions will decline in the future. However, our analysis indicates that for scenarios where the grid's carbon intensity declines by less than 50%, the anticipated rate of MPG improvements for HEVs published in the literature will roughly keep pace with the rate of grid decarbonization. Figure 4.7 plots greenhouse emissions per mile for three powertrains using MPG projections from three different sources: MIT (Heywood and MacKenzie 2015), the National Research Council (2013), and the National Petroleum Council (2012). All scenarios in the figure assume the same 34% decline in the average carbon intensity of the U.S. grid (from 436 $gCO_2e/kWh$ in 2018 to 290 $gCO_2e/kWh$ in 2050), based on the *Reference* climate policy scenario described in Chapter 2.

Depending on MPG assumptions, the BEV-to-HEV emissions ratio (green curves) is projected to change from 0.75 to 0.71 between 2018 and 2050 (using the NPC values), from 0.75 to 0.76 (using the MIT values), and from 0.75 to 0.73 (using the NRC values). In other words, none of the three MPG projections shows a significant increase in the carbon advantage of BEVs relative to HEVs over the next 30 years. If we were to assume no change in vehicle MPG, a 34% reduction in grid carbon intensity would lower the ratio of BEV-to-HEV emissions from 0.75 to 0.57. However, the green lines in Figure 4.7 show that projected changes in MPG counter this grid decarbonization effect.

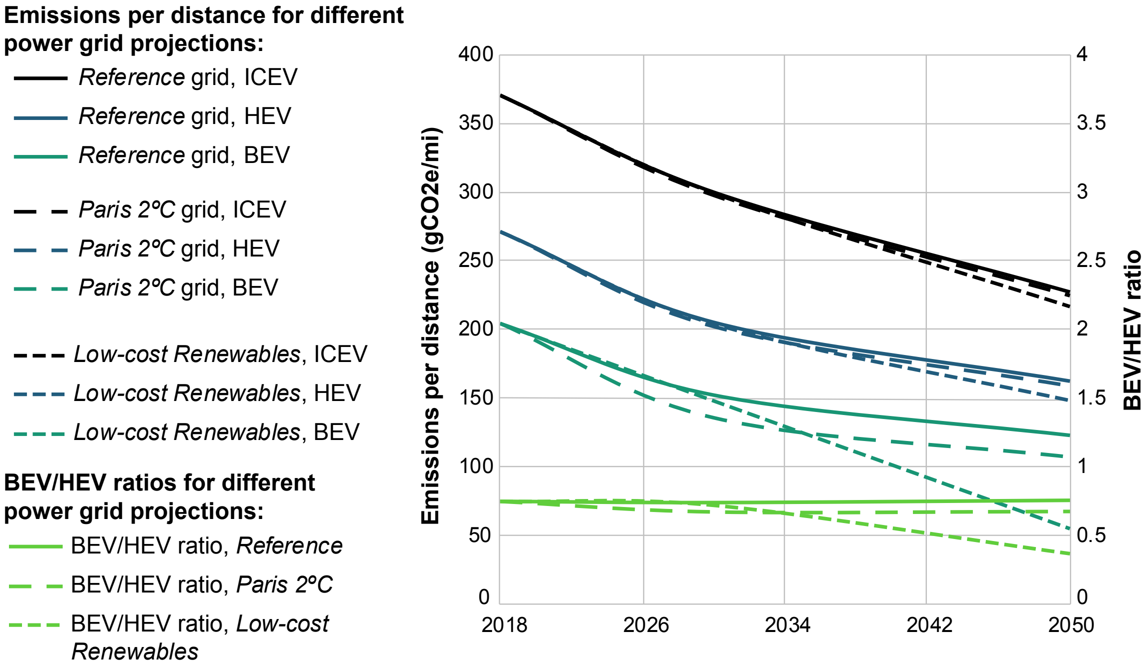
**Figure 4.7: Vehicle emissions in the U.S. given different MPG projections**



Note: Each powertrain is shown in the same color and the three sets of MPG projections are shown as solid, dashed, and dotted lines. MPG improvements are assumed to be 28%, 71%, and 73% for ICEVs in the National Petroleum Council (NPC), National Research Council (NRC), and MIT projections, respectively; 37%, 75%, and 90% for HEVs; and 6%, 42%, and 47% for BEVs. Emissions ratios for BEVs relative to HEVs are shown on the secondary y-axis. The carbon intensity of the U.S. grid declines by 34% in the *Reference* scenario and is used to calculate emissions from vehicle manufacturing for all powertrain vehicles as well as operating emissions for the BEV. In 2014, approximately 45% of greenhouse gas emissions for vehicle manufacturing came from electricity use (Nealer, Reichmuth, and Anair 2015). The contribution to vehicle manufacturing emissions from electricity use has since decreased to approximately 40% in 2018 and is expected to decline further in the future, depending on the extent of electricity decarbonization. For all curves, the estimates assume vehicle and battery life of 180,000 miles.

The rate of decarbonization in the electric power sector is an important unknown that will be driven by policy, technology, and economics. Figure 4.8 shows projected greenhouse gas emissions per mile for the three types of powertrains under three scenarios for grid evolution taken from the EPPA model outlined in Chapter 2. In the *Reference* scenario, the carbon intensity of the U.S. grid is assumed to fall 34% from 2018 to 2050, from 436 g$CO_2$e/kWh to 290 g$CO_2$e/kWh. In the *Paris to 2°C* scenario, the assumed decline is 47%. And in the *Low-cost Renewables* scenario, the assumed decline is 92%. All plotted scenarios use the MIT projections for MPG gains by 2050 (Heywood and MacKenzie 2015): a 73% increase for ICEVs, a 90% increase for HEVs, and a 47% increase for BEVs. As discussed earlier, emissions from ICEVs and HEVs are not sensitive to the carbon intensity of the power mix, because most of their emissions come from fuel combustion in the vehicle. BEV emissions, on the other hand, are sensitive to the makeup of the power mix, as shown by the dotted blue curve. A 92% decline in grid carbon intensity would overwhelm projected MPG effects, such that the BEV-to-HEV emissions ratio would drop by approximately half by 2050 (from 0.75 to 0.37). In other words, a dramatic reduction in grid carbon intensity would indeed give BEVs a much larger carbon advantage over HEVs.

**Figure 4.8: Vehicle emissions in the U.S. given different power grid projections**



Note: Each powertrain is shown in the same color and the three sets of grid carbon intensity are shown as solid, dashed, and dotted lines. The emissions ratio for BEVs relative to HEVs is shown in green. The carbon intensity of the U.S. grid decreases by 34%, 47%, and 92% for the three scenarios. MPG improvements are assumed to be 73%, 90%, and 47% for ICEVs, HEVs, and BEVs respectively. Grid carbon intensity is used to calculate manufacturing emissions for all types of vehicles as well as operating emissions for the BEV. For all curves, the estimates assume vehicle and battery life of 180,000 miles.

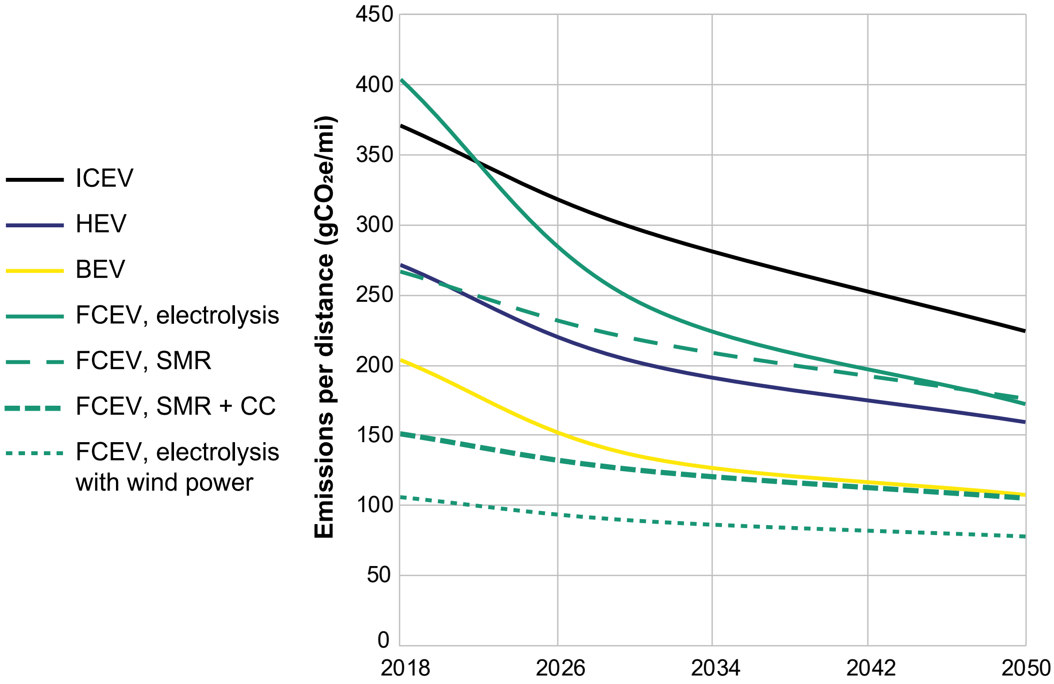
There are also large uncertainties about the future of FCEVs, both in terms of their market share and in terms of the methods used to produce hydrogen fuel for these vehicles. Figure 4.9 plots greenhouse gas emissions per mile for FCEVs assuming four different hydrogen production methods: SMR, SMR with carbon capture (CC), electrolysis using electricity with grid-average carbon intensity, and electrolysis using wind power (and other similarly very low-carbon electricity). We assume changes in grid carbon intensity consistent with the *Paris to 2°C* scenario (with a 47% decline from 2018 to 2050) and use the MIT values for MPG improvement (Heywood and MacKenzie 2015).

Figure 4.9 illustrates three important takeaways:

1. The hydrogen source that minimizes FCEV carbon emissions is electrolysis supplied with very low-carbon power such as wind.
2. Compared to SMR, electrolysis with the grid-average power mix does not result in carbon benefits for FCEVs, even with a 47% decline in grid carbon intensity from 2018 to 2050 (from 436 $gCO_2e/kWh$ to 230 $gCO_2e/kWh$).
3. Capturing and storing 90% of the $CO_2$ generated from SMR reduces FCEV emissions to a similar level as BEV emissions.

Note that the current cost and availability of low-carbon hydrogen production pathways means that achieving emissions consistent with the early years of some of the curves is unlikely.

**Figure 4.9: Vehicle emissions for FCEVs using hydrogen produced via different methods**



Note: The ICEV, HEV, and BEV powertrains are shown in this figure to provide context for the FCEV curves. MPG improvements are assumed to be 73%, 90%, 47%, and 63% for ICEVs, HEVs, BEVs, and FCEVs, respectively. Hydrogen production methods include SMR, SMR with CC, electrolysis using U.S. grid-average electricity, and electrolysis using wind power. All vehicles in this figure are manufactured with the power mix projected under the *Paris to 2°C* scenario—that is, assuming a 47% reduction in carbon intensity in 2050. The same average power mix is also used to estimate operating emissions for BEVs and FCEVs using fuel produced by electrolysis. The only curve that does not assume grid-average electricity for vehicle operation is the "electrolysis w/ wind power" curve, where the electricity source for hydrogen-via-electrolysis is wind power (with 12 $gCO_2e/kWh$) instead of the grid-average power mix. For all curves, the estimates assume vehicle and battery life of 180,000 miles.

### 4.2.5 Summary

In the U.S. today, greenhouse gas emissions per mile for BEVs are approximately 55% of emissions per mile for a similarly sized ICEVs. Per-mile greenhouse gas emissions for HEVs, PHEVs, and FCEVs are all approximately 72%–73% of emissions from ICEVs. These comparisons are for similarly sized vehicles. In the case of BEVs and FCEVs, greenhouse gas emissions come mainly from the production of electricity and hydrogen, respectively; by contrast, most ICEV and HEV emissions come from the combustion of fuel on board the vehicle. Emissions associated with vehicle manufacture, including the manufacture of batteries, vary substantially across powertrains but these differences are generally dwarfed by greenhouse gas emissions from the fuel lifecycle. However, the relative contribution from vehicle production becomes more substantial as the fuels used to operate different vehicles become less carbon intensive.

Compared to other vehicle types, BEV emissions are much more sensitive to the carbon intensity of the power grid. As a result, BEV emissions show much greater geographic variation. For example, a BEV manufactured and charged with U.S.-average electricity would have 25% lower emissions than a comparable HEV, whereas a BEV manufactured and charged with China-average electricity would have 13% higher greenhouse gas emissions than a comparable HEV. These results reflect large differences in the carbon intensity of the power mix between these two countries.

Due mainly to projected reductions in grid carbon intensity and increases in MPG, greenhouse gas emissions from all types of vehicles are projected to decline over the next three decades (to 2050): by 30%–47% for BEVs, by 20%–40% for ICEVs, and by 25%–40% for HEVs. If the carbon intensity of the U.S. grid declines by less than 50% by 2050, the carbon benefits of BEVs relative to ICEVs and HEVs will likely not increase significantly, due to changes in other factors including relative MPG. On average in the U.S., BEVs would likely continue to emit roughly 70%–75% of the greenhouse gases emitted by similar-sized HEVs on a per-mile basis, even as emissions from both declined on an absolute basis. If, on the other hand, grid carbon intensity declines dramatically, by 92% from 2018 to 2050, BEV emissions would decline from roughly 75% to 37% of HEV emissions.

Emissions for an FCEV depend on how its hydrogen fuel is produced. The hydrogen source that minimizes FCEV greenhouse gas emissions is electrolysis with renewable power, such as wind. Hydrogen via wind-powered electrolysis results in FCEV emissions that are 61% lower than HEV emissions. The hydrogen source that produces the highest FCEV greenhouse gas emissions is coal gasification, which yields FCEV emissions that are 56% higher than HEV emissions and 14% higher than ICEV emissions. The high emissions of hydrogen production from coal gasification can be reduced by capturing and storing the $CO_2$ generated. Hydrogen production via steam methane reforming results in FCEV emissions that are roughly equal to HEV emissions. Adding carbon capture to steam methane reforming reduces FCEV lifecycle emissions by approximately half.

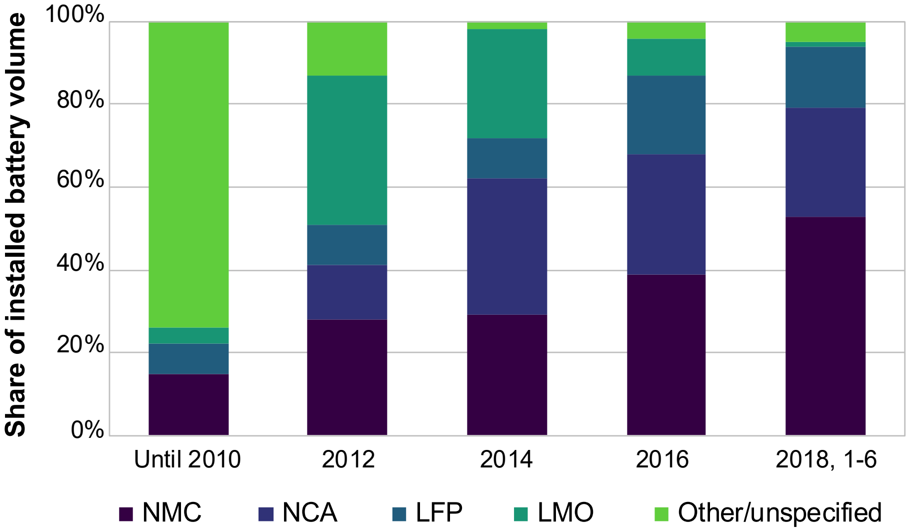
## 4.3 THE OUTLOOK FOR VEHICLE BATTERIES

Growing global awareness of the environmental impacts of combustion is accelerating the adoption of plug-in electric vehicles (EVs). However, widespread market penetration remains a challenge for these vehicles due to high purchase prices. The U.S. DOE has a battery price target of $125/kWh by 2022 for clean transportation applications (Chu, Cui, and Liu 2017). Given that the price of battery packs ranged from $200–$300/kWh in 2016 and 2017, a recurring question is how quickly battery costs can be expected to drop to the U.S. DOE's target of $125/kWh and how much lower battery costs can be expected to go. Conventional one-stage learning curves, which depict declining cost as a function of production volume, are widely applied to project future battery prices (Nykvist and Nilsson 2015; Schmidt, et al. 2017; Kittner, Lill, and Kammen 2017; Berckmans, et al. 2017). All of the models published in the literature thus far that are based on one-stage learning curves predict that battery prices will fall below $100/kWh by about 2030, which would bring BEVs closer to price parity with ICEVs in the absence of incentives (Knupfer, et al. 2017). However, these projections might be too optimistic since the conventional learning curve model implies the potential for unlimited cost reductions. It is unrealistic to expect that battery prices can drop *below* the price of the materials they are made of and continue falling toward $0/kWh as cumulative production volumes increase. Clearly, a reassessment is needed. Therefore, this section presents an overview of the current market for EV batteries, discusses projections for future battery costs that account for the base cost of materials, describes the techno-economic characteristics of different battery chemistries for EVs, and considers issues related to recycling batteries at the end of their useful life.

### 4.3.1 The Current Market for EV Batteries

Lithium-ion batteries (LIBs) are considered the best available battery technology for EVs because of the advantages they offer in terms of high energy density, long cycle life, and low self-discharging rate (Chen and Sen 2016). Several

Figure 4.10: Global installed battery volume in the private light-duty vehicle sector by cathode chemistry



Note: NMC = lithium nickel manganese cobalt oxide; NCA = lithium nickel cobalt aluminum oxide; LFP = lithium iron phosphate; LMO = lithium manganese oxide.

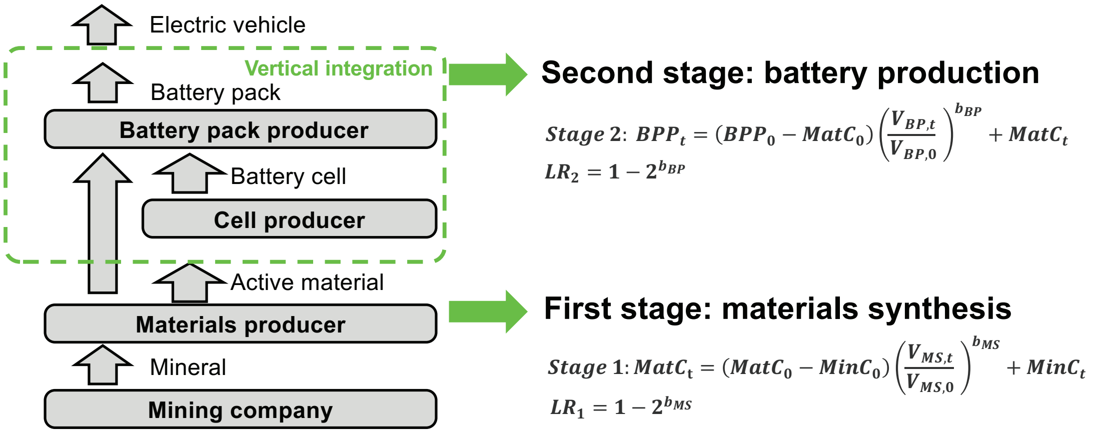
types of LIBs have been used in EV models over the past decade; Figure 4.10 breaks down the global market for EV batteries by cathode chemistry (Irle 2018). A wide variety of types of rechargeable batteries (such as lead acid, nickel metal hydride, and lithium ion) were used during the early experimental phase of EV development (i.e., prior to the end of 2010). Thanks to the introduction of two EVs—the Nissan Leaf and Chevrolet Volt—in 2011, lithium manganese oxide (LMO) became the first dominant battery chemistry. Most batteries identified as LMO actually blend some amount of lithium nickel manganese cobalt oxide (NMC) into the cathodes to enhance EV performance—both specific energy and life span. However, LMO-NMC blends have been gradually phased out and replaced by pure NMC cathodes. Batteries with NMC-only cathode chemistries have been deployed in a variety of EV models, from the 2012 Honda Fit to the 2017 Chevrolet Bolt. Around 2013, when Tesla increased production, the output of lithium nickel cobalt aluminum oxide (NCA) batteries expanded, until this type of battery reached 33% of market share in 2014. Starting in 2015, production of lithium iron phosphate (LFP) batteries also increased because this type of battery was widely adopted by Chinese vehicle manufacturers. However, LFP batteries lost market share to NMC batteries in China because China's EV subsidies favor longer driving range, which requires high energy density. LFP batteries have higher thermal stability, but lower energy density than batteries with nickel and cobalt content. NMC and NCA batteries have high energy density but are more expensive per kWh owing to their reliance on cobalt. As shown in Figure 4.10, NMC is currently the most popular battery chemistry in the light-duty vehicle sector, reaching 53% market share in the first half of 2018 from only 15% at the end of 2010.

### 4.3.2 Two-Stage Learning Curve Model

To evaluate the potential for further reductions in battery cost, we analyzed the various steps involved in battery production. As shown in Figure 4.11, the battery supply chain consists of four steps:

1. Mining the necessary minerals
2. Converting the minerals to active ingredients with the required purities
3. Processing the active ingredients to fabricate the electrodes and other components that make up the battery cells
4. Assembling battery cells into battery packs

**Figure 4.11: Structure of the battery supply chain and mathematical model of a two-stage learning curve**



$$Stage\ 2\colon BPP_t = (BPP_0 - MatC_0)\left(\frac{V_{BP,t}}{V_{BP,0}}\right)^{b_{BP}} + MatC_t$$

$$LR_2 = 1 - 2^{b_{BP}}$$

$$Stage\ 1\colon MatC_t = (MatC_0 - MinC_0)\left(\frac{V_{MS,t}}{V_{MS,0}}\right)^{b_{MS}} + MinC_t$$

$$LR_1 = 1 - 2^{b_{MS}}$$

This supply chain is expected to undergo some consolidation in the years ahead, given that many automakers have declared their intent to pursue vertical integration with battery and electrode producers to reduce battery costs. We therefore expect that the future battery supply chain for EV applications will consist of two main steps: (1) production of active materials by mining companies and materials producers, and (2) fabrication of the battery packs by integrated battery-automotive corporations.

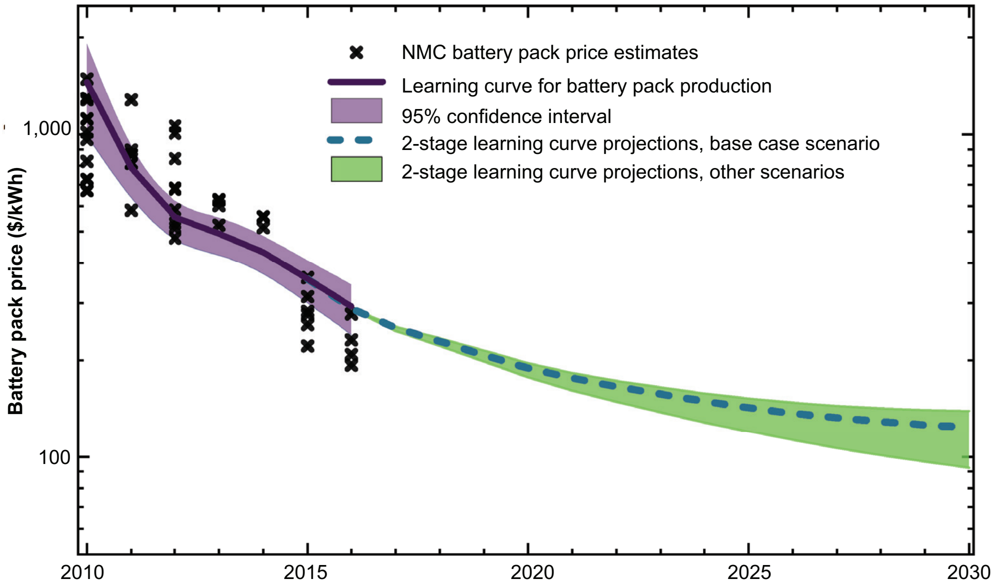
Based on the battery supply chain structure shown in Figure 4.11, we developed a two-stage learning curve model to capture the practical limits to further reducing battery cost (Hsieh, et al. 2019). In the first stage of learning, materials synthesis (*MS*), mineral costs (*MinC*) are considered a floor for active materials costs (*MatC*). In the second stage of learning, battery pack production (*BP*), the active materials costs from the first-stage calculation are taken as a floor for the battery pack price (*BPP*). Learning rates (*LR*) are defined as the cost reduction that occurs as the cumulative production volume doubles. *V* denotes cumulative production volume and *b* represents the technology-specific experience index.

### *Trajectory of battery development to 2030*

Since NMC-based LIBs are expected to dominate the private EV battery market for roughly the next decade, our analysis for the 2020–2030 time period focuses on the lithium-ion NMC battery platform. We derived learning rates for the two stages of our learning model by performing a regression analysis of production cost and cumulative production volume. The results indicate a 3.5% learning rate for the materials synthesis stage and a 16.5% learning rate (±4.5%) for the battery production stage. This implies that learning effects and potential cost reductions are significantly greater in battery production (second stage) than in the chemical synthesis process (first stage), which is more mature.

Within the lithium-ion NMC battery platform, we consider four specific cathode compositions: NMC111, NMC532, NMC622, and NMC811 (where, as noted previously, the numbers denote the molar ratio of nickel, manganese, and cobalt within the cathode). The molar ratio of these elements determines the battery's level of capacity (nickel), safety (manganese), and charging/discharging rate (cobalt). A clear trend within the EV LIB industry is to increase nickel content to boost energy density (for increased driving range) while reducing the amount of expensive cobalt required. However, higher nickel content creates tradeoffs in terms of lower structural and thermal stability as a result of decreasing cobalt and manganese content (Schipper, et al. 2017; Hou, et al. 2017). The quantity of cathode elements required for a unit of energy (kWh) differs across different compositions—therefore, the effects of mineral prices on active materials costs are different. The two-stage learning curve model constructs a projected floor price for battery packs by using the

Figure 4.12: Past and projected price trajectory for lithium-ion NMC battery packs



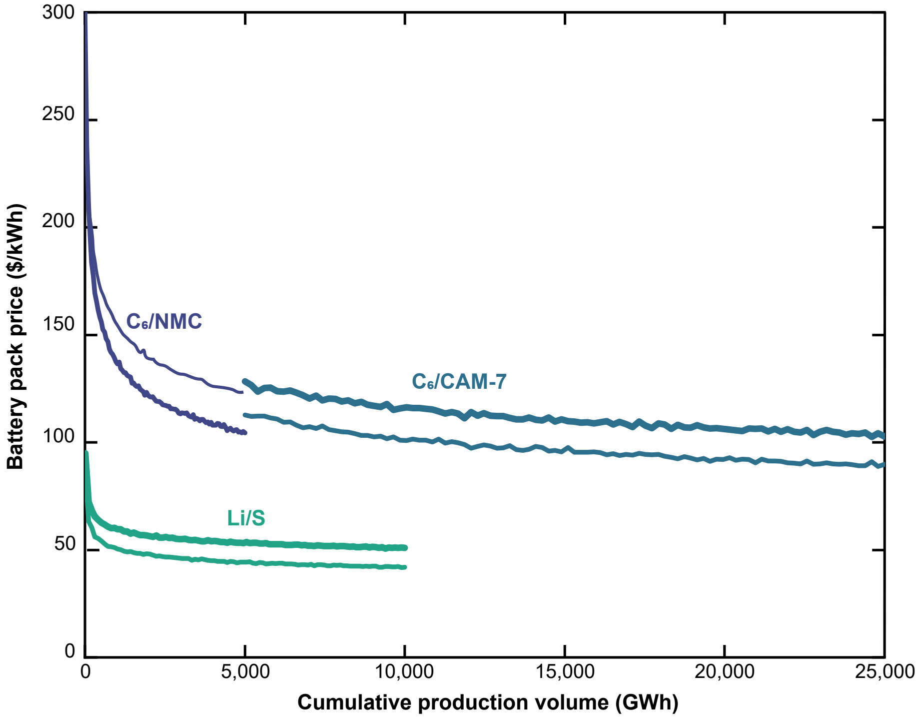
NMC variant with the lowest materials cost at different times as mineral costs evolve. We assume that there is no delay for development time to address safety issues related to NMC811. Our projections generally show a shift toward nickel-rich compounds with higher specific capacity and less cobalt content in the future. Figure 4.12 depicts our price projection for NMC-based LIBs in the 2030 timeframe, adapted from Hsieh, et al. (2019). Strong learning effects in battery manufacturing ($LR_2 = 16.5\% \pm 4.5\%$) continue to drive price reductions over time, such that battery prices approach $124/kWh in 2030. Other scenarios suggest a price range between $93/kWh and $140/kWh in 2030 (Hsieh, et al. 2019). According to our two-stage learning curve model, the rate of price reductions slows significantly around 2025–2030 due to the growing contribution of active materials costs. As these costs account for a larger share of the total battery price, the much lower learning rate of 3.5% for the materials synthesis process ($LR_1$) will slow further reductions in battery price with the costs of expensive cathode elements (lithium, nickel, and cobalt), eventually setting a lower bound on NMC battery prices.

Therefore, our analysis, which captures practical limits on battery prices, suggests that a price target of $100/kWh for widespread EV adoption is very unlikely to be achieved by 2030 with the continued maturation of existing NMC-based LIB technology. The $100/kWh target can be achieved only if mineral prices stay roughly the same as in 2016; however, significant uncertainty remains about the steady-state price of cobalt in the future as demand and supply continue to increase.[4] Under our base case scenario, global demand for cobalt in 2030 from new EV sales (even if all EVs use batteries with the high nickel content of NMC811) would reach approximately 80% of the world's total cobalt output in 2016.[5] Considering that only 15% of the worldwide demand for cobalt in 2017 was used in EV batteries (Jackson 2019), an increase in demand of this magnitude might result in higher prices for cobalt. Thus, automakers may need to move to different battery chemistries that are less reliant on cobalt to avoid raw materials shortages and price volatility.

[4] Global cobalt prices have fluctuated dramatically in the past few years. Cobalt prices skyrocketed in early 2018, hitting a 10-year high, but have since fallen more than 40% (Slav 2019).

[5] Global cobalt production per year has increased by more than 25% since 2016 (U.S. Geological Survey 2019).

**Figure 4.13: Battery pack prices with selected disruptive chemistries and stages of maturity**



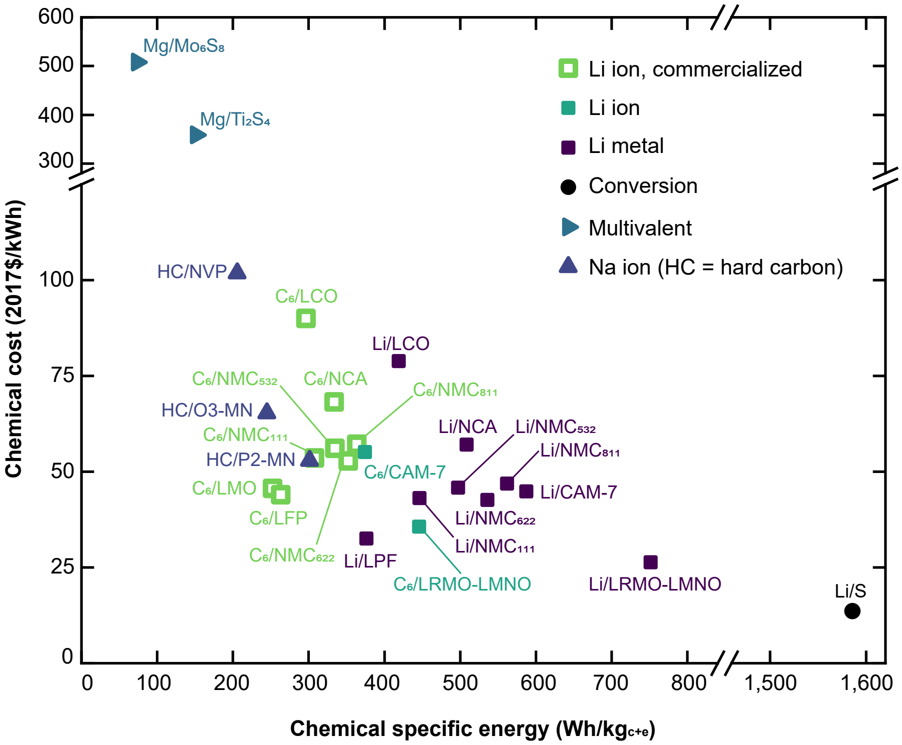
Note: Lower-bound estimates assume current materials prices, using data on lithium and manganese taken from the U.S. Geological Survey (2018) and nickel and cobalt prices retrieved from the London Metals Exchange (2019). The upper-bound estimates assume a doubling of current materials prices.

### *Trajectory of battery development from 2030 to 2050*

Since NMC-based LIBs are dependent on expensive metals, innovations in battery chemistry will need to accelerate to lower the floor price of batteries and enable broader electrification of the transportation sector. Unfortunately, it is difficult to predict which battery chemistry will become prevalent for EV applications beyond 2030. Several other battery chemistries may emerge as the mainstream choice for EV manufacturers, including lithium metal, solid state, sodium ion, multivalent-based, and lithium sulfur.

For illustrative purposes, we consider a scenario in which lithium ion CAM-7 (graphite/dopant stabilized lithium nickel oxide) and lithium sulfur (Li/S) batteries would be introduced in 2030 and 2040, when cumulative battery production for EV applications is assumed to reach five terawatt-hours (TWh) and 25 TWh, respectively. The CAM-7 battery exemplifies the continuing trend toward intercalation compounds that are even more nickel-rich than NMC811. Still more notable, the Li/S battery is a potentially disruptive technology that can provide very high energy density at very low cost; at present, however, this chemistry still suffers from severe capacity fading. Figure 4.13 shows ranges of estimated battery prices with these select chemistries as a function of cumulative production volume. Lacking other data, we assume that the learning rates that characterized lithium-ion NMC development can be applied to other chemistries, however it is important to note that cost reductions from learning effects in battery production may not be additive across different chemistries. We expect that efforts to develop $C_6$/CAM-7 might be able to leverage learning from the cumulative production of lithium-ion NMC batteries owing to the similarities between these chemistries, but the learning process for Li/S production might have to start anew because the manufacturing steps for this chemistry are mostly

Figure 4.14: Chemical cost of storage and chemical specific energy in 2017 for representative electrochemical couples for EV applications



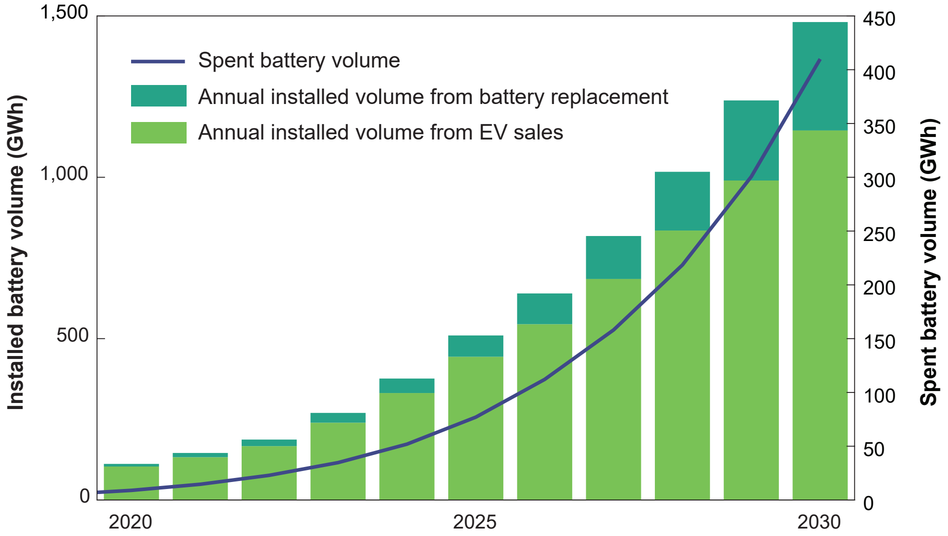
Note: Of the six categories represented in this figure, only the open square symbols represent commercially available batteries; the closed symbols are chemistries under development.

different. As a result, we expect that Li/S batteries will not enter the EV market until they are price competitive with the existing lithium-ion NMC platform or $C_6$/CAM-7. A range of average costs for these possible outcomes is depicted in Figure 4.13: the lower bounds are derived using current mineral costs for the active materials used in battery production (see figure note for sources), while the upper bounds assume a doubling of current mineral costs. As battery chemistries change, the materials synthesis contribution to overall battery cost is projected to rise back to the level of NMC811 costs in 2015: the small jump in battery pack price during the switch from lithium-ion NMC811 to CAM-7 is due to the higher materials synthesis cost of the new chemistry. On the other hand, as the figure indicates, Li/S batteries will only enter the market when their production costs are lower than those of the $C_6$/CAM-7. Battery price projections past 2030 are subject to significant uncertainties, especially since Li/S technology is still in its infancy.

### 4.3.3 Techno-Economic Characteristics of Different EV Battery Chemistries

Several attributes are considered when evaluating the performance of different battery chemistries, including specific energy (which determines vehicle driving range), lifespan (which reflects cycle life), safety, cost, and specific power. Given that the two most important issues currently impeding EV adoption are maximum driving range and purchase price (Schoettle and Sivak 2018), we evaluate the techno-economic performance (i.e., energy density and cost) of promising battery chemistries for EV applications, as indicated in Figure 4.14. We use the term “chemical” in this context to denote the active materials in the battery, including the cathode-active material, anode-active material, and electrolyte. Whereas chemical cost, or the cost of these materials, represents a floor on the cost of the complete battery, chemical specific energy (plotted on the x-axis in Figure 4.14) is for the chemical mass of the battery only, not the full weight of the battery. For reasons

**Figure 4.15: Projected installed and spent battery volumes from the EV market**



Note: Annual installed capacity of lithium-ion batteries is depicted as bars (left y-axis) and annual volume of spent batteries is depicted as a line (right y-axis).

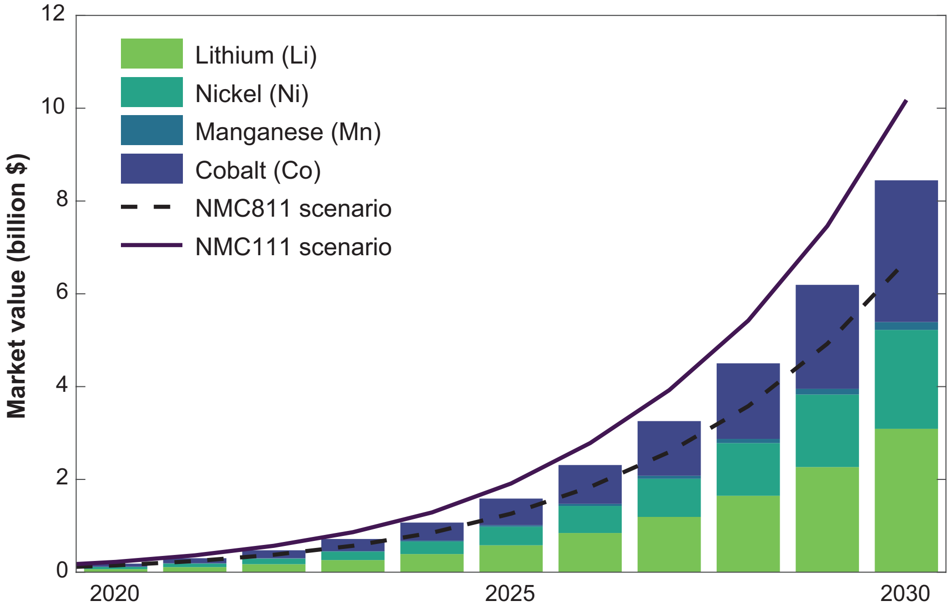
of data availability, our analysis focuses on conventional liquid electrolytes. However, it should be noted that solid-state batteries, which use solid electrolytes such as ceramics or glass, represent a potentially transformative technology evolution for the next generation of electric cars. The advantages of solid-state batteries over conventional LIBs include two-to-three times higher energy density, improved safety, capability for faster charging, and longer cycle life (Symes 2018; Bullis 2011).

We estimate chemical costs (in 2017 dollars) based on the prices offered by the materials supplier with the highest transaction volumes and information provided by Li, et al. (2017). The battery chemistries included in Figure 4.14 are at different stages of maturity. While we expect chemical costs for most of them to decline in the future, we also expect chemical specific energy to improve as the technologies further mature. For example, LIBs that use nickel-rich NMC811 currently incur a slightly higher chemical cost than the other NMC compositions, because this chemistry is less developed. But nickel-rich NMC batteries will likely become more cost competitive in the foreseeable future as a result of continued development and larger production volumes. More details can be found in Li, et al. (2017) and Hsieh, et al. (2019).

### 4.3.4 Battery Recycling for Electric Vehicles

Driven by increasing demand for consumer electronic devices and electric vehicles, the global market for lithium-ion batteries (LIBs) has grown dramatically. Even with continued LIB development, however, the battery recycling industry is lagging. Most of the LIBs produced in the past decade have been for use in portable electronics, and few of them are recycled—the vast majority of batteries are discarded along with the devices that contain them. The battery-recycling rate in Australia, for example, is just 2% (King, Boxall, and Bhatt 2018). The automotive sector is expected to be the fastest-growing source of spent LIBs over the next three decades, mainly due to the movement toward vehicle electrification. We estimate that the recycling market for LIBs from private cars will grow from around 9 gigawatt-hours (GWh) in 2020 to nearly 80 GWh in 2025 and 410 GWh in 2030 as a result of wider adoption of electric vehicles. Figure 4.15 shows the volume of spent and installed LIB capacity from battery replacements and sales of new electric vehicles. For this analysis, we used a two-parameter logistic model to simulate scrappage patterns for vehicles and batteries. We assume a median vehicle life of 12 years and a battery life of 8 years (Hsieh, Pan, and Green 2019). Our estimate of annual

**Figure 4.16: Potential market value of battery recycling in the global private car sector**



Note: The lines represent two scenarios: one assumes all spent batteries are NMC811 (dashed), the other assumes all spent batteries are NMC111 (solid). Market value is broken down by key cathode elements where the bar chart is based on the average from the two NMC composition scenarios.

installed capacity from new-car sales in Figure 4.15 assumes that China continues to dominate the global market for electric vehicles through 2030 (Hsieh, et al. 2019).

Since LIBs contain toxic substances, environmental concerns arise if large volumes of spent LIBs go to landfills instead of being recycled. In landfills, LIBs may catch fire and lithium can leach into groundwater (Heelan, et al. 2016). Environmental regulations and a scarcity of metals for automotive applications may provide business opportunities for reclaiming spent batteries, potentially creating a global market for LIB recycling. Because cathode materials are the most expensive battery component, we investigated the potential market for LIB recycling based on key cathode elements.

Lithium-ion nickel manganese cobalt (NMC) batteries are expected to dominate the private electric vehicle market to 2030. Assuming that all the spent battery capacity shown in Figure 4.15 is either NMC111 or NMC811 (where the numbers denote the molar ratio of nickel, manganese, and cobalt within the cathode), we project that a global industry for recycling batteries from privately owned electric light-duty vehicles could be worth $8.4 billion (plus or minus $1.7 billion) by 2030 (Figure 4.16). Assumptions about commodity market prices for this analysis are: $82,000/metric ton for lithium, $12,000/metric ton for nickel, $2,270/metric ton for manganese, and $44,000/metric ton for cobalt (U.S. Geological Survey 2018; London Metals Exchange 2019). Figure 4.16 breaks down our estimate of potential market value by essential cathode metals; the bar chart presents average values derived from two NMC composition trajectories. We note that these numbers likely understate the actual business opportunity for battery recycling since our analysis considers only the most expensive cathode materials. Other metals used in battery manufacture, such as aluminum and copper, also have value. This suggests that the current low rate of battery recycling is not only creating a number of serious environmental problems, it also risks missing a significant economic opportunity.

The variety of materials used in battery cathodes (such as lithium iron phosphate, lead acid, and lithium cobalt oxide) creates a challenge for recycling; this complexity, together with low yields for individual materials, helps to explain why battery recycling has not been widely practiced (Battery University 2019). To handle mixed cathode chemistry, current recycling processes require expensive organic reagents for solvent extraction to separate cobalt, nickel, and manganese (Chagnes and Pospiech 2013). There is an urgent need to develop cost-effective methods for recycling batteries on an industrial scale. In addition, these methods must be capable of handling a growing volume and variety of spent LIBs. One solution that has been proposed is to develop closed-loop recycling processes in which cathode and anode materials are recovered directly from spent LIBs; this has advantages over industrialized recycling processes that are only capable of recovering secondary raw materials (such as cobalt and nickel) that need further processing to produce new cathode materials (Heelan, et al. 2016). A study has shown that recycling LIBs via a closed-loop process is feasible, regardless of cathode chemistry, with high recovery efficiencies (on the order of 90%), and a potential profit margin of $5,525 per metric ton of LIBs based on a material balance analysis (Gratz, et al. 2014).

Interest is also growing in potential "second-life" applications for spent batteries from EVs. While second-life batteries would have lower energy density and would continue to lose capacity, they may be a safe, adequate, and economic product for alternative uses—in grid-level energy storage devices, for example (Olsson, et al. 2018). Even with second-life applications, however, EV batteries will eventually have to be recycled or disposed of. Integrating the entire industry chain among automakers, battery producers, used-car dealers, and scrap companies so that batteries become part of a circular economy, rather than creating a new source of hazardous waste, remains an important technical, economic, and policy challenge.

### 4.3.5 Summary

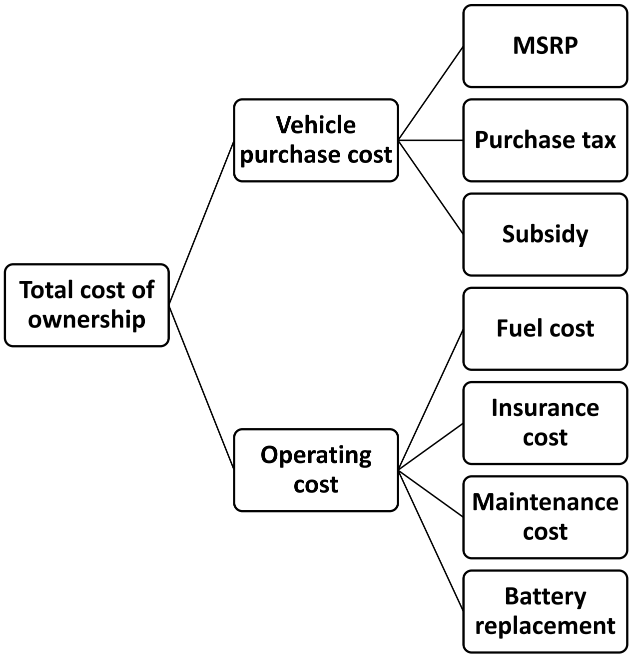
Lithium-ion batteries (LIBs) are currently considered the best battery technology available for EVs because of the advantages they offer in terms of high energy density, long cycle life, and low self-discharging rate. Of the many potential LIB chemistries, nickel manganese cobalt (NMC) is currently the most popular in the light-duty vehicle sector due to its high energy density, which allows for longer vehicle range. However, NMC batteries also carry a high cost per kWh owing to their reliance on cobalt.

As demand for EVs increases, we expect that production volumes for EV batteries will likewise increase and that the supply chain for battery production will consolidate. Greater production volumes and improvements in manufacturing efficiency will drive down costs, but the ultimate potential for cost reductions is bound by the base cost of input materials, particularly cobalt. Our analysis, which captures limits on battery prices by using a two-stage learning curve model, suggests that a price target of $100/kWh for widespread EV adoption is not likely to be achieved by 2030 with the continued maturation of existing NMC-based LIB technology. Instead, we project battery prices to approach $124/kWh in 2030.

Since NMC-based LIBs are dependent on expensive metals, innovations in battery chemistry are needed to lower the floor price of batteries and enable broader electrification of the transportation sector. To achieve even greater cost reductions, several other battery chemistries (such as lithium metal, solid state, sodium ion, multivalent-based, or lithium sulfur) may emerge as the mainstream choice for EV manufacturers beyond 2030.

In the meantime, lithium-ion NMC batteries are expected to dominate the private EV market. As the light-duty EV market matures and as environmental concerns regarding battery disposal and the battery supply chain grow, technical and business solutions for battery recycling are expected to emerge, with significant profit potential.

Figure 4.17: Purchase cost and operating cost contributors to total cost of ownership



## 4.4 TOTAL COST OF OWNERSHIP

Our analysis of the relative cost of various powertrains in Section 4.1 demonstrates that advanced powertrain vehicles currently cost more to manufacture than conventional ICEVs. There is potential for continued cost reductions with these advanced powertrain technologies, but there are limits on the cost reductions that can be achieved in the next decade, as demonstrated in Section 4.3, which explored the future cost of batteries. Although manufacturing costs for advanced powertrains are higher than for ICEVs, advanced powertrains often have the potential to lower vehicle operating costs.

Total cost of ownership (TCO) is a metric that allows for quantitative assessment of the economics of vehicle ownership based on both upfront costs and operating costs. This section examines the many factors that determine TCO. As with any evolving technology, cost analysis is only as good as the assumptions and parameters that are used to estimate costs. Therefore, our analysis identifies nominal values and performs parametric analysis to understand the impact of key factors.

### 4.4.1 Cost Contributors

The upfront cost of a vehicle to the buyer generally includes the purchase price, which corresponds to the manufacturer's suggested retail price (MSRP) for the vehicle, less any negotiated discount, plus the taxes paid on the purchase. Sales taxes effectively amplify the price premium for advanced powertrain vehicles, except in states and countries that apply a reduced sales tax rate or provide a sales tax exemption for advanced powertrain vehicles. An additional upfront cost for many first-time BEV buyers is the installation of a Level 2 charger at home, since home charging is typically the most convenient and lowest-cost means of fueling a BEV. Another factor in upfront cost is potential government subsidies. For our nominal cases, we assume no subsidies since subsidies are not permanent and because they differ by location, vehicle characteristics, and purchase date. Figure 4.17 shows the primary costs that contribute to TCO.

Vehicle operating costs include the cost of fuel, vehicle maintenance, and insurance. Fuel costs depend on the number of miles traveled, the fuel efficiency of the vehicle, and the fuel price. The

**Table 4.6: Parametric values for total cost of ownership analysis**

| Variable | Low value | 2018 nominal | 2030 nominal | High value |
|---|---|---|---|---|
| Gasoline ($/gallon) | 2.00[a] | 2.87[b] | 3.62[bb] | 7.42[c] |
| Electricity ($/kWh) | 0.08[d] | 0.12[e] | 0.15[ee] | 0.50[f] |
| Battery cost ($/kWh) | 80 | 229 | 124[g] | 250 |
| Range (miles) | 100 | 238[h] | 350 | 400 |
| Discount rate (%) | 4 | 5 | 5 | 15[hh] |
| Subsidies ($) | 0 | 0 | 0 | 7500[i] |
| Lifetime miles without replacement | 100,000[j] | 150,000 | 150,000 | 180,000 |
| Lifetime miles with replacement | 150,000 | No replacement | No replacement | 180,000 |
| Home charger ($) | 0[k] | 1,000[k] | 1,000[k] | 4,000[k] |
| ICEV MPG | 28[l] | 34[m] | 42.7[n] | 58.7[nn] |
| BEV MPGe | 112[o] | 119[p] | 144.7[q] | 175.1[qq] |
| Purchase tax (% of vehicle cost) | 0 | 7[r] | 7[r] | 50[s] |
| Carbon tax ($/$tCO_2e$) | 0 | 0 | 0 | 57t |
| Maintenance savings for BEV relative to ICEV (%) | 30 | 58.2[tt] | 58.2[tt] | 65 |
| e-powertrain saving relative to ICEV ($) | 700[u] | 700[u] | 2,100[uu] | 2,100[uu] |
| Insurance dependence on vehicle value (%) | 0 | 2[v] | 2[v] | 2[v] |

Note: [a] Average regular gasoline in U.S. for week of March 21, 2016 (U.S. EIA 2019a); [b] average regular gasoline in U.S. for week of May 13, 2019 (U.S. EIA 2019a); [bb] projected price of gasoline in U.S. in 2030 for the *Paris Forever* scenario as described in Chapter 2; [c] price in Norway (GlobalPetrolPrices.com 2019); [d] price in China (GlobalPetrolPrices.com 2019); [e] electricity price is based on U.S. average electricity price in 2018 for all sectors and all states at $0.105/kWh and assuming a mix of 85% home charging and 15% Level 2 public charging with a retail price of $0.21/kWh (U.S. EIA 2019d); [ee] projected electricity price in U.S. in 2030 for the *Paris Forever* scenario as described in Chapter 2; [f] based on heavy reliance (~60%) on fast charging (see Section 5.1 for retail costs for fast charging and Level 2 charging); [g] based on 2030 battery pack price projection from Section 4.3; [h] 238 miles is based on the range for a 2018 Chevrolet Bolt with a 60 kWh battery, 119 MPG, and 89% charging efficiency; [hh] Allcott and Wozny (2014); [i] maximum U.S. tax credit in 2018; [j] 100,000 miles corresponds to the warranty for the 2018 Chevrolet Bolt and for models from other manufacturers (e.g., BMW, Kia, Volkswagen, Tesla Model 3); [k] Table 5.2; [l] 2018 Volkswagen Golf MPG (U.S. EPA 2018); [m] 2018 Toyota Camry (U.S. EPA 2018); [n] MPG projected for 2030 based on 2018 Toyota Camry and Heywood and MacKenzie (2015); [nn] MPG projected for 2050 based on 2018 Toyota Camry and Heywood and MacKenzie (2015); [o] 2018 Nissan Leaf, 2019 Kia Niro, 2018 BMW i3s, 2018 Fiat 500e (U.S. EPA 2018); [p] 2018 Chevrolet Bolt, Volkswagen e-Golf (U.S. EPA 2018); [q] MPG projected for 2030 based on 2018 Chevrolet Bolt and Heywood and MacKenzie (2015); [qq] MPG projected for 2050 based on 2018 Chevrolet Bolt and Heywood and MacKenzie (2015); [r] 7% combined state and local sales taxes for median state within the U.S.; [s] 50% corresponds to combined India national tax plus state tax based on Delhi (the actual value is 49%, but we rounded to 50%) (Agnihotri 2017); [t] based on Baker, et al. (2017); [tt] Hummel, et al. (2017); [u] 2018 nominal value of the e-powertrain savings is based on Hummel et al. (2017); [uu] the 2030 nominal and high value is based on the Hummel, et al. (2017) estimate for e-powertrain cost reductions for 2025; [v] Cover (2018).

price of fuel can vary widely from one powertrain technology to another. Likewise, as seen in Section 4.2, vehicle fuel efficiency can differ by more than a factor of three (between a BEV and an ICEV, for example).

Vehicle maintenance costs are a major contributor to the annual operating costs of any vehicle. For ICEVs, maintenance data indicate that these costs increase throughout the life of the vehicle. Maintenance data on BEVs and FCEVs are limited because of the limited number of these vehicles on the road and because most of them are relatively young. Using the number of wearing parts, number of recommended inspections, and fluid replacements, however, Hummel, et al. (2017) estimated relative maintenance costs for a Chevrolet Bolt at 58.2% less than for a Volkswagen Golf.

**Table 4.7: Vehicle parameters for 2018 mid-size models with different powertrains selected for the TCO analysis**

| | ICEV | HEV | PHEV | BEV |
|---|---|---|---|---|
| Make and model | Toyota Camry | Toyota Camry HEV | Honda Clarity PHEV | Chevrolet Bolt |
| MSRP ($) | 23,645 | 27,950 | 33,400 | 36,620 |
| Gasoline MPG | 34 | 52 | 42 | — |
| Electric MPGe | — | — | 110 | 119 |

Note: — = not applicable. In Section 4.2, we used the Honda Clarity BEV as the basis for our lifecycle analysis to maximize comparability of car models across powertrains. For our cost analysis, we selected the Chevrolet Bolt BEV because costs for this vehicle have been extensively analyzed by Hummel, et al. (2017) and because the Bolt has a driving range of more than 200 miles. The Bolt's MSRP is identical to that of the Clarity BEV and both vehicles have similar MPG-equivalent (MPGe) values; thus, our TCO results should provide a good approximation for both models. MSRP and MPGe values are from the U.S. EPA (2018).

Beyond routine maintenance, there is an ongoing question about the life of batteries for BEVs and PHEVs. The most common warranty terms across the major BEV models cover retention of at least 70% of battery capacity for eight years or 100,000 miles, whichever comes first. A conservative estimate of ownership cost should either limit the vehicle life to the warranty mileage or assume battery replacement immediately after the warranty mileage is exceeded. The current literature does not provide a definitive analysis of the actual life of lithium-ion NMC batteries, but anecdotal data suggest that degradation rates are better than the warranties would imply and that many BEVs can operate beyond the warranty mileage with moderate loss of battery capacity (Lambert 2018). Used car resale values can serve as a proxy for vehicle life. Based on *Kelley Blue Book* data, a 2017 Chevrolet Bolt with 100,000 miles on it has a higher resale value than a 2017 Toyota Camry with the same mileage, although the decline in value, in percentage terms, relative to the vehicle's original MSRP is higher for the Bolt. Battery life is dependent on chemistry, battery management systems, usage patterns, and charging patterns; thus, battery life will vary by manufacturer, model, and owner.

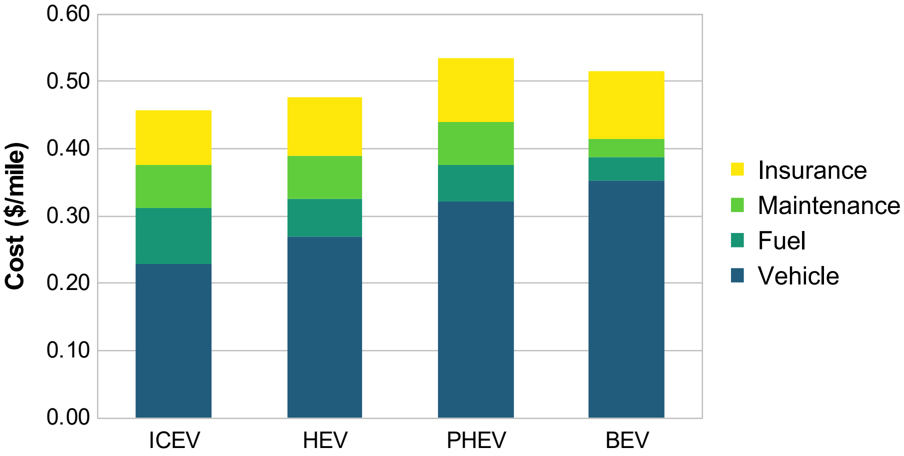
Vehicle insurance is another major operating expense for vehicle owners. A portion of the insurance cost covers repair or replacement of the vehicle in the event of collision, theft, vandalism, or fire. Logically, the cost of insurance should be related to the value of the car. However, insurance rates are set by actuaries based on claim data. In our examination of actual insurance rates in Massachusetts for similar vehicles with different powertrains, we could not discern a correlation between the value of the vehicle and the insurance rates quoted by GEICO in April 2019. Others have found that the incremental value of a BEV relative to a comparable ICEV increases insurance costs by 0% to 2% of the incremental cost of the vehicle (Cover 2018).

The values used in our TCO parametric analysis are provided in Table 4.6. For our current-day analysis across powertrains, we selected a set of 2018 car models that are of similar size (111–117 ft$^3$) and have a range of at least 200 miles. Vehicle parameters are provided in Table 4.7. The representative vehicle models used for our TCO analysis are similar to, but not an exact match to those used for our analysis of relative powertrain costs in Section 4.1 and our analysis of lifecycle emissions in Section 4.2. We did not include FCEVs in our TCO comparison because low current production volumes and low technology maturity would not fairly reflect on the future potential for this powertrain.

### 4.4.2 Cost Comparison Based on Current Car Models

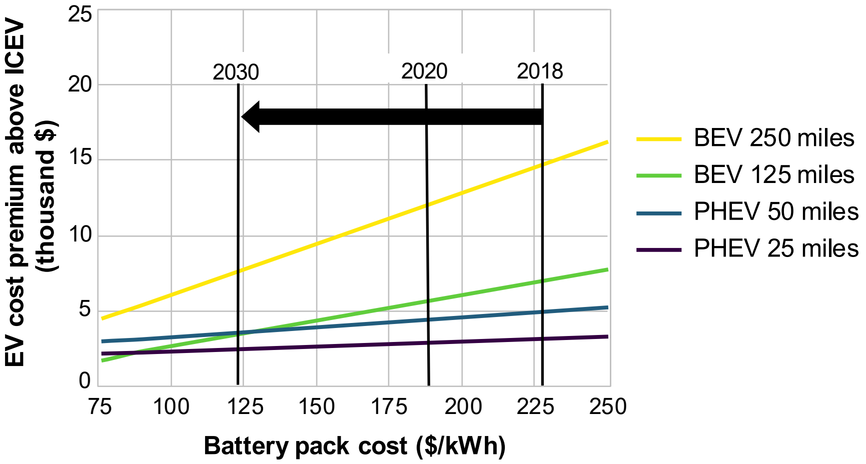
To combine purchase costs and operating costs into a single number representing total cost of ownership for each of these vehicles, we distributed all costs over all miles for the life of the car and used a nominal discount rate of 5% to determine the levelized cost per mile. These

**Figure 4.18: Total cost of ownership comparison without subsidies**



Note: Based on 150,000-mile vehicle life without battery replacement; $2.87/gal gasoline; $0.121/kWh electricity; the insurance cost of each vehicle increases by 2% of the incremental purchase cost of that vehicle relative to the others; car sales tax is 7%; no purchase subsidies; vehicle purchase price is based on MSRP for 2018 Camry for ICEVs and HEVs, on the Clarity for PHEVs, and on the Bolt and Clarity for BEVs; 58.2% savings on maintenance costs for BEVs.

**Figure 4.19: Impact of battery costs and vehicle range on the cost of plug-in EVs**

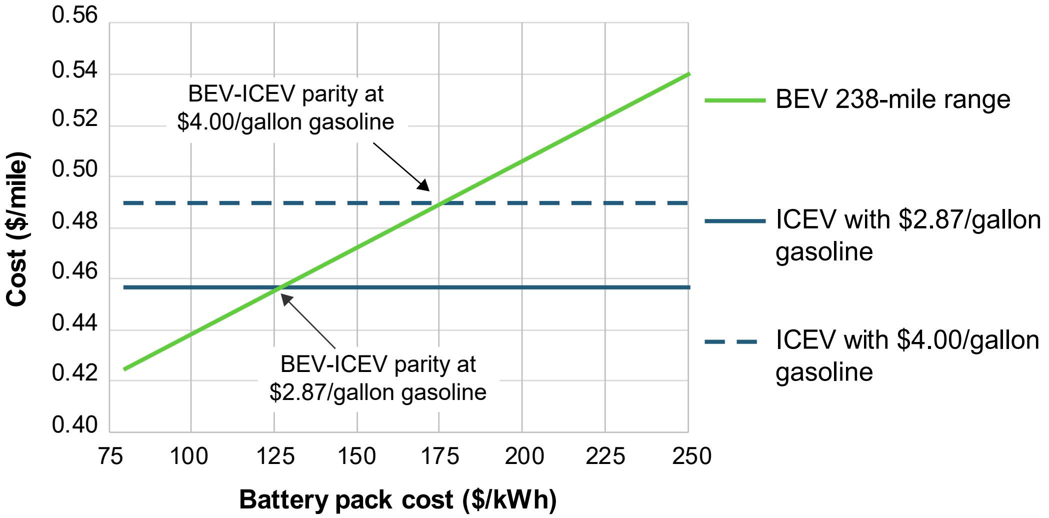


costs included vehicle purchase, maintenance, insurance, and fuel. Figure 4.18 shows the resulting cost per mile for these four powertrains based on the nominal values from Table 4.6. It should be noted, however, that these results are highly dependent on our assumptions about fuel prices, vehicle life, actual on-road MPG and MPGe, relative maintenance costs, and subsidies. We illustrate the strong influence of these variables on ownership costs throughout the remainder of this section.

### 4.4.3 Sensitivity to Battery Cost

As discussed in Section 4.3, battery costs are expected to continue to decline. We estimate the most probable cost of lithium-ion battery packs in 2030 at $124/kWh. To illustrate the importance of battery cost, Figure 4.19 shows how the relative cost of PHEVs and BEVs declines as the cost of battery packs falls. The slope of our cost curves reflects battery size; larger batteries are needed to achieve higher driving range, which means overall vehicle cost is more sensitive to battery prices. In Figure 4.19, EV range values

**Figure 4.20: Examples of BEV–ICEV cost parity**



Note: Based on 150,000-mile vehicle life without battery replacement; $0.121/kWh electricity; insurance cost increases by 2% of the incremental purchase cost of that vehicle; vehicle sales tax is 7%; no purchase subsidies; ICEV MPG is 34; BEV MPGe is 119; purchase price for mid-size BEVs is based on battery pack cost, with a $700 savings for the BEV powertrain relative to the Camry ICEV powertrain; 58.2% savings on maintenance costs for BEVs.

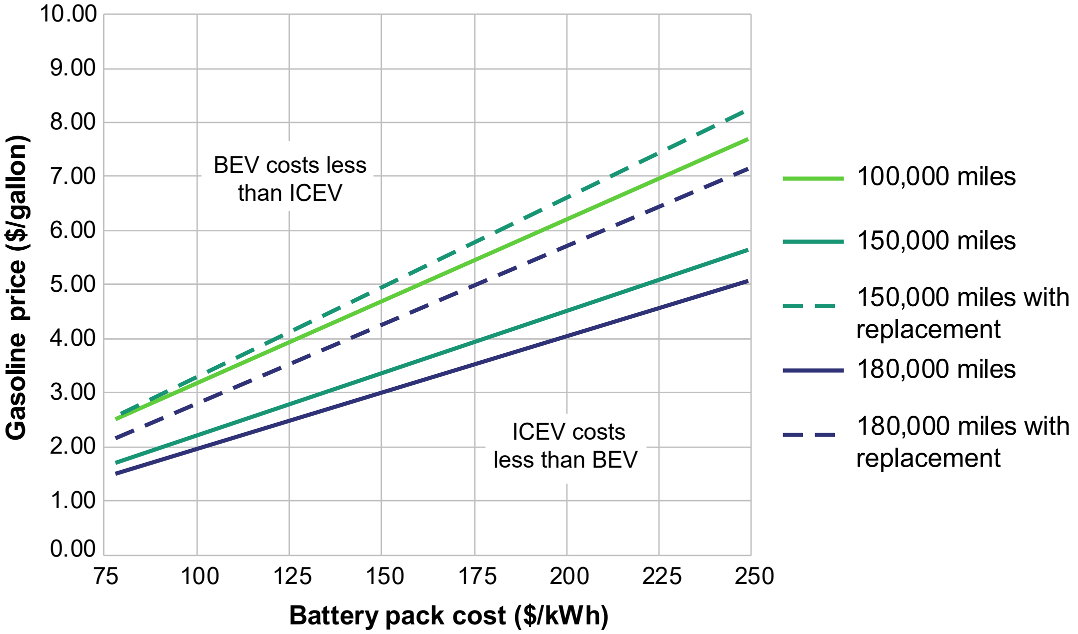
of 25, 50, 125, and 250 miles correspond to battery sizes of approximately 6.3, 12.6, 31.5, and 63 kWh, respectively.

Assessing the impact of battery cost on costs to own and operate a BEV, we find that each $25/kWh reduction in the cost of the battery pack reduces the vehicle's cost per mile by about 1.8¢. To put this cost sensitivity in perspective, a $25/kWh change in battery cost corresponds to a gasoline price change of almost $0.60/gallon. As illustrated by the line intersections in Figure 4.20, BEVs and ICEVs would reach cost parity (at a TCO of 49¢ per mile) when battery costs are $175/kWh and gasoline is $4/gallon. Likewise, BEV–ICEV parity would be reached when battery cost is $127/kWh and gasoline is $2.87/gallon, if all other parameters remain at the 2018 nominal values.

### 4.4.4 Sensitivity to Vehicle Life and Battery Replacement

If the operating life of advanced powertrain vehicles can be extended, their higher purchase cost can be spread over more miles to effectively reduce the cost per mile. Figure 4.21 explores BEV–ICEV cost parity for five different sets of assumptions concerning vehicle life and battery replacement. The most conservative, or "worst case" assumption sets vehicle life at eight years and 100,000 miles; as noted earlier, this assumption is based on typical battery warranties for current-model BEVs. The nominal case assumes a vehicle life of 150,000 miles without battery replacement. The best case assumes a vehicle life of 180,000 miles without battery replacement. We also consider long vehicle life scenarios with the assumption that batteries would need to be replaced once during vehicle's lifetime. The cost to replace a battery is expected to be less than the cost of the battery at the time of the original vehicle purchase, primarily because new battery costs are expected to continue to decline in the future. A further consideration is that used batteries can have a second life in stationary applications and their value for these secondary applications could partially offset the cost of replacement batteries. An additional cost of replacement is the labor to remove old batteries and install new ones. We estimate the overall cost to replace a BEV battery at 75% of the original battery cost. We also acknowledge that consumers may be unlikely to invest as much as $6,000 in a used electric vehicle with 100,000

**Figure 4.21: Influence of vehicle life and battery replacement on BEV–ICEV cost parity**



Note: Based on $0.121/kWh electricity; insurance cost increases by 2% of the incremental purchase cost of that vehicle; car sales tax is 7%; no purchase subsidies; ICEV MPG is 34; BEV MPGe is 119; purchase price for mid-size BEVs is based on battery pack cost, with a $700 savings for the BEV powertrain relative to the Camry ICEV powertrain; 58.2% savings on maintenance costs for BEVs.

**Table 4.8: Local conditions relevant to total cost of ownership**

| | Electricity ($/kWh) | Gasoline ($/gallon) | Purchase tax (%) |
|---|---|---|---|
| U.S. | 0.13 | 2.87 | 7 |
| Norway | 0.15 | 7.42 | 25 |
| China | 0.08 | 4.13 | 27 |
| Japan | 0.27 | 5.07 | 3 |
| Germany | 0.25 | 6.36 | 19 |

Sources: GlobalPetrolPrices.com (2019); U.S. EIA (2019a).

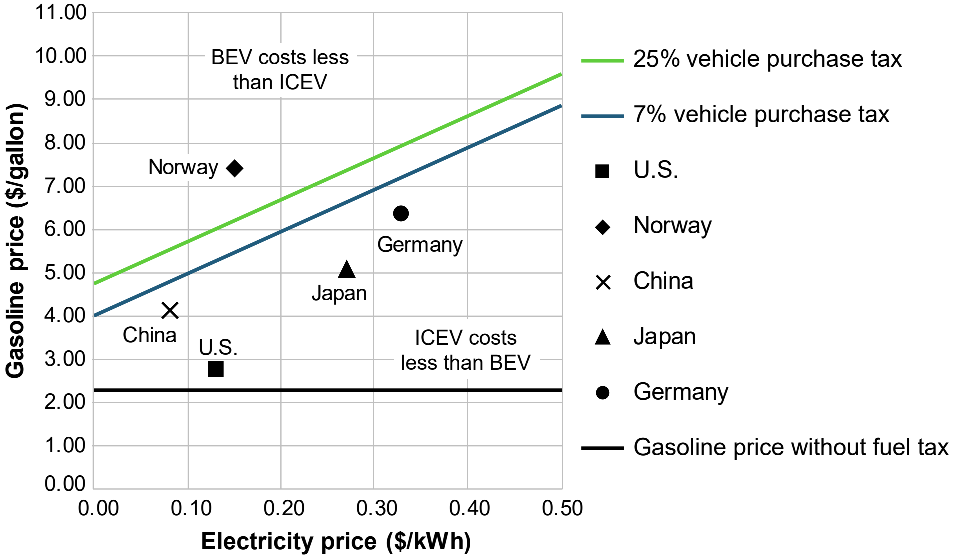
miles on it if the vehicle is fully functional but has a reduced range of 150 miles, for example. Such a vehicle would likely be sold to a household or business that would be satisfied with reduced range. Nevertheless, battery replacement cases are included here to understand the cost of ownership under various scenarios.

As shown in Figure 4.21, the 100,000-mile case and the two battery replacement cases have relatively high BEV–ICEV parity lines, while the 150,000-mile and 180,000-mile cases without battery replacement have substantially lower parity lines, meaning that cost of ownership for BEVs is attractive even when gasoline is priced at $3.00/gallon and battery cost is $124/kWh.

### 4.4.5 Sensitivity to Local Factors

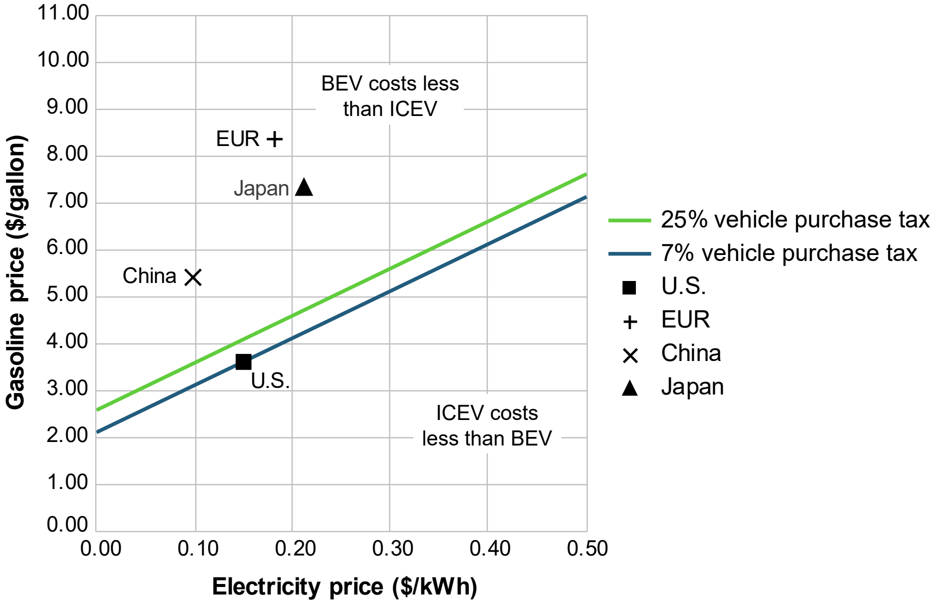
The total cost of ownership for ICEV and BEV vehicles is highly dependent on location. This is because gasoline and electricity prices vary widely across countries and within countries. Relative to the U.S., many countries levy substantially higher fuel taxes—for a multitude of reasons that may include energy security, balance of trade, local air pollution, climate change, and government revenue. The tax rate applied to vehicle purchases also varies widely across countries and within the U.S. These taxes amplify the cost burden for more expensive powertrains. Table 4.8 provides a few examples of variation in these three factors across nations.

**Figure 4.22: Influence of vehicle purchase taxes and fuel prices on BEV–ICEV cost parity in the absence of subsidies in 2018**



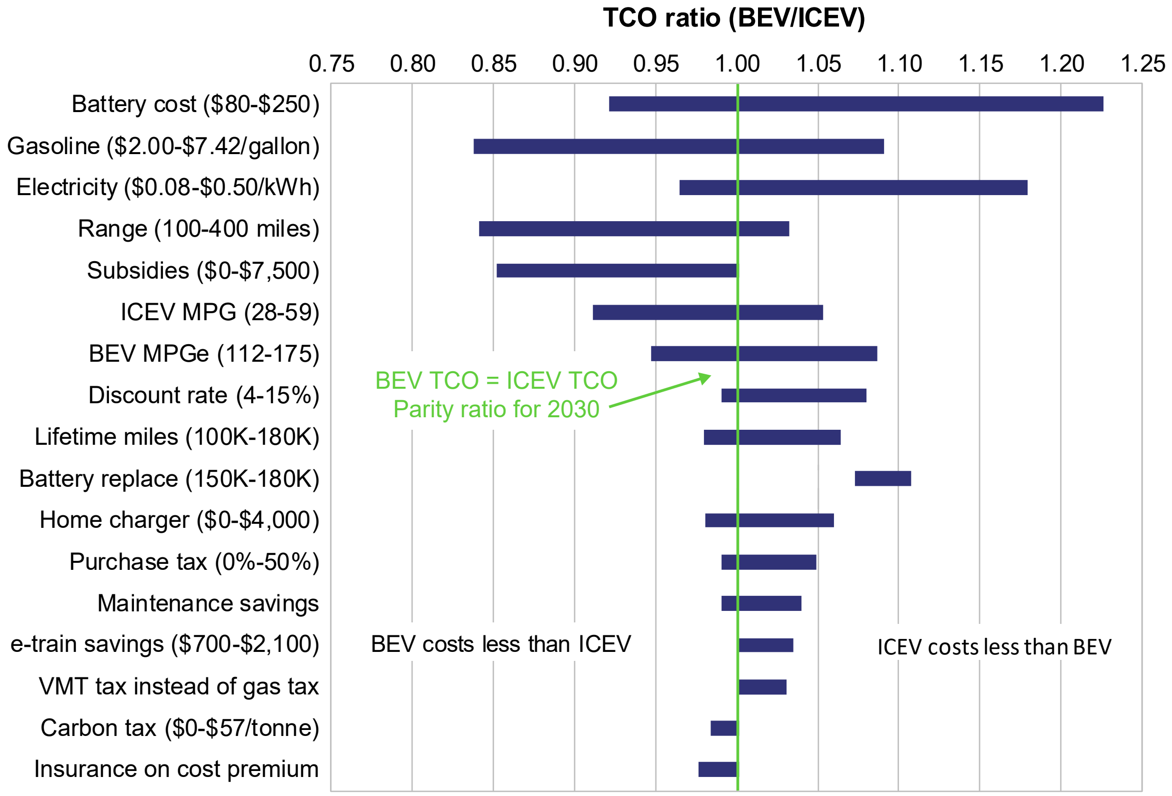
Note: Based on 150,000-mile vehicle life without battery replacement; insurance cost increases by 2% of the incremental purchase cost of that vehicle; no purchase subsidies; ICEV MPG is 34; BEV MPGe is 119; BEV range is 238 miles; purchase price for mid-size BEVs is based on battery pack cost of $229/kWh and a $700 savings for the BEV powertrain relative to the Camry ICEV powertrain; 58.2% savings on maintenance costs for BEVs.

**Figure 4.23: Influence of vehicle purchase taxes and fuel prices on BEV–ICEV cost parity in the absence of subsidies, assuming battery pack costs of $124/kWh in 2030**



Note: Based on 150,000-mile vehicle life without battery replacement; insurance cost increases by 2% of the incremental purchase cost of that vehicle; no subsidies; ICEV MPG is 42.7; BEV MPGe is 144.2; BEV range is 350 miles; purchase price for mid-size BEVs is based on battery pack cost of $229/kWh and a $2,100 savings for the BEV powertrain relative to the Camry ICEV powertrain; 58.2% savings on maintenance costs for BEVs; gasoline prices of $3.62, $5.43, $10.69 and $8.36 per gallon of gasoline for U.S., China, Japan, and Europe, respectively; electricity prices of $0.15, $0.099, $0.212, and $0.182/kWh for U.S., China, Japan, and Europe, respectively, based on the *Paris Forever* scenario as described in Chapter 2.

**Figure 4.24: Sensitivity analysis for BEV-to-ICEV total cost of ownership ratio**



Note: Base values for this tornado diagram are estimated values for 2030: $3.62/gallon for the price of gasoline; $0.15/kWh for the price of electricity; $124/kWh for the cost of the battery pack; vehicle range of 350 miles; no purchase subsidy; 150,000-mile vehicle life without battery replacement; $1,000 installed cost for home charger: fuel economy of 42.7 MPG for ICEV, 144 MPGe for BEV; 7% tax on vehicle purchase; 58.2% maintenance savings for BEV; electric powertrain savings of $2,100 per vehicle; insurance cost increases by 2% of the incremental purchase cost of that vehicle; for the complete set of 2030 nominal values, low values and high values, see Table 4.6.

To illustrate the sensitivity of BEV–ICEV cost parity to these factors, Figure 4.22 shows two cost parity curves that combine a range of values for gasoline price, electricity price, and purchase taxes. This figure is based on the approximate price of battery packs in 2018 at $229/kWh. It indicates that in the five countries considered, assuming no subsidies, BEVs are financially more attractive than ICEVs only in Norway. The figure also shows the U.S. average cost of gasoline, excluding federal and state fuel taxes (as of May 2019) to illustrate that in the absence of such taxes, ICEVs would have a lower cost of ownership than BEVs even if electricity were free.

Reexamining these comparisons in the context of 2030 projected battery costs, projected improvements in fuel economy for ICEVs and BEVs and increasing prices of energy per the *Paris Forever* scenario, a very different picture emerges with BEVs on the border of achieving cost parity with ICEVs in the U.S. and more economical than ICEVs in Europe, China, and Japan, as shown in Figure 4.23.

### 4.4.6 General Sensitivity Analysis

The number of factors that contribute to TCO is substantial. Therefore, we use a tornado diagram (Figure 4.24) to illustrate the sensitivity of TCO to all major factors. The sensitivity range for each variable is based on the low and high values provided in Table 4.6. The 2030 nominal values from Table 4.6 are used to calculate the base of the tornado diagram; the base TCO ratio is approximately 1.

Figure 4.24 shows that the three variables with the largest impact on the TCO ratio are gasoline price, electricity price, and battery cost. As is evident in Table 4.8, electricity prices vary by country, but also vary substantially based on the method used to charge BEVs. Many current BEV owners in the U.S. predominately charge at home, while some also have the opportunity to charge for free at some locations (e.g., at their workplace). As discussed in the next chapter, public charging stations typically collect a premium on the cost of the electricity—the premium tends to be related to the power level of the charger. Therefore, a BEV driver who relies heavily on public fast changers could be paying an average of $0.50/kWh or more for vehicle charging. In such situations, the per-mile fuel costs for a BEV can be greater than the per-mile costs for an ICEV.

Vehicle range is also an important factor and it amplifies the impact of battery prices. Although a BEV with a range of 100 miles would have a much lower TCO than an equivalent vehicle with a range of 400 miles, the trend among BEV manufacturers is to produce cars with longer range (200+ miles) because this is a feature that buyers value so BEV average range will continue to grow (McDonald 2018). Purchase subsidies are currently a major factor in enabling BEVs to compete with ICEVs in markets across the world. However, this analysis has not focused on subsidies because as BEV manufacturing costs fall and BEV market share increases, nations are expected to phase out their BEV purchase incentive programs. Therefore, our 2030 nominal case with battery costs at $124/kW does not include BEV purchase subsidies. For the sensitivity analysis in Figure 4.24, we include the current U.S. federal tax credit of $7,500 solely to illustrate the sensitivity, although such a subsidy is unlikely in 2030.

The discount rate, used to calculate the levelized cost per mile, dictates the relative importance of the upfront cost versus annual savings on fuel and maintenance. In the 2030 nominal case, we assume a discount rate of 5%. Although 5% is a reasonable discount rate in the U.S. where car loan rates are currently less than 5% (for consumers with good credit ratings), this discount rate does not reflect the car purchasing behavior of the typical American consumer. Studies have shown that consumers are willing to pay more for a fuel-efficient vehicle but that they undervalue those future savings (Allcott and Wozny 2014). In our sensitivity analysis, we examined the impact of the 15% implicit discount rate suggested by Allcott and Wozny (2014). Increasing the discount rate from 5% to 15% increases the BEV–ICEV TCO ratio from 1.00 to 1.08. This result suggests that although a financially reasonable discount ratio would yield TCO parity in the U.S. in 2030, the reality of how consumers value current costs versus future savings indicates that ICEVs will continue be the more affordable powertrain from the perspective of the typical American consumer.

Figure 4.24 does not explicitly include annual miles driven, but as seen with our results for sensitivity to lifetime mileage, the TCO ratio is very sensitive to this variable because it amplifies the BEV versus ICEV purchase cost differential. In other words, the TCO analysis tends to favor lower-priced vehicles when annual vehicle usage is very low.

As discussed in Chapter 5, the cost of installing a home charger is highly variable and situation specific. This cost can contribute 8% to the TCO for BEVs, although a typical value is only 2%; in addition, an investment in a home charger will have value beyond the first BEV purchase.

As discussed in Section 4.2, the efficiency of BEVs and ICEVs is expected to improve. The impact of fuel economy (MPG and MPGe) improvements on TCO is strong for both ICEVs and BEVs. Although the relative improvement in fuel economy is expected to be higher for ICEVs than for BEVs, the impact on TCO is almost the same for both powertrains. The reason for this is that an improvement in MPGe for BEVs translates to a smaller battery, if the vehicle range specification is constant. Therefore, any improvement in the MPGe for a BEV reduces the battery contribution to vehicle purchase cost, as well as electricity cost per mile.

Although BEVs are expected to offer maintenance cost savings relative to ICEVs, the numbers remain uncertain. The range of uncertainty is about 5% of TCO. Likewise, e-powertrain manufacturing costs are expected to decline in the future as BEV manufacturing matures, but these improvements are uncertain and relatively small at a little more than 3% of TCO.

As discussed in Chapter 2, many countries collect substantial taxes on gasoline and diesel to support road infrastructure and other government programs. As BEVs achieve greater market penetration, revenues from gasoline taxes will decline. Reductions in government revenues from fuel taxes could be offset by new taxes, such as on vehicle miles traveled (VMT). If U.S.-average gasoline taxes were converted to an equivalent tax on VMT for all vehicle powertrains, this would increase the TCO for BEVs by about 3%. The impact on TCO would be larger in high fuel-tax countries if those taxes were converted to an equivalent VMT tax.

We also consider sensitivity to possible carbon taxes in the future. There are various proposals for a carbon tax in the U.S. and similar proposals are being deployed or developed in other parts of the world. The Climate Leadership Council, for example, has proposed a 2030 projected carbon tax of \$57/$tCO_2e$ for the U.S. (Baker, et al. 2017). As shown in Figure 4.24, a carbon tax of this magnitude would have a relatively small impact of about 2% on TCO.

### 4.4.7 Summary

Future reductions in battery cost and improvements to battery life will likely enable BEVs to be cost competitive with ICEVs in more countries in the absence of subsidies. However, total cost of ownership is sensitive to many factors, including gasoline price, electricity price, fuel economy, discount rate, vehicle and battery life, battery size, maintenance costs, taxes, and insurance. Countries with very high gasoline prices and low electricity prices are generally more favorable for BEV ownership in the case of high-mileage households. A potential downside of BEV ownership for such high-mileage households, however, is that drivers could incur high charging fees at public charging stations; high costs for charging can give the TCO advantage to ICEVs.

Although total cost of ownership is an important metric for determining the economic competitiveness of BEVs, it is only one of multiple factors that contribute to consumer decisions concerning vehicle purchases. Utility and familiarity are also important to the selection of alternative powertrain vehicles; these topics are addressed in Chapter 5.

## 4.5 CONCLUSION

Internal combustion engines fueled with gasoline will likely remain the least expensive propulsion system to manufacture for light-duty vehicles for many years to come. While emissions controls and fuel economy regulations are adding to manufacturing costs for vehicles using petroleum-based fuels, the upfront cost of ICEVs that comply with criteria pollutant (CO, HC, $NO_x$, and PM) regulations are expected to remain less than the upfront cost of comparable BEVs and FCEVs beyond 2030. However, the current price premium for BEVs and FCEVs over ICEVs will diminish as increasing production volumes reduce battery and fuel cell stack costs. For example, the price of lithium-ion battery packs is expected to drop to \$124/kWh by about 2030. Even with this cost reduction, a BEV with 200 miles of range will remain thousands of dollars more expensive than a comparable ICEV in 2030. Although there are several proposed battery chemistries that look promising and could offer lower costs than their lithium-based counterparts, none are likely to achieve large-scale deployment in vehicle applications by 2030, given the long lead times and manufacturing scale-up challenges involved.

Manufacturing costs for BEVs are expected to remain higher than for ICEVs well beyond 2030, but lower operating costs help to offset higher BEV purchase prices. Specifically, lower per-mile costs for fuel (electricity) and lower maintenance costs can enable BEVs to reach parity with ICEVs in terms of total cost of ownership or TCO. However, TCO depends on many factors, including subsidies, fuel economy, gasoline price, electricity price, and battery costs—all of which are subject to uncertainty. Currently, BEVs cannot compete with ICEVs on TCO without the support of subsidies and regulations, except in a few countries, such as Norway, that have very high gasoline prices and low electricity prices. As battery costs decline in the future, BEVs will reach TCO parity, even without subsidies in additional countries where gasoline prices are high, but this estimate is sensitive to many uncertainties. In particular, there is uncertainty regarding the appropriate discount rate. A financially reasonable discount rate would yield TCO parity in the U.S. in 2030, but a discount rate derived from consumer behavior implies that ICEVs will continue to be viewed as the more affordable powertrain through 2030 and beyond from the perspective of the typical American consumer. Nevertheless, cost parity alone cannot be expected to drive widespread adoption of any new powertrain. Other factors besides TCO, such as the availability and convenience of charging and fueling infrastructure and consumer perceptions, will likely shape the adoption curve for new vehicle technologies, as described in Chapter 5.

Lifecycle greenhouse gas emissions from BEVs and FCEVs are highly sensitive to the carbon intensity of the electricity and hydrogen used to power these vehicles. We explored this sensitivity by considering lifecycle emissions based on the carbon intensity of electricity and hydrogen production today and based on some possible production pathways in the future. At present, a BEV operating on the most carbon-intensive state-level power mix in the U.S. can emit 30% more $CO_2$ than a comparable HEV. If the same BEV runs on electricity from the least carbon-intensive state-level power mix, on the other hand, its emissions performance can be about 61% better than a comparable HEV. A FCEV that runs on hydrogen generated via steam methane reforming has roughly the same lifecycle emissions as a comparable HEV, but these emissions could be reduced by about 44% if steam methane reforming is combined with carbon capture; alternatively, FCEV emissions could be 61% lower than for a comparable HEV if hydrogen is produced by electrolysis solely from wind power (or from other similarly low-carbon electricity). In stark contrast, FCEV emissions would be 49% higher than a comparable HEV if hydrogen is produced via electrolysis using electricity with the carbon intensity of the current U.S.-average power mix. Therefore, any programs that promote the adoption of advanced vehicle powertrains for purposes of climate change mitigation should be undertaken in concert with corresponding efforts to decarbonize the supply of electricity and hydrogen. In other words, the justification for deploying alternative powertrains is not based on the electricity and hydrogen supply as it exists today; rather, it relies on a vision and program of decarbonization that extends beyond the transportation sector alone.

## 4.6 REFERENCES

Agnihotri, Aradhya. 2017. "GST on Cars: What's Getting Cheaper and What's Not." *The Times of India*, June 27. https://timesofindia.indiatimes.com/auto/cars/gst-on-cars-whats-getting-cheaper-and-whats-not/articleshow/59319171.cms

Allcott, Hunt, and Nathan Wozny. 2014. "Gasoline Prices, Fuel Economy, and the Energy Paradox." *The Review of Economics and Statistics* 96, no. 5 (Dec): 779–795. https://doi.org/10.1162/REST_a_00419

Arvesen, Anders, and Edgar G. Hertwich. 2012. "Assessing the Life Cycle Environmental Impacts of Wind Power: A Review of Present Knowledge and Research Needs." *Renewable and Sustainable Energy Reviews* 16, no. 8 (Oct): 5994–6006. https://doi.org/10.1016/j.rser.2012.06.023

Baker, James A., Martin Feldstein, Ted Halstead, N. Gregory Mankiw, Henry M. Paulson, George P. Shultz, Thomas Stephenson, and Rob Walton. 2017. *The Conservative Case for Carbon Dividends*. Washington, D.C.: Climate Leadership Council. https://clcouncil.org/media/2017/03/The-Conservative-Case-for-Carbon-Dividends.pdf

Battery University. 2019. "BU-705a" Battery Recycling as a Business." Last updated June 21. https://batteryuniversity.com/index.php/learn/article/battery_recycling_as_a_business

Berckmans, Gert, Maarten Messagie, Noshin Omar Jelle Smekens, Lieselot Vanhaverbeke, and Joeri Van Mierlo. 2017. "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles up to 2030." *Energies* 10, no. 9: 1314–1334. https://doi.org/10.3390/en10091314

Bullis, Kevin. 2011. "Solid-State Batteries: High-Energy Cells for Cheaper Electric Cars." *MIT Technology Review*, April 19. http://www2.technologyreview.com/news/423685/solid-state-batteries/

Chagnes, Alexandre, and Beata Pospiech. 2013. "A Brief Review on Hydrometallurgical Technologies for Recycling Spent Lithium-Ion Batteries." *Journal of Chemical Technology and Biotechnology* 88, no. 7(Feb): 1191–1199. https://doi.org/10.1002/jctb.4053

Chen, Aoxia, and Pankaj K. Sen. 2016. "Advancement in Battery Technology: A State-of-the-Art Review." *IEEE Industry Applications Society Annual Meeting 2016*. https://doi.org/10.1109/IAS.2016.7731812

Chu, Steven, Yi Cui, and Nian Liu. 2017. "The Path towards Sustainable Energy." *Nature Materials* 16 (Jan): 16–22. https://doi.org/10.1038/NMAT4834

Cover. 2018. "Does Electric Car Insurance Cost More?" July 19. https://cover.com/blog/does-electric-car-insurance-cost-more/

Gençer, Emre, and Francis M. O'Sullivan. 2019. "A Framework for Multi-Level Life Cycle Analysis of the Energy System." *Computer Aided Chemical Engineering* 46: 763–768. https://doi.org/10.1016/B978-0-12-818634-3.50128-4

German, John. 2015. *Hybrid Vehicles: Technology Development and Cost Reduction*. Technical Brief No. 1. Washington, D.C.: International Council on Clean Transportation. https://www.theicct.org/sites/default/files/publications/ICCT_TechBriefNo1_Hybrids_July2015.pdf

GlobalPetrolPrices.com. 2019. "Gasoline Prices, U.S. Gallon, May-13-2019." https://www.globalpetrolprices.com/gasoline_prices/

Gratz, Eric, Qina Sa, Diran Apelian, and Yan Wang. 2014. "A Closed Loop Process for Recycling Spent Lithium Ion Batteries." *Journal of Power Sources* 262, no. 15 (Sept): 255–262. https://doi.org/10.1016/j.jpowsour.2014.03.126

Heelan, Joseph, Eric Gratz, Zhangfeng Zheng, Qiang Wang, Mengyuan Chen, Diran Apelian, and Yan Wang. 2016. "Current and Prospective Li-Ion Battery Recycling and Recovery Processes." *JOM (The Journal of The Minerals, Metals, & Materials Society)* 68, no. 10 (Oct): 2632–2638. https://doi.org/10.1007/s11837-016-1994-y

Heywood, John, and Don Mackenzie, eds. 2015. *On the Road toward 2050: Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions*. Cambridge, MA: Massachusetts Institute of Technology. http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/On-the-Road-toward-2050.pdf

Hou, Peiyu, Jiangmei Yin, Meng Ding, Jinzhao Huang, and Xijin Xu. 2017. "Surface/Interfacial Structure and Chemistry of High-Energy Nickel-Rich Layered Oxide Cathodes: Advances and Perspectives." *Small* 13, no. 45. https://doi.org/10.1002/smll.201701802

Hsieh, I-Yun Lisa, Menghsuan Sam Pan, and William H Green. 2019. "Transition to Electric Vehicles in China: Implications for Private Motorization Rate and Battery Market" [working paper].

Hsieh, I-Yun Lisa, Menghsuan Sam Pan, Yet-Ming Chiang, and William H. Green. 2019. "Learning Only Buys You So Much: Practical Limits on Battery Price Reduction." *Applied Energy* 239, (April): 218–224. https://doi.org/10.1016/j.apenergy.2019.01.138

Hummel, Patrick, David Lesne, Julian Radlinger, Chervine Golbaz, Colin Langan, Kohei Takahashi, David Mulholland, Andrew Stott, Geoff Haire, and Markus Mittermaier, Nicholas Gaudois, Lachlan Shaw. 2017. *UBS Evidence Lab Electric Car Teardown—Disruption Ahead?* Zurich, Switzerland: UBS Global Research. https://neo.ubs.com/shared/d1wkuDIEbYPjF/

International Energy Agency (IEA). 2018. *$CO_2$ Emissions from Fuel Combustion 2018 Highlights*. Paris, France: IEA. https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018-highlights

Irle, Roland. 2018. "Global EV Sales for 2018 – Final Results." *EVvolumes.com: The Electric Vehicle World Sales Database*.

Isenstadt, Aaron, John German, Mihai Dorobantu, David Boggs, and Tom Watson. 2016. *Downsized, Boosted Gasoline Engines*. Washington, D.C.: International Council on Clean Transportation. https://www.theicct.org/publications/downsized-boosted-gasoline-engines

Jackson, Maurice. 2019. "Cobalt, the Electric Vehicle, and Ways to Profit from Both." *Streetwise Reports*, March 30. https://www.streetwisereports.com/article/2019/03/30/cobalt-the-electric-vehicle-and-ways-to-profit-from-both.html

James, Brian D., Jennie M. Huya-Kouadio, Cassidy Houchins, and Daniel A. DeSantis. 2017. *Mass Production Cost Estimation of Direct $H_2$ PEM Fuel Cell Systems for Transportation Applications: 2017 Update*. Arlington, VA: Strategic Analysis Inc. https://doi.org/10.13140/RG.2.2.36532.55683

Jody, Bassam J., Edward J. Daniels, Claudia M. Duranceau, Joseph A. Pomykala, Jr., and Jeffrey S. Spangenberger. 2010. *End-of-Life Vehicle Recycling: State of the Art of Resource Recovery from Shredder Residue*. Lemont, IL: Argonne National Laboratory, Energy Systems Division. https://publications.anl.gov/anlpubs/2011/02/69114.pdf

King, Sarah, Naomi J. Boxall, and Anand I. Bhatt. 2018. *Lithium-Ion Battery Recycling in Australia: Current Status and Opportunities for Developing a New Industry*. Report EP181926. Canberra: Australia: The Commonwealth Scientific and Industrial Research Organisation (CSIRO). http://hdl.handle.net/102.100.100/86974?index=1

Kittner, Noah, Felix Lill, and Daniel M. Kammen. 2017. "Energy Storage Deployment and Innovation for the Clean Energy Transition." *Nature Energy* 2 (July). http://hdl.handle.net/102.100.100/86974?index=1

Klemola, Kimmo. 2016. *Life-Cycle Impacts of Tesla Model S 85 and Volkswagen Passat." Life-Cycle Impacts of Tesla Model S 85 and Volkswagen Passat*. https://kimmoklemola.fi/data/documents/SF-comparison-USA-20160110.pdf

Knupfer, Stefan M., Russell Hensley, Patrick Hertzke, Patrick Schaufuss, Nicholas Laverty, and Nicolaas Kramer. 2017. *Electrifying Insights: How Automakers Can Drive Electrified Vehicle Sales and Profitability*. McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/electrifying-insights-how-automakers-can-drive-electrified-vehicle-sales-and-profitability

Lambert, Fred. 2018. "Tesla Battery Degradation at Less than 10% after over 160,000 Miles, According to Latest Data." *Electrek*, April 14. https://electrek.co/2018/04/14/tesla-battery-degradation-data/

Li, Zheng, Menghsuan Sam Pan, Liang Su, Ping-Chun Tsai, Andres F. Badel, Joseph M. Valle, Stephanie L. Eiler, Kai Xiang, Fikile R. Brushett, and Yet-Ming Chiang. 2017. "Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long-Duration Electrical Storage." *Joule* 1, no. 2 (Oct): 306–327. https://doi.org/10.1016/j.joule.2017.08.007

London Metals Exchange. 2019. *Metals*. https://www.lme.com/Metals/

Martinez-Anido, Carlo Brancucci, Gred Brinkman, and Bri-Mathias Hodge. 2016. "The Impact of Wind Power on Electricity Prices." *Renewable Energy* 94 (Aug): 474–487. https://doi.org/10.1016/j.renene.2016.03.053

McDonald, Loren. 2018. "US Electric Car Range Will Average 275 Miles by 2022, 400 Miles By 2028." *Clean Technica*, October 27. https://cleantechnica.com/2018/10/27/us-electric-car-range-will-average-275-miles-by-2022-400-miles-by-2028-new-research-part-1/

Mehmeti, Andi, Athanasios Angelis-Dimakis, George Arampatzis, Stephen J. McPhail, and Sergio Ulgiati. 2018. "Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies." *Environments* 5, no. 2 (Feb): 1–19. https://doi.org/10.3390/environments5020024

National Petroleum Council (NPC). 2012. *Advancing Technology for America's Transportation Future*. Washington, D.C.: NPC. https://www.npc.org/reports/trans.html

National Research Council (NRC). 2013. *Transitions to Alternative Vehicles and Fuels*. Washington, D.C.: National Academies Press. https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

Nealer, Rachael, David Reichmuth, and Don Anair. 2015. *Cleaner Cars from Cradle to Grave*. Cambridge, MA: Union of Concerned Scientists. http://www.ucsusa.org/EVlifecycle

Nørregaard, Kjeld, Bjarne Johnsen, and Christian Hedegaard Gravesen. 2016. *Battery Degradation in Electric Buses*. Aarhus, Denmark: Danish Technological Institute. https://www.trafikstyrelsen.dk/~/media/Dokumenter/06%20Kollektiv%20trafik/Forsogsordningen/2013/Elbusser/Battery%20degradation%20in%20electric%20buses%20-%20final.pdf

Nykvist, Björn, and Måns Nilsson. 2015. "Rapidly Falling Costs of Battery Packs for Electric Vehicles." *Nature Climate Change* 5 (March): 329–332. https://doi.org/10.1038/nclimate2564

Olsson, Linda, Sara Fallahi, Maria Schnurr, Derek Diener, and Patricia van Loon. 2018. "Circular Business Models for Extended EV Battery Life." *Batteries* 4, no. 4 (Nov): 57–71. https://doi.org/10.3390/batteries4040057

Posada Sanchez, Francisco, Anup Bandivadekar, and John German. 2012. *Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles*. Washington, D.C.: International Council on Clean Transportation. https://www.theicct.org/sites/default/files/publications/ICCT_LDVcostsreport_2012.pdf

———. 2013a. *Estimated Cost of Emission Control Technologies for Light-Duty Vehicles Part 1 – Gasoline*. Warrendale, PA: Society of Automotive Engineers (SAE) International. https://doi.org/10.4271/2013-01-0534

———. 2013b. *Estimated Cost of Emission Control Technologies for Light-Duty Vehicles Part 2 – Diesel*. Warrendale, PA: Society of Automotive Engineers (SAE) International. https://doi.org/10.4271/2013-01-0539

Qiao, Qinyu, Fuquan Zhao, Zongwei Liu, Shuhua Jiang, and Han Hao. 2017. "Cradle-to-Gate Greenhouse Gas Emissions of Battery Electric and Internal Combustion Engine Vehicles in China." *Applied Energy* 204, (Oct): 1399–1411. https://doi.org/10.1016/j.apenergy.2017.05.041

Satyapal, Sunita. 2016. *Hydrogen and Fuel Cell Overview*. Washington, D.C.: U.S. Department of Energy, Fuel Cell Technologies Office. https://www.energy.gov/sites/prod/files/2016/03/f30/fcto_fc_expo_2016_satyapal.pdf

Schipper, Florian, Evan M. Erickson, Christoph Erk, Ji-Yong Shin, Frederick Francois Chesneau, and Doron Aurbach. 2017. "Review—Recent Advances and Remaining Challenges for Lithium Ion Battery Cathodes I. Nickel-Rich, $LiNi_xCo_yMn_zO_2$." *Journal of the Electrochemical Society* 164, no. 1 (1): A6220–A6228. https://doi.org/10.1149/2.0351701jes

Schmidt, Oliver, Adam Hawkes, Ajay Gambhir, and Iain Staffell. 2017. "The Future Cost of Electrical Energy Storage Based on Experience Rates." *Nature Energy* 2 (July). https://doi.org/10.1038/nenergy.2017.110

Schoettle, Brandon, and Michael Sivak. 2018. *Resale Values of Electric and Conventional Vehicles: Recent Trends and Influence on the Decision to Purchase a New Vehicle*. Technical Report SWT-2018-4. Ann Arbor, MI: University of Michigan. http://umich.edu/~umtriswt/PDF/SWT-2018-4.pdf

Slav, Irina. 2019. "What's Behind the Cobalt Price Crash?" *Oilprice.com*, March 4. https://oilprice.com/Energy/Energy-General/Whats-Behind-The-Cobalt-Price-Crash.html#

Symes, Steven. 2018. "Is the Solid State Battery Revolution Right around the Corner?" *GrabCAD Blog*, November 6. https://blog.grabcad.com/blog/2018/11/06/is-the-solid-state-battery-revolution-right-around-the-corner/

U.S. Department of Energy (DOE). 2013. "Internal Combustion Engine Basics," Last updated November 22. https://www.energy.gov/eere/vehicles/articles/internal-combustion-engine-basics

U.S. Energy Information Administration (EIA). 2016. "Chapter 8. Transportation sector energy consumption." In *International Energy Outlook 2016*. Washington, D.C.: U.S. DOE. https://www.eia.gov/outlooks/archive/ieo16/transportation.php

———. 2018. "Independent Statistics & Analysis - For Transportation" Last updated May 23.

———. 2019a. "Petroleum & Other Liquids: Weekly Retail Gasoline and Diesel Prices (March 21, 2016 and 2019)." Accessed June 17, 2019. https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm

———. 2019b. State Electricity Profiles: Washington Electricity Profile 2017. Last updated January 8. https://www.eia.gov/electricity/state/washington/

———. 2019c. "State Electricity Profiles: West Virginia Electricity Profile 2017." Last updated January 8. https://www.eia.gov/electricity/state/westvirginia/

———. 2019d. "Electricity: Data." Accessed September 3, 2019. https://www.eia.gov/electricity/data.php

U.S. Environmental Protection Agency (EPA). 2018. "Fuel Economy Data." https://www.fueleconomy.gov/feg/download.shtml

———. 2019. "Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2017." Last updated April 12. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017

———. 2014. *Final Rule for Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards*. Docket Number EPA-HQ-OAR-2011-0135. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-control-air-pollution-motor-vehicles-tier-3

U.S. Geological Survey (USGS). *Mineral Commodity Summaries 2018*. Reston, VA: USGS. https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/mcs/mcs2018.pdf

———. 2019. *Mineral Commodity Summaries 2019*. Reston, VA: USGS. https://doi.org/10.3133/70202434

Wang, Ning, Zaiyan Gong, Jun Ma, and Jie Zhao. 2012. "Consumer Total Ownership Cost Model of Plug-In Hybrid Vehicle in China." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 226, no. 5 (May): 591–602. https://doi.org/10.1177/0954407011421859

Wolfram, Paul, and Nic Lutsey. 2016. *Electric Vehicles: Literature Review of Technology Costs and Carbon Emissions.* Washington, D.C.: The International Council on Clean Transportation (ICCT). https://theicct.org/lit-review-ev-tech-costs-co2-emissions-2016

Xiao, Guowei, Zifei Yang, and Aaron Isenstadt. 2018. *Fuel-Efficiency Technology Trend Assessment for LDVs in China: Advanced Engine Technology*. Washington, D.C.: International Council on Clean Transportation. https://www.theicct.org/publications/fuel-efficiency-tech-china-engine

## Chapter 5

# Fueling and Charging Infrastructure

This chapter examines the important relationship between consumer uptake of alternative fuel vehicles and the infrastructure required to fuel and charge those vehicles. The chicken-and-egg problem of introducing alternative fuel vehicles while simultaneously providing the necessary infrastructure to fuel those vehicles involves multiple parties, which must risk large, long-term investments in parallel with each other in the face of great uncertainty about future demand. For example, vehicle manufacturers must invest in developing new powertrain technologies and building out factories and supply chains to produce those alternative fuel vehicles; the energy industry must produce and distribute new fuels. Given these deployment hurdles, governments may need to provide support to overcome externalities and system-wide inertia.

In short, though the techno-economic and environmental case for adopting a given alternative fuel technology may be compelling, the pathway for transitioning to that technology may be fraught with potential obstacles for the involved parties. The risks stem from numerous key areas of uncertainty, including future policy, future costs, potential breakthroughs from competitive technologies, and, perhaps most importantly, consumer behavior. Examples abound of technologies that achieved widespread adoption not because they represented the optimal technology solution, but because they offered the lowest-risk pathway for transitioning away from the status quo. Therefore, we begin this chapter with an overview of the infrastructure used for fueling and charging the main alternative vehicle technologies under development today, including current fueling infrastructure availability and characteristics. Section 5.2 then examines consumer behavior under various scenarios by using a System Dynamics model to represent the co-evolution of the vehicle fleet and fueling and charging infrastructure. Section 5.3 explores the economics of battery swapping for the specific case of taxi operations in a large, dense Chinese city where taxi electrification has been mandated. Our findings are summarized in the concluding section (Section 5.4). In this chapter, the term "fueling" refers to any means of transferring energy to vehicles, including in the form of electricity, liquid fuels, and gaseous fuels.

## 5.1 INFRASTRUCTURE OVERVIEW

Fueling and charging infrastructure will have a significant impact on the rate of deployment of alternative vehicle powertrains that are currently available or in development. Since new infrastructure will evolve from the current base of built infrastructure, an assessment of the current state of infrastructure buildout, by geographic region and by fuel type, is necessary.

As of 2017, private passenger light-duty vehicles (LDVs) on the road numbered approximately 270 million in the U.S., 250 million in the E.U., and 170 million in China. Approximately 99% of these vehicles were internal combustion engine vehicles (ICEVs) powered by liquid fuels—primarily gasoline or diesel. Although the number of public electric vehicle (EV) charging plugs in Europe and China has increased substantially in recent years, the capacity of these chargers in terms of energy throughput is still dwarfed by the energy throughput of conventional gasoline and diesel fueling stations.

To put these relative capacities in context, a gasoline pump for LDV fueling in the U.S. has a maximum energy transfer rate of 20 MW. By comparison, the maximum charging rate for most public EV plugs ranges from 0.004 to 0.35 MW (see further discussion in Section 5.1.1).

Biodiesel (such as B20), gasoline/ethanol blends (such as E85), compressed natural gas (CNG), liquefied natural gas (LNG), electricity, and hydrogen are all examples of alternative fuels that have attracted investment from original equipment manufacturers and infrastructure companies. Table 5.1 compares the number of public fueling locations that provide each fuel option within the U.S., the E.U., and China. While these numbers are useful, direct comparisons across fuel types should be made with caution, given that different fueling stations may have very different fueling or charging capacities depending on the number of pumps or plugs they offer and on typical fueling or charging times at each pump or plug.

Our scenario analysis and our projections for fueling and charging infrastructure focus primarily on petroleum products, the dominant incumbent fuel, as well as electricity and hydrogen, the two alternatives that are seen as offering the greatest potential for scalable deep decarbonization of the light-duty vehicle fleet. We do not examine fueling facilities for natural gas or biofuels, which have lower potential for large-scale decarbonization of the LDV fleet.

Vehicles fueled by natural gas (CNG or LNG) offer advantages over gasoline- and diesel-fueled vehicles in terms of local pollutant emissions—including emissions of nitrogen oxides, carbon monoxide, and particulate matter—and fuel costs. In many countries, these advantages have driven most of the natural gas vehicle deployment that has occurred to date. Natural gas technologies may also continue to attract investment as a promising option for heavy-duty vehicles (Heywood and MacKenzie 2015). However, greenhouse gas emissions from natural gas vehicles are almost as high as from gasoline- and diesel-powered vehicles (Heywood and MacKenzie 2015). Vehicles that run on methane produced from biomass, by contrast, do offer substantial potential for reducing greenhouse gas emissions relative to gasoline and diesel. However, the biomethane supply remains limited. Other second-generation biofuels such as cellulosic ethanol offer potential benefits with respect to greenhouse gas emissions, but the biofuels industry has encountered challenges in developing scalable and economic fuel production pathways. Even within the category of climate-friendlier, second-generation biofuels, greenhouse gas benefits may be limited by land-use requirements and by the farming intensity required for large-scale biofuels crop production (Martin 2017).

### 5.1.1 EV Charging

EV service equipment can be differentiated by location and power level, where power-level designations range from Level 1 for low power, to Level 2 for medium power, Level 3 for high power, and XFC for extreme fast charging (Table 5.2). Four types of charging infrastructure are currently available for plug-in EVs, which include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs):

1. *Home charging:* Typically a wall plug or a dedicated Level 2 charger installed at a residence that is intended to charge EVs when they are parked for extended periods. So far, more than 80% of EV charging in the U.S. occurs while the car is parked at home (U.S. Department of Energy [DOE], Office of Energy Efficiency and Renewable Energy [EERE] 2019). With development of a public charging network still in its early stages, access to home charging is the most reliable power source for current BEV owners. The ability to charge at home is a feature that is not shared by other alternative fuels and it offers a clear advantage for the proliferation of EVs. However, this option is limited to homes with parking space close to a power supply that is adequate to accommodate an EV charger.

2. *Workplace charging:* Typically a set of Level 2 chargers installed at a business center parking lot and intended to charge EVs when parked during work hours. These stations are installed by employers and are usually available only to their employees. In some cases, free use of workplace chargers is provided as an employee benefit, but the feasibility of extending this practice is uncertain.

**Table 5.1: Buildout of public light-duty vehicle fueling and charging infrastructure**

| | Number of public fueling or charging stations | | |
|---|---|---|---|
| **Fuel type** | **U.S.** | **E.U.** | **China** |
| Gasoline[aa] | 156,065 (2012)[a] | 75,396[c] | 98,595 (2015)[i] |
| Biodiesel[bb] | 195 (2019)[b] | n.a. | n.a. |
| E85[cc] | 3,390 (2019)[b] | n.a. | n.a. |
| CNG | 900 (2019)[b] | 3,420 (2019)[d] | 5,200 (2015)[h] |
| LNG | 65 (2019)[b] | 211 (2019)[d] | 2,460 (2016)[g] |
| Electricity (stations/plugs) | 22,267/66,462 (2019)[b] | n.a./143,693 (2018)[f] | n.a./275,000 (2018)[e] |
| Hydrogen | 46 (2019)[b] | 47 (2018)[f] | 12 (2018)[j] |

Note: n.a. = not available; [a] Alternative Fuels Data Center (2019b); [aa] gasoline includes ethanol blends up to 10%; many gasoline stations also sell diesel; biodiesel blends up to 5% are called diesel in the U.S.; [b] Alternative Fuels Data Center (2019c); [bb] biodiesel refers to biodiesel blends of 20% and higher; [cc] E85 is an ethanol-gasoline blend containing anywhere from 51% to 83% ethanol (Alternative Fuels Data Center 2019a); [c] Cooper (2019); [d] NGVA Europe (2019); [e] International Energy Agency (IEA) (2019a); [f] European Alternative Fuels Observatory (2019); [g] Zhou Chuang Information (2017); [h] Zhiyan Consulting Group (2015); [i] bosidata.com (2017); [j] baijiahao.baidu (2018).

**Table 5.2: Characteristics of different types of EV charging stations**

| | **Home or workplace** | **Home or workplace** | **Public** | **Fast** | **DC fast and extreme fast** |
|---|---|---|---|---|---|
| **Level** | **1** | **2** | **2** | **3** | **3+** |
| Power (kW) | <3.7 | <22 | 3.7-22 | 22-43.5 | 43.5-150+ |
| Miles per hour of charging[a] | <11.7 | <69.3 | 11.7-69.3 | 69.3-137 | 137+ |
| Unit cost (2015, $) | 0-1,500 | 500-1,500 | 500-7,000 | 500-6,500 | 10,000-40,000 |
| Installation cost (2015, $) | 0-3,000 | 200-4,000 | 1,000-8,000 | 4,500 | 21,000 |

Note: [a] Assuming an average BEV driving efficiency of 3.15 miles/kWh. Data from IEA (2018a) and Smith and Castellano (2015).

3. *Public charging:* Typically a set of publicly available (but not necessarily publicly funded) Level 2 chargers installed at a shopping mall or parking lot and intended to partially charge vehicles while drivers are shopping or running errands. To defray the fixed costs of using parking spaces and installing chargers, drivers who use these stations are likely to pay a higher fee per kilowatt-hour (kWh) than they would for home or workplace charging. In the continental U.S., for example, the price of electricity for residential customers ranges from $0.09/kWh to $0.21kWh (U.S. Energy Information Administration [EIA] 2019a); by contrast, prices at ChargePoint public charging stations range from $0.15/kWh to $0.49/kWh.

4. *Fast charging:* Typically a set of Level 3 chargers installed along a highway or potentially at a mall or other public destination. While fast charging provides the convenience of shorter charging times, these types of stations have higher fees per kWh than public Level 2 charging stations due to the high capital cost of charging equipment and the electricity demand charges associated with placing relatively high power demands on the grid. For example, in Massachusetts, charging at EVgo's CHAdeMO station, which has a maximum power level of 50 kilowatts (kW), costs about $0.35/minute. If the average charge rate is 60% of the maximum, the driver is paying $0.70/kWh.

Two more charging methods are emerging that aim to increase the convenience of charging.

5. *Battery swapping:* This concept envisions a network of battery swapping stations that hold an inventory of fully charged batteries. Customers could swap their depleted EV batteries for a fully charged battery at one of these stations using a robotic automated system in a matter of minutes. This approach could reduce EV charging time such that it is comparable to traditional gasoline fueling. The number of batteries that would need to be held in inventory would depend on the time needed to swap and charge depleted batteries using a Level 2 charger inside the station. In addition, this approach requires vehicles and battery systems that are designed for easy and fast swapping. An Israeli company called Better Place piloted the swapping station concept but the company went bankrupt in 2013. More recently, the Chinese EV manufacturers NIO and BJEV have begun building battery swapping stations to serve their domestic customers. However, the broad applicability of battery swapping remains uncertain. We explore the potential of battery swapping for commercial vehicle fleets in Section 5.3.

6. *Wireless charging:* This approach involves charging EVs through induction without the need to physically connect cars to a power source. Wireless charging is possible while the vehicle is stationary or while the vehicle is being driven.

    a. Currently, stationary wireless charging technology is available for a limited number of EV models, such as the BMW 530e. Additional manufacturers are developing EV models with this capability. To implement stationary wireless charging, induction coils (and power electronics) need to be installed in the vehicle as well as in the parking location. The primary advantage of stationary wireless charging is that it can make the charging process seamless. In the more distant future, stationary wireless charging may be an attractive option for electric autonomous vehicles, enabling them to charge while parked without human intervention.

    b. Wireless charging while the car is in motion (dynamic wireless charging) is currently being explored. To implement this approach, various cost and engineering challenges need to be overcome. Specifically, embedding wireless charging systems in road infrastructure is expensive; according to one estimate, the cost of installing wireless charging for electric buses could be as high as 1.2 million euros per kilometer per lane (Shekhar, et al. 2016). Engineering challenges for achieving efficient energy transfer using dynamic wireless charging include the wide range of ground clearances for different vehicles and the potential for misalignment between coils in the moving vehicle and the stationary coils embedded in the road infrastructure (Panchal, Stegen, and Lu 2018). If cost-effective solutions can be found for overcoming these and other challenges, dynamic wireless charging could possibly enable extended vehicle range with a modestly sized battery. However, major questions remain about the long-term economic viability, durability, safety, and compatibility of embedding inductive systems in roadways on a large scale.

### *Charger specifications*

Power ratings and miles of range per hour of charging time for different charging options (summarized in Table 5.2) can also vary based on ambient conditions, the battery's state of charge, and the number of vehicles using a given charging station. As a battery approaches 80% charge, the charging speed tapers off significantly. Additionally, some vehicles are not equipped to handle higher power charging and in 2019 there are no production EV models that can accommodate the highest advertised charging speed of 350 kW (Electric Vehicle Database 2019). Because there are also a number of different standards for charging infrastructure, a given vehicle model may need adapters to use a given charging station, or could be completely incompatible with some charging facilities.

### *Public charging infrastructure in the U.S.*

As of August 2019, the U.S. had more than 22,000 public charging stations with about 68,000 individual charging plugs—of these, 80% are Level 2 chargers, 18% are Level 3, and 2% are Level 1 (Alternative Fuels Data Center 2019c). The maximum power for most Level 1 public chargers is less than 2 kW. The majority of Level 2 chargers have an advertised maximum power of 6.6 or 7.2 kW (ChargePoint 2019), while the Tesla destination chargers have higher advertised powers of 8–16 kW (Tesla Motors 2019). The majority of Level 3 chargers currently available in the U.S. are Tesla Superchargers with advertised maximum power of 72 kW, 120 kW, and 150 kW (Tesla Motors 2019). EVgo and ChargePoint have the next largest U.S. networks of Level 3 chargers, with advertised maximum power levels of 50 kW and 62.5 kW, respectively (EVgo 2019; ChargePoint 2019). However, these maximum charging rates, especially with respect to Level 3 chargers, must be viewed with caution since actual charging rates typically fall short of these advertised maxima for several reasons:

1. Many chargers have two plugs, which may be shared by two vehicles charging simultaneously. In that situation, the available power must be divided between the two vehicles. For example, a Tesla Supercharger may split its 120 kW power such that each vehicle receives 60 kW.

2. The battery's state of charge has an impact on the charge rate especially when the battery is more than 80% charged.

3. If battery voltage is less than that for the charger, the power delivered to the battery will be less than the charger's nameplate capacity.

4. Energy received and stored in the battery will always be less than the power drawn from the charger, since various losses occur during energy transfer.

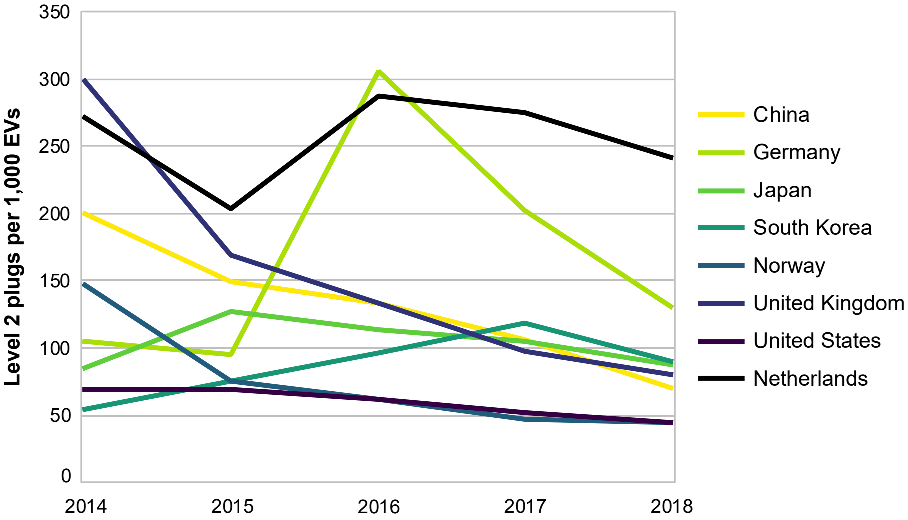
5. Ambient temperature can reduce both charging efficiency and the rate at which energy is delivered; sensitivity to temperature varies depending on specific battery chemistry and the vehicle's battery management system (Motoaki, Yi, and Salisbury 2018; Trentadue, et al. 2018).

## 5.1.2 Global Development of EV Charging Infrastructure

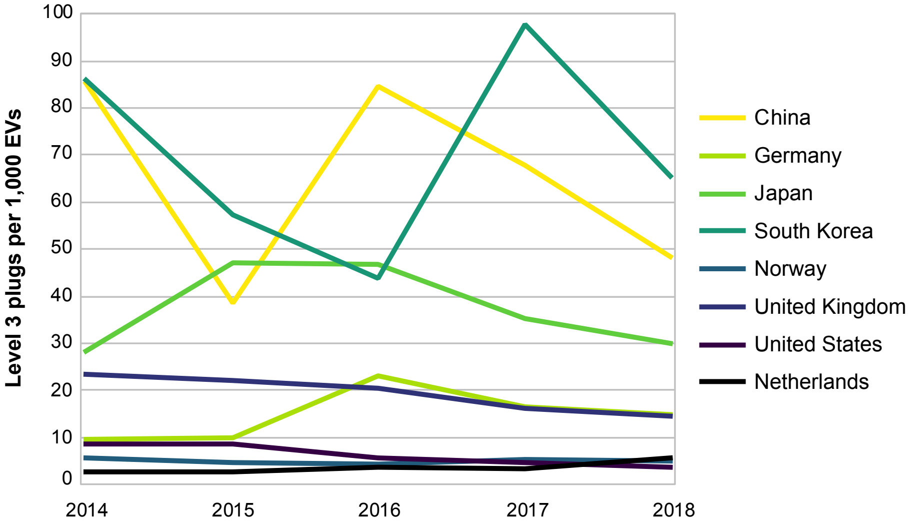
The development of charging infrastructure has proceeded at different rates in countries around the world. A number of factors contribute to this variation, including EV market share, government incentives for investment in charging infrastructure, the size of the country, the availability of home charging, and local driving habits, including driving distances. The deployment of different types of chargers has also been uneven, with China and South Korea having the highest ratio of Level 3 plugs to EVs, and the Netherlands having the highest ratio of Level 2 plugs to EVs (Figure 5.1). Studies that have looked at the issue of charging infrastructure in the U.S. context suggest that the required density of charging infrastructure—assuming Level 2 chargers—is 36 plugs per 1,000 EVs in cities, 54 plugs per 1,000 EVs in towns, and 79 plugs per 1,000 EVs in rural areas (Wood, et al. 2017). As can be seen in Figure 5.1a, many countries including the Netherlands, Germany, South Korea, Japan, and the U.K. currently exceed these targets for Level 2 plugs and even more countries exceed these targets if Level 3 plugs are included (Figure 5.1b). It is possible that countries with the highest penetrations of plug-in EVs (as shown in Table 5.3) may owe part of their success in EV deployment to their pre-emptive buildout of public charging infrastructure.

**Figure 5.1: Recent trends in the global buildout of charging infrastructure**

**(a) Public Level 2 charging stations**



**(b) Public Level 3 charging stations**



Note: Data from IEA (2019a).

### 5.1.3 Barriers to EV Adoption

*Home charging availability*

Home charging is not available to all consumers, and even in cases where it is, installing the necessary equipment might involve significant expense. For BEVs, eight hours of trickle charging through a standard wall outlet might provide as little as 40 miles of range (Alternative Fuels Data Center 2018). A dedicated high voltage (240-volt) circuit is typically needed to enable the use of Level 2 charging, which can fully charge a longer-range BEV overnight. Depending on the physical layout of a home's circuitry relative to the parking space, however, substantial work might be required to make a charging point accessible. Variability in the need for upgrades of this type drives the wide range of costs given for home charger installations (Table 5.2). In some cases, the EV owner may lack a dedicated parking space, making access to home charging unreliable. This is an issue for residents of multi-unit dwellings and

**Table 5.3: Global sales of plug-in EVs in 2018**

| | 2018 BEV sales | 2018 PHEV sales | 2018 BEV market share (%) | 2018 PHEV market share (%) | BEV to PHEV ratio |
|---|---|---|---|---|---|
| China | 815,870 | 262,660 | 3.4 | 1.1 | 3.1 |
| Germany | 36,060 | 31,440 | 1.1 | 0.9 | 1.1 |
| Japan | 26,530 | 23,220 | 0.6 | 0.5 | 1.1 |
| South Korea | 29,630 | 4,050 | 2.0 | 0.3 | 7.3 |
| Norway | 46,140 | 26,550 | 29.5 | 17.0 | 1.7 |
| United Kingdom | 15,740 | 34,620 | 0.7 | 1.4 | 0.5 |
| United States | 238,820 | 122,490 | 1.6 | 0.8 | 1.9 |
| Netherlands | 25,070 | 4,090 | 5.7 | 0.9 | 6.1 |

Note: Data from IEA (2019a).

in areas where street parking is common. In these situations, EV owners may need to rely on workplace charging, assuming that option is available, to meet their daily charging needs. If home charging and workplace charging are not available, EV owners must rely on public chargers. This may be an inherent limit to the penetration of BEVs.

### *Range anxiety and extreme fast charging*

"Range anxiety" is the fear of running out of energy before reaching a destination or a convenient charging or fueling station. At present, the relatively low range and long charging time for BEVs contribute to this fear, making BEVs unattractive for longer trips. For example, charging during an extended trip can take roughly 10 hours with a typical Level 2 charger (6 kW) or roughly 1 hour with a fast charger (60 kW) to add 150 miles of range to the battery.[1] Infrastructure providers are attempting to build a network that serves longer journeys with faster charging times, in an effort to reduce the fueling-time differential between BEVs and ICEVs. Led by Ionity in Europe and Electrify America in the U.S., efforts are underway to begin developing 350 kW extreme fast charging (XFC) networks. Currently available BEV models cannot charge at these high-power rates, but compatible vehicles have been prototyped.

Substantial improvements in battery technology and higher battery cooling rates will be needed to enable extreme fast charging so that EVs can compete with the fueling speed consumers associate with petroleum-based fuels. When vehicles become available that can fully utilize the XFC power output (350 kW), these vehicles may be capable of charging up to 150 miles of range in 10 minutes.[1] However, it is likely that the batteries of vehicles capable of using XFC chargers would be up to 90% more expensive than the batteries found in current BEVs. In addition, high power charging may cause battery performance to degrade much more quickly (Ahmed, et al. 2017).

### *Vehicle price and government incentives*

The higher price of alternative fuel vehicles relative to comparable internal combustion vehicles is often cited as the chief barrier to consumer adoption (Singer 2017). This price discrepancy is likely to shrink as advances in battery, fuel cell, and hydrogen storage technologies and economies of scale reduce the cost of producing and operating electric and fuel cell vehicles and their respective

---

[1] This assumes the average charge rate is 70% of the advertised maximum. Actual charging rates can be much lower than the charger nameplate capacity and depend on the battery's initial state of charge, its capacity, ambient temperature, the battery management system, and other factors. Vehicle fuel efficiency is assumed to be 3.5 miles per kWh or 118 miles per gallon equivalent (MPGe).

infrastructures. Various government subsidies and incentive programs for these vehicles have been introduced around the world to help lower deployment barriers in the short term. In the U.S., federal tax credits are available for up to $7,500 on qualifying EVs; some states offer their own incentives that can add as much as $5,000 to the federal credit. Norway, Sweden, and other countries with significantly higher BEV and PHEV sales (EVs now account for close to 50% of new LDV sales in Norway) offer larger subsidies as well as incentives such as access to high occupancy vehicle lanes and priority parking.

However, these subsidies are beginning to phase out in the U.S. and will be under review in other countries in the next few years as EVs become more competitive with ICEVs. Additional subsidies and government programs exist for the construction and operation of EV charging stations. These government incentives are motivated by many policy objectives, including reducing air pollution and greenhouse gas emissions, reducing dependence on imported petroleum, and utilizing excess electricity generating capacity.

### 5.1.4 Hydrogen Fueling Stations

The buildout of hydrogen fueling infrastructure has been limited to date, with 376 (public and private) stations installed globally as of the end of 2018 (Advanced Fuel Cells Technology Collaboration Partnership [AFC TCP] 2019). For the most part, hydrogen-fueling equipment has standardized around the world and dispenses fuel at pressures of 350 and 700 bar. The U.S. and Japan are the largest markets for FCEVs with 5,899 vehicles in the U.S. and 2,926 in Japan out of a global fleet of 12,952 at the end of 2018 (AFC TCP 2019). Despite limited penetration thus far worldwide, nations around the world have announced plans to invest significantly in hydrogen fueling infrastructure, with approximately 1,500 stations planned by 2025 between the U.S., Japan, France, China, Germany, and South Korea (IEA 2018b). Due to high capital cost and the likely continuation of low utilization rates in the near term, it may be 10–15 years before hydrogen infrastructure providers see a positive return on their investment. Therefore, government partnerships and public support are likely to be essential to the future expansion of FCEVs and related hydrogen fueling infrastructure (IEA 2015).

#### *Comparing hydrogen FCEVs to BEVs*

One primary advantage that hydrogen vehicles offer over BEVs is their 3- to 7-minute fueling time and more than 300-mile range (Saur, et al. 2019). These numbers are comparable to current gasoline vehicles and the overall fueling experience for FCEVs is similar to ICEVs so vehicle owners do not need to make significant changes to their habits, as they do with BEVs (James 2016). These range and fueling time characteristics give FCEVs an advantage over BEVs by reducing range anxiety. However, hydrogen vehicles cannot be fueled at home and must rely on a fueling infrastructure network that is still in its infancy. Additionally, hydrogen fueling stations with 700 bar delivery pressure cost between $0.6 and $2.0 million to build, depending on the fueling capacity of the station (IEA 2019b).

During the early stages of EV deployment, charging demands on the electric power system are expected to be relatively modest in regions of the world where excess capacity exists. However, large-scale EV deployment will require significant investment to upgrade and reinforce the power distribution system. Our analysis does not account for these costs, nor does it tackle the question of who will pay for them, but other researchers have concluded that supply infrastructure costs for the large-scale deployment of FCEVs would be lower than for the large-scale deployment of plug-in EVs (Robinius, et al. 2018).

#### *Hydrogen fuel production and distribution*

Currently, steam methane reforming of natural gas is the primary production method for making hydrogen in the U.S. and in many parts of the world, because it is the least expensive, most efficient method available (IEA 2015). Coal gasification is currently the dominant and least expensive production method for generating hydrogen in China, but it has twice the carbon intensity of steam methane reforming (IEA

2019b). To achieve significant reductions in greenhouse gas emissions by using hydrogen fuels, production methods with lower carbon intensity will be needed.

As discussed in Section 4.2.5, there are currently two primary options for reducing the carbon-intensity of hydrogen production. One option is to capture and store the carbon dioxide generated from the steam methane reforming process (referred to as SMR + CC in Section 4.2). Likewise, carbon dioxide from coal gasification could be captured and stored, although economic and environmental challenges remain. The other option is to generate hydrogen by electrolysis using a low-carbon source of electricity. If electrolysis is used, the carbon intensity of the generated hydrogen is strongly dependent on the carbon intensity of the electricity source. The carbon intensity of the electricity source is amplified by inefficiencies in the electrolysis process and in the tank-to-wheel conversion of hydrogen energy to vehicle propulsion, as discussed in Section 4.2. Hydrogen produced via water electrolysis remains expensive thus far relative to conventional transportation fuels in the U.S., but costs are continuing to come down.

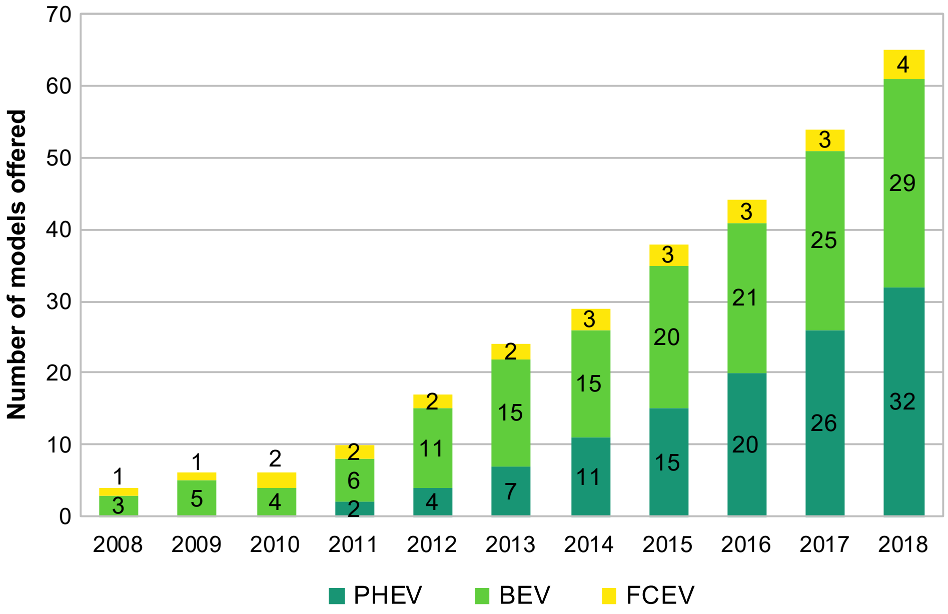
One of the challenges for hydrogen as a transportation fuel for LDVs is delivering hydrogen to dispersed vehicle fueling locations. Although hydrogen, a gaseous fuel, has higher energy content *by mass* than any other fuel, its energy content *by volume* is very low. Consequently, distribution and storage costs for hydrogen are a significant issue, and one that has received substantial attention from academia, industry, and governments. Centralized hydrogen production has the advantage of economies of scale, for both production and storage, and also provides better synergy with the kind of broader hydrogen ecosystem that is central to various visions for a future decarbonized world. Industrial uses currently account for most hydrogen demand, but as part of efforts to decarbonize the overall economy, hydrogen may be increasingly used for heating, energy storage, and additional industrial applications. An expanding market for hydrogen in other applications might support the buildout of hydrogen production and distribution networks, making it easier to scale the fuel supply and fueling infrastructure needed for FCEVs (de Valladeres 2017).

Nevertheless, substantially expanding hydrogen distribution networks will require investment and time. Truck transport is expected to be the main method used to deploy hydrogen for vehicle fueling, at least initially. This will have energy and cost implications. The other option is to generate hydrogen on site, at hydrogen fueling stations. This approach has the advantage of eliminating the need for a hydrogen distribution system, but would result in higher fuel production costs due to smaller scale operations. Furthermore, local generation may not leverage the benefits of developing a broader hydrogen ecosystem. Regardless of eventual production and distribution methods, substantial work is underway to reduce hydrogen costs. For example, the U.S. Department of Energy (DOE) is currently funding a $39 million program that includes research into low-emission production and distribution pathways for hydrogen in an effort to lower operational costs for FCEVs.

### 5.1.5 Available Vehicle Models

At the end of 2018, 29 BEV models, 32 PHEV models, and 4 FCEV models were available in the U.S. (Figure 5.2). However, FCEVs are currently available for purchase only in California, and dealerships generally push sales of conventional vehicles more than EVs, so the actual availability of alternative fuel vehicles may be limited in many areas of the U.S. (Lunetta and Coplon-Newfield 2016). A narrow range of choices is another significant barrier to the increased adoption of such vehicles (Singer 2017). A number of large automakers have, however, stated that they intend to significantly increase their offerings in this category (IEA 2018a). Based on these statements, as many as 75 BEV models could be available to U.S. car buyers by 2023 (Naughton 2017).

**Figure 5.2: Recent trends in model offerings for BEVs, PHEVs, and FCEVs in the U.S.**



Note: Data from Bloomberg New Energy Finance and Business Council for Sustainable Energy (2019).

## 5.2 CONSUMER ADOPTION OF ALTERNATIVE FUEL VEHICLES IN THE U.S.

### 5.2.1 A System Dynamics Model for Understanding Consumer Choice

To analyze the role of consumer choices in the diffusion of new powertrain technologies, we expanded the Bass-type diffusion model (a differential equation that describes how new products are adopted by individuals) developed at the MIT Sloan School of Management (Keith 2012). The model simulates the U.S. market for LDVs by representing two primary factors as determinants for consumer choice regarding alternative powertrains.

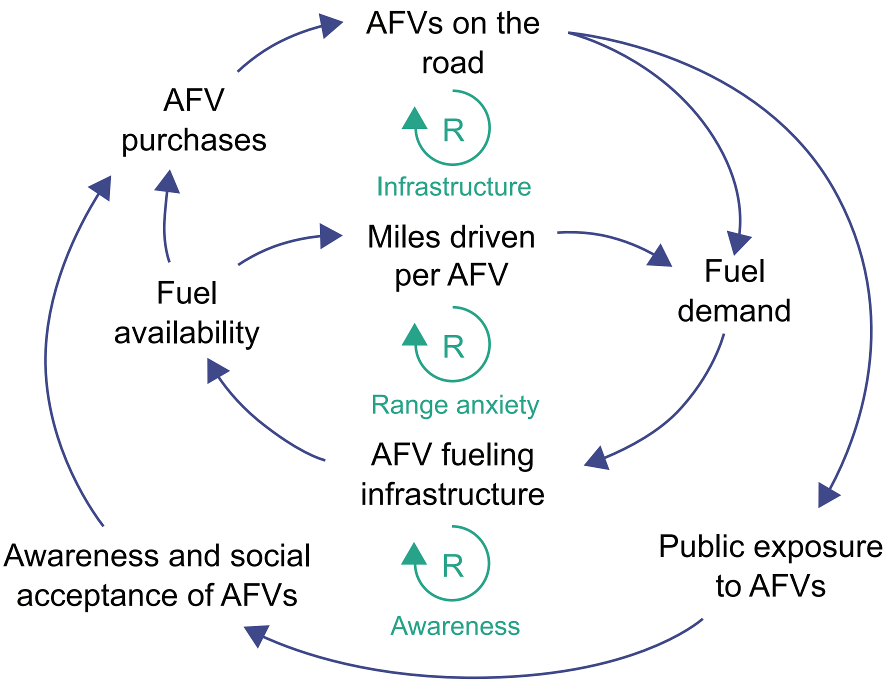
The first factor is the *utility* of a particular powertrain. Utility captures the attractiveness of a particular vehicle powertrain based on attributes such as purchase price, fuel cost, range, and availability of fueling infrastructure (Brownstone, Bunch, and Train 2000). The second factor is consumer *familiarity*, which is influenced by marketing and by word-of-mouth awareness about a given technology's advantages over competing technologies.

Decisions are derived from feedback loops of interconnected differential equations that update over time throughout each simulation until the year 2050 (Figure 5.3). The powertrains considered include gasoline-fueled ICEVs, hybrid electric vehicles (HEVs), PHEVs, BEVs, and hydrogen-powered FCEVs. All of the vehicles are assumed to be mid-size cars to eliminate other vehicle attributes that factor into consumer purchasing decisions, such as size and style.

#### *Key parameters of the System Dynamics model*

The System Dynamics (SD) model uses a number of exogenous parameters to define the context within which consumers make their vehicle purchase decisions. Table 5.4 summarizes some assumptions that are particularly important for analyzing the impact of developments in vehicle technology, the evolution of fueling infrastructure, and consumers' willingness to purchase alternative fuel vehicles.

**Figure 5.3: Simplified diagram illustrating some of the feedback loops in the System Dynamics model**



Note: R = reinforcing loop; AFV = alternative fuel vehicle.

In the SD model, car buyers make purchase decisions based on the relative attractiveness of the vehicle technologies available at that time. Assumptions about range and new vehicle fuel economy (Table 5.5) are based on nominally reported values for comparable mid-size cars in the U.S. market (U.S. DOE, EERE 2018). As the simulation progresses toward 2050, these attributes improve to reflect technological advances, changing consumer preferences, and more stringent Corporate Average Fuel Economy (CAFE) standards.

Assumptions about fueling and charging infrastructure in the SD model are approximately representative of the U.S. (Table 5.6). The attributes of this infrastructure also evolve over time as vehicle technology develops, market shares of the powertrains change, and demand for corresponding fueling and charging infrastructure shifts in response. Fueling and charging considerations have an important influence on vehicle purchasing decisions because consumers place weight on the relative convenience and cost of operating the vehicle.

### *Model limitations*

A few limitations of the SD model are worth noting. First, the model works with average values of vehicle characteristics, vehicle use patterns, and fueling and charging station density across a given area (the continental U.S. for most of these results). Second, charging power is represented as a national average rather than being differentiated by level. Third, the model assumes year-over-year growth in the U.S. vehicle stock at a rate of 0.7% per year. The model does not attempt to account for the effect of various factors on future vehicle ownership, such as developments in public transportation, access to ride-hailing services, the introduction of autonomous vehicle technologies, and other alternative modes of transportation. Finally, our representation of the LDV market does not distinguish between cars and light trucks. Our entire LDV fleet consists of mid-sized cars, with the powertrain being the sole feature that differentiates models and the sole basis for vehicle selection. This simplification in the fleet representation does not account for issues of

**Table 5.4: General model assumptions for characterizing the U.S. consumer market for light-duty vehicles**

| Model parameter | Assumed value |
|---|---|
| Vehicle lifetime (years) | 15 |
| Value of time ($/hour) | 40 |
| Annual vehicle miles traveled (VMT) (miles/year) | 12,000 |
| LDV fleet growth rate (%/year) | 0.7 |
| Alternative fuel vehicle purchase incentive sunset date | 2030 |
| Median household income (2018, $/year) | 57,000 |
| EV home charger cost ($) | 1,000 |
| Price multiplier for public level 2 charging | 2 |
| Breakdown of energy used to charge BEVs for households *with* a home charger (% at home/% at public charger) | 85[a]/15 |
| Breakdown of energy used to charge BEVs for households *without* a home charger (% at home/% at public charger) | 0/100 |
| Percent of all households in the U.S. with the ability to charge at home (%) | 70[b] |

Note: [a] U.S. DOE, EERE (2019); [b] based on difference in parking availability between owned (~60%) and owned and rental homes (~80%) (Traut, et al. 2013).

**Table 5.5: Powertrain characteristics applied in SD model (for mid-sized U.S. vehicles)**

| Parameter | ICEV | HEV | PHEV | BEV | FCEV |
|---|---|---|---|---|---|
| Purchase incentive ($/vehicle)[a] | 0 | 0 | 4,000 | 7,500 | 7,500 |
| Vehicle MSRP (2018 $)[b] | 20,000 | 22,500 | 26,500 | 37,000 | 58,000 |
| Maximum range, ideal conditions (2018, miles/fuel)[c] | 400 | 580 | 45 electric,<br>460 gas | 225 electric | 360 |
| New vehicle fuel economy (2018, miles/GGE)[c] | 32 | 55 | 124 electric<br>55 gas | 124 | 75 |

Note: GGE = gallons of gasoline equivalent (based on energy content); [a] based on U.S. federal tax credits (U.S. DOE, EERE 2018) (the SD model assumes tax credits ramp down to zero from 2020 to 2030 as an approximation of the actual phase out of these incentives, which is based on cumulative sales by manufacturer rather than time); [b] nominal prices are based on the relative costs of powertrains in Figure 4.1 and U.S. DOE, EERE (2018); [c] range and fuel economy are nominal values and do not represent specific car models (U.S. DOE, EERE 2018).

powertrain availability in all classes of LDVs, which may be particularly important as the U.S. market continues to trend toward larger personal vehicles.

### 5.2.2 The Co-Evolution of Powertrains and Infrastructure

Generally, a powertrain technology and the fueling or charging infrastructure required to support deployment of that technology will co-evolve as each side of the market strengthens: As the stock of vehicles with a certain type of powertrain grows, demand increases for the corresponding fueling or charging infrastructure, and as more infrastructure is built, it becomes more convenient to own vehicles that can use that infrastructure. Of course, powertrain–infrastructure combinations can also devolve if widespread adoption of alternative technologies weakens each side of the market. To understand the dynamics of co-evolution, we structured our analysis in three parts:

1. Inter-powertrain competition
2. Inter-infrastructure competition
3. Powertrain–infrastructure interaction

**Table 5.6: Initial fueling infrastructure characteristics applied in SD model**

| Parameter | Gas station | Public charging station | $H_2$ station |
|---|---|---|---|
| Available stations (2018) | 160,000[a] | 16,000[b] | 50[c] |
| Infrastructure lifetime | 20 years | 20 years | 20 years |
| Pumps per station | 8[d] | 3[b] | 2[e] |
| Fueling time or rate (2018) | 5 minutes | 26.5 kW[f] | 6 minutes[g] |
| Fuel price (2018) | $2.87/gallon[h] | $0.21/kWh[i] | $15.50/kg[j] |

Note: [a] 160,000 is rounded up and based on Alternative Fuels Data Center (2019b); [b] 16,000 was the approximate number of charging stations at the end of 2017 and the ratio of plug to stations is roughly 3 based on Alternative Fuels Data Center (2018a); [c] 50 is rounded up from the number of public hydrogen stations based on Alternative Fuels Data Center (2019c); [d] 8 is a typical number of gasoline pumps in a two-island station in the U.S.; [e] the typical number of hydrogen dispensers per station in California is two, but usually one is 350 bar and the other is 700 bar, and both dispensers cannot be used simultaneously (California Fuel Cell Partnership 2019); [f] based on the rough weighted average of power of all public charging stations reported in the Alternative Fuels Data Center (2018b); [g] value is within the 3- to 7-minute range of hydrogen fueling times based on Saur, et al. (2019); [h] average price of regular gasoline in U.S. for week of May 13, 2019 from the Energy Information Administration (U.S. EIA 2019b); [i] assumes that the retail price of public charging is two times the U.S. 2018 average price of $0.105/kWh for electricity (U.S. EIA 2019c); [j] Yi and Shirk (2018). A kilogram (kg) of hydrogen contains approximately the same amount of chemical energy as one gallon of gasoline. The retail price of hydrogen is assumed to decline to $7/kg in the SD model as FCEV deployment increases, whereas the price of gasoline and electricity both increase with time.

### *Inter-powertrain competition*

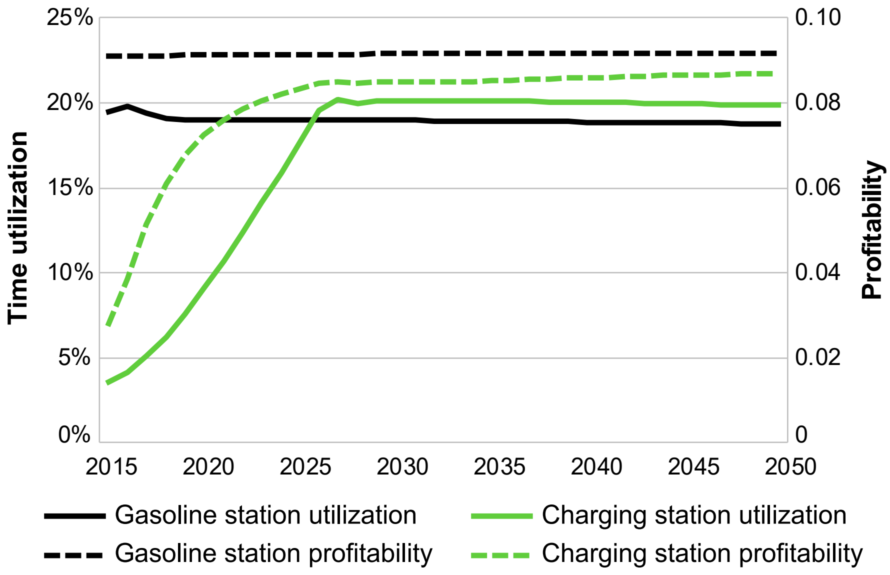
A given powertrain's ability to compete with other powertrains depends on car buyers' perception of utility and their familiarity with different powertrain technologies. As we noted at the outset of this section, the utility of a powertrain represents its usefulness to the buyer, and reflects various specific parameters, such as vehicle price, operating cost, speed, acceleration, range, emissions, and the time cost incurred in searching for and fueling or charging at a station. Familiarity is a measure of the customer's awareness of a given powertrain's advantages over other powertrains; it is commonly influenced by word-of-mouth and by manufacturers' marketing efforts.

### *Inter-infrastructure competition*

Similar to the competition between different powertrains, fueling and charging infrastructures compete to attract investment and expand networks by infrastructure providers. In our study, the attractiveness of different types of fueling or charging infrastructure (for gasoline versus electricity, for instance) is determined by a combination of two related metrics: *profitability* and *utilization*. *Profitability* depends on profit margins for each unit of fuel sold, the amount of fuel sold, and profits from ancillary revenue sources such as convenience stores. *Profitability* is defined as the ratio of station net profit to total costs (including operating costs and amortized fixed costs). *Utilization* is the percentage of time that the infrastructure is in use—it depends on the number of customers per day and the average time spent to fuel or charge a vehicle. Figure 5.4 shows projected changes in the *profitability* and *utilization* of gasoline fueling stations and public charging stations over the simulation period.

It is important to note that the total number of fueling and charging stations in an area changes dynamically as the market share of the corresponding vehicle powertrain changes. This is because when the market share of a particular type of vehicle increases, the demand for corresponding infrastructure also increases, resulting in higher utilization and attracting investors to build more of that infrastructure. In this way, inter-powertrain competition cascades down to inter-infrastructure competition.

**Figure 5.4: Inter-infrastructure competition between gasoline and charging stations in the U.S.**



*Powertrain–infrastructure interaction*

The interaction between BEV sales and the proliferation of charging infrastructure provides a useful example for illustrating the powertrain–infrastructure interaction more broadly (Figure 5.5). During the initial years of the simulation, government funding provides support for new charging stations as a way to encourage people to buy BEVs, but the charging stations have low utilization (Figure 5.4). This makes it difficult to attract private investment in additional charging infrastructure absent government support. Once BEV vehicle density increases and the existing charging network reaches a modest utilization threshold, the business opportunity for expanding the charging network reaches a breakthrough. From that point forward, the attractiveness of purchasing BEVs and investing in public charging infrastructure become mutually reinforcing and we see a strong correlation between BEV sales and the number of charging stations.

Until this process of co-evolution takes hold and the industry matures, government-initiated policy incentives (for vehicles and/or infrastructure) will likely continue to be required. In the U.S., however, several government incentives are currently being phased out—a case in point is the federal credit for automobile manufacturers who have sold 200,000 EVs (Kane 2018). In this context, private-sector initiatives, especially on the infrastructure side, are needed. But private-sector investment is unsustainable without a clear economic rationale; thus, we explore some alternative strategies for developing charging infrastructure in Section 5.3.

The remainder of this section describes the policy scenarios we tested using the SD model; we also present results from a sensitivity analysis of the major factors that influence consumer adoption of alternative fuel vehicles.

### 5.2.3 Climate Policy Scenario Analysis

We ran the SD model for the U.S. under the three climate policy scenarios defined in Chapter 2 of this report: *Reference*, *Paris Forever*, and *Paris to 2°C*. As discussed in detail in Chapter 2, the *Reference* scenario embodies moderate improvements and changes in technology, but without strong policies such as carbon pricing. *Paris to 2°C*, by contrast, assumes very aggressive climate policies and substantial emissions reductions. *Paris Forever* represents a middle approach: It assumes no further policy actions beyond those already pledged under the Paris Agreement. For purposes of the SD model, the only difference between the scenarios is in the retail fuel prices for gasoline and electricity that result under more or less stringent

**Figure 5.5: Co-evolution of BEV sales and public charging infrastructure expansion in the U.S.**

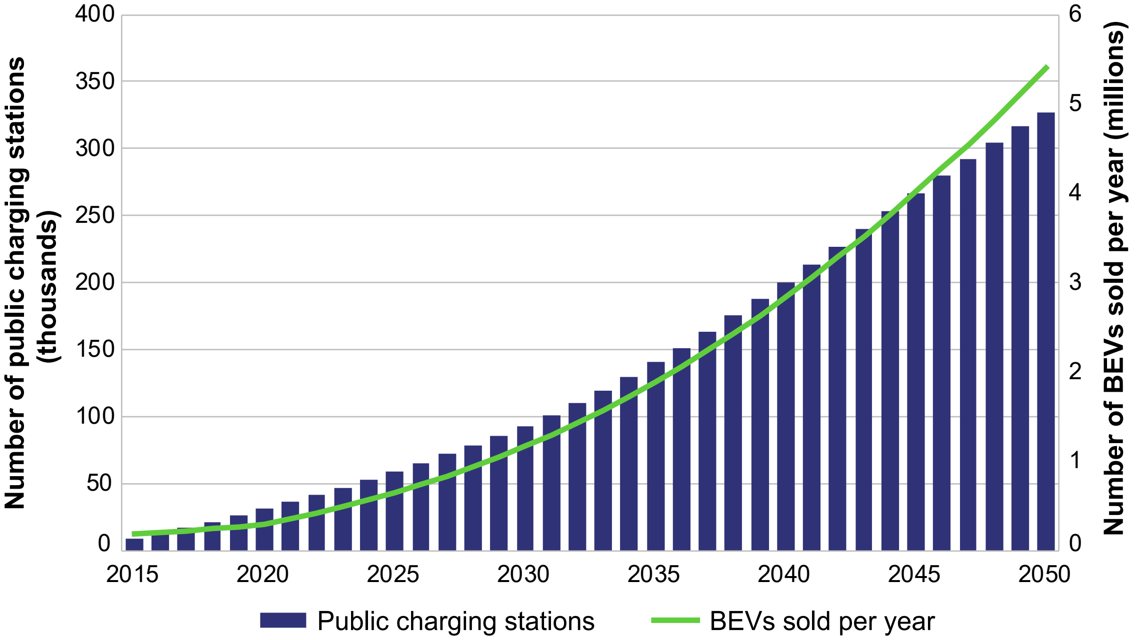


**Table 5.7: U.S. energy prices in 2050 under three climate policy scenarios**

| **Retail price** | ***Reference*** | ***Paris Forever*** | ***Paris to 2°C*** |
|---|---|---|---|
| Electricity (cents/kWh)[a] | 13.80 | 15.80 | 19.10 |
| Gasoline ($/gallon)[a] | 3.00 | 3.60 | 4.50 |
| Hydrogen ($/kg)[b] | 7.00 | 7.00 | 7.00 |

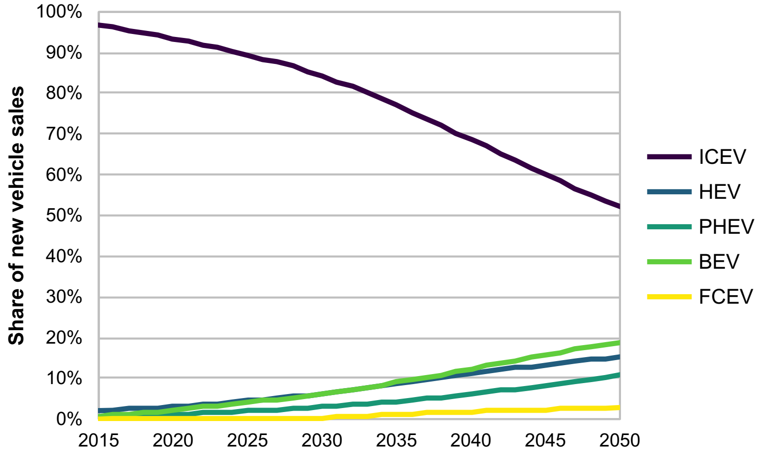
Note: [a] EPPA model (see Chapter 2); [b] based on an estimated long-term retail hydrogen price of $5–$8 per kg (Ogden 2018). The hydrogen price in the SD model decreases most rapidly in the initial years and reaches $7/kg in less than 20 years for all scenarios.

climate policies. These prices are given in Table 5.7. The same hydrogen prices are used in all the scenarios because there is a great deal of uncertainty about the future carbon intensity of different hydrogen production pathways (IEA 2015). This makes it difficult to forecast how retail hydrogen prices would be affected by the different levels of carbon prices that apply in each of the scenarios. The price trajectory for hydrogen depends on the rate of adoption of FCEV vehicles and corresponding shifts in demand for hydrogen fuel under a given scenario.

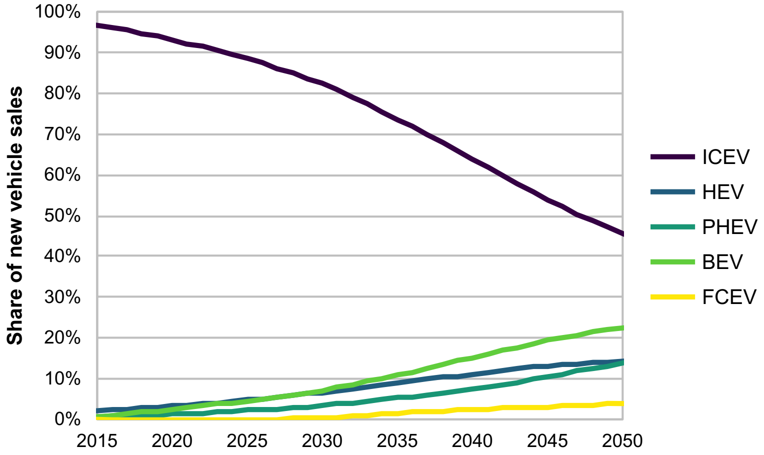
Projected market shares for new vehicle sales from our *Reference* scenario are shown in Figure 5.6(a). For the duration of the modeling period, gasoline ICEVs comprise the majority of new vehicle sales but their share declines as other powertrains become more attractive and consumers become more aware of alternatives. BEVs account for the second largest market share, growing from 6% of vehicle sales in 2030 to 19% by 2050—a reflection of their lower operating costs relative to traditional ICEVs and a projected steep decline in battery prices over the next decade. PHEVs and HEVs follow similar growth patterns, comprising approximately 3% and 6% of sales respectively by 2030, according to our modeling results. A less developed fueling network, high fuel prices, and low consumer awareness relative to other powertrain options restricts the FCEV market share to a modest 0.5% of sales by 2030 and 2.5% of sales by 2050.

**Figure 5.6: Share of U.S. new vehicle sales for different powertrains under different climate policy scenarios**

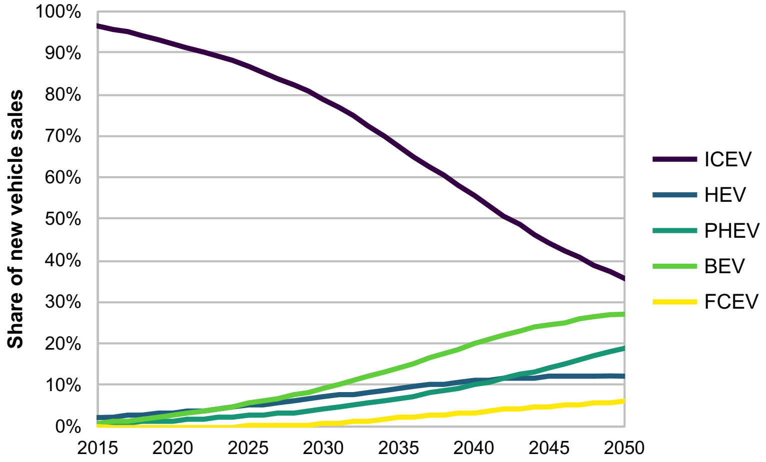
**(a)** ***Reference***



**(b)** ***Paris Forever***



**(c)** ***Paris to 2°C***



SD modeling results for the U.S. under the *Paris to 2°C* scenario are shown in Figure 5.6(c). Relative to the *Reference* scenario, the market share of ICEVs falls more rapidly as the price of gasoline increases over time. Sales of different types of EVs are boosted by their lower relative cost of ownership, with BEVs approaching ICEVs in total market share by mid-century. As a percentage of new vehicle sales, ICEVs account for 36% of the market and BEVs for 27% by the end of the simulation. In this scenario, the rising price of gasoline makes PHEVs more attractive and they surpass HEVs in market share before 2045 (by 2050, PHEVs have 19% market share compared to 12% for HEVs). FCEVs enter the market in greater numbers under these conditions and exceed 6% of new vehicle sales by 2050.

### 5.2.4 Critical Sensitivities

For reasons discussed in previous sections, the future adoption of PHEVs and BEVs (together categorized as “EVs” in this report) will depend on a number of factors. At present, lack of public charging infrastructure and higher vehicle prices are the two greatest barriers to EV adoption (Singer 2017). The need for home charging capability is another important factor. We used the SD model to conduct a set of sensitivity analyses to assess the impact of these three factors on EV adoption.

Two additional factors have received growing attention in the literature and we briefly summarize their potential impacts on EV adoption (without explicit model results). First, we discuss the potential role of workplace charging as a substitute for home charging where home charging capability is limited. Second, we consider range anxiety, or consumers’ aversion to the perceived risk of running out of fuel or electric charge while on the road. While shown to be a critical factor when considering the uptake of early EV models with very limited range, range anxiety may play a lesser role in future purchase decisions as longer-range vehicles become standard and consumers gain experience and familiarity with BEVs (Franke and Krems 2013).

#### *Sensitivity to charging infrastructure*

We find that charging speed and proximity of charging stations to other common destinations have more influence on EV adoption than the total number of public charging stations.

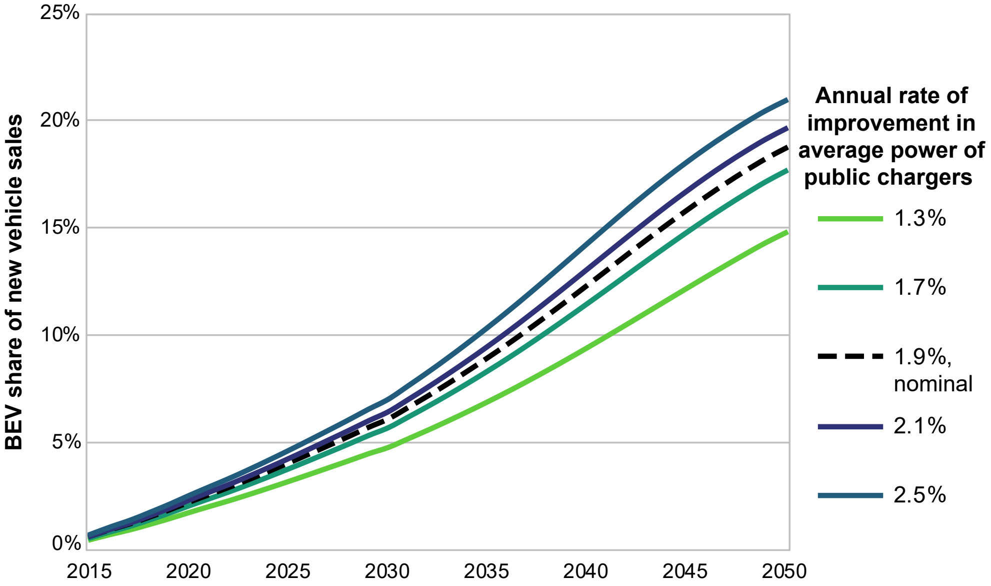
Charging stations could be located as “destination” chargers and placed in parking lots for use while the vehicle owner engages in activities such as shopping, dining, or watching a movie. Careful placement of such destination chargers could reduce the time cost to EV owners who would otherwise need to wait until their vehicles are sufficiently charged to complete their trip.

On the other hand, findings from Idaho National Laboratory suggest that the optimal placement for fast chargers is within a half-mile of high-traffic corridors (Francfort, et al. 2017). Strategic placement is an important factor in determining the profitability of electric vehicle charging infrastructure. Optimal placement of charging infrastructure is also highly sensitive to the charger’s speed and drivers’ travel patterns.

As Level 3 fast chargers become more abundant, the average charging rate at public charging stations will likely increase. We assume a nominal rate of improvement in the average power of public chargers of 1.9% per year, but we also test how different rates of annual improvement in the average charging rate at public charging stations might affect the market share of new BEVs (Figure 5.7). At higher charging speeds, our modeling predicts an increase in BEV sales paired with a slight decrease in PHEV sales. The sensitivity analysis tells us that although faster charging makes all EVs more attractive, it does more to boost BEV adoption because their larger battery capacity makes faster charging more beneficial.

The current prevalence of home charging—which is estimated to supply more than 80% of EV charging in the U.S. today (U.S. DOE, EERE 2019)—reduces the need for daily charging at public locations (Wood, et al. 2017). However, new public charging stations are still needed to provide

**Figure 5.7: Share of BEVs in the U.S. assuming different rates of improvement in the average charging power available at public charging stations under our *Reference* scenario**



visible evidence of charging availability and build confidence among consumers who may be considering whether to purchase an EV (Morrissey, Weldon, and O'Mahony 2016). At the same time, it may be difficult for public charging stations to be profitable in the early stages of EV deployment, given EV owners' reliance on home charging, low profit margins in the sale of electricity, and infrastructure installation and maintenance costs.

### *Sensitivity to vehicle price*

Vehicle cost dynamics are built into the SD model. For example, as alternative fuel vehicles are purchased in greater numbers in the SD simulation, their production costs decline as a function of learning and economies of scale. Price reductions for EVs are driven by an expected rapid decline in lithium-ion battery prices from approximately $290/kWh in 2018 to $124/kWh in 2030, as discussed in Section 4.3. FCEV prices are likewise expected to decline based on our assumptions about similarly rapid developments in hydrogen storage and fuel cell technology. We also assume that government incentives begin at the values shown in Table 5.5 and then ramp down to zero from 2020 to 2030.

Price is an extremely important factor in terms of making alternative powertrains competitive with ICEVs beyond the small number of consumers who constitute the "early adopter" market. For instance, if vehicle subsidies are held constant from 2020 to 2030, as we assumed in our sensitivity analysis, annual sales of the affected powertrains increase significantly. While the market share for BEVs is approximately 8% higher when the subsidy is held constant, the difference for the FCEV market is small at 1% to 2%. Simulated market shares in 2050 under different policy assumptions and government incentives are displayed in Table 5.8.

### *Sensitivity to the availability of home charging*

Access to home charging represents a unique advantage for EVs among the array of other alternative vehicle technologies that require large-scale buildout of new fuel infrastructure and distribution networks. However, estimates of the number of U.S. households that have access to dedicated parking with a power supply for reliable daily home charging vary widely. In our nominal case, we assume 70% of U.S. households have the ability to charge at home, but others have argued that the actual number may be as low as 40% (Traut, et al. 2013). We therefore ran a

**Table 5.8: Impact of government subsidies on 2050 U.S. market share by powertrain and scenario**

| Policy scenario | Government subsidies | New vehicle market share (%) | | | | |
|---|---|---|---|---|---|---|
| | | ICEV | HEV | PHEV | BEV | FCEV |
| ***Reference*** | Incentives decline 2020-2030 | 52 | 15 | 11 | 19 | 3 |
| | Incentives stay constant | 46 | 13 | 12 | 26 | 4 |
| ***Paris Forever*** | Incentives decline 2020-2030 | 46 | 14 | 14 | 22 | 4 |
| | Incentives stay constant | 39 | 11 | 15 | 30 | 5 |
| ***Paris to 2°C*** | Incentives decline 2020-2030 | 36 | 12 | 19 | 27 | 6 |
| | Incentives stay constant | 30 | 9 | 19 | 34 | 8 |

sensitivity analysis to assess how changes in home charging availability might affect the need for public charging infrastructure. In our simulations, we assume that the cost to the consumer at public charging stations is, on average, twice as high as the cost of charging at home. Figure 5.8 shows the results of this analysis in terms of BEV market share as a percent of new vehicle sales and the buildout of public charging stations to 2050.

Lower availability of home charging increases the demand for public charging infrastructure. Public charging network providers construct additional stations to meet this demand and maintain the 20% utilization rate per public charging plug that we assume in the SD model. At the same time, the market share of BEVs declines because lack of access to home charging means reduced convenience and increased fueling costs for vehicle owners. In the *Reference* scenario, the market share of BEVs in the U.S. decreases from 19% to 13% of new vehicle sales in 2050 as the percent of households with the ability to charge at home decreases from 70% (our nominal value) to 35% (Figure 5.8).

Home charging is not as critical for PHEVs which can operate on gasoline as needed; nonetheless, home charging, if available, may lower operating costs for these vehicles by reducing their reliance on gasoline for daily trips (Morrow, Darner, and Francfort 2008).

### *Workplace charging*

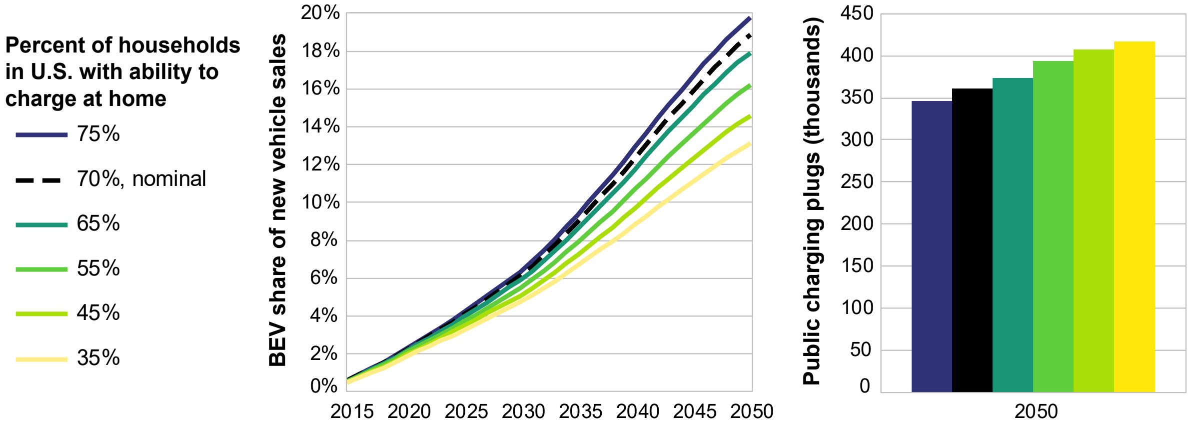
Workplace charging could serve as a substitute for those EV owners who do not have access to home charging. Like the home, the workplace is a regular destination where people frequently stay long enough to replenish their EV battery. Given that reliable access to a daily charging source is critical for BEV adoption, the expansion of workplace charging could help increase the market for BEVs among drivers without access to home charging.

Additionally, it may be in an employer's interest to provide EV charging, both as an indication of corporate environmental responsibility and as a workplace benefit for attracting and retaining employees (National Research Council 2015). For employers this could be as cheap and relatively simple as assigning dedicated parking spaces within cord-reach of a regular electrical outlet (Smith 2016). Alternatively, it could involve installing Level 2 charging stations, but this option is limited by the current power distribution system since each additional charger may draw around 7 kW of power.

### *Driving range*

A commonly cited barrier to BEV adoption is these vehicles' limited range given the potential unavailability of public charging stations and long charging times (Singer 2017). The average daily driving distance per vehicle in the U.S. for single-vehicle households is estimated to be 30 miles; the average driver's commute distance is approximately 12 miles (McGuckin and Fucci 2018). Current BEVs have enough range to cover these distances but occasional trips can exceed the single-charge range and there are additional considerations that a discussion of average driving distances doesn't capture.

**Figure 5.8: Sensitivity of BEV market share and number of public charging stations to assumptions about the availability of home charging in the U.S.**



First, the actual driving range available for a given battery capacity can be greatly reduced when the vehicle is operating under sub-optimal conditions, including in hilly terrain or in temperature extremes that reduce the efficiency of the battery and its thermal management system. The use of auxiliary systems such as heating/air conditioning, and driving behaviors such as rapid acceleration or braking, also affect range. Weather variations alone can impact range by as much as 30% (Yi and Shirk 2018).

Another concern is the trade-off between increasing battery size and vehicle price. Although it is generally attractive from the consumer's perspective to own a longer-range vehicle, especially if the consumer is concerned about covering 100% of their daily driving needs, larger batteries are expensive and high vehicle prices are a more significant barrier to BEV adoption than range (Adepetu and Keshav 2017). Higher capacity batteries also add weight, which reduces vehicle efficiency and diminishes returns in incremental driving range, especially in hilly areas.

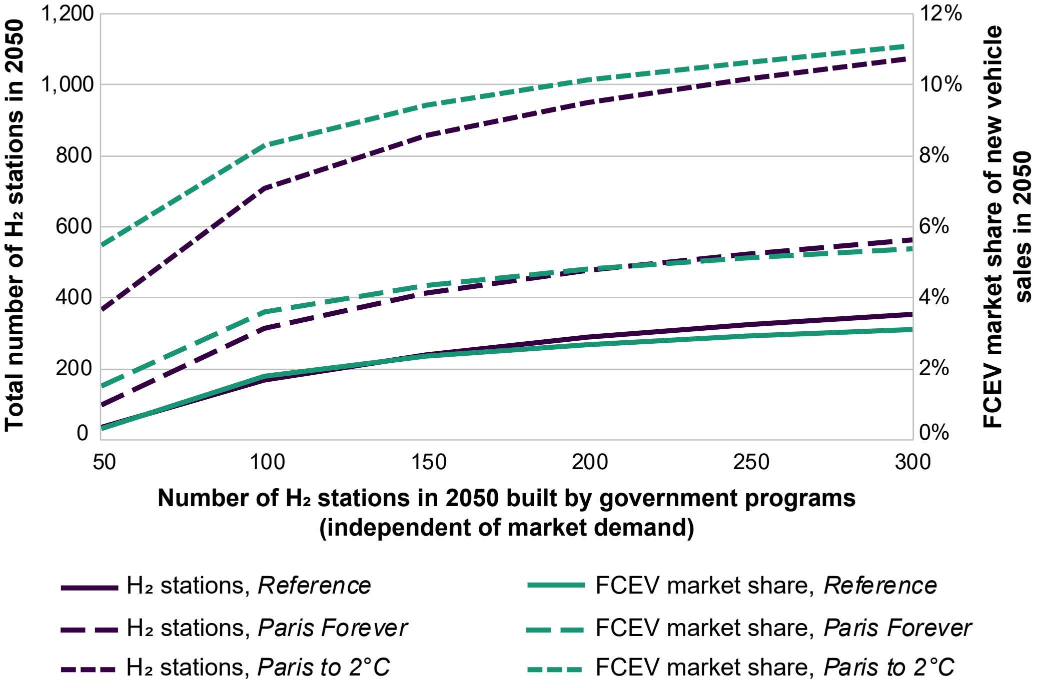
### 5.2.5 Hydrogen Fuel Cell Electric Vehicle Analysis

In all three of our basic modeling scenarios, FCEVs struggle to enter the market due to limited availability of fueling stations, high capital costs for fueling infrastructure, and high cost of vehicle ownership.

In contrast to EVs, access to public fueling infrastructure is necessary for FCEVs. The high investment required to create a usable network of stations is a large barrier to adoption; currently, only a limited number of providers are pursuing these investments, mostly in the form of public–private partnerships (Ogden 2018). Due to infrastructure limitations, it is likely that early FCEV adoption for personal vehicles will be driven by the concentration and expansion of stations around centralized nodes as has been occurring in the Los Angeles metropolitan area (see case study below). This is one of the only regions where FCEVs are currently being sold in the U.S. There are plans to build hydrogen fueling stations in cities on the east coast of the U.S., so adoption could continue to expand from these hubs.

The price of hydrogen fuel in the U.S. is currently estimated at $15.50 per kilogram (Yi and Shirk 2018). Although FCEVs are more efficient than ICEVs, they are still significantly more expensive to operate per mile of travel in the U.S. based on current retail hydrogen prices. This has led early FCEV manufacturers to cover the first three years of fuel expenses for early adopters. Continued uncertainty about future hydrogen prices and availability of fueling stations will likely inhibit initial sales of FCEVs, although substantial cost reductions are expected in the future.

**Figure 5.9: Government hydrogen station construction impacts on FCEV sales and overall station buildout in Los Angeles model for 2050**



## *Case study: Los Angeles*

To simulate hydrogen infrastructure buildout and adoption from a concentrated node, we parameterized the SD model to reflect the market size, incentives, infrastructure buildout, and travel behavior that characterize the Los Angeles metropolitan area.

Many of the hydrogen fueling stations constructed in California so far have been assisted by government funding. Figure 5.9 shows our model projections when we varied the level of government investment in hydrogen stations in Los Angeles, as measured by the number of stations constructed annually through government programs. In this case study, stations are assumed to be built over a period of ten years from 2018 until 2027. Additional stations beyond those introduced in the program are built to meet increased fueling demand as the number of FCEVs in the fleet grows out to 2050. The addition of new stations has the largest impact in the early years of FCEV deployment, when there are very few stations available and when marginal increases in station availability can make larger differences. In the long run, we see that near-term government support for building hydrogen stations has a substantial impact on projected FCEV market penetration in 2050. In the absence of a strong climate policy, however, this support produces diminishing returns in eventual station buildout and vehicle adoption as the number of government-built stations in the Los Angeles region exceeds 150. For reference, about 3,000 of the approximately 10,000 total gasoline stations in California are located in the Los Angeles region, which consists of Los Angeles, Orange, and Ventura counties (California Energy Commission 2019). These results indicate that substantial ongoing government investment in hydrogen fueling infrastructure, combined with climate policies that have the effect of driving up retail prices for gasoline, may be critical to significantly expand FCEV market share. Absent strong climate policies, on the other hand, programs to build out hydrogen fueling infrastructure will have a limited impact.

## *Next steps for FCEVs*

FCEVs are a promising vehicle technology that may eventually play an important role in achieving emission reductions. The most significant advantage of this technology over BEVs is rapid fueling speed, which is similar to the five-minute timeframe ICEV owners are used to. However, the future of FCEV technology is highly dependent on government support and private investment to develop hydrogen production pathways, build fueling stations, and promote public awareness. Our modeling results suggest that without extensive government support, U.S. sales of passenger light-duty FCEVs are unlikely to grow significantly within the 2050 timeframe.

The development of hydrogen uses for other sectors, however, could greatly assist FCEV proliferation. For example, hydrogen has potential as a clean solution for long-haul, heavy-duty vehicles, which are more challenging to electrify. Investment in other applications for hydrogen, such as for energy storage, industrial uses, heating, or fuel for freight and fleet vehicles, could have spill-over effects that benefit the commercialization of hydrogen-fueled passenger vehicles (de Valladares 2017). Also, the emergence of more efficient and cost-effective local hydrogen production methods, such as electrolysis using low-emission electricity sources, could alleviate distribution barriers for fueling locations located far from centralized hydrogen production facilities. These potential hydrogen-enhancing developments are not considered directly in the SD model but could result in more rapid growth of FCEV market share than projected in our scenarios.

## 5.3 CHARGING MODELS FOR BEV FLEETS

While the discussion in previous sections has focused on infrastructure needs for personal, light-duty alternative fuel vehicles, this section considers infrastructure implications for commercial fleets of alternative fuel vehicles. We take as our case study the Beijing taxi market. As part of a drive to cut air pollution, the Beijing municipal government has announced plans to replace all 67,000 ICEV taxis in the city with battery electric models (Hanley 2017). This change will take place under a mandate that all newly added or replaced taxis in the city must be BEVs. While Beijing and other cities are taking steps to support BEV deployment, the technology still faces challenges due to long battery charging times and limited charging infrastructure. Long charging times are particularly problematic for taxi and on-demand fleet owners because charging time is time that vehicles and drivers are not generating revenue. Combined with higher purchase costs for BEVs, it is not surprising that most fleet operators prefer internal combustion vehicles over electric ones.

### 5.3.1 Business Models

We conducted a techno-economic analysis in the context of Beijing's taxi industry, examining the economic competitiveness of alternative BEV charging techniques against the existing ICEV fueling system. Beijing taxi companies operate some vehicles in two 12-hour shifts and other vehicles in one 12-hour shift. The analysis presented here focuses on double-shift taxis since these vehicles have the highest utilization rate in the taxi fleet. A full analysis of single- and double-shift taxis is presented in Hsieh, et al. (2019a).

#### *BEV fleet with conventional Level 2 charging*

In this scenario, the BEV taxi fleet relies on a network of Level 2 chargers, which have an assumed average charging rate of 7 kW and provide about 44 kilometers (km) of driving range per hour of charging. Unless otherwise stated, the assumption for this and other business models is that the driver remains with the taxi while it charges.

#### *BEV fleet with Level 2 charging with extra vehicles*

In this scenario, the BEV fleet also relies on Level 2 chargers, but idle time is avoided by providing standby taxis so that drivers can switch to a fully charged vehicle when their current vehicle is almost out of charge. This is important for double-shift operations because it ensures that all drivers have a taxi available to continue generating revenue. A double-shift of taxi drivers will operate an average of 570 km per day if not encumbered by charging idle time. The time needed to charge for 570 km is 13.2 hours. In this business model, the taxi company purchases extra vehicles, and always has a rotation of vehicles being charged, to avoid the opportunity costs associated with Level 2 charging times. In this business model, 1.55 taxis are required to cover vehicle needs for each double-shift (0.55 = 13.2 hours per 24 hours).

#### *BEV fleet with conventional fast charging*

In this scenario, the taxi fleet uses a network of fast chargers. The fast chargers are assumed to charge a BEV from 20% to 80% of battery capacity in 22.5 minutes; another 30 minutes is required to charge from 80% to 100%.

#### *BEV fleet with fast charging with extra vehicles*

Similar to the scenario for Level 2 charging with extra vehicles, the fleet in this scenario avoids idle time by having a sufficient (but smaller) number of charged and available vehicles standing by. The cumulative time needed to charge with a fast charger to deliver 570 km of driving range is about 2.4 hours, so each double-shift requires 0.10 extra vehicles (equal to 2.4 hours per 24 hours).

#### *BEV fleet with battery swapping*

This scenario assumes that depleted batteries can be replaced with fully charged batteries at swapping stations in a matter of a few minutes. The battery charging rate and the quantity of batteries in stock determine the average time required to provide a fully charged battery. Battery swapping stations are assumed to have 28 swappable batteries in stock and host 28 chargers, each with a one-third charge rate (meaning that they require three hours for a full charge); further we assume that batteries are swapped out when they have 20% of charge remaining. Based on these assumptions, a fully charged battery can be provided every 5.14 minutes (Table 5.9).

#### *ICEV fleet*

This scenario represents the business-as-usual case: It envisions a conventional operation in which the taxi fleet is made up of ICEVs that can be fueled in a matter of minutes at a conventional gas station.

### 5.3.2 Cost Components

Our cost analysis considers taxi operations and charging systems as a combined ecosystem; we do not consider a scenario in which charging resources are shared with other non-fleet customers.

1. *Vehicle procurement cost* is the upfront cost to purchase a base car (BEV without battery). The cost of the vehicle battery is captured in other cost categories, distinct from the cost of the vehicle, as discussed below.

2. *Battery cost* is determined by battery characteristics including cycle life, degradation rate, and design. Fast charging is assumed to degrade battery life at a 25% higher rate than Level 2 charging, and thus decreases the cycle life. For the business case that assumes fueling via battery swapping, we assume battery lifetime is the same as for Level 2 charging based on the idea that swappable batteries would be charged under optimal conditions (i.e., constant humidity and constant temperature) so as to maximize their useful life (Aulton New Energy 2019). Swappable batteries were estimated to be approximately $95/kWh more expensive than standard, non-swappable batteries in 2016 because of their lower production volumes (Zhou 2016; Hsieh, et al. 2019b). The battery cost category accounts for battery usage for delivering kilometers; in this context, batteries are treated as consumables. The batteries that are kept in extra vehicles or in a swapping station are instead represented as capital investments; their costs are captured in the extra battery cost category.

3. *Extra battery cost* is the capital investment for the batteries in extra vehicles and for the battery inventory in swapping stations.

4. *Electricity cost* is calculated using the current price of electricity for commercial customers during the shoulder peak time period in Beijing. For simplicity, charging efficiency is assumed to be the same across different BEV charging options.

**Table 5.9: Assumptions governing cost calculations for BEV fleet charging**

| | Parameter | Assumed value |
|---|---|---|
| **BEV model (BAIC BJEV EU260)** | MSRP ($)[a] | 32,600 |
| | Fuel economy (MPGe)[a] | 132 |
| | Battery capacity (kWh)[a] | 41.4 |
| | Driving range per full charge (km)[a] | 260 |
| **ICEV model (BAIC Senova D50)** | MSRP ($)[a] | 15,340 |
| | Fuel economy (on-road) (MPG)[a] | 31.4 |
| | Driving range per full fuel (km)[a] | 670 |
| | Retail gasoline price ($/liter)[b] | 1.14 |
| **Taxis in Beijing** | Daily distance driven by double shift taxi (km)[bb] | 570 |
| | Distance driven per active hour of taxi time (km/hour)[bb] | 23.8 |
| | Vehicle lifespan (years)[e] | 6 |
| | Annual productivity (days) | 350 |
| | Operating revenue ($/hour)[c] | 8.2 |
| | Labor cost ($/hour)[c] | 5.1 |
| **Charging vehicle attributes** | Changes in state of charge (%) | 20–100 |
| | Range per charge (km) | 208 |
| **Charging system attributes** | Level 2 charging rate (kW)[f] | 7 |
| | Fast charging rate (kW)[f] | 45 |
| | Swap station battery inventory (#)[g] | 28 |
| | Swap station battery charging rate (kW) | 14 |
| | Charging time with Level 2 (hours for 208 km range)[h] | 4.8 |
| | Charging time with fast charge (hours for 208 km range)[h] | 0.875 |
| | Charging time with swapping (minutes for 208 km range)[h] | 5.14 |
| | EV charging land use ($m^2$)[i] | 25–40 |
| | Swap station land use ($m^2$)[g] | 150–200 |
| | Level 2 charging system cost ($/plug)[i] | 820–1,300 |
| | Fast charging system cost ($/plug)[i] | 16,300–24,200 |
| | Swap station cost ($/station)[g] | 997,400 |
| | Battery inventory cost ($/station)[g] | 443,970 |
| | Charging system lifespan (years) | 8 |
| | Annual unit land use cost ($/$m^2$/year)[f] | 88 |
| | Electricity cost ($/kWh)[k] | 0.135 |
| **Battery parameters** | Non-swappable battery cost ($/kWh)[aa,d] | 288 |
| | Swappable battery cost ($/kWh)[aa,g] | 383 |
| | Level 2 battery cycle life (# cycles) | 1,155 |
| | Fast charge battery cycle life (# cycles) | 865 |
| | Swappable battery cycle life (# cycles) | 1,155 |

Note: [a] Based on a vehicle model search on Autohome.com conducted on February 28, 2018; [b] chemcp.com (2018); [c] Beijing Municipal Commission of Development and Reform (2013); [d] Hsieh, et al. (2019b); [e] Beijing Ministry of Transport (2015); [f] Ming and Wang (2016); [g] Qian and Lu (2017); [h] estimated in Hsieh, et al. (2019a); [i] Xinhua News Agency (2017) and Ming and Wang (2016); [j] Yang and Lu (2017); [k] Beijing Municipal Commission of Development and Reform (2018); values without an indicated source are based on professional judgment. [aa] = for car model year 2017; [bb] from the fact that 60% of Beijing taxis run single shift and the rest, 40%, work double shifts (Lee 2013), we infer that the average taxi operates 16.8 hours per day. Assuming a taxi travels 400 km daily (Lee 2013), the distance driven per active hour of taxi time is estimated to be 23.8 km/hr (=400 km/16.8 hr). This suggests that the daily distance driven is about 285 km for single-shift taxis and 570 km for double-shift taxis.

5. *Charging system cost* includes equipment procurement and associated installation expenses. The cost of a fast charger is about 20 times the cost of a Level 2 charger (Ming and Wang 2016). The cost of a battery swapping station does not include the significant expense of procuring batteries to maintain a battery inventory (as previously noted, we assume an inventory of 28 swappable batteries per station in this study) (Zhou 2016); this cost is considered in the "extra battery cost" category.

6. *Land cost* represents the expenditures associated with using land for charging operations. For BEV charging alternatives (i.e., Level 2 and fast charging), the land-to-vehicle ratio is similar to that of a parking garage. Battery swapping stations require more space to accommodate a building with an inventory of 28 swappable batteries and 28 chargers. However, since each vehicle spends only a few minutes at the swapping station, the land requirement per vehicle in the fleet is much less than the other charging options. The ratio of land required per vehicle supported is about half as much for a swapping station compared to a fast charger and only one-tenth as much as the land needed to support a fleet using Level 2 chargers.

7. *Maintenance cost* is the cost associated with maintaining battery charging/swapping infrastructure. This cost is assumed to be 10% of charging system cost, excluding battery inventory expenditures for the swapping station approach.

8. *Labor cost* captures drivers' earnings, which are about 62% of the total operating revenue of a taxi (Lee 2013).

9. *Opportunity cost* is the total revenue lost by a taxi operator owing to time spent to fuel or charge the vehicle. The model does not attempt to address variations in consumer demand for taxi services based on time of day or day of the week.

10. *Gasoline cost* is calculated using the current retail price of gasoline in Beijing; this represents the business-as-usual cost to fuel ICEVs.

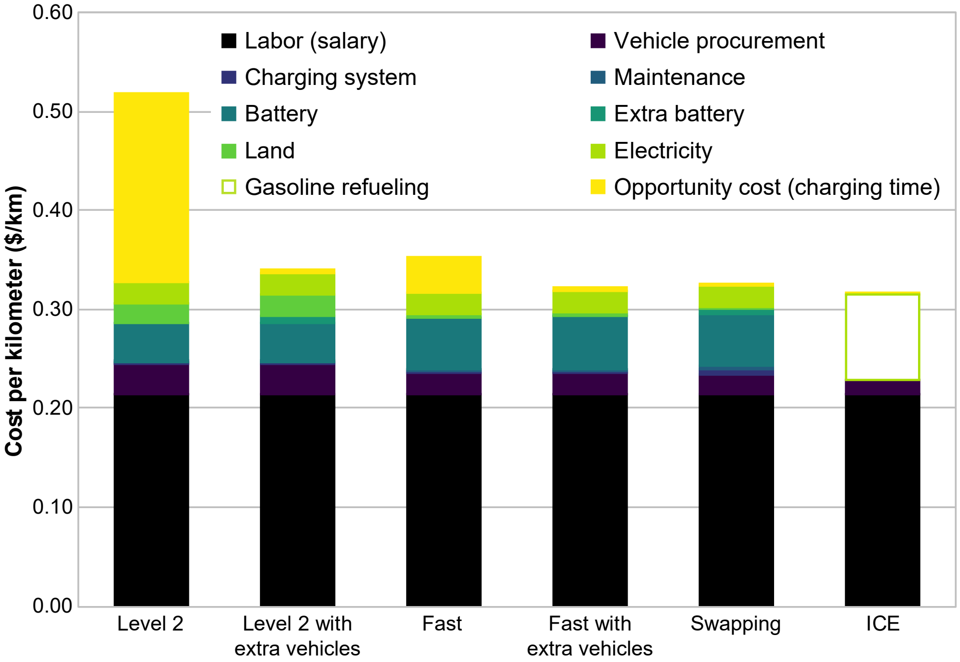
### 5.3.3 Assumptions

Table 5.9 lists the key parameters that govern our cost analysis of BEV charging models in the context of a commercial taxi fleet. The values used for most of these parameters are based on real-world data from Beijing (complete data sources can be found in Hsieh, et al [2019a]). BAIC BJEV EU260 was chosen as the representative BEV because the manufacturer can deliver this model with the capability to use either battery swapping or battery charging. Uncertainties with respect to certain charging system attributes (i.e., land use and system cost) are assumed to be uniformly distributed over the range. For this analysis, we ran 1,000 Monte Carlo simulation runs for each of the five business cases. The resulting mean values are plotted in Figure 5.10.

### 5.3.4 Results and Discussion

To compare cost-effectiveness across business models, we report each cost component on a per-kilometer basis by applying conversion factors. Conversion factors vary depending on the cost category and the achievable throughput of the charging systems. Detailed calculations can be found in Hsieh, et al. (2019a). To combine upfront investments and operating costs into a single number, we distributed all costs over all kilometers by using a 5% discount rate to determine costs per kilometer. Figure 5.10 presents our results, comparing cost structures for taxis with double 12-hour shifts—on a per-kilometer basis—for different approaches to BEV charging relative to a conventional fueling setup for a fleet of gasoline taxis. The figure reveals that the two most cost-effective options for double-shift BEV taxi operations in Beijing are battery swapping and fast charging with extra vehicles, although both of these options incur a larger upfront cost for extra batteries or extra vehicles.

**Figure 5.10: Cost breakdown per kilometer under different charging scenarios for double-shift taxis in the context of Beijing's taxi industry**



Several additional observations are worth highlighting. First, when it comes to the different components of per-kilometer costs, we find that:

- Per-kilometer battery cost for the fast charging business case is higher than both Level 2 charging scenarios owing to the higher degradation rate and thus shorter battery cycle life that comes with fast charging. But per-kilometer battery costs are comparable between the fast charging and battery swapping systems even though the swapping approach allows for longer battery cycle life. This is because swappable batteries are more expensive per kWh than non-swappable ones.
- Electricity costs on a per-kilometer basis are the same across all alternatives, reflecting our assumption that electricity costs and charging efficiency are homogeneous across all charging modes. In reality, however, electricity costs for fast charging may be higher than for Level 2 charging due to lower charging efficiencies (higher losses) (Chlebis, et al. 2014) and due to the potential for higher demand charges in the electricity price.
- Labor cost is the most significant cost contributor, accounting for up to 68% of total per-kilometer costs in China's taxi business. However, these costs are constant across different business models, so they do not impact the relative costs of different charging scenarios.
- Opportunity costs associated with charging times are non-negligible when the taxis are relying upon conventional BEV charging (without extra vehicles). Opportunity costs are highest for the scenario with conventional Level 2 charging because this scenario creates much longer idle times for drivers during BEV charging.

Second, when we add up all the different cost components to compare total cost per kilometer across different business models (Figure 5.10), we find that:

- The scenario that relies on extra vehicles with Level 2 charging imposes higher upfront capital costs to purchase the extra vehicles than the conventional approach (i.e., Level 2 charging with no extra vehicles). Nonetheless, this model dramatically improves cost-effectiveness by mitigating the opportunity cost of having drivers idle during vehicle charging. As a result, it becomes more cost-attractive than fast charging.

- The attractiveness of battery swapping from a cost perspective is because a swapping station can serve 10 times as many BEVs as a fast charger and 56 times as many BEVs as a Level 2 charger. The higher cost of a swapping system is largely balanced by cost savings from improved battery life relative to the fast charging case.
- The cost gap between a BEV taxi fleet and a conventional ICEV fleet depends on the charging ecosystem; this gap will shrink as battery costs drop in the future. Lower battery costs will mean that a BEV taxi fleet that is charged either through battery swapping (for double-shift taxis) or using fast chargers (conventional fast charger for single-shift taxis and fast charger with extra vehicles for double-shift taxis) becomes cost-competitive with Beijing's existing ICEV taxi fleet in 2022 (see Hsieh, et al. [2019a] for more details).

Chinese automakers (such as BAIC BJEV) are testing the swappable battery idea in fleet applications—specifically, in taxi fleets—with the aim of developing a solid prototype for a closed-collaboration network before trying to expand to a more extensive network that could serve personal vehicle owners. At this moment, battery swapping does not seem suitable for privately owned vehicles due to significant concerns about cross-brand compatibility and battery ownership. However, our analysis shows that it is already economically favorable where electrification is mandated in large, dense, closed fleet systems.

## 5.4 CONCLUSION

A major challenge for any alternative vehicle fuel is the lack of fueling infrastructure for early adopters. For car-owning households that have ready access to overnight charging, BEVs have an advantage over other alternative fuel vehicles. Although about 85% of BEV charging in the U.S. currently occurs at home, consumer confidence to purchase a BEV is highly sensitive to the availability of charging infrastructure when away from home. As BEV market penetration rises well above the current level of less than 1% in the U.S., public charging will become more important, since achieving greater market penetration requires that high-mileage drivers and drivers who don't have the option of home charging see BEVs as a viable option. Increased reliance on public charging presents its own challenges, however, due to inconvenience (if charging times are long) and higher operating costs (because charging costs at public stations are likely to be higher than at home). In many U.S. locations, the retail cost of fast charging for a BEV rivals or exceeds the cost of fueling a comparable ICEV on a per-mile basis.

Unlike BEVs, FCEVs do not benefit from the option of home charging, nor do FCEVs have the ability to use two fuels as PHEVs do. FCEVs require hydrogen fueling stations, of which there are currently only 376 worldwide, including both public and private fueling stations (AFC TCP 2019). This lack of fueling infrastructure limits the uptake of FCEVs today. Only with large upfront investments in fueling infrastructure can hydrogen FCEVs thrive in the passenger vehicle market. Much as the buildout of charging infrastructure has benefited from support from governments, utility companies, and public utility commissions, building out a hydrogen fueling infrastructure will require ongoing support from governments and hydrogen suppliers. Light-duty FCEVs can, however, benefit from the development of a broader hydrogen ecosystem, which might be needed to solve other decarbonization challenges, particularly with respect to energy storage and industrial, heating, and freight transport applications. The difficulty then becomes advancing cost-effective hydrogen production and distribution pathways and resolving the tightly coupled timing of various elements of a future hydrogen economy.

In a low-carbon future, the evolution toward zero-carbon ground transportation technologies is likely to include hydrogen (for heavy- and light-duty vehicles) in long-haul and high-mileage applications that require fast fueling, while the market for short-haul and low-mileage applications is likely be captured by plug-in electric vehicles.

Continued penetration of BEVs and FCEVs in the U.S. market is sensitive to various government policies including federal and state incentives, fuel economy mandates, and private–public partnerships to support the buildout of fueling and charging infrastructure. For example, our modeling indicates that the projected BEV market share in 2050 can change by as much as eight percentage points depending on assumptions about the phase-out of federal purchase incentives. Likewise, programs to kick-start the buildout of hydrogen fueling stations in the next 10 years could help boost projected FCEV market share in the year 2050.

While the above discussion is focused on light-duty alternative fuel vehicles for personal use, the infrastructure implications for commercial vehicle fleets could be quite different. Our analysis of the Beijing taxi fleet demonstrates that, although battery swapping does not currently appear to be a viable business model for personal vehicles, this approach could be feasible in large, dense, closed systems where fleet electrification has been mandated (as in Beijing's taxi fleet). The business case for swappable battery systems depends on situations where there is high value to avoiding downtime for charging.

This chapter highlights the importance of convenient and available charging and fueling options in supporting the future penetration of alternative fuel vehicles. In turn, greater demand for these vehicles and rapid technological development will influence the business case for installing charging and fueling infrastructure. In the near term, plug-in electric vehicles have a head start in the U.S. LDV market given the potential for home charging. However, as EV market shares grow, there is likely to be increased need for workplace or other destination charging, or for fast public charging. In the long term, there is potential for FCEVs to enter the market if the costs of hydrogen fuel production, storage, and distribution systems continue to decline (likely driven by hydrogen applications in other sectors of the economy). In either case, government support for alternative fuel vehicles and for associated charging and fueling infrastructure will be critical to decarbonize the future LDV fleet.

## 5.5 REFERENCES

Adepetu, Adedamola, and Srinivasan Keshav. 2017. "The Relative Importance of Price and Driving Range on Electric Vehicle Adoption: Los Angeles Case Study." *Transportation* 44, no. 2: 353–373. https://doi.org/10.1007/s11116-015-9641-y

Advanced Fuel Cells Technology Collaboration Partnership (AFC TCP). 2019. *Survey on the Number of Fuel Cell Vehicles, Hydrogen Refueling Stations and Targets*. http://www.ieafuelcell.com/fileadmin/publications/2019-04_AFC_TCP_survey_status_FCEV_2018.pdf

Ahmed, Shabbir, Ira Bloom, Andrew N. Jansen, Tanvir Tanim, Eric J. Dufek, Ahmad Pesaran, Andrew Burnham, Richard B. Carlson, Fernando Dias, Keith Hardy, Matthew Keyser, Cory Kreuzer, Anthony Markel, Andrew Meintz, Christopher Michelbacher, Manish Mohanpurkar, Paul A. Nelson, David C. Robertson, Don Scoffield, Matthew Shirk, Thomas Stephens, Ram Vijayagopal, and Jiucai Zhang. 2017. "Enabling Fast Charging – A Battery Technology Gap Assessment." *Journal of Power Sources* 367, no. 1 (Nov): 250–262. https://doi.org/10.1016/j.jpowsour.2017.06.055

Alternative Fuels Data Center. 2019a. “E85 (Flex Fuel).” U.S. Department of Energy, Vehicle Technologies Office. Accessed August 20, 2019. https://afdc.energy.gov/fuels/ethanol_e85.html

———. 2019b. “Public Retail Gasoline Stations by State and Year.” U.S. Department of Energy, Vehicle Technologies Office. Accessed August 20, 2019. https://afdc.energy.gov/files/u/data/data_source/10333/10333_gasoline_stations_year.xlsx

———. 2019c. “Alternative Fueling Station Counts by State.” U.S. Department of Energy, Vehicle Technologies Office. Accessed August 13, 2019. https://afdc.energy.gov/stations/states

———. 2018a. “Alternative Fueling Station Locator.” U.S. Department of Energy, Vehicle Technologies Office. Accessed January 15, 2018. https://afdc.energy.gov/stations/#/analyze

———. 2018b. “Developing Infrastructure to Charge Plug-In Electric Vehicles.” U.S. Department of Energy, Vehicle Technologies Office. https://afdc.energy.gov/fuels/electricity_infrastructure.html#level1

Aulton New Energy. 2019. “Aulton New Energy.” Accessed February 28, 2019. http://www.aulton.com/aulton.html

Beijing Ministry of Transport (交通运输部). 2015. “北京：出租车报废年限从8年降至6年 [Beijing: Taxi Retirement Age Has Dropped from 8 Years to 6 Years].” *ChinaHighway.com*, April 13. Accessed February 27, 2018. http://www.chinahighway.com/news/2015/921727.php

Beijing Municipal Commission of Development and Reform (北京市发展和改革委员会). 2018. 关于合理调整电价结构有关事项的通知 [*Beijing’s Multi-Step Electricity Price Standard*].

———. 2013. 北京市出租汽车租价调整和完善燃油附加费动态调整机制方案 [*Taxi Fare Adjustment and Improvement of Dynamic Adjustment Mechanism of Fuel Surcharge in Beijing*]. https://max.book118.com/html/2017/0822/129393297.shtm

baijiahao.baidu. 2018. “中国加氢站建设进展及分布(截至2018年2月) [Progress and Distribution of China’s Hydrogen Refueling Station Construction (as of February 2018)].” http://www.sohu.com/a/226814738_233844

Bloomberg New Energy Finance (BNEF) and the Business Council for Sustainable Energy (BCSE). 2019. *Sustainable Energy in America Factbook*. London, United Kingdom: BNEF. https://www.bcse.org/factbook/

bosidata.com. 2017. “中国加油站行业发展现状及企业分布统计 [China Gas Station Industry Development Status and Enterprise Distribution Statistics].” http://www.bosidata.com/news/T12853JR50.html

Brownstone, David, David S. Bunch, and Kenneth Train. 2000. "Joint Mixed Logit Models of Stated and Revealed Preferences for Alternative-Fuel Vehicles." *Transportation Research Part B: Methodological* 34, no. 5 (June): 315–338. https://doi.org/10.1016/S0191-2615(99)00031-4

California Energy Commission. 2019. “California Retail Fuel Outlet Annual Reporting (CEC-A15) Results.” Accessed July 19, 2019. https://ww2.energy.ca.gov/almanac/transportation_data/gasoline/piira_retail_survey.html

California Fuel Cell Partnership.2019. “CAFCP Station Status.” Accessed September 3, 2019. https://m.cafcp.org/

ChargePoint. 2019. “ChargePoint Station Locator.” Accessed August 20, 2019. https://na.chargepoint.com/charge_point

chemcp.com, 2018. “Today’s Beijing Gasoline Price.” Accessed March 26, 2018. http://youjia.chemcp.com/beijing/

Chlebis, Petr, Martin Tvrdon, Ales Havel, and Katerina Baresova. 2014. "Comparison of Standard and Fast Charging Methods for Electric Vehicles." *Advances in Electrical and Electronic Engineering* 12, no. 2 (June): 111–116. https://doi.org/10.15598/aeee.v12i2.975

Cooper, John, ed. 2019. *Statistical Report 2019*. Brussels, Belgium: FuelsEurope. https://www.fuelseurope.eu/publication/statistical-report-2019/

de Valladares, Mary-Rose. 2017. *Global Trends and Outlook for Hydrogen.* Paris, France: IEA Hydrogen Technology Collaboration Program. https://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_WEB.aspx

Electric Vehicle Database. 2019. https://ev-database.org

European Alternative Fuels Observatory. 2019. "European Union Statistics: Total Number of Alternative Fuel Infrastructure." https://www.eafo.eu/countries/european-union/23640/summary

EVgo. 2019. "EVgo Charging Locations." Accessed September 3, 2019. https://www.evgo.com/charging-locations/

Francfort, Jim, Shawn Salisbury, John Smart, Thomas Gareston, and Donald Karner. 2017. *Considerations for Corridor and Community DC Fast Charging Complex System Design*. Idaho Falls, Idaho: Idaho National Laboratory. https://avt.inl.gov/sites/default/files/pdf/reports/DCFCChargingComplexSystemDesign.pdf

Franke, Thomas, and Josef F. Krems. 2013. "What Drives Range Preferences in Electric Vehicle Users?" *Transport Policy* 30 (Nov): 56–62. https://doi.org/10.1016/j.tranpol.2013.07.005

Hanley, Steve. 2017. "China Will Replace All 67,000 Fossil-Fueled Taxis in Beijing with Electric Cars." *CleanTechnica*, March 1.

Heywood, John, and Don Mackenzie, eds. 2015. *On the Road Toward 2050: Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions*. Cambridge, MA: Massachusetts Institute of Technology. http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/On-the-Road-toward-2050.pdf

Hsieh, I-Yun Lisa, Ashley Nunes, Menghsuan Sam Pan, and William H. Green. 2019a. "Recharging Options to Improve the Economics of Electrified Fleet Ecosystem: A Case Study of Battery Swapping Deployment in the Taxi Industry." [working paper].

Hsieh, I-Yun Lisa, Menghsuan Sam Pan, Yet-Ming Chiang, and William H. Green. 2019b. "Learning Only Buys You So Much: Practical Limits on Battery Price Reduction." *Applied Energy* 239, no. 1 (April): 218–224. https://doi.org/10.1016/j.apenergy.2019.01.138

International Energy Agency (IEA). 2019a. *Global EV Outlook 2019: Scaling Up the Transition to Electric Mobility*. Paris, France: IEA. https://www.iea.org/publications/reports/globalevoutlook2019/

———. 2019b. *The Future of Hydrogen: Seizing Today's Opportunities*. Paris, France: IEA. https://webstore.iea.org/the-future-of-hydrogen

———. 2018a. *Global EV Outlook 2018: Towards Cross-Modal Electrification*. Paris, France: IEA. https://doi.org/10.1787/9789264302365-en

———. 2018b. "Hydrogen: Tracking Clean Energy Progress." *IEA.org*. Last updated June 19, 2019. https://www.iea.org/tcep/energyintegration/hydrogen/

———. 2015. *Technology Roadmap: Hydrogen and Fuel Cells*. Paris, France: IEA. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf

James, Will. 2016. *An Introduction to SAE Hydrogen Fueling Standardization*. Washington, D.C.: U.S. Department of Energy, Fuel Cell Technologies Office. https://www.energy.gov/sites/prod/files/2014/09/f18/fcto_webinarslides_intro_sae_h2_fueling_standardization_091114.pdf

Kane, Mark. 2018. "November Update – 4 Automakers Closest to Losing Federal Tax Credit." *Inside EVs*, December 6. https://insideevs.com/features/337511/november-update-4-automakers-closest-to-losing-federal-tax-credit/

Keith, David Ross. 2012. *Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid-Electric Vehicles in the United States*. Ph.D. dissertation. Cambridge, MA: Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/79546

Lunetta, Mary, and Gina Coplon-Newfield. 2016. *Rev Up Electric Vehicles: Multi-State Study of the Electric Vehicle Shopping Experience*. Washington, D.C.: Sierra Club. https://www.sierraclub.org/sites/www.sierraclub.org/files/uploads-wysiwig/1371%20Rev%20Up%20EVs%20Report_09_web%20FINAL.pdf

Martin, Jeremy. 2017. *Fueling a Clean Transportation Future*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/sites/default/files/attach/2016/02/Fueling-Clean-Transportation-Future-full-report.pdf

McGuckin, Nancy, and Anthony Fucci. 2018. *Summary of Travel Trends: 2017 National Household Travel Survey*. FHWA-PL-18-019. Washington, D.C.: U.S. Federal Highway Administration. https://nhts.ornl.gov/assets/2017_nhts_summary_travel_trends.pdf

Ming, Duo (窦明) and Xi Wang (王溪) (ed). 2016. "充电桩网点6年才能收回成本 投资人称补贴落地迟缓 [It Takes 6 Years to Recoup the Costs of Building Public EV Charging Station]," *People.cn*, July 5. http://auto.people.com.cn/n1/2016/0705/c1005-28524666.html

Morrissey, Patrick, Peter Weldon, and Margaret O'Mahony. 2016. "Future Standard and Fast Charging Infrastructure Planning: An Analysis of Electric Vehicle Charging Behaviour." *Energy Policy* 89 (Feb): 257–270. https://doi.org/10.1016/j.enpol.2015.12.001

Morrow, Kevin, Donald Darner, and James Francfort. 2008. *U.S. Department of Energy Vehicle Technologies Program – Advanced Vehicle Testing Activity – Plug-in Hybrid Electric Vehicle Charging Infrastructure Review*.

Technical Report INL/EXT-08-15058. Washington, D.C.: U.S. Department of Energy. https://www.osti.gov/biblio/946853-a8SWxB/

Motoaki, Yutaka, Wenqi Yi, and Shawn Salisbury. 2018. "Empirical Analysis of Electric Vehicle Fast Charging Under Cold Temperatures." *Energy Policy* 122 (Nov): 162–168. https://doi.org/10.1016/j.enpol.2018.07.036

National Research Council. 2015. *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*. Washington, D.C.: The National Academies Press. https://doi.org/10.17226/21725

Naughton, Keith. 2017. "The Near Future of Electric Cars: Many Models, Few Buyers." *Bloomberg*, December 19. https://www.bloomberg.com/news/features/2017-12-19/the-near-future-of-electric-cars-many-models-few-buyers

NGVA Europe. 2019. "CNG and LNG Stations in Europe." Accessed August 13, 2019. https://www.ngva.eu/stations-map/

Ogden, Joan M. 2018. *Prospects for Hydrogen in the Future Energy System*. Research Report UCD-ITS-RR-18-07. Davis, CA: University of California Davis, Institute of Transportation Studies. https://itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2892

Panchal, Chirag, Sascha Stegen, and Junwei Lu. 2018. "Review of Static and Dynamic Wireless Electric Vehicle Charging System." *Engineering Science and Technology* 21, no. 5 (Oct): 922–937. https://doi.org/10.1016/j.jestch.2018.06.015

Qian, Yu (钱瑜), and Jiale Yu (鲁佳乐). 2017. "北汽新能源百亿豪赌换电模式 [BAIC BJEV Invests Billion RMB on Battery Swapping]." *BBT News*, edited by Yin Wenwu (尹文武). Accessed April 7, 2019. http://www.bbtnews.com.cn/2017/1106/216930.shtml

Robinius, Martin, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz, and Detlef Stolten. 2018. *Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles*. Julich, Germany: Forschungszentrum Jülich GmbH. https://www.researchgate.net/publication/322698780_Comparative_Analysis_of_Infrastructures_Hydrogen_Fueling_and_Electric_Charging_of_Vehicles

Saur, Genevieve, Sam Sprik, Jennifer Kurtz, Shaun Onorato, Spencer Gilleon, and Erin Winkler. 2019. *Hydrogen Station Data Collection and Analysis*. Presentation at the DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting, April 30. National Renewable Energy Laboratory. https://www.hydrogen.energy.gov/pdfs/review19/ta014_sprik_2019_o.pdf

Shekhar, Aditya, Venugopal Prasanth, Pavol Bauer, and Mark Bolech. 2016. "Economic Viability Study of an On-Road Wireless Charging System with a Generic Driving Range Estimation Method." *Energies* 9 no. 2 (Jan): 76–95. https://doi.org/10.3390/en9020076

Singer, Mark. 2017. *The Barriers to Acceptance of Plug-in Electric Vehicles: 2017 Update*. Technical Report NREL/TP-5400-70371. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70371.pdf

Smith, Margaret. 2016. *Level 1 Electric Vehicle Charging Stations at the Workplace*. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://afdc.energy.gov/files/u/publication/WPCC_L1ChargingAtTheWorkplace_0716.pdf

Smith, Margaret, and Jonathan Castellano. 2015. *Costs Associated With Non-Residential Electric Vehicle Supply Equipment*. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf

Tesla Motors. 2019. "Tesla Destination Charging." Accessed September 3, 2019. https://www.tesla.com/destination-charging

Traut, Elizabeth J., TsuWei Charlie Cherng, Chris Hendrickson, and Jeremy J. Michalek. 2013. "US Residential Charging Potential for Electric Vehicles." *Transportation Research Part D: Transport and Environment* 25 (Dec): 139–145. https://doi.org/10.1016/j.trd.2013.10.001

Trentadue, Germana, Alexandre Lucas, Marcos Otura, Konstantinos Pliakostathis, Marco Zanni, and Harald Scholz. 2018. "Evaluation of Fast Charging Efficiency under Extreme Temperatures." *Energies* 11, no. 8 (July): 1937–1949. https://www.mdpi.com/1996-1073/11/8/1937

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE). 2019. "Charging at Home." *Energy.gov*. Accessed September 3, 2019. https://www.energy.gov/eere/electricvehicles/charging-home

———. 2018. "Fuel Economy." https://www.fueleconomy.gov

U.S. Energy Information Administration (EIA). 2019a. "Electric Power Monthly." January 2019. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

———. 2019b. "Petroleum & Other Liquids: Weekly Retail Gasoline and Diesel Prices (March 21, 2016 and 2019)." Accessed June 17, 2019. https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm

———. 2019c. "Electricity Data." Accessed September 3, 2019 https://www.eia.gov/electricity/data.phpMing

Wood, Eric W., Clément L. Rames, Matteo Muratori, Seshadri Srinivasa Raghavan, and Marc W. Melaina. 2017. *National Plug-In Electric Vehicle Infrastructure Analysis*. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/69031.pdf

Xinhua News Agency (新华社). 2017. “北京形成六环内5公里公用充电桩网络 [Beijing Six Ring Has Formed an Average of 5 Km Service Radius of the Public Charging Network],” *d1ev.com*. Accessed March 7, 2018. https://www.d1ev.com/news/shichang/54718

Yang, Yongjun (杨永军) and Shixiong Lu (卢世雄). 2017. 2016年北京土地市场回 顾及 2017年展望 [*2016 Beijing Land Market Review and 2017 Outlook*]. Accessed March 26, 2018. https://max.book118.com/html/2017/0523/108582020.shtm

Yi, Zonggen, and Matthew Shirk. 2018. "Data-Driven Optimal Charging Decision Making for Connected and Automated Electric Vehicles: A Personal Usage Scenario." *Transportation Research Part C: Emerging Technologies* 86 (Jan): 37–58. https://doi.org/10.1016/j.trc.2017.10.014

Zhiyan Consulting Group (智研咨询). 2015. 2016-2022年中国CNG加 气站行业发展现状及投资战略咨询报告 [*2016-2022 China CNG Refueling Station Industry Development Status and Investment Strategy Advisory Report*]. http://www.chyxx.com/research/201512/373456.html

Zhou Chuang Information (卓创资讯). 2017. “2016年中国LNG加气站发展情况分析 [Analysis of the Development of China’s LNG Refueling Stations in 2016],” *CHEM99.com*. http://www.chem99.com/news/23887379.html

Zhou, Wei (周奕). 2016. "北汽新能源 奥动 电巴三方的强强联手合作 [BAIC, Aulton, and Dianba are Working Together on Commercializing Battery Swapping Technology and Service]." *12365auto.com*, August 10. http://www.12365auto.com/news/20160810/243984.shtml

## Chapter 6

# Urban Mobility and Autonomous Vehicles

Urban areas worldwide face ever-growing challenges in planning and designing passenger mobility systems that will sustainably, safely, efficiently, affordably, and equitably meet the mobility needs of their growing populations. This is no small task, given that many cities today struggle with congestion, air pollution, and other negative externalities of urban transportation systems that are only expected to worsen as urban populations continue to grow. The United Nations estimates that by 2050, 68% of the world's population will live in cities (2018). Urbanization is likely to bring with it changes in consumer preferences and travel patterns that will increase demand for urban mobility. At the same time, urban transportation systems are already being disrupted by emerging technologies (including vehicle electrification) and service innovations (such as on-demand car- and ride-sharing services, as well as shared scooter and bike systems). Cities around the world are struggling to figure out where these new services will fit into existing transportation systems, while individuals are being presented with a wider array of transportation choices than ever before. Even as society learns to cope with current disruptors, planning for the future requires additional consideration of how automated and connected vehicles will interact with existing travel modes, urban infrastructure, regulatory frameworks, and consumer behaviors.

### New on-demand services

Advances in information and communication technology have substantially increased the range of mobility solutions on offer in an urban environment. These advances have enabled a proliferation of on-demand shared mobility platforms (such as car-sharing, ride-sharing, ride-pooling, and scooter and bicycle rentals) (Smith 2016). Such mobility-on-demand (MOD) systems have increased accessibility for some, including for individuals who have difficulty accessing existing modes of transport or in communities that were previously underserved by traditional taxi and transit services. However, concerns about the negative impacts of MOD on mass transit ridership and congestion are growing (Barrios, Hochberg, and Yi 2019; Schaller 2018).

These negative impacts are likely to intensify if on-demand services incorporate autonomous vehicles. Depending on cost and level of service, autonomous mobility-on-demand (AMOD) systems could reduce the use of more sustainable modes, such as mass transit, cycling, and walking (Le Vine and Polak 2014). Basu, et al. (2018) have shown that the extreme case of outright substitution of mass transit by AMOD is unsustainable in dense, transit-oriented cities. However, significant uncertainty remains in terms of how future trips will be allocated among AMOD, mass transit, and other existing modes in different urban environments, and what the overall impact will be in terms of congestion, vehicle kilometers traveled (VKT), and environmental impacts. This chapter explores the uncertainty surrounding interactions among AMOD, mass transit, and private vehicle ownership in different urban environments. The urban typology and simulation framework presented in this chapter is designed to quantify the unknown impacts of introducing AMOD (alone or coupled with complementary policy interventions) in different cities.

### Autonomous and connected vehicles

The development of autonomous and connected vehicle technology still faces many challenges before fully self-driving vehicles become a reality (Marshall 2017). However, extensive simulation experiments and field trials are helping to push the technology forward. As of August 2019, as many as 90 cities around the world had active autonomous vehicle pilot programs, a number that has continued to increase in the past few years (Bloomberg Aspen Initiative on Cities and Autonomous Vehicles 2019).[1] While some expect fully autonomous vehicles will be widely available by 2050 (Lanctot 2017), others emphasize that major obstacles must still be overcome, including additional technology improvement, public acceptance, appropriate regulations, provision of enabling infrastructure, and proof of economic viability before fully self-driving vehicles will be widely available (Fagnant and Kockelman 2015).

While autonomous and connected vehicles could operate within traditional paradigms of personal vehicle ownership, many envision that these types of vehicles will be widely deployed in fleets that provide on-demand mobility services in urban areas. However, the interaction of autonomous on-demand services with existing transportation modes and resulting impacts on mobility patterns and overall transportation system performance are still unclear. While some researchers estimate that the reduced cost of autonomous vehicles (Pavone 2015) could increase total distance travelled (Wadud, MacKenzie, and Leiby 2016), others anticipate benefits from greater sharing of vehicles and rides, reduced car ownership, and less urban land use for parking (Zhang and Guhathakurta 2017). The impacts of vehicle automation on congestion, in particular, remain uncertain. On one hand, connected vehicles that communicate with other vehicles and transportation infrastructure have the potential to increase road capacity by traveling closer together (platooning). On the other hand, cheaper on-demand services might induce additional demand and underutilized fleets could mean more vehicles traveling empty on the road.

### Roadmap

This chapter focuses on issues of mobility innovation within the context of cities. Recognizing that cities across the globe are diverse, we begin by identifying an urban typology that captures key patterns in economic and transportation characteristics across cities (Section 6.1). Next, we build prototype city simulation models for a select subset of our city types. The simulation models enable us to explore trip-level supply and demand interactions for cities with different mobility patterns and transportation networks. We then use scenario analysis to measure the potential impact of disruptive technologies within each of our prototype cities. In particular, we focus on the potential impacts of introducing AMOD in terms of travel by existing modes, congestion, travel by private and on-demand vehicles (in VKT), as well as energy consumption and emissions (Section 6.2). We complement these simulation studies with a discussion of existing and necessary regulatory frameworks to ensure the safe operation of autonomous vehicle fleets (Section 6.3) and results from an international public opinion survey about autonomous vehicle safety (Section 6.4).

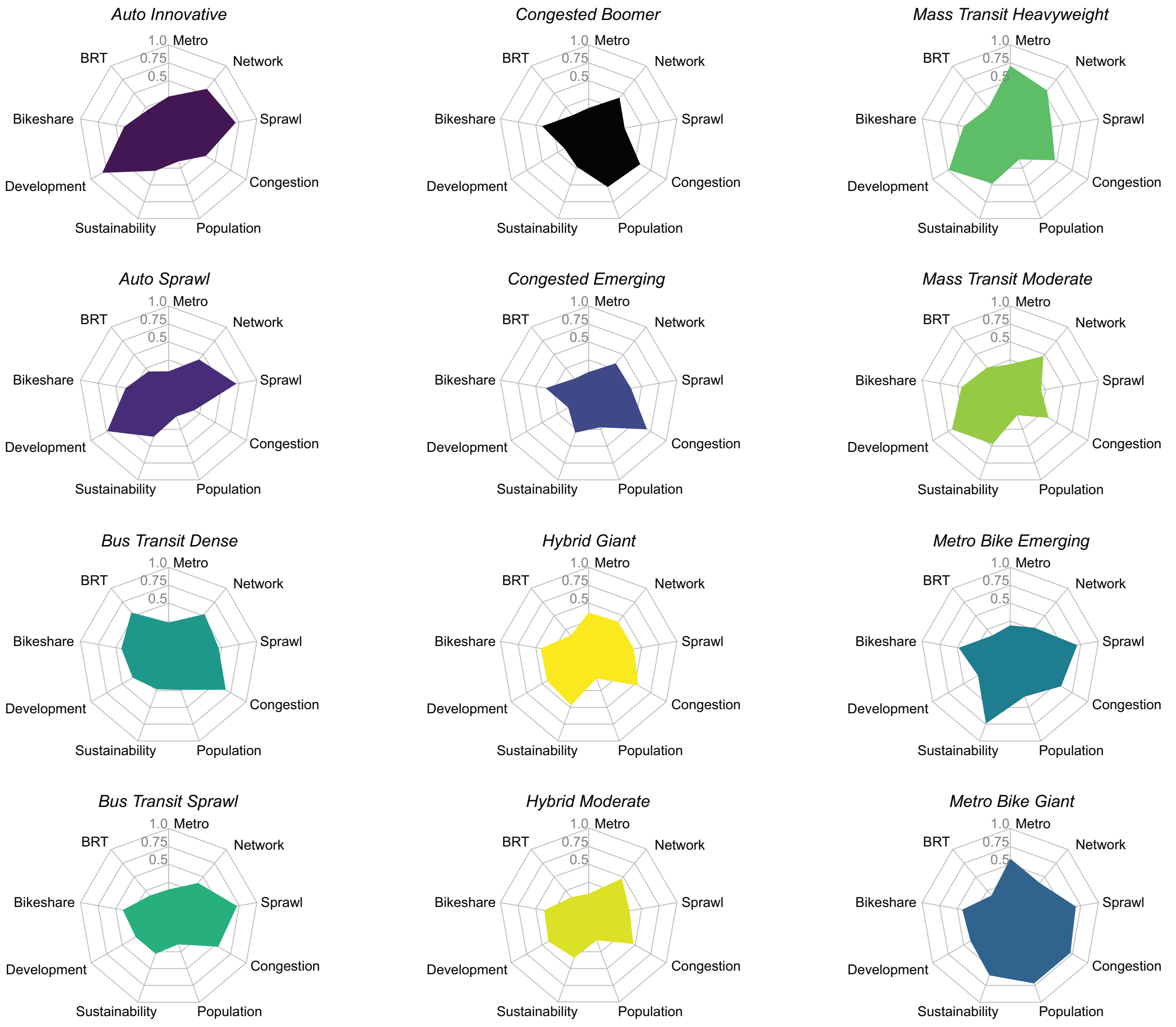
## 6.1 URBAN TYPES

Cities around the world exhibit significant variation in their socio-demographic composition, transportation networks, and urban mobility patterns. Urban mobility solutions must adequately account for this diversity. However, diversity also presents a dilemma for the systematic study of future mobility systems at the urban level. Considering the unique context of every city in the world is impractical and could overlook valuable opportunities for identifying trends across cities. On the other hand, a one-size-fits-all strategy

---

[1] Over the past few years, leading testers include Waymo—7 million miles, 10 years, 25 U.S. cities (Silver 2018); Uber—2 million miles, 3 years, 4 U.S. cities (Wakabayashi 2018); Cruise—3 U.S. states (Norman 2018); and nuTonomy—5 years, Singapore and Boston (Vincent 2016).Though field tests of AMOD technology are becoming more common, they are often limited in scope. In December 2018, for instance, Waymo One began its first commercial deployment of an AMOD service in metropolitan Phoenix, Arizona (Sage 2018). The service has been limited to fair-weather operations with safety drivers in the vehicles at all times, plus oversight by a control center (Windsor 2018). Despite these precautions, the Waymo service has still encountered public resistance (Romero 2018).

**Figure 6.1: Radar plots of urban types based on identified factors**



Note: Radar plots indicate normalized factor scores (from 0 to 1) averaged for all cities in each type; adapted from Oke, et al. (2018).

for urban mobility systems is equally untenable and would inevitably fail to address the array of challenges that face individual cities.

Therefore, some degree of categorization is necessary to reduce the complexity and diversity inherent in global cities. We take the approach of classifying cities on a global scale using a clustering analysis that is based on indicators of urban form and travel behavior. From this analysis, we are able to identify a manageably small, yet diverse set of "city types" that broadly represent the defining patterns of urban form and travel patterns seen in cities around the world. For selected city types, we develop "prototype cities" that represents the average or general characteristics of cities of each type. The prototype cities can then be used to analyze scenarios and generate results that are relevant to actual cities of the same type.

**Table 6.1: Descriptions of city types**

| City type | Key features | Primary geographic concentration | Example cities |
|---|---|---|---|
| ***Auto Innovative*** | **Auto-dependent, higher mass transit mode share, metro and population density** | **U.S., Canada** | **Washington, D.C., Atlanta, Boston, Toronto** |
| ***Auto Sprawl*** | **Sprawling, extremely low mass transit mode share** | **U.S., Canada** | **Baltimore, Tampa, Raleigh, Kuwait City** |
| *Bus Transit Dense* | Large population, high BRT mode share, fairly congested | South America | Rio de Janeiro, Jakarta, Sao Paulo, Tehran |
| *Bus Transit Sprawl* | Lower population, moderate mass transit mode share | Middle East, Central Asia | Mecca, Shiraz, Mashhad, Cape Town |
| *Congested Boomer* | Rapid growth, congestion, moderate car mode share | India, Africa | Bangalore, Lahore, Chennai, Mumbai, Lagos |
| *Congested Emerging* | High growth, lower population, developing | Africa, Southeast Asia | Phnom Penh, Kumasi, Port-au-Prince |
| *Hybrid Giant* | Mix of mode shares, dense transport networks, high population density | Europe, East Asia | Busan, Lisbon, Santiago, Warsaw |
| *Hybrid Moderate* | Mix of mode shares, lower population | Central America, Southeast Europe | Havana, Cordoba, Montevideo, Panama City |
| *Metro Bike Emerging* | Metro and bike have dominant mode shares, moderate population, fairly wealthy | China | Ningbo, Zhengzhou, Shenyang, Harbin |
| *Metro Bike Giant* | Metro and bike have dominant mode shares, very large population, wealthy | China | Shenzhen, Guangzhou, Chongqing, Beijing |
| ***Mass Transit Heavyweight*** | **High mass transit mode share, pervasive metro, high bike mode share, fairly high $CO_2$ emissions per capita** | **Europe, Southeast Asia** | **Singapore, Madrid, Seoul, Berlin, London** |
| *Mass Transit Moderate* | Equitable, high bike mode share, moderate metro and BRT mode shares, low congestion | Western Europe, Israel | Tel-Aviv, Turin, Liverpool, Amsterdam |

Note: BRT = bus rapid transit; **bolded** typologies were selected for prototype city development.

### 6.1.1 Twelve City Types

We define a “city” as an urban agglomeration with at least 750,000 inhabitants. From the 700 cities worldwide that fit this definition, we analyze 331 cities (in 124 countries) for which consistent and comparable data are available. For each city we collect information on 64 urban indicators, from which we identify nine dominant factors: metro, bus rapid transit (BRT), bikeshare, development, population, sustainability, congestion, sprawl, and network density (Oke, et al. 2018). We then cluster the 331 cities on these nine factors, producing 12 unique city types (Figure 6.1).

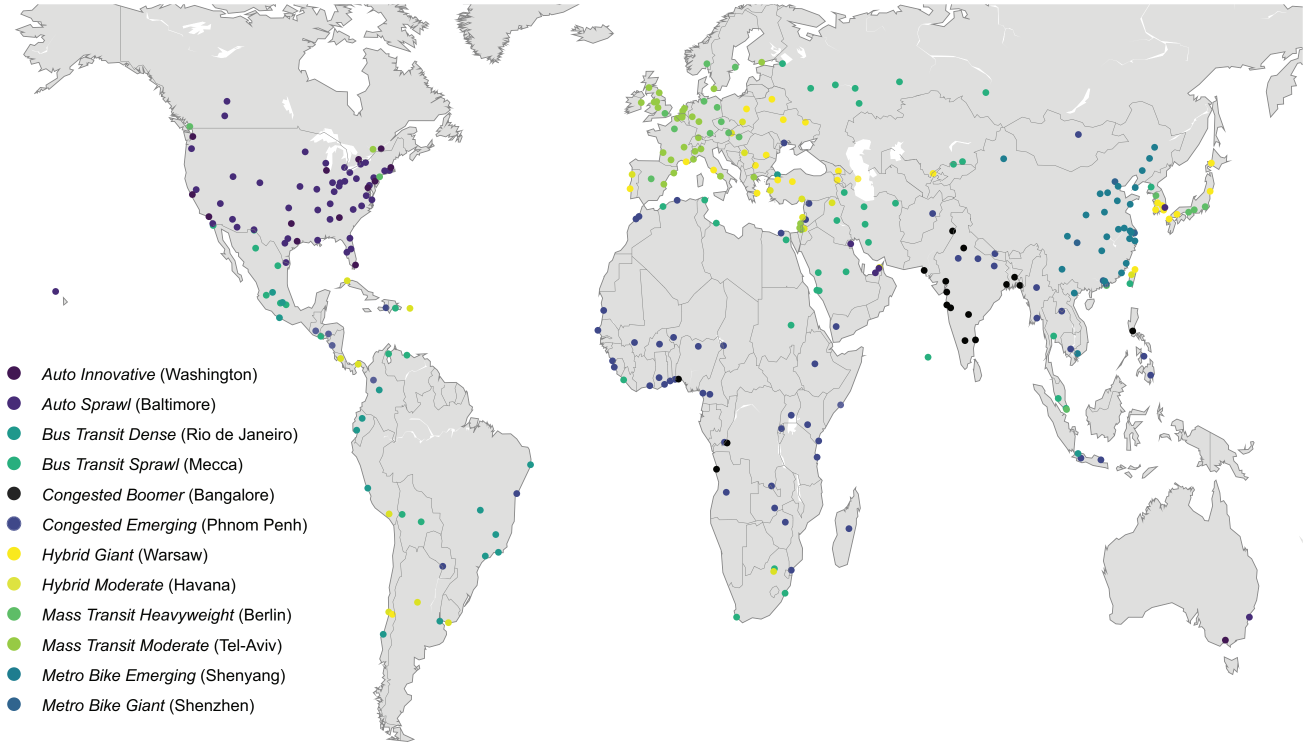
Table 6.1 summarizes key features and example cities for each type, and Figure 6.2 indicates the geographic distribution of different city types. There are two *Auto* types that encompass cities with very high car mode share; both are largely found in North America. The *Auto Innovative* type represents larger and denser cities that have greater mass transit availability (including heavy rail) and mode share relative to their *Auto Sprawl* counterparts. The *Mass Transit Heavyweights* are a select group of megacities from all over the world[2] that have the highest factor scores for metro, bikeshare, and sustainability compared to the other types. In contrast, *Mass Transit Moderates* are smaller cities with fairly high shares of both transit (bus and rail) and active mobility; these are found primarily in Europe and Israel.

The *Congested Boomer* type represents rapidly growing megacities with severe congestion problems and low metro availability, particularly in India; notable members are Bangalore, Mumbai, and Delhi. Most sub-Saharan African cities are in

---

[2] New York City and Vancouver have the distinction of being the only North American cities in this typology.

**Figure 6.2: World map indicating the 12 urban types**



the *Congested Emerging* category, highlighting the fact that many of these not-yet-megacities will soon face the challenges of the *Congested Boomers* due to their rapid rates of population growth and urbanization. *Hybrid* cities exhibit comparable characteristics across private and public mode shares, with relatively lower incomes. The *Hybrid Giant* cities have denser networks with greater population density than the *Moderates*. They are mostly found in Latin America, Eastern Europe, and Central Asia. China is home to *Metro Bike* cities, which are distinct in their availability of bikeshare coupled with extensive urban rapid transit development. The *Giants* subgroup includes China's largest megacities, with extremely high scores in terms of population. The *Emerging* subgroup represents other Chinese cities that score lower in terms of population, but show otherwise similar trends across the nine factors. Finally, both the *Bus Transit Dense* and *Bus Transit Sprawl* types are largely represented in Latin America. The *Dense* cities are the much larger and more densely populated cities within the two *Bus Transit* types; notable cities of this type outside of Latin America include Jakarta and Tehran.

### 6.1.2 Three Prototype Cities

We select three of the 12 city types presented in Table 6.1 for additional analysis: *Auto Sprawl*, *Auto Innovative*, and *Mass Transit Heavyweight*. We select these cities to focus on how the introduction of new mobility technologies and services may play out in cities with substantially different levels of private automobile versus mass transit use (Table 6.2). The *Auto Sprawl* and *Auto Innovative* cities both represent cities (primarily in the U.S. and Canada) that have high car mode shares as a percentage of total trips. The key difference between these two types is in their level of mass transit use, with *Auto Innovative* at about 10% in mode share compared to 3% for *Auto Sprawl*. However, transit usage in both of these auto-oriented city types is dwarfed by the nearly 40% transit mode share typical of *Mass Transit Heavyweight* cities.

For each of the three selected types, we create a prototype city that best represents the characteristics of that city type. The procedure used to generate prototype cities consists of three

**Table 6.2: Key features of the three city types selected for simulation and scenario analysis**

| Characteristics | *Auto Sprawl* | *Auto Innovative* | *Mass Transit Heavyweight* |
|---|---|---|---|
| Car mode share (% of trips) | 86.0 | 79.0 | 32.0 |
| Mass transit mode share (% of trips) | 3.5 | 11.0 | 37.0 |
| Bike mode share (% of trips) | 0.5 | 0.9 | 7.6 |
| Walk mode share (% of trips) | 3.3 | 3.3 | 23.0 |
| Population density (1,000 persons/km$^2$) | 1.4 | 1.5 | 5.5 |
| GDP per capita ($1,000) | 51 | 61 | 53 |
| $CO_2$ emissions per capita (metric tons per annum) | 16 | 15 | 10 |

Note: All values reported represent the average across cities in the respective typologies.

steps: population and land-use synthesis, demand model calibration, and transit supply system development and model calibration (Oke, et al. 2019). Activity and mode shares of the prototype city are calibrated to the average for cities of that type (Table 6.2). Then for each prototype city, we carry out detailed, large-scale, agent-based simulations of trip-level decision-making for a weekday using the SimMobility platform (Adnan, et al. 2016). We use SimMobility to assess a set of scenarios that look at the introduction of new AMOD services and their impacts on urban mobility patterns.

## 6.2 URBAN MOBILITY SCENARIO ANALYSIS

In this section, we use scenario analysis to investigate how AMOD may interact with existing urban mobility systems and new mobility policies. Our scenarios consider not only how the introduction of AMOD might change the use of existing modes in different urban environments, but also how the benefits and consequences of AMOD might change depending on whether it is introduced as a competitor or complement to mass transit and private vehicle ownership.

### 6.2.1 Scenario Descriptions

Is AMOD better when integrated with transit or when left to compete directly? Should transit be abandoned in favor of AMOD? How would a policy to reduce household car ownership interact with the introduction of AMOD? We answer these questions by comparing simulation results—including mode shares and shifts, congestion, vehicle kilometers traveled, and energy and emissions—among the following scenarios:

1. *Base Case:* The Base Case simulation for each of the prototype cities represents conditions and services offered in each city as they existed in the year 2016.

2. *AMOD Intro:* This scenario simulates what would happen if an AMOD service were offered in each prototype city and the use of that service was determined solely by market forces. This scenario also includes a shared ride (pooling) AMOD option for the consumer to enable further reductions in fares and energy consumption. The model assumes that consumers' preference for AMOD service is the same as their preference for human-driven MOD service.

3. *AMOD No Transit:* Here, AMOD is introduced, not only in place of existing MOD services, but also as a substitute for mass transit—thus, we remove the entire transit network. This scenario attempts to answer the question of whether AMOD can wholly replace mass transit and under what urban conditions, if any, this replacement would result in a sustainable outcome.

4. *AMOD Transit Integration:* In this scenario, an integrated fare structure incentivizes the use of AMOD as a first-/last-mile solution for transit.

**Table 6.3: Scenarios evaluated by prototype city**

| Scenario | *Auto Sprawl* | *Auto Innovative* | *Mass Transit Heavyweight* |
|---|---|---|---|
| Base Case | ● | ● | ● |
| AMOD Intro | ● | ● | ● |
| AMOD No Transit | ● | ● | |
| AMOD Transit Integration | ● | ● | ● |
| AMOD + Car Reduction | | | ● |

Note: An ● means the scenario–city pair is evaluated; a blank means it is not evaluated.

Specifically, a 20% subsidy applies when AMOD is used for access/egress connectivity to rail stops. Non-integrated AMOD is restricted to only local trips, defined as trips shorter than 7.5 miles in *Auto Sprawl* and *Auto Innovative* cities and shorter than 3 miles in the *Mass Transit Heavyweight* city. In this scenario, AMOD is introduced as a complement to mass transit (via integration) rather than as a competitor.

5. *AMOD + Car Reduction:* This scenario simulates the impacts of restricted car ownership along with the introduction of a low-cost AMOD service in place of traditional MOD. A 25% reduction in household car ownership is actualized by an increase of $12,000 in the average annual cost to own a vehicle in the model. Our simulations assume that the supply of AMOD services will increase to match new demand created by reductions in car ownership. This scenario is developed and evaluated only for the *Mass Transit Heavyweight* city type, because a number of cities of this type have already implemented policies that restrict car ownership or use (e.g., Singapore and London).

To understand how these different scenarios interact with different urban environments, we simulate the scenarios in each of the applicable prototype cities: *Auto Innovative*, *Auto Sprawl*, and *Mass Transit Heavyweight* (Table 6.3). We do not simulate the AMOD No Transit scenario for the *Mass Transit Heavyweight* prototype, since gridlock would ensue if the mass transit network were entirely removed in this type of city (Basu, et al. 2018). Instead, we simulate the AMOD + Car Reduction scenario in the *Mass Transit Heavyweight* city, since many cities of this type (e.g., Singapore and London) already limit car usage and/or ownership. In each simulation, the fleet of autonomous, on-demand vehicles was sized to serve the demand for AMOD services in that particular scenario (Oke, et al. 2019).

### 6.2.2 Scenario Assumptions

This section provides an overview of the critical assumptions regarding mode availability (Table 6.4) and costs or fares (Table 6.5) underlying the scenario analysis. Additional technical details can be found in Appendix C.

In the Base Case, all existing modes are available, including privately owned vehicles, taxis, human-driven MOD, mass transit (including bus and train), and active travel modes such as walking and biking (Table 6.4). In the AMOD scenarios, all taxis and human-driven MOD services are replaced by AMOD, which can serve single-party, exclusive trips or multiple-party, pooled trips. In the AMOD No Transit scenario, bus and train options are also removed.

While mode availability across scenarios is the same for each prototype city, the relative costs of different modes vary by city type. For each city type, Base Case costs are derived from publicly available data (Table 6.5). In the context of our scenarios, the key difference between AMOD and human-driven MOD is the fare. The nominal assumption is that the AMOD service will cost riders half as much as existing taxi services. This assumption presumes high maturation of

**Table 6.4: Mode availabilities across scenarios**

| Mode category | Mode | Base Case | AMOD Intro | AMOD No Transit | AMOD Transit Integration | AMOD + Car Reduction |
|---|---|---|---|---|---|---|
| **Car (private)** | Drive alone | ● | ● | ● | ● | ● |
| | Carpool | ● | ● | ● | ● | ● |
| **Mass transit** | Bus | ● | ● | | ● | ● |
| | Train | ● | ● | | ● | ● |
| **On-demand** | Taxi | ● | | | | |
| | MOD | ● | | | | |
| | AMOD: exclusive | | ● | ● | ● | ● |
| | AMOD: pooled | | ● | ● | ● | ● |
| **Active** | Bicycle | ● | ● | ● | ● | ● |
| | Walk | ● | ● | ● | ● | ● |
| **Other** | Private bus | ● | ● | ● | ● | ● |
| | Motorcycle | ● | ● | ● | ● | ● |

Note: ● means the mode is available in the given scenario; blank means the mode is unavailable.

**Table 6.5: Costs/fares (U.S. dollars) per mode among prototype cities**

| Mode | *Auto Sprawl* | | | | *Auto Innovative* | | | | *Mass Transit Heavyweight* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fixed | Per km | Per min | Parking per hr | Fixed | Per km | Per min | Parking per hr | Fixed | Per km | Per min | Parking per hr |
| Car | | 0.26 | | 0.20 | | 0.37 | | 2.50 | | 0.17 | | 0.88 |
| Carpool | | 0.17 | | 0.13 | | 0.25 | | 1.67 | | 0.11 | | 0.58 |
| Taxi | 1.80 | 1.38 | 0.40 | | 2.60 | 1.75 | 0.47 | | 1.65 | 0.12 | 0.16 | |
| Human-driven MOD | 3.45 | 1.38 | 0.12 | | 3.95 | 1.35 | 0.21 | | 1.37 | 0.28 | 0.09 | |
| Mass transit | 0.05 | 0.12 | | | 0.83 | 0.28 | | | 0.07 | 0.02 | | |
| AMOD: | | | | | | | | | | | | |
| Exclusive | 0.83 | 0.63 | 0.18 | | 1.20 | 0.81 | 0.21 | | 0.76 | 0.06 | 0.07 | |
| Pooled | 0.58 | 0.44 | 0.13 | | 0.84 | 0.56 | 0.15 | | 0.53 | 0.04 | 0.05 | |
| AMOD + transit | 0.33 | 0.28 | 0.07 | | 0.72 | 0.39 | 0.06 | | 0.31 | 0.03 | 0.03 | |

Note: Taxi costs from taxi-calculator.com (2019) and human-driven MOD costs from Uber Technologies, Inc. (2019) for *Auto Sprawl* and *Auto Innovative* cities and from Grab (2019) for the *Mass Transit Heavyweight* city. Per-minute costs estimated using an expected speed of travel of 40 km/h in the *Auto Sprawl* and *Auto Innovative* cities and 25 km/h in the *Mass Transit Heavyweight* city.

autonomous vehicle technology, low cost of future autonomous vehicle equipment, and a developed and supportive regulatory framework (Pavone 2015).

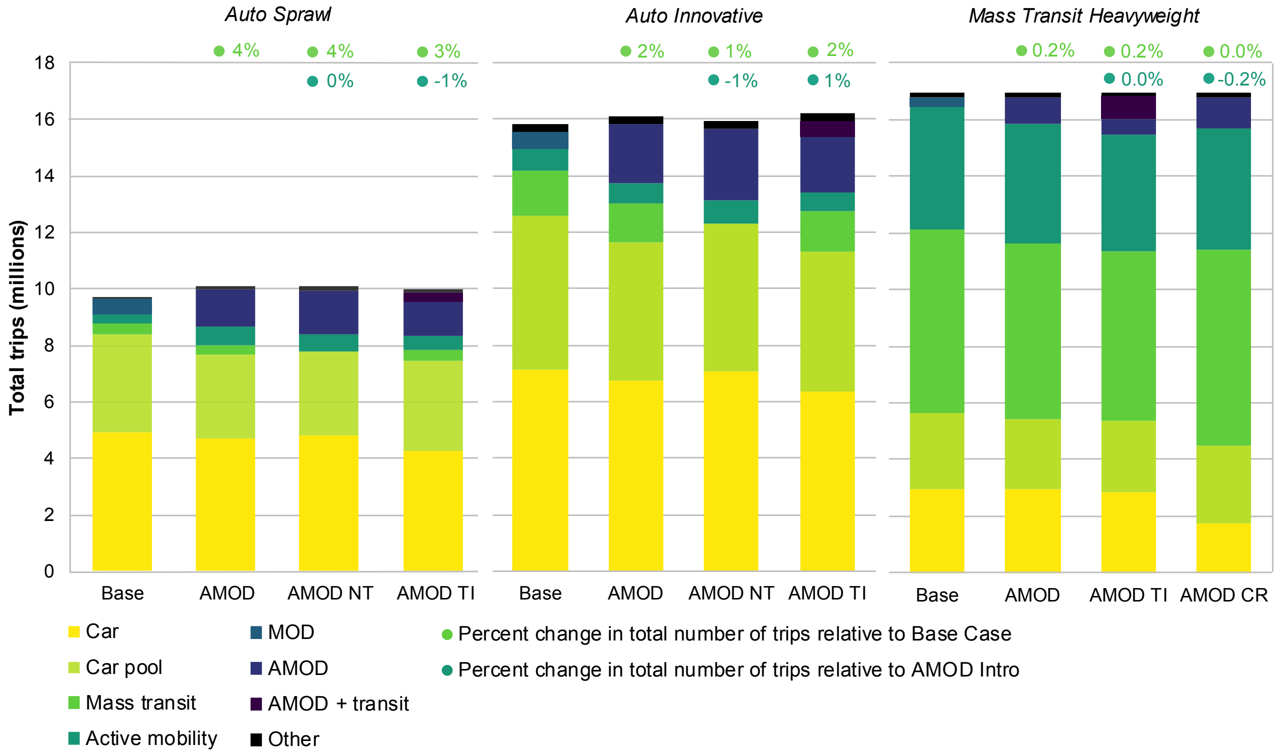
### 6.2.3 Scenario Results

We compare the scenarios across our three prototype cities—*Auto Sprawl*, *Auto Innovative* and *Mass Transit Heavyweight*—to examine the impacts of AMOD in distinct urban settings. For each scenario, we consider impacts on demand (including shift in mode shares), congestion, VKT (by privately-owned and on-demand vehicles), and energy and emissions across our three prototype cities.

#### *Demand*

First we consider whether the introduction of AMOD service induces demand for trips (Figure 6.3). We find that the likelihood of latent demand for AMOD is much lower in cities where mass transit

**Figure 6.3: Number of daily trips by mode across scenarios for each prototype city**



Note: Base = Base Case; AMOD = AMOD Intro; AMOD NT = AMOD No Transit; AMOD TI = AMOD Transit Integration; AMOD CR = AMOD + Car Reduction.

is widely available compared to cities with greater dependence on automobiles. In particular, we find that the introduction of AMOD induces an increase in demand (as measured by total number of trips) of 4% in the *Auto Sprawl* city and 2% in the *Auto Innovative* city, relative to the Base Case.[3] On the other hand, we observe negligible induced demand with the introduction of AMOD in the *Mass Transit Heavyweight* city. Next we consider mode shares and shifts (Figures 6.4 through 6.6) in each prototype city across our scenarios.

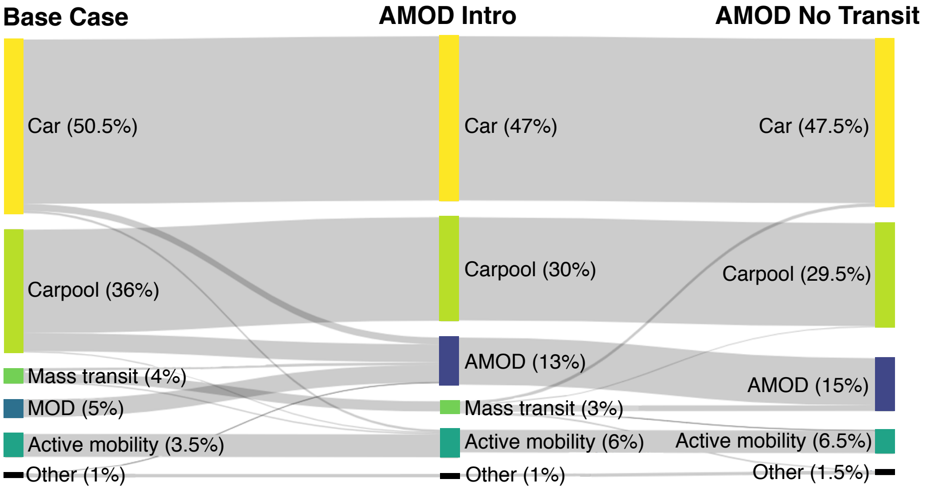
We start by comparing the AMOD Intro scenario to the Base Case. We observe that the introduction of AMOD increases ridership for on-demand trips (replacing human-driven MOD or taxis with AMOD) in all three prototype cities, but has the greatest impact in dense, auto-dependent cities where AMOD primarily replaces private car trips (Figure 6.4). In the *Auto Sprawl* city, the share of on-demand trips increases eight percentage points: from 5% by human-driven MOD and taxi in the Base Case to 13% by AMOD in the AMOD Intro scenario. On the other hand, the share of private car trips (car and carpool) decreases 9.5 percentage points from 86.5% to 77%. In the *Auto Innovative* prototype city, the share of on-demand trips increases nine percentage points from 4% to 13%, but the share of private car trips decreases only from 79.5% to 72.5% (a difference of seven percentage points) in the same scenario. In the *Mass Transit Heavyweight* city, the share of on-demand trips increases from 2% to 6%, while the share of private car trips sees only a small reduction from 33.5% to 32%.

---

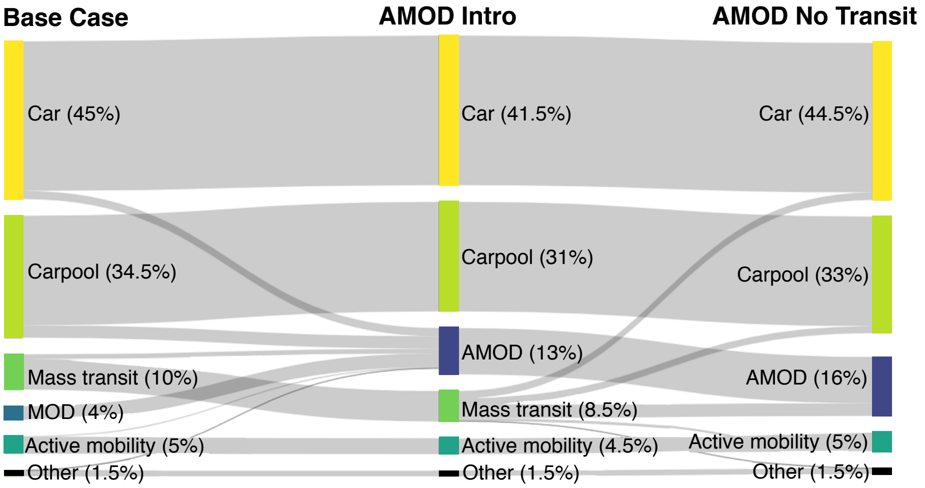
[3] Unless otherwise noted, all percent changes given in this section are relative to the Base Case scenario.

**Figure 6.4: Modal shifts among the Base Case, AMOD Intro, and AMOD No Transit scenarios**

(a) *Auto Sprawl* prototype city



(b) *Auto Innovative* prototype city



We also observe that the introduction of AMOD cannibalizes mass transit ridership in all three prototype cities. The share of trips served by transit decreases from 4% to 3% (equivalent to a loss of more than 77,000 daily trips) in the *Auto Sprawl* prototype city, from 10% to 8.5% (a loss of more than 210,000 trips) in the *Auto Innovative* city, and from 38% to 36% (a loss of more than 260,000 trips) in the *Mass Transit Heavyweight* city.

When mass transit is removed in the AMOD No Transit scenario, the share of on-demand trips increases significantly in the *Auto Sprawl* city—from 5% in the Base Case or 13% in AMOD Intro to 15% in AMOD No Transit—while the share of private car trips (77%) is smaller compared to the Base Case (86.5%) but the same as in AMOD Intro (77%). This suggests that AMOD can replace transit in low-density, auto-dependent cities where transit trips, which already have a small mode share, are predominantly replaced by AMOD and private car trips (Figure 6.4a). However, in dense, auto-dependent cities, transit is more critical. Removing transit in our *Auto Innovative* prototype city results in an increase in the share of on-demand trips from 4% in the Base Case or 13% in AMOD Intro to 16% in AMOD

No Transit. Furthermore, the share of private car trips (at 77.5%) is only slightly reduced compared to the Base Case (79.5%), but increased compared to AMOD Intro (72.5%). In this case, transit trips shift significantly to private car and carpool in addition to active mobility and other (see Figure 6.4b).

In the AMOD Transit Integration scenario, the cannibalization of transit mode share is reversed in all cities while private car trips are significantly reduced in auto-dependent cities (Figure 6.5). In the *Auto Sprawl* city, the share of on-demand trips is 12% (compared to 13% in AMOD Intro), the share of private car trips is 75% (compared to 77% in AMOD Intro), and the share of transit trips is 3.5% plus an additional 3.5% from AMOD-to-transit connections (compared to just 3% in AMOD Intro). In the *Auto Innovative* city, the share of on-demand trips is 12% (compared to 13% in AMOD Intro), the share of private car trips is 69.5% (compared to 72.5% in AMOD Intro), and the share of transit trips is 9% plus an additional 4% of AMOD-transit (compared to 8.5% in AMOD Intro). In contrast to the *Auto* cities, in the *Mass Transit Heavyweight* city the share of trips served by private vehicles (car and carpool) does not change with the integration of AMOD and transit. However, the integration does lead to a reduction in the share of trips served by AMOD (from 6% in the AMOD Intro scenario to 3.5% in the AMOD Transit Integration scenario) and an increase in the share of trips served by mass transit (from 36% in the AMOD Intro scenario to 35% plus 4.5% AMOD-transit in the AMOD Transit Integration scenario). The mitigating effect of first/last-mile AMOD integration on transit mode share is less stark in the *Mass Transit Heavyweight* city compared to the *Auto Innovative* city, further highlighting how different levels of baseline transit availability imply very different modal shifts with the introduction and even integration of AMOD into existing multimodal mobility systems.

Finally, we consider the impact of the AMOD + Car Reduction scenario in the *Mass Transit Heavyweight* city. First, we note that the number of trips does not change significantly, indicating that even though we reduce household car ownership by 25%, there is minimal impact on accessibility with respect to the Base Case (Figure 6.3). Next, considering mode share and shifts (Figure 6.6), we find that the share of AMOD trips increases marginally from 6% in AMOD Intro to 6.5% in AMOD + Car Reduction, the share of private car trips declines from 32% to 26.5%, and the share of mass transit trips increases from 26% to 41%. Overall, we find a similar impact in the AMOD + Car Reduction scenario to that observed in the AMOD Transit Integration scenario: both scenarios reduce a significant reduction of private car trips and an increase in transit ridership relative to the Base Case.

### *Congestion*

To evaluate the congestion impacts of AMOD in our scenarios, we consider relative changes in the travel time index (TTI), where TTI represents the ratio of distance-weighted averages of actual trip travel times to free-flow trip travel times (Figure 6.7). The simulations run with an iterative solving technique so the agents in our model make travel choices based on congestion and travel times for each available mode. Each prototype city has a different baseline level of congestion based on existing travel patterns. In the *Auto Sprawl* city, the Base Case TTI is 1.10;[4] in the *Auto Innovative* city it is 1.13; and in the *Mass Transit Heavyweight* city it is 1.39.

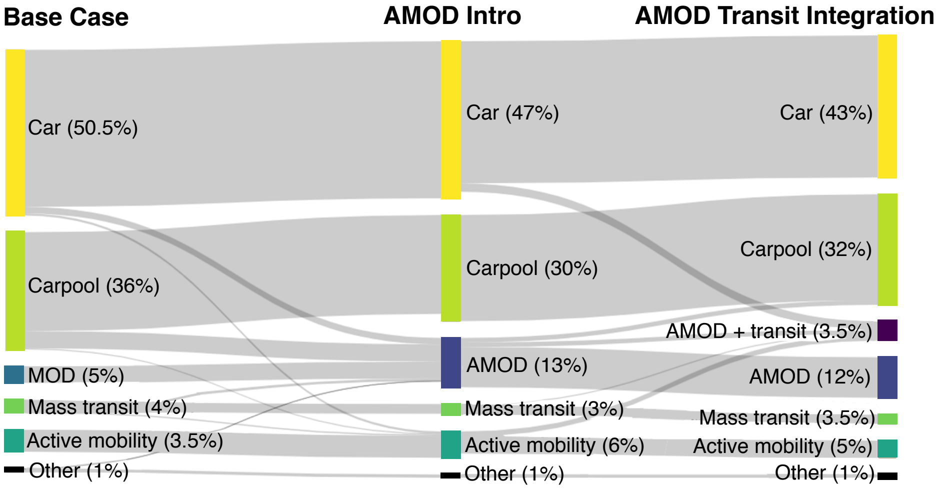
With the introduction of AMOD, we find that congestion increases in all three prototype cities, but the effect is largest in dense auto-dependent cities. In the AMOD Intro scenario, TTI increases by 9% in the *Auto Sprawl* city (from 1.10), 43% in the *Auto Innovative* city (from 1.13) and 8% in the *Mass Transit Heavyweight* city (from 1.39).

---

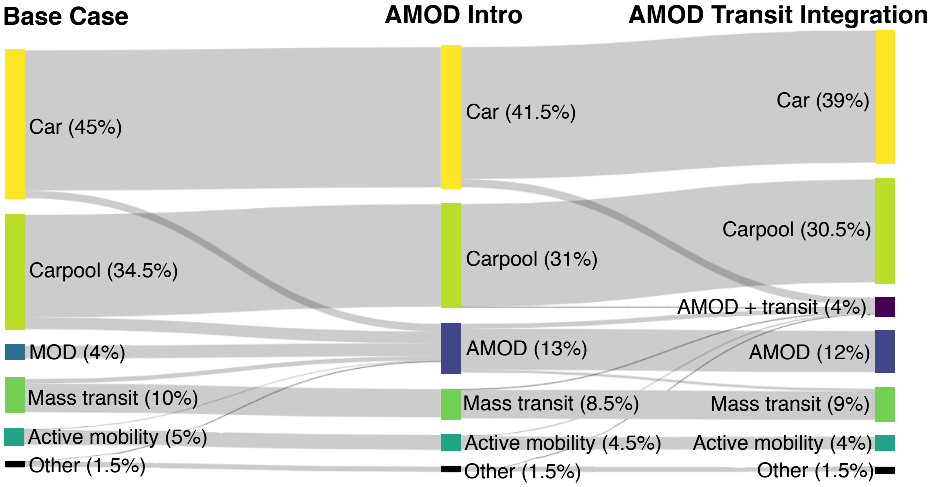
[4] This means that the average trip takes 10% longer than under free-flow conditions. For example, a 20-minute trip under free-flow would take about 22 minutes in the Base Case.

**Figure 6.5: Modal shifts among the Base Case, AMOD Intro, and AMOD Transit Integration scenarios**

**(a)** ***Auto Sprawl*** **prototype city**



**(b)** ***Auto Innovative*** **prototype city**



**(c)** ***Mass Transit Heavyweight*** **prototype city**

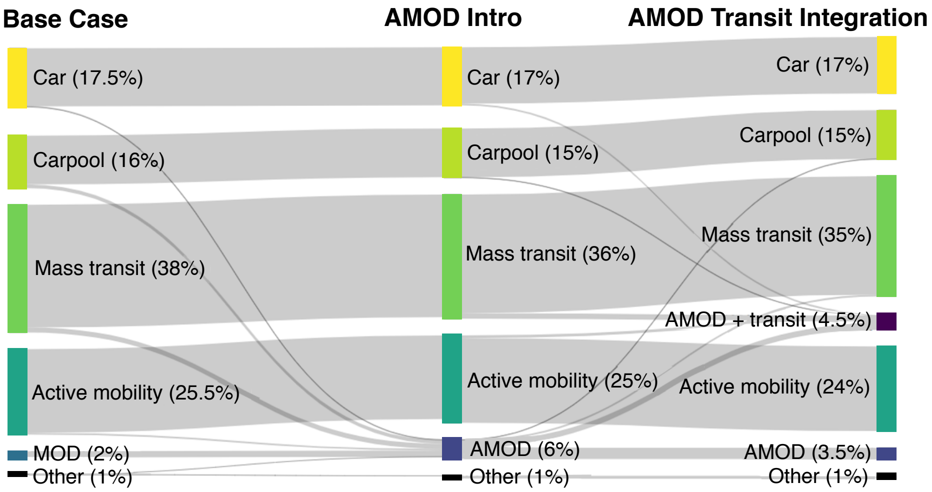


**Figure 6.6: Modal shifts among the Base Case, AMOD Intro, and AMOD + Car Reduction scenarios for the *Mass Transit Heavyweight* city**

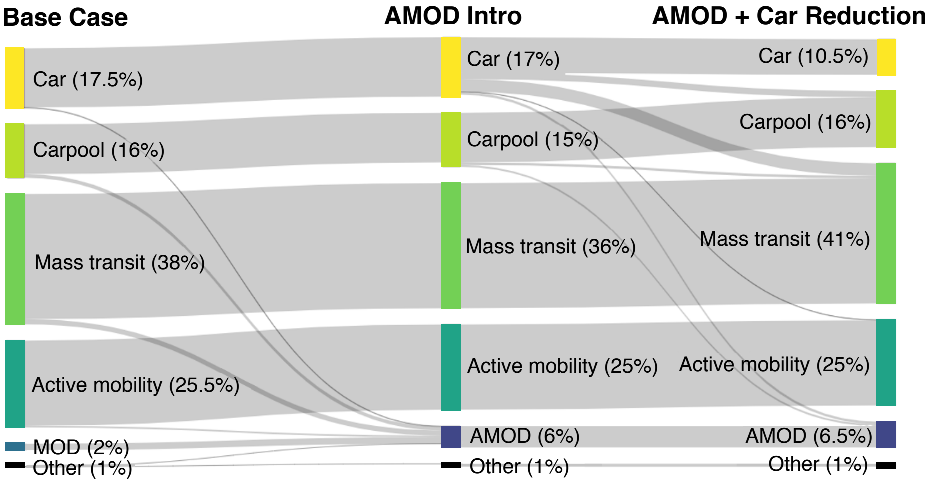
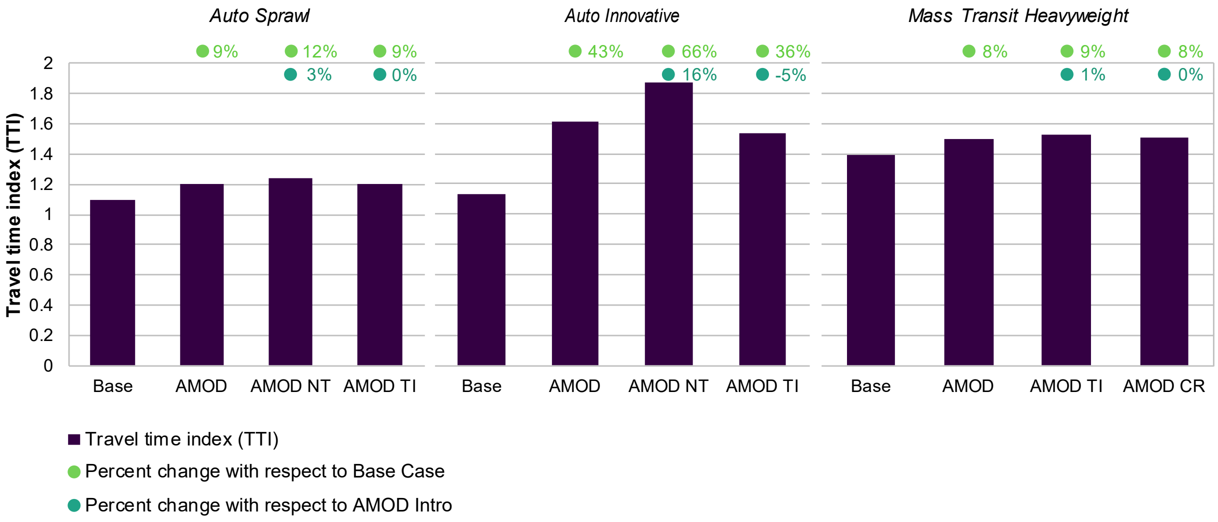


**Figure 6.7: Travel time index (congestion) across scenarios for each prototype city**



Note: Base = Base = Base Case; AMOD = AMOD Intro; AMOD NT = AMOD No Transit; AMOD TI = AMOD Transit Integration; AMOD CR = AMOD + Car Reduction.

We find that traffic conditions deteriorate even more if mass transit is removed as AMOD is introduced; moreover, this effect scales with the existing share of trips being served by mass transit. In the AMOD No Transit scenario, congestion (TTI) increases by only 12% (compared to 9% in AMOD Intro) in the *Auto Sprawl* city. This suggests that the removal of mass transit does not significantly impact travel times when AMOD is introduced in heavily auto-dependent cities where the baseline transit mode share is low.

On the other hand, congestion increases by 66% (compared to 43% in AMOD Intro) in the *Auto Innovative* prototype city, indicating that AMOD services cannot fully replace mass transit systems in denser cities with higher baseline transit mode share.

Next, we consider whether integrating AMOD with transit can reduce some of the negative congestion impacts of introducing AMOD. We find that the AMOD Transit Integration scenario does mitigate the impact of introducing AMOD on congestion, but only in dense, auto-dependent cities. While in the *Auto Sprawl* city, we observe that TTI is unchanged compared to AMOD Intro, in the *Auto Innovative* city it increases only 36%, which is less than the 43% observed in the AMOD Intro scenario. However, we see no positive effect of AMOD Transit Integration in the *Mass Transit Heavyweight* prototype city (9% compared to 8% in AMOD Intro). This might suggest that cities that already have high accessibility to transit and high baseline levels of congestion do not see significant benefits to traffic conditions from integrating AMOD with transit.

Given that the integration of AMOD with mass transit does not show significant congestion benefits in the *Mass Transit Heavyweight* prototype city, we consider whether AMOD accompanied by reductions in car ownership might improve traffic conditions. Again we find that the TTI in the *Mass Transit Heavyweight* city is unchanged in the AMOD + Car Reduction scenario compared to AMOD Intro. In other words, congestion worsens with the introduction of AMOD even when household car ownership is simultaneously reduced. This higher congestion is due to a number of factors, including the fact that AMOD vehicles (unlike personal cars) can run empty between trips, causing further delays in travel time, particularly for shorter trips.

### *Vehicle kilometers traveled*

We also assess the impacts of AMOD on vehicle kilometers traveled (VKT) by privately owned cars and on-demand vehicles (with and without passengers) over the course of an entire weekday. Figure 6.8 compares VKT across all scenarios in the three prototype cities.

We find that VKT increases significantly across all cities with the introduction of AMOD, but the impacts are greater in cities where AMOD replaces non-vehicular modes like transit, walking, and biking. In the *Auto Sprawl* city, VKT increases by only 9% compared to the Base Case because many trips served by the new AMOD service displace trips that would otherwise be made in private cars (VKT for private cars decreases by 14% relative to the Base Case). On the other hand, in denser cities where AMOD serves a greater volume of trips, as in the *Auto Innovative* and *Mass Transit Heavyweight* cities, VKT increases by 26% and 29%,[5] respectively.

Removing transit along with the introduction of AMOD increases VKT even further, particularly in prototype cities that have higher baseline transit mode share. VKT increases by 14% (compared to 9% in AMOD Intro) in the *Auto Sprawl* city, but by 39% (26% in AMOD Intro) in the *Auto Innovative* city, resulting in severe gridlock. We do not run this scenario in the *Mass Transit Heavyweight* prototype city, where we would expect to see extremely high levels of gridlock as the large number of trips currently served by transit shift to AMOD, causing additional vehicles to flood the roads (Basu, et al. 2018).

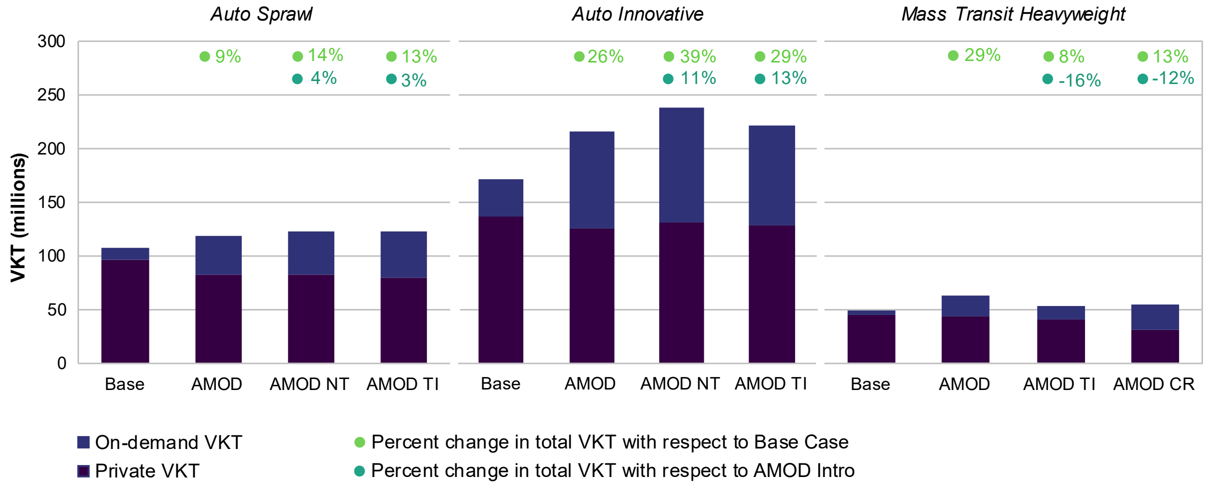
In the AMOD Transit Integration scenario, the VKT impacts from AMOD are significantly moderated in transit-oriented cities, while they are mildly increased in auto-dependent cities. Thus, VKT increases by 13% (compared to 9% in AMOD Intro) in the *Auto Sprawl* city and by 29% (26% in AMOD Intro) in the *Auto Innovative* city. However, in the *Mass Transit Heavyweight* city, VKT increases by only 8% (compared to 29% in AMOD Intro). AMOD + Car Reduction also results in a similar but less drastic moderating effect on VKT in the *Mass Transit Heavyweight* prototype city: VKT increases by only 13% (compared to 29% in AMOD Intro and 8% in AMOD Transit Integration).

In summary, introducing AMOD has a relatively lower impact on VKT in low-density, auto-dependent cities compared to dense, transit-oriented cities. If AMOD replaces transit, VKT increases in all cities, resulting in levels of congestion that are unsustainable in dense, auto-dependent cities. If, instead, AMOD is introduced

---

[5] The 29% VKT increase seen in the *Mass Transit Heavyweight* city represents only an additional 10 million vehicle kilometers, given relatively low baseline private-car usage in this prototype city.

**Figure 6.8: Vehicle kilometers traveled daily in all scenarios for each prototype city**



Note: Base = Base Case; AMOD = AMOD Intro; AMOD NT = AMOD No Transit; AMOD TI = AMOD Transit Integration; AMOD CR = AMOD + Car Reduction. "Private VKT" refers to VKT by privately owned passenger vehicles and "on-demand VKT" refers to VKT by taxis and MOD vehicles (Base Case) or AMOD vehicles (all other scenarios).

with complementary measures such as transit integration and car reduction policies, VKT impacts can be partially mitigated in dense cities.

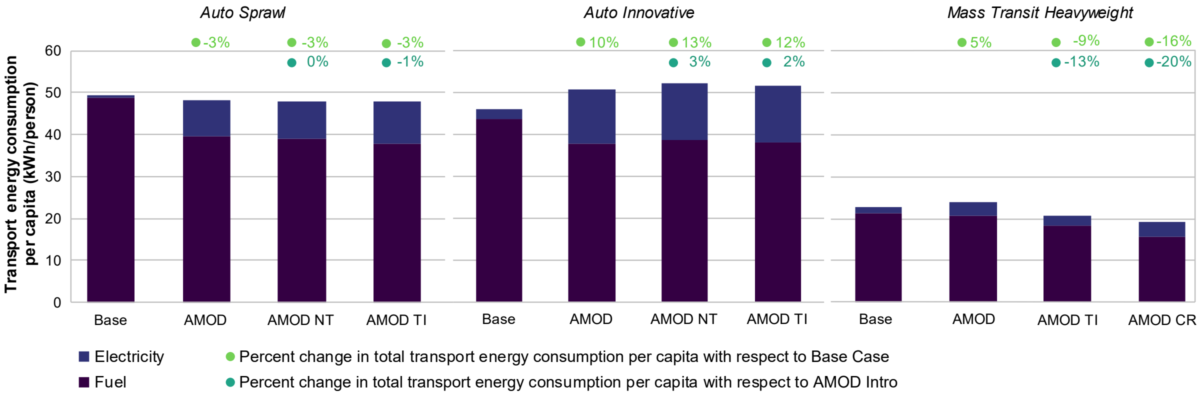
### *Energy and emissions*

Finally, we consider the impact of AMOD introduction on transportation-related energy consumption and emissions in each of our prototype cities. In all scenarios and prototype cities, we assume the AMOD fleet is fully electrified, the MOD and taxi fleets consist of all hybrid electric vehicles, private cars operate on a mix of powertrains consistent with the Chapter 2 *Reference* scenario base year, buses are diesel, and trains are electric. We then use results from the lifecycle analysis of internal combustion engine vehicles and battery electric vehicles in Chapter 4 to calculate energy consumption and greenhouse gas emissions, considering the use of primary energy sources for the production, transmission and distribution of fuels (Table 6.6). Our measure of energy consumption and emissions accounts for "well-to-tank" contributions based on inputs from the lifecycle analysis in Chapter 4 and "tank-to-wheels" contributions from our agent-based simulation results. To facilitate comparisons across scenarios and across city types, we present results on a per-capita basis (Figures 6.9 and 6.10).

With the introduction of fully electrified AMOD, energy consumption and emissions decrease in sprawling cities. In the *Auto Sprawl* city, energy consumption decreases by 3%, while emissions per capita decrease by 10%. In dense cities, on the other hand, energy consumption increases (by 10% in the *Auto Innovative* city and 5% in the *Mass Transit Heavyweight* city), while emissions do not exhibit a significant change (–1% and +1% in the *Auto Innovative* and *Mass Transit Heavyweight* cities, respectively). These outcomes indicate that policies aimed at ensuring that future AMOD fleets are strictly composed of battery electric vehicles (BEVs) will not necessarily save energy or emissions because AMOD may replace trips by more sustainable modes such as mass transit, biking, and walking.

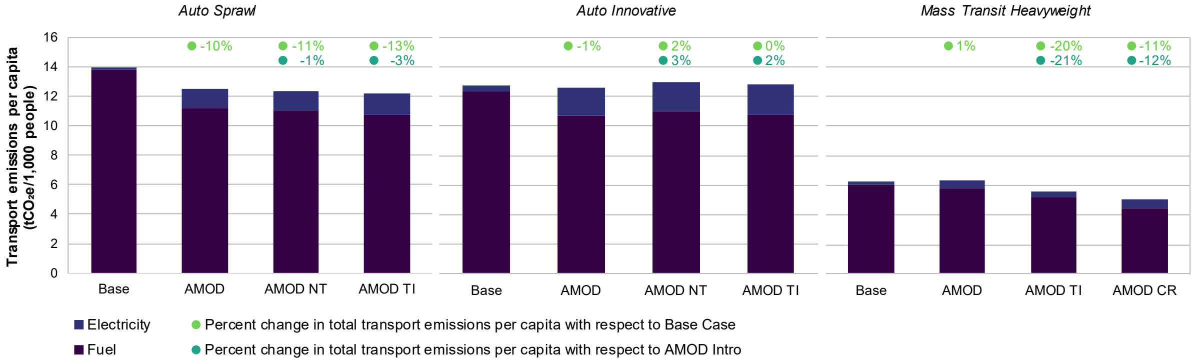
Comparing the AMOD No Transit scenario to the AMOD Intro scenario, we find that energy and emissions impacts in the *Auto Sprawl* city do not change significantly, while energy and emissions in the *Auto Innovative* city increase only modestly (+13% in energy consumption compared to +10% in AMOD Intro and +2% in emissions compared to –1% in AMOD Intro). While the energy and emissions impacts of removing transit in the *Auto Innovative* city are mitigated somewhat

Figure 6.9: Per-capita energy consumption by vehicular and public transportation for a typical weekday across the prototype cities



Note: Base = Base Case; AMOD = AMOD Intro; AMOD NT = AMOD No Transit; AMOD TI = AMOD Transit Integration; AMOD CR = AMOD + Car Reduction. Privately owned vehicles are assumed to have powertrains distributed according to the *Reference* scenario in the base year, as described in Chapter 2; buses are all assumed to be diesel-powered; trains are electric; AMOD uses only battery-electric vehicles; and taxis and human-driven MOD in the Base Case are hybrid-electric vehicles. Well-to-tank energy efficiencies for gasoline, diesel, and electricity are 85.5%, 95.2%, and 33.4%, respectively. Total populations for the prototype cities are 2.77 million for *Auto Sprawl*, 4.60 million for *Auto Innovative*, and 5.61 million for *Mass Transit Heavyweight.*

Figure 6.10: Per-capita greenhouse gas emissions from transport for a typical weekday across the prototype cities



Note: Base = Base Case; AMOD = AMOD Intro; AMOD NT = AMOD No Transit; AMOD TI = AMOD Transit Integration; AMOD CR = AMOD + Car Reduction. Privately owned vehicles are assumed to have powertrains distributed according to the *Reference* scenario in the base year, as described in Chapter 2; buses are all assumed to be diesel-powered; trains are electric; AMOD uses only battery-electric vehicles; and taxis and human-driven MOD in the Base Case are hybrid-electric vehicles. Lifecycle emissions intensity (in grams carbon dioxide equivalent per kilowatt hour) for gasoline/diesel is 331 gCO$_2$e/kWh for all prototype cities; lifecycle emissions intensity for electricity is 438 gCO$_2$e/kWh for the *Auto* cities and 447 gCO$_2$e/kWh for the *Mass Transit Heavyweight* city. Total populations for the prototype cities are 2.77 million for *Auto Sprawl*, 4.60 million for *Auto Innovative*, and 5.61 million for *Mass Transit Heavyweight*.

by a shift to carpool and electrified AMOD, congestion effects still render the AMOD No Transit scenario unsustainable for this type of city.

Next, we consider the impact of requiring that AMOD be integrated with mass transit. We find that AMOD Transit Integration has minimal impacts on energy consumption and emissions in auto-dependent cities, but reduces energy consumption per capita compared to AMOD Intro in dense, transit-oriented cities. In the *Auto Sprawl* city, energy consumption decreases by 3% (the same as in AMOD Intro), while emissions decrease by 13% (–10% in AMOD Intro). In the *Auto Innovative* city, energy consumption increases by 13% (compared to 10% in AMOD Intro), while

**Table 6.6: Key assumptions related to energy consumption and greenhouse gas emissions calculations**

| | Gasoline | Diesel | Electricity |
|---|---|---|---|
| Well-to-tank energy efficiency (%) | 85.5 | 95.2 | 33.4 |
| Lifecycle emissions intensity ($gCO_2e/kWh$) | 331 | 331 | 438 (*Auto Sprawl, Auto Innovative*)<br>447 (*Mass Transit Heavyweight*) |

emissions remain unchanged compared to the Base Case (–1% in AMOD Intro). However, in our *Mass Transit Heavyweight* prototype city, integration of AMOD with transit decreases energy consumption by 9% (compared to +5% in AMOD Intro) and decreases emissions by 11% (+1% in AMOD Intro).

Finally, we consider whether accompanying the introduction of AMOD with policies that reduce household car ownership has an effect on energy consumption and emissions in our *Mass Transit Heavyweight* prototype city. We find that the AMOD + Car Reduction scenario results in a 16% reduction in energy consumption and a 20% reduction in emissions (compared to increases of 5% and 1%, respectively, in AMOD Intro). This suggests that an aggressive policy intervention to reduce household car ownership in combination with the introduction of an all-electrified AMOD fleet could produce significant reductions in energy consumption and emissions.

### 6.2.4 Summary

In the past few years, mobility on-demand services have grown rapidly in urban areas worldwide. At the same time, questions have arisen regarding the long-term viability of mass transit in cities. While significant uncertainty still surrounds autonomous vehicle (AV) technology, service models, and regulations, automation is expected to further reduce the costs of mobility on-demand, increasing its adoption in the future. Cities must be ready to adjust to the emergence of AMOD systems in order to ensure equitable levels of service and mitigate adverse environmental impacts. But significant uncertainty remains regarding how the introduction of AMOD services will interact with existing modes and complementary policy interventions, all in different urban environments. Therefore, this section discusses the results of a scenario analysis to investigate the impacts of AMOD introduction in three prototype cities: *Auto Sprawl*, *Auto Innovative*, and *Mass Transit Heavyweight*.

Our results show that in low-density auto-oriented cities in North America (represented by the *Auto Sprawl* prototype), AMOD will fill a latent demand for travel. In fact, AMOD services priced at 50% of current taxi fares could fully replace underutilized mass transit services in cities of this type, while retaining comparable levels of service. In dense, auto-dependent North American cities (the *Auto Innovative* prototype), introducing AMOD as a mode that competes with all other existing services will mildly increase congestion. However, AMOD cannot completely replace mass transit because this would lead to unacceptable increases in average travel time. The ensuing network congestion will also result in fewer trips being generated, thereby reducing accessibility. In both of these auto-oriented city types, introducing AMOD will increase VKT and congestion.

In the very large, densely populated, and transit-oriented cities of the world (such as London, Paris, Singapore, New York), which are represented by our *Mass Transit Heavyweight* prototype, the introduction of AMOD services will increase congestion, VKT by privately-owned cars and on-demand vehicles, energy consumption, and emissions. And these cities' high baseline levels of transit use make replacing mass transit with AMOD infeasible.

Given that introducing AMOD as a direct competitor to other existing modes generally leads to mild if not severe increases in congestion and VKT in our simulations, cities may consider complementary policies that can harness the accessibility gains of AMOD services while mitigating the negative impacts of these services on congestion and pollution. One such complementary policy could involve integrating AMOD services with existing mass transit. In all prototype cities, integrating AMOD with mass transit mitigates some, but not all, of the negative impacts of AMOD introduction.

Finally, as AMOD is introduced, some cities may consider complementary policies to reduce private car ownership as a way to mitigate congestion and pollution by shifting private vehicle trips to shared modes. We examined such a scenario in our *Mass Transit Heavyweight* prototype city to understand the consequences of this approach and to explore how mode share would shift to AMOD versus mass transit services. Our results show that, despite the displacement of private car use, the impact of empty AMOD miles between occupied trips still results in increased congestion relative to current conditions when AMOD introduction is coupled with a 25% reduction in car ownership. However, this scenario results in the greatest energy savings and emissions reductions under the assumption that the AMOD fleet is fully electrified.

As car ownership is projected to increase over the next several decades, cities will increasingly grapple with managing congestion. Strategies for integrating AMOD with mass transit and for encouraging the replacement of privately owned vehicles with on-demand services require exploration. Given that transit cannot and should not be eliminated in dense cities where transit already has significant mode share, the integration approach promises to boost existing transit ridership while efficiently deploying AMOD for shorter intra-zonal trips and first/last mile connectivity to transit stations. Thus, AMOD Transit Integration shows the most promise for dense and transit-oriented cities, as it mitigates some of the VKT and congestion impacts of AMOD introduction. It reverses the loss of transit ridership to AMOD services in all cities and significantly reduces private car trips in auto-dependent cities. Even with significant transit integration and significant reductions in car ownership, however, AMOD still results in increased congestion and VKT. So additional policies, such as congestion pricing strategies, may be needed to deliver more sustainable outcomes. Continued exploration of uncertainties in autonomous vehicle technology, policies, service characteristics, and consumer adoption is needed.

## 6.3 OBSTACLES FOR AUTONOMOUS VEHICLES

Autonomous vehicles (AVs) have the potential to transform the mobility landscape. Worldwide, more than 1.2 million people die annually in automobile-related road crashes. In the U.S. alone, road crashes claim the lives of more than 30,000 Americans each year while injuring millions more (Kalra and Groves 2017). The ensuing costs are significant. Medical bills, legal fees, property damage, and insurance administration costs (to name just some of the costs) total nearly $242 billion annually in the U.S. This figure rises to $1 trillion when quality of life valuations are considered (Blincoe, et al. 2015).

The overwhelming majority of road crashes can be blamed on human errors, such as driving while under the influence, drowsy, or distracted. Eliminating the dangers posed by such behaviors would, by some accounts, make AV technology among the most transformative public health developments in human history. The safety benefit comes from the fact that AVs promise to replace fallible human drivers with sensors, cameras, and radar—none of which can get drunk, bored, or distracted. Put simply, AV technology isn't bound by human error.

### 6.3.1 Autonomous Does Not Mean Humanless

However, fully autonomous technology—the kind that requires no human involvement—is a rarity in every sector of the economy. Autonomous does not mean humanless for two reasons (Nunes, Reimer, and Coughlin 2018). First, humans are more flexible, adaptable, and creative than

**Table 6.7: Types of intervention in a robo-taxi system**

| Intervention type | Safety related | Description |
|---|---|---|
| AV-initiated disengagement | Yes | AV system detects onset of a malfunction or encounters a situation that is beyond its operational parameters and hands vehicular control back to human operator. |
| Teleoperator-initiated | Yes | Teleoperator detects onset of an automation failure and takes back control of the vehicle. |
| Rider-initiated | No | Teleoperator takes control of the vehicle owing to a rider-initiated query/request. |

machines and thus are better able to respond to changing or unforeseen conditions (Chui, Manyika, and Miremadi 2016; Autor 2015; Wickens, et al. 2012). Second, machines can (and indeed, do) break down, making human oversight and intervention a social and regulatory necessity (Wickens, et al. 2012; Parasuraman and Wickens 2008).[6] Consequently, while industries including energy, manufacturing, and agriculture rely heavily on machines to turn a profit, human operators continue to exert an important influence (Flemisch, et al. 2012). This will, in our view, remain unchanged where AVs and the transportation sector are concerned (Nunes, Reimer, and Coughlin 2018).

Continued human involvement has safety and cost implications. We explored these implications in a shared mobility scenario—one where AVs are owned and operated by a firm, rather than by an individual consumer. This scenario is based on the expectation that AV ownership will be unaffordable for the general public during the early stages of AV deployment (Fagnant and Kockelman 2015). Although price drops are likely, AVs are expected to remain more costly than non-AVs for the foreseeable future. This is already reflected in existing vehicle prices where the inclusion of certain automated features, such as adaptive cruise control, night vision, and pedestrian detection, make vehicles equipped with these systems more expensive (Fagnant and Kockelman 2015).

### 6.3.2 Remote Oversight of Robo-taxis

To address the requirement for continued human involvement and oversight, we expect that for-hire, on-demand AVs (i.e., robo-taxis) will be overseen by so-called “teleoperators.” These individuals will watch over all aspects of robo-taxi operation from a remote control center and will intervene when conditions dictate (Table 6.7).

Safety-related interventions will involve activities like checking the operating status of the AV fleet, diagnosing the severity of AV sensor malfunctions and failures, and, in extreme cases, remotely maneuvering an AV to safety when onboard systems malfunction. Rider support will encompass situations such as responding to route selection inquiries and alleviating service performance concerns (for example, a rider may believe the AV is moving too slowly). Some AV developers have already assigned multiple human operators to guide AVs around unexpected obstacles, respond to rider requests, and solicit feedback (Higgins 2018). This type of setup will, we believe, continue to be needed as long as safety concerns surrounding AV technology persist. Our work explores the regulatory framework required to support teleoperated robo-taxi operations.

### 6.3.3 Current State of AV Regulations

To date, over $80 billion has been invested in developing AV technology (Kerry and Karsten 2017). While the level of future investment remains uncertain, the technology is developing

---

[6] There are no known instances where automation retains absolute control over safety-critical systems. Existing aircraft autopilot certification, for example, is based on human pilots identifying system failures and disabling the automation when appropriate. Fly-by-wire technology, often cited as affording protections against human error, only does so within specified parameters. Outside these parameters, human intervention is required.

rapidly enough that these investment trends are expected to continue ticking upwards (Kerry and Karsten 2017). Consequently, legislatures are—owing to fiscal and safety considerations—working to adopt appropriate supporting regulatory frameworks.

In 2017, Singapore, a leader in technology innovation, amended its Road Traffic Act to state that vehicles need not have a human driver. In exchange, AV operators must ensure that their vehicles either have appropriate levels of liability insurance or place a bond with local authorities that may be forfeited in the event of an accident. An emergency driver must also be available at all times to take control of the vehicle when necessary and AV operations are restricted to specified public roads.

China has adopted a similar approach. The central government, which had initially banned AVs from public roads, has since reversed course. AV companies may apply for permission to test AVs on a pre-approved set of roads. As in Singapore, each AV must carry sufficient liability insurance and have a human behind the wheel to intervene in the event of an emergency.

The regulatory landscape in the U.S. is more complex. As of August 2019, the first and only piece of AV legislation considered by Congress passed the U.S. House of Representatives in 2017 (H.R. 3388) but failed in the U.S. Senate in 2018 (S. 1885). The bill's future remains uncertain as some lawmakers oppose exempting AVs from certain existing safety requirements (a key component of the proposed legislation).

### 6.3.4 Legislative Gaps

The same questions regarding AV policy come up in different countries. Automakers and legislatures continue to debate what constitutes a driver, whether AVs can operate under existing law and, if not, whether exemptions should be granted to speed up AV deployment. However, two issues remain on the sidelines—issues that ultimately affect the financial viability of the robo-taxi concept in particular.

#### *Vehicle-to-human ratio*

Because autonomous does not mean humanless, teleoperators will be needed to oversee robo-taxi operation. However, this raises the issue of vehicle-to-teleoperator ratio: namely, how many robo-taxis should one teleoperator watch? The economics of the business seek cost savings on labor. Absent these savings, firms are better off using conventional vehicles. But if teleoperator costs can be spread over more robo-taxis—if the vehicle-to-human-oversight ratio is high enough to overcome the additional costs associated with remote oversight—AV fleets become more feasible. Maximizing this ratio, however, is likely to raise regulatory concerns over safety (Nunes 2018a). Hence, fleet operators must be prepared to assuage these concerns using evidence-based methods.

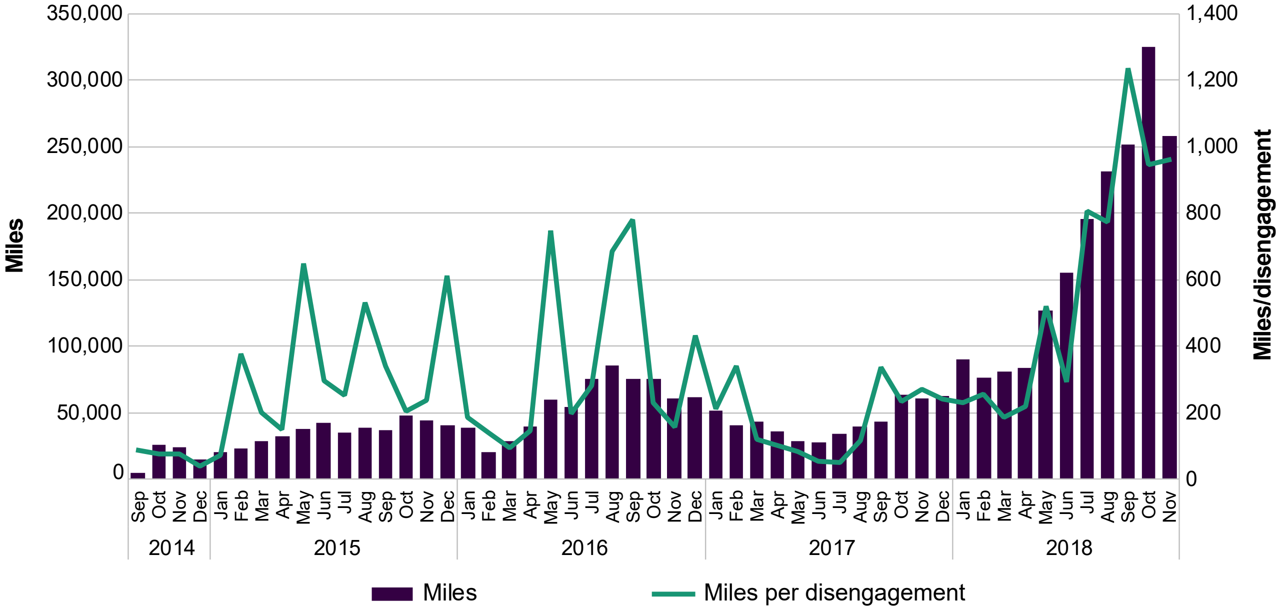
#### *Workforce classification*

Another unaddressed issue is the occupational cataloging of teleoperators. A patchwork of collective bargaining agreements and state laws caps the maximum number of working hours across professions. These caps are often more stringent for transportation-related professions, owing to the mental focus and concentration these professions demand and the risks entailed. Giving transportation workers—particularly drivers—more time off keeps them sharp and the public safe. The rise of robo-taxis would raise the question of whether teleoperators should be considered transportation workers (Nunes 2018a). Doing so would grant them the same downtime as taxi drivers and, many would say, help keep the roads safe. But the move would also cut into profit margins, as more staff must be hired to keep the business going.

### 6.3.5 Teleoperation Contributing Factors

Legislative efforts to resolve the aforementioned issues will depend on a complex interplay of psychological, technological, and sociological factors.

**Figure 6.11: Autonomous vehicle mileage and disengagement rate in California**



### *Monitoring load*

A setup with a high number of AVs per teleoperator raises safety concerns, since overseeing more AVs demands more mental effort from the teleoperator. This setup has been linked to lapses in human performance in other professions that can result in accidents (Ball, et al. 2013). Leveraging computer interfaces that reduce the mental demands of monitoring multiple AVs will be key to alleviating regulatory concerns over load maximization.

### *Disengagement frequency*

The likelihood that robo-taxis will require human intervention will be an important determinant of vehicle-to-operator ratios and worker classification. In California, a state where AV testing has become increasingly widespread, the law requires that companies testing AVs on public roads self-report miles driven autonomously as well as the number of incidents that cause the vehicle's self-driving system to disengage (California Department of Motor Vehicles 2019). We compiled this data and found that an increase in AV miles driven is positively correlated with the number of miles per disengagement, as shown in Figure 6.11. This means that the AVs being tested are recording fewer disengagements per mile, as the number of miles increases. Recent data show incidents of disengagement occurring once every close-to-1,000 miles driven. Further improvement in the disengagement rate is anticipated, but the rate is unlikely to reach zero anytime soon. Thus, some level of continued human oversight will be required.

### *Disengagement severity*

Disengagement severity refers to the level of effort a teleoperator must exert to resolve a disengagement. A minimal level of effort may involve, for example, pressing a button to ensure service continuity. By contrast, a high level of effort would require performing a complex series of mental and physical steps to keep the robo-taxi safe, such as steering the robo-taxi to the side of the road and bringing it to a safe stop when self-driving algorithms fail. Higher disengagement severity is expected to limit the vehicle-to-human ratio that is deemed safe.

### *Infrastructure integrity*

Robo-taxis must provide teleoperators with real-time data on what is happening around the vehicle to ensure effective safety oversight. This requires access to a fast and robust telecommunications network (i.e., 5G). However, geographical differences in network access and quality are likely to impede reliable, high-quality access in all locations. Travel through "dead zones" or areas where cellular reception is intermittent or unavailable, for example, could compromise a teleoperator's ability to determine if/when intervention is necessary. So could potential network reliability issues if demand for increased telecommunications bandwidth from both robo-taxis and the public at large exceeds supply. Digital inequity issues (Mabud and Seitz-Brown 2017) will need to be resolved for robo-taxis to achieve widespread adoption. While the anticipated rollout of 5G networks may help mitigate some of these concerns, ensuring integrity of communications may ultimately depend on the public sector's willingness and ability to spend taxpayer funds on infrastructure improvements.

#### *Public perception*

Surveys that measure public perceptions of AV safety are numerous, but their results show significant heterogeneity based on survey method and sample. Some surveys suggest a trend toward increased willingness to use AV technology (Edmonds 2018), whereas others suggest consumer hesitation (Smith and Anderson 2017). Our study of public perceptions of AV safety, which included individuals in 51 countries, serves to highlight the importance of disaggregating survey results by individual and context (Section 6.4). However, no studies to date have gauged public perception of a setup in which one teleoperator monitors many robo-taxis. Consumer acceptance of this type of setup will be an important determinant of robo-taxi success.

### 6.3.6 Operational Constraints

In lieu of the aforementioned issues, we envision operational constraints on robo-taxi operations. These constraints may be self-imposed (i.e., undertaken at the fleet operator's prerogative), imposed by fleet insurance companies, or required by law. Three operational constraints are—in our view—likely.

#### *Geofencing*

Robo-taxis will be geofenced—that is, operationally restricted to areas that have been properly mapped out and that have reliable telecommunication networks. Geofencing will allow fleet owners to limit robo-taxi exposure to edge cases—complex, potentially dangerous scenarios and situations that the vehicle (and teleoperator) may be ill-equipped to handle. This constraint may ease regulatory concerns over safety, particularly in environments where the consequences of an AV failure can be high. Fleet operators will likely geofence their operations to urban areas. This is because, despite their more complex environments, urban areas are able to more predictably sustain higher demands (and therefore revenues) throughout the day compared to rural areas. This will have a significant impact on the market share of AVs.

#### *Speed limits*

Owing to safety concerns, robo-taxi operations are likely to be speed restricted. Higher driving speeds lead to disproportionate increases in the number and severity of crashes (Richards 2010; International Traffic Safety Data and Analysis Group 2018). Consequently, speed caps are anticipated to help manage the technical and human-related safety risks posed by the technology. Speed caps may also help increase road capacity, since vehicles traveling at lower speeds can travel closer to each other, thereby increasing road throughput.

Speed restrictions notwithstanding, a key selling of point of AV technology is its potential to reduce the opportunity costs of driving. This allows for productivity gains as commuters' time is freed up to engage in other activities during the ride. By equipping the interior of their robo-taxis with productivity-enhancing amenities (Simlett 2017), robo-taxi operators might temper consumer concerns over longer-than-current commuting times.

*Weather, wildlife, and environmental conditions*

Restrictions may also be placed on the environmental conditions under which robo-taxis can operate. Snow, for example, changes how AV cameras and sensors perceive the street (World Economic Forum and Boston Consulting Group 2018). Similar problems are currently encountered by cameras and lasers in fog and heavy rain (Stock 2018). Although efforts are underway to address these issues (e.g., ground penetrating radar is currently being developed to improve navigation under snowy conditions), robo-taxi responsiveness is expected to be lower in inclement weather conditions. As a result, fleet operators may be forced to be more selective in where and when robo-taxis are deployed. Similar restrictions are envisioned in the presence of wildlife (World Economic Forum and Boston Consulting Group 2018).

### 6.3.7 Summary

In this section, we argue that no matter the sophistication of AV technology, the operation of for-hire, on-demand autonomous mobility services (or robo-taxis) will always require human oversight in the form of teleoperators. However, legislation still lags behind in terms of defining vehicle-to-human ratios, workforce classifications, and other key aspects of such teleoperations. New regulatory frameworks should account for monitoring load, disengagement frequency and severity, and public perceptions (particularly of AV safety) when addressing these aspects. Other operational constraints on robo-taxis may be imposed for safety reasons, including geofencing, speed limits, and operating restrictions under certain environmental conditions. Therefore, AV technology and AV-related regulations still have a long way to go before robo-taxi services can be widely and safely deployed.

However, the issues raised here should not detract from the value AV technology could offer. These systems could improve human quality of life, most notably by paring down road fatalities (Nunes 2018b; Kalra and Groves 2017; Fagnant and Kockelman 2015). But realizing these benefits requires widespread consumer adoption and a sound regulatory framework. Successful deployment of AV technology will require mature technology, remote oversight of AV operations, and supporting infrastructure to ensure robust communications.

## 6.4 INTERNATIONAL COMPARISON OF PERCEPTIONS OF AUTONOMOUS VEHICLE SAFETY

Numerous studies have investigated what factors correspond with increased interest in AVs, more positive attitudes regarding AV technology, and higher willingness to adopt, use, and buy AVs. In general, individuals who are younger, male, college-educated, and live in urban areas have more positive perceptions of AVs, including fewer concerns about AV safety and greater willingness to use the technology (Hulse, Xie, and Galea 2018; Kyriakidis, Happee, and de Winter 2015; Schoettle and Sivak 2014; Payre, Cestac, and Delhomme 2014; Nielsen and Haustein 2018; Smith and Anderson 2017). While most of these studies have been conducted in single cities or regions, some surveys have been conducted across multiple countries. Their findings suggest that public perceptions of AVs and the socio-demographics that predict these perceptions might vary widely between countries (Haboucha, Ishaq, and Shiftan, 2017; Sommer 2013; Lang, et al. 2016; Kyriakidis, Happee, and de Winter 2015). However, studies that do look across multiple regions often fail to partition observed variance in public attitudes into individual- and region-specific components, making it difficult to know whether observed differences reflect true differences in social and cultural context or simply differences in the individuals that reside in these regions.

For this study, we use data from the international mobility survey presented in Chapter 3 to construct a multilevel structural equation model that investigates people's self-reported awareness of AV technology, their perceptions of current AV safety, and their predictions about when AVs will be safe enough to use in the future. We center each of the socio-demographic variables by their country mean to remove any country variation from the estimation of individual-level regressions and estimate fixed effects (i.e., average trends across all individuals and countries in our international sample). Therefore, in contrast to results in the existing literature, our findings carefully address the nested structure of the data (with individuals within countries) and partition observed variance in awareness and perceptions of AV safety into individual and country components (Moody, Bailey, and Zhao 2019).

### 6.4.1 Trends Across Individuals

Across our international sample, we find that individuals who are younger, male, highly educated, fully employed, and who have higher than average household incomes report higher awareness of AV technology and more favorable perceptions of current AV safety. These individuals also predict a smaller number of years until AVs will be safe enough to use. Taken together, these individual-level results suggest that early adopters of AVs (across all countries) might be younger, wealthier, and more educated males. In addition, we find that individuals who currently own or lease a car (car owners), as well as individuals who drive a car as their typical weekday mode of transport (car users), have greater awareness of AV technology and more optimistic perceptions of current and future AV safety.

Looking at correlations among outcome variables, we find that an individual's level of awareness of AVs is moderately correlated with current perceptions (0.374) and future predictions of AV safety (-0.253). This means that individuals who are more aware of AV technology have more positive current perceptions of AV safety and more optimistic predictions about how soon AVs will be safe enough to use. These results might suggest that increasing levels of awareness and familiarity with AV technology could help mitigate concerns about AV safety, reducing this attitudinal barrier to the technology's rapid adoption.

### 6.4.2 Trends Across Countries

Our multilevel modeling structure allows us to determine what percentage of observed variance in our outcome variables is attributable to individuals or to countries. We find that most of the variance in awareness of AV technology, perceptions of current AV safety, and predictions of future AV safety is attributable to differences across individuals rather than countries. However, small but statistically significant variations do exist across countries after controlling for individual-level factors (Figure 6.12).

In particular, we find that North Americans report high awareness of AV technology, but are relatively pessimistic in their views of current and future AV safety. On the other hand, residents of large developing countries in the global south—particularly, Brazil, India, and China—report high awareness of AV technology as well as optimistic views of future AV safety. Considering bivariate correlations between our country intercepts and indicators of national wealth, income inequality, motorization levels, and road safety, we find that respondents in countries with lower GDP per capita (adjusted by purchasing power parity), higher income inequality (as measured by Gini indices), lower vehicle usage and ownership, and greater numbers of road deaths—all common characteristics of developing countries—are more optimistic about current and future AV safety.

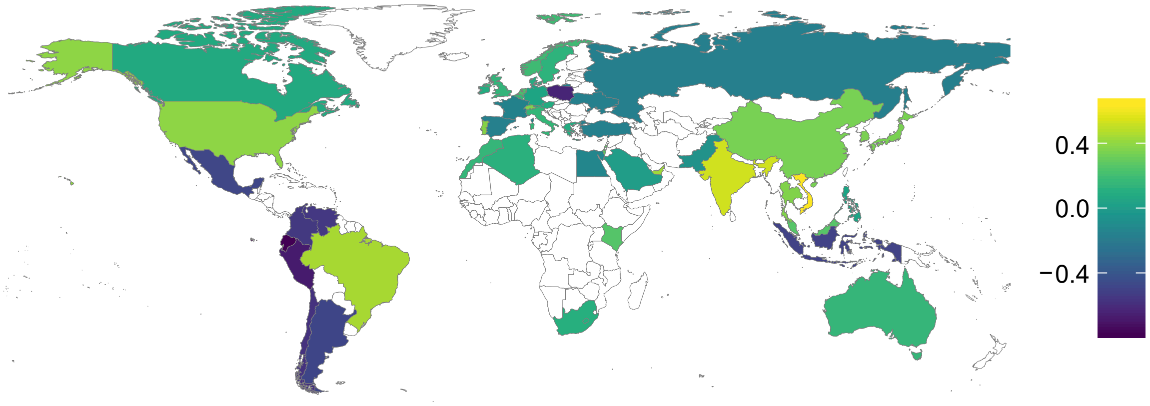
### 6.4.3 Summary

Our results suggest that optimistic public perceptions and predictions of AV safety may create a market for early adoption among individuals who are young, male, highly educated, high-income, urban, and car consuming across all countries. For the rest of the population, AVs have yet to demonstrate their safety and viability as an alternative mode of transportation.

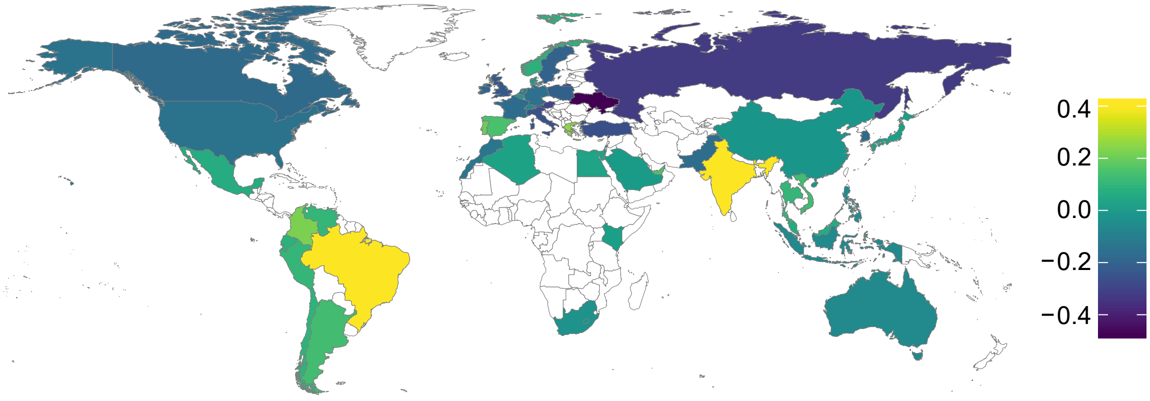
While most of the variation in AV awareness and perceptions of current and predictions of future AV safety are attributable to individuals, we do find small, but significant variation at the country level. We find that people in developing countries with lower national wealth, greater income inequality, lower car ownership and usage, and higher rates of road accidents also exhibit more optimistic perceptions and predictions of AV safety. Thus, our survey provides initial evidence that public perception may drive faster adoption of AVs in developing countries, which could

**Figure 6.12: Country variation in (a) AV awareness, (b) perceptions of current AV safety, and (c) predictions of years until AVs will be safe enough to use**

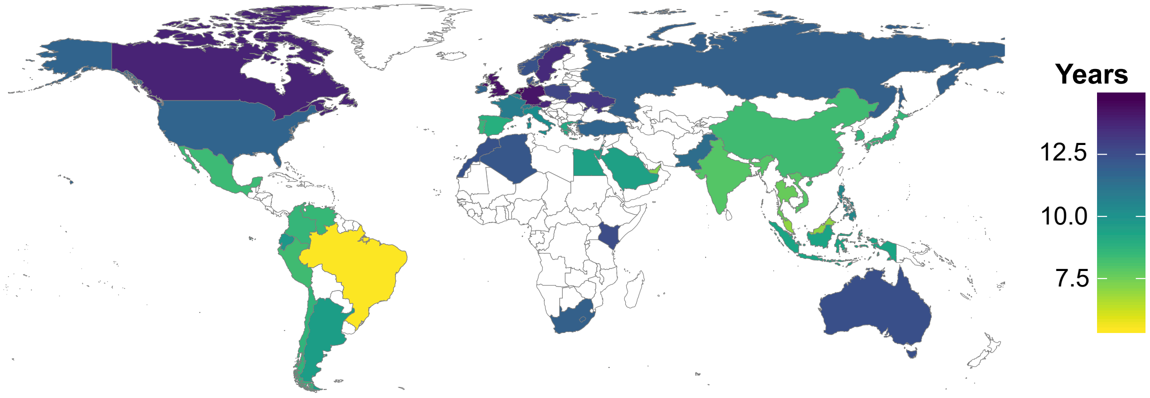
**(a) AV awareness**



**(b) Perceptions of current AV safety**



**(c) Years until AVs are safe enough to use**



improve road safety in those countries that face the greatest road safety challenges. However, public perception is only one of many barriers to AV implementation. The benefits of this technology will be realized only if legal, economic, and political barriers are resolved and if AVs are truly safer than human-driven vehicles on the road.

## 6.5 CONCLUSION

Urban mobility systems and the challenges they face vary significantly from city to city and from country to country. To provide a framework for investigating current and future urban mobility systems, we perform a clustering analysis using data from 331 cities around the world. We identify 12 city types that capture key differences in urban travel and economic characteristics. For three of these city types, we create prototype cities—*Auto Sprawl*, *Auto Innovative*, and *Mass Transit Heavyweight*—and develop simulation models that allow us to capture trip-level decision-making in existing mobility systems and explore scenarios of future mobility service disruptions. In particular, we consider different ways in which autonomous mobility on demand (AMOD) services may be introduced into existing urban mobility systems, and how the impacts of AMOD services might vary based on existing transportation modes and infrastructure conditions across city types.

In low-density, auto-oriented cities in North America (consistent with our *Auto Sprawl* prototype), our results suggest that AMOD will fill a latent demand for travel and could replace current low-frequency mass transit service. In denser North American cities with higher baseline mass transit mode share (the *Auto Innovative* prototype city), introducing AMOD as a direct competitor to, or complete substitute for, mass transit leads to severe increases in traffic congestion and kilometers traveled by privately-owned and on-demand vehicles. These impacts are even more significant in large, densely populated, and transit-oriented cities (the *Mass Transit Heavyweight* prototype). Therefore, in dense cities with established mass transit services, policies that require new AMOD to be integrated with existing mass transit systems (for example, as a complementary first-/last-mile connector in a multimodal system) can bring mobility benefits while partially mitigating negative consequences in terms of congestion, vehicle kilometers traveled, energy consumption, and emissions. Cities may also consider policies, such as restricting private vehicle ownership or use, to encourage the use of AMOD as a way to replace single-occupancy vehicle trips, rather than as a way to replace trips that would otherwise be made using mass transit or non-motorized modes (such as walking or bicycling).

We complemented these demand–supply scenarios by exploring other uncertainties related to the regulatory and consumer environment for AMOD services. We argue that there will be a need for teleoperators to oversee AMOD operations, and that operational limits may need to be imposed to ensure the safety of these services. We also look at how individuals in different countries perceive AV safety. At the level of individual consumers, our results suggest that optimistic perceptions of AV safety may create a market for early adoption among young, male, highly educated, high-income, urban, and car-consuming individuals across all countries. The rest of the population remains more skeptical of the potential for AVs to be a safe alternative mode of transportation. At the country level, our survey provides initial evidence that public perception may drive faster adoption of AVs in developing countries, potentially improving road safety in countries that face the greatest road safety challenges.

Overall, this chapter highlights the fact that the development of AV technology is only one of many areas of uncertainty with respect to when and how AVs will disrupt existing urban mobility systems. Planning for an AV future requires additional consideration of how AVs will operate in a fleet context and how they will interact with existing travel modes, urban infrastructure, regulatory frameworks, and consumer behaviors.

## 6.6 REFERENCES

Adnan, Muhammad, Francisco C. Pereira, Carlos Lima Azevedo, Kakali Basak, Milan Lovric, Sebastian Reveau Feliu, Yi Zhu, Joseph Ferreira, P. Christopher Zegras, and Moshe E. Ben-Akiva. 2016. "SimMobility: A Multi-Scale Integrated Agent-Based Simulation Platform." Paper presented at the 95th Annual Meeting of the Transportation Research Board, Washington, D.C., January 10–14. https://pdfs.semanticscholar.org/9fdf/aef2ca681cac53ea83a6bbf814f0f8aaff13.pdf

Autor, David. 2015. "Why Are There Still So Many Jobs? The History and Future of Workplace Automation." *Journal of Economic Perspectives* 29, no. 3 (Summer): 3–30. https://doi.org/10.1257/jep.29.3.3

Ball, Jane E., Trevor Murrells, Anne Marie Rafferty, Elizabeth Morrow, and Peter Griffiths. 2013. "'Care Left Undone' During Nursing Shifts: Associations with Workload and Perceived Quality of Care." *BMJ Quality and Safety* 23, no. 2: 116–125. https://doi.org/10.1136/bmjqs-2012-001767

Barrios, John Manuel, Yael V. Hochberg, and Hanyi Yi. 2019. "The Cost of Convenience: Ridesharing and Traffic Fatalities." Working Paper No. 2019-49. Chicago, IL: University of Chicago, Becker Friedman Institute for Economics. https://bfi.uchicago.edu/working-paper/the-cost-of-convenience-ridesharing-and-traffic-fatalities/

Basu, Rounaq, Andrea Araldo, Arun Prakash Akkinepally, Bat Hen Nahmias Biran, Kalaki Basak, Ravi Seshadri, Neeraj Deshmukh, Nishant Kuman, Carlos Lima Azevedo, Moshe Ben-Akiva. 2018. "Automated Mobility-on-Demand vs. Mass Transit: A Multi-Modal Activity-Driven Agent-Based Simulation Approach." *Transportation Research Record: Journal of the Transportation Research Board* 2672, no. 8 (Dec): 608–618. https://doi.org/10.1177/0361198118758630

Blincoe, Lawrence J., Ted R. Miller, Eduard Zaloshnja, and Bruce A. Lawrence. 2015. *The Economic and Societal Impact of Motor Vehicle Crashes, 2010 (Revised)*. DOT HS 812 013. Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA). https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812013

Bloomberg Aspen Initiative on Cities and Autonomous Vehicles. 2018. "Is Your City Getting Ready for AVs? This Is a Guide to Who's Doing What, Where, and How." *Bloomberg.org Group*. Accessed August 29, 2019. https://avsincities.bloomberg.org/

California Department of Motor Vehicles. 2019. "Testing of Autonomous Vehicles with a Driver." Accessed August 29, 2019. https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/testing

Chui, Michael, James Manyika, and Mehdi Miremadi. 2016. "Where Machines Could Replace Humans—and Where They Can't (Yet)." *McKinsey Quarterly*, July. https://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/where-machines-could-replace-humans-and-where-they-cant-yet

Edmonds, Ellen. 2018. "More Americans Willing to Ride in Fully Self-Driving Cars." *AAA NewsRoom*, January 24. https://newsroom.aaa.com/2018/01/americans-willing-ride-fully-self-driving-cars/

Fagnant, Daniel J., and Kara Kockelman.2015. "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations." *Transportation Research Part A: Policy and Practice* 77 (July): 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Flemisch, Frank, Matthias Heesen, Tobias Hesse, Johann Kelsch, Anna Schieben, and Johannes Beller. 2012. "Towards a Dynamic Balance Between Humans and Automation: Authority, Ability, Responsibility and Control in Shared and Cooperative Control Situations." *Cognition, Technology & Work* 14, no. 1 (March): 3–18. https://doi.org/10.1007/s10111-011-0191-6

Grab. 2019. "GrabCar: Chauffeured Cars for Your Every Need." www.grab.com/sg/car/

Haboucha, Chana J, Robert Ishaq, and Yoram Shiftan. 2017. "User Preferences Regarding Autonomous Vehicles." *Transportation Research Part C: Emerging Technologies* 78 (May): 37–49. https://doi.org/10.1016/j.trc.2017.01.010

Higgins, Tim. 2018. "Driverless Cars Still Handled by Humans—From Afar." *Wall Street Journal*, June 5. https://www.wsj.com/articles/who-does-a-driverless-car-call-when-it-needs-help-a-human-1528191000

Hulse, Lynn M., Hui Xie, and Edwin R. Galea. 2018. "Perceptions of Autonomous Vehicles: Relationships with Road Users, Risk, Gender and Age." *Safety Science* 102 (Feb): 1–13. https://doi.org/10.1016/j.ssci.2017.10.001

International Traffic Safety Data and Analysis Group (IRTAD). 2018. *Speed and Crash Risk*. Research Report. Paris, France: International Transport Forum (ITF). https://www.itf-oecd.org/sites/default/files/docs/speed-crash-risk.pdf

Kalra, Nidhi, and David G. Groves. 2017. T*he Enemy of Good: Estimating the Cost of Waiting for Nearly Perfect Automated Vehicles*. Santa Monica, CA: RAND Corporation. https://www.rand.org/pubs/research_reports/RR2150.html

Kerry, Cameron F., and Jack Karsten. 2017. *Gauging Investment in Self-Driving Cars*. Washington, D.C.: The Brookings Institution. https://www.brookings.edu/research/gauging-investment-in-self-driving-cars/

Kyriakidis, Miltos, Riender Happee, and Joost C F de Winter. 2015. "Public Opinion on Automated Driving: Results of an International Questionnaire among 5000 Respondents." *Transportation Research Part F: Traffic Psychology and Behaviour* 32 (July): 137–140. https://doi.org/10.1016/j.trf.2015.04.014

Lanctot, Roger. 2017. *Accelerating the Future: The Economic Impact of the Emerging Passenger Economy*. Newton, MA: Strategy Analytics. https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/05/passenger-economy.pdf

Lang, Nikolaus, Michael Rüßmann, Antonella Mei-Pochtler, Thomas Dauner, Satoshi Komiya, Xavier Mosquet, and Xanthi Doubara. 2016. "Self-Driving Vehicles, Robo-Taxis, and the Urban Mobility Revolution." The Boston Consulting Group (BCG) and the World Economic Forum (WEF). https://www.bcg.com/en-us/publications/2016/automotive-public-sector-self-driving-vehicles-robo-taxis-urban-mobility-revolution.aspx

Le Vine, Scott, and John Polak. 2014. "Automated Cars: A Smooth Ride Ahead? ITC Occasional Paper No 5." London, UK: Independent Transport Commission. http://www.theitc.org.uk/docs/114.pdf

Mabud, Rakeen, and Marybeth Seitz-Brown. 2017. *Wired: Connecting Equity to a Universal Broadband Strategy*. New York, NY: Roosevelt Institute. https://rooseveltinstitute.org/wp-content/uploads/2017/09/Wired_Roosevelt-Institute.pdf

Marshall, Aarian. 2017. "After Peak Hype, Self-Driving Cars Enter the Trough of Disillusionment." *Wired*, December 29. https://www.wired.com/story/self-driving-cars-challenges/

Moody, Joanna C, Nathaniel K Bailey, and Jinhua Zhao. 2019. "Public Perceptions of Autonomous Vehicle Safety: An International Comparison." *Safety Science*. https://doi.org/10.1016/j.ssci.2019.07.022

Nielsen, Thomas Alexander Sick, and Sonja Haustein. 2018. "On Sceptics and Enthusiasts: What Are the Expectations towards Self-Driving Cars?" *Transport Policy* 66 (Aug): 49–55. https://doi.org/10.1016/j.tranpol.2018.03.004

Norman, Hannah. 2018. "General Motors' Robo-Taxis to Take on Uber, Lyft in San Francisco." *San Francisco Business Times*, July 5. https://www.bizjournals.com/sanfrancisco/news/2018/07/05/gm-robo-taxis-uber-lyft-sf.html

Nunes, Ashley. 2018a. "Robotaxis Are Coming. So Why Are We Still So Unprepared?" *Wired*, November 2. https://www.wired.com/story/robotaxis-are-coming/

———. 2018b. "Self-Driving Cars Are on the Road to Nowhere." *Foreign Policy*, July 19. https://foreignpolicy.com/2018/07/19/self-driving-cars-are-on-the-road-to-nowhere/

Nunes, Ashley, Bryan Reimer, and Joseph F. Coughlin. 2018. "People Must Retain Control of Autonomous Vehicles." *Nature* 556 (April): 169–171. https://doi.org/10.1038/d41586-018-04158-5

Oke, Jimi B, Youssef M. Aboutaleb, Arun Akkinepally, Carlos Lima Azevedo, Yafei Han, P. Christopher Zegras, Joseph Ferreira, and Moshe E. Ben-Akiva. 2018. "A Novel Global Urban Typology Framework for Sustainable Mobility Futures." *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab22c7

Oke, Jimi B., Arun Akkinepally, Siyu Chen, Youssef M. Aboutaleb, Yifei Xie, Carlos Lima Azevedo, P. Christopher Zegras, Joseph Ferreira, and Moshe E. Ben-Akiva. 2019. "Evaluating Systemic Effects of Automated On-Demand Services through Large-Scale, Agent-Based Simulation of Auto-Dependent, Prototype Cities." [working paper].

Parasuraman, Raja and Christopher D. Wickens. 2008. "Humans: Still Vital after All These Years of Automation." *Human Factors* 50, no. 3 (June): 511–520. https://doi.org/10.1518/001872008X312198

Pavone, Marco. 2015."Autonomous Mobility-on-Demand Systems for Future Urban Mobility." In *Autonomes Fahren: Technische, Rechtliches und Gesellschaftliche Aspekte*, edited by Markus Maurer, J. Christian Gerdes, Barbara Lenz, and Hermann Winner, 399–416. Berlin, Germany: Springer Vieweg. https://doi.org/10.1007/978-3-662-45854-9_19

Payre, William, Julien Cestac, and Patricia Delhomme. 2014. "Intention to Use a Fully Automated Car: Attitudes and *a priori* Acceptability." *Transportation Research Part F: Traffic Psychology and Behaviour* 27, no. B (Nov): 252–263. https://doi.org/10.1016/j.trf.2014.04.009

Richards, D. C. 2010. *Relationship between Speed and Risk of Fatal Injury: Pedestrians and Car Occupants*. Road Safety Web Publication No. 16. London, United Kingdom: Department for Transport, Transport Research Laboratory. https://webarchive.nationalarchives.gov.uk/20121105041920/http://assets.dft.gov.uk/publications/pgr-roadsafety-research-rsrr-theme5-researchreport16-pdf/rswp116.pdf

Romero, Simon. 2018. "Wielding Rocks and Knives, Arizonans Attack Self-Driving Cars." *The New York Times*, December 31. https://www.nytimes.com/2018/12/31/us/waymo-self-driving-cars-arizona-attacks.html

Sage, Alexandria. 2018. "Waymo Unveils Self-Driving Taxi Service in Arizona for Paying Customers." *Reuters*, December 5. https://www.reuters.com/article/us-waymo-selfdriving-focus/waymo-unveils-self-driving-taxi-service-in-arizona-for-paying-customers-idUSKBN1O41M2

Schaller, Bruce. 2018. *The New Automobility: Lyft, Uber, and the Future of American Cities*. Brooklyn, NY: Schaller Consulting. http://www.schallerconsult.com/rideservices/automobility.htm

Schoettle, Brandon, and Michael Sivak. 2014. *Public Opinion about Self-Driving Vehicles in China, India, Japan, the U.S., the U.K., and Australia*. Technical Report UMTRI-2014-30. Ann Arbor, MI: University of Michigan Transport Research Institute. https://core.ac.uk/download/pdf/73941168.pdf

Silver, David. 2018. "Waymo Has the Most Autonomous Miles, by a Lot." *Forbes*, July 26. https://www.forbes.com/sites/davidsilver/2018/07/26/waymo-has-the-most-autonomous-miles-by-a-lot/#1c1283ef7ee5

Simlett, John. 2017. "Can Driverless Cars Be the Destination?" *Ernst & Young*, October 1. https://www.ey.com/en_gl/automotive-transportation/can-driverless-cars-be-the-destination

Smith, Aaron. 2016. *Shared, Collaborative, and On-Demand: The New Digital Economy*. Washington, D.C.: Pew Research Center. https://www.pewinternet.org/2016/05/19/the-new-digital-economy/

Smith, Aaron, and Monica Anderson. 2017. *Automation in Everyday Life*. Washington, D.C.: Pew Research Center. https://www.pewinternet.org/2017/10/04/automation-in-everyday-life/

Sommer, Klaus. 2013. *Continental Mobility Study 2013*. Hanover, Germany: Continental AG. https://www.continental.com/resource/blob/7380/6cddc571cd3d3b5cacd279fe0d1a00c1/mobility-study-2013-data.pdf

Stock, Kyle. 2018. "Self-Driving Cars Can Handle Neither Rain nor Sleet nor Snow." *Bloomberg Businessweek*, September 17. https://www.bloomberg.com/news/articles/2018-09-17/self-driving-cars-still-can-t-handle-bad-weather

Taxi-calculator.com. 2019. "Get Your Taxi Fare Now!," *SIR Media GmbH*. www.taxi-calculator.com

Uber Technologies, Inc. 2019. "How Much Does a Ride with Uber Cost?" https://www.uber.com/us/en/price-estimate/

United Nations, Department of Economic and Social Affairs, Population Division. 2018. *World Urbanization Prospects: The 2018 Revision*. https://population.un.org/wup/

Vincent, James. 2016. "World's First Self-Driving Taxi Trial Begins in Singapore." *The Verge*, August 25. https://www.theverge.com/2016/8/25/12637822/self-driving-taxi-first-public-trial-singapore-nutonomy

Wadud, Zia, Don MacKenzie, and Paul Leiby. 2016. "Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles." *Transportation Research Part A: Policy and Practice* 86 (April): 1–18. https://doi.org/10.1016/j.tra.2015.12.001

Wakabayashi, Daisuke. 2018. "Uber's Self-Driving Cars Were Struggling before Arizona Crash." *The New York Times*, March 23. https://www.nytimes.com/2018/03/23/technology/uber-self-driving-cars-arizona.html

Wickens, Christopher D., Justin G. Hollands, Simon Banbury, and Raja Parasuraman. 2012. *Engineering Psychology and Human Performance*, Fourth edition. London, United Kingdom: Routledge.

Windsor, Richard. 2018. "If Waymo Is Having Difficulty, Everyone Else Must Be in a Right Autonomous Driving Pickle." *Forbes*, November 28. https://www.forbes.com/sites/richardwindsoreurope/2018/11/28/if-waymo-is-having-difficulty-everyone-else-must-be-in-a-right-autonomous-driving-pickle/#2fa8896d8b54

World Economic Forum (WEF) and Boston Consulting Group (BCG). 2018. *Reshaping Urban Mobility with Autonomous Vehicles: Lessons from the City of Boston*. Geneva, Switzerland: WEF. https://www.weforum.org/reports/reshaping-urban-mobility-with-autonomous-vehicles-lessons-from-the-city-of-boston

Zhang, Wenwen, and Subhrajit Guhathakurta. 2017. "Parking Spaces in the Age of Shared Autonomous Vehicles: How Much Parking Will We Need and Where?" *Transportation Research Record: Journal of the Transportation Research Board* 2651, no. 1 (Jan): 80–91. https://doi.org/10.3141/2651-09

## Chapter 7

# Conclusion

Mobility is central to human wellbeing: It enables access to opportunities and fosters prosperity, quality of life, and social connections. Today, billions of people around the world enjoy a level of personal mobility that would have been unimaginable just a few generations ago. But the technologies and infrastructure that have evolved over the last one hundred years to deliver personal mobility fall short of satisfying the demands of the 21st century. In many countries, access to transportation remains highly unequal, reflecting and perpetuating larger socio-economic disparities. At the same time, traffic congestion plagues millions of commuters and impacts the economies of large metropolitan areas around the world. Private motor vehicles, despite significant advances in performance, comfort, and safety, remain a major source of negative externalities. They cause millions of road injuries and fatalities each year and contribute to both unhealthy levels of local air pollution and rising emissions of planet-warming greenhouse gases.

As the world's population continues to grow and incomes rise, vehicle ownership is within reach of hundreds of millions more consumers. It is also clear that existing mobility systems that rely on the petroleum-powered, privately owned vehicle will need to change. What remains highly uncertain, albeit profoundly consequential, is how future mobility might evolve—and what those changes in mobility could mean in terms of addressing related public policy imperatives, from reducing congestion to mitigating global climate change.

This study focused on light-duty vehicles, which are both the main mode of personal transportation in most of the world and the largest source of mobility-related externalities. Our analysis has explored some of the key drivers that are likely to influence personal transportation systems and individual travel behavior over the next three decades. Rather than predict the most likely future, or attempt to present a vision for the "best" future, we adopted a "what if" approach. That is, our analyses are designed to identify the main drivers of change (i.e., technology, economics, policy, and consumer behavior/preference), assess their potential impacts, and develop insights about how they interact with one another.

Our analysis produced several key findings. Through modeling the effect of climate change policies, we find that reducing the carbon intensity of the light-duty vehicle fleet—through fuel efficiency improvements and increased uptake of alternative fuel vehicles—contributes to mitigation goals, but is only part of the solution to achieving global emission reduction targets. Current international goals for limiting future warming will require aggressive policy actions. We modeled a scenario that is consistent with limiting expected global average warming to 2°C—a widely cited international goal. In this scenario, global carbon dioxide emissions from fossil fuel combustion and industrial processes were reduced by approximately 50% below 2015 emissions levels by 2050, or by approximately 60% relative to projected 2050 emissions in our modeling scenario that assumes the world does not follow commitments made under the Paris Agreement.

In that timeframe, the largest contribution to global emission reductions is expected to come from the electricity sector, where mitigation options are more abundant and less expensive than in the transportation sector. Decarbonization of the electric grid is also a major motivator to use hydrogen for large-scale energy storage, with potential benefits for transportation and other segments of the economy. Coupled with substantial reductions in the carbon intensity of the electricity supply, large-scale electrification of the light-duty vehicle fleet is expected to play an important role. However, ongoing improvements in fuel economy for internal combustion engine vehicles will also be critical in the near- to mid-term. To produce these outcomes, market forces will not be enough. Substantial uptake of plug-in electric vehicles or hydrogen fuel cell vehicles, for example, will require continued policy and financial support, given their cost and charging and fueling disadvantages relative to conventional internal combustion engine vehicles and the hurdles involved in building out the necessary infrastructure. Our analysis indicates that battery electric vehicles are likely to remain more expensive for consumers to purchase than internal combustion engine vehicles for at least the next decade. Moreover, even with cost parity between alternative fuel vehicles and conventional vehicles, other factors such as driving range and convenience of charging or fueling will shape the adoption curve for alternative fuel vehicles, including plug-in electric, battery electric, and hydrogen fuel cell vehicles.

Advances in powertrain technologies and fuels will not have a direct effect on road safety, congestion, and other challenges related to light-duty vehicle use. To address these issues, many look to the future convergence of autonomous vehicle technology and on-demand service models. Autonomous vehicles have drawn considerable interest for their potential to radically alter patterns of vehicle use and potentially improve road safety. We find, however, that autonomous vehicle technology is not as close to maturity as is sometimes portrayed. Significant technical, regulatory, and public perception issues need to be addressed before we will see significant deployment. Even if these hurdles can be overcome, the potential for unintended consequences, as with all transformative technologies, must also be considered. For example, our models suggest that using fleets of autonomous vehicles to provide door-to-door ride-hailing services in competition with mass transit and non-motorized transport would be unsustainable in large, dense cities, and would lead to significant congestion challenges. On the other hand, deploying advanced autonomous vehicles as part of an integrated multimodal system with mass transit as its backbone could hold promise for expanding access to personal mobility and improving the efficiency of the overall transport system.

More broadly, we find that major shifts in consumer perceptions and behaviors are needed to enable new technologies and business models for personal mobility to achieve adoption at scale. Conversely, symbolic and emotional factors that drive the desire to own a personal vehicle (such as car pride), particularly among individuals in emerging economies, could be a significant barrier to the widespread adoption of more sustainable technologies and services. Additional analysis in the U.S. finds no difference in vehicle ownership preferences between millennials and baby boomers after controlling for socio-economic circumstances. The results suggest that changes in attitudes and consumer behaviors are unlikely to happen organically absent proactive efforts to shape new social norms through, for example, policies aimed at pricing mobility-related externalities.

In drawing conclusions from these findings and identifying priorities for future research, it is useful to review some of the limitations of our study. First, the data-driven nature of much of our analysis is built on historical trends and current conditions rather than conceptual or theoretical projections. This approach could fail to capture drastic shocks to the evolution of future personal mobility, should new technologies or business models penetrate much faster and on a larger scale than historic and current market conditions suggest. For example, we did not examine changes that could radically reshape the landscape for personal transportation such as a scenario in which ride-hailing services and the sharing economy largely replace private vehicle ownership and use, or a scenario in which autonomous vehicle technology becomes ubiquitous. Likewise, we do not consider the possibility that renewable-powered electrolysis becomes a low-cost power source for distributed hydrogen fuel or the possibility that most cities around the world impose pricing schemes or restrictions on car ownership and use. Second, it is important to note that, while some of the studies and modeling tools we used account for heterogeneity across individual tastes and contexts, most of our analyses are designed to estimate aggregate impacts. Thus, further research would be needed to break down these benefits and costs and to look at how impacts are distributed across socio-demographic groups and geographies.

Finally, given that our scope was light-duty vehicles, further research could expand our analyses to look at additional important questions related to personal mobility by other modes, such as mass transit. For example, future research could explore the evolution of new technologies, systems, and business models for mass transit and other shared mobility platforms and their implications for personal vehicle use. Furthermore, other studies could consider the role of additional factors—from urban design and land-use planning, to changing household structures and workplace norms—that will play a role in shaping future mobility choices.

Our assessment of emerging mobility challenges and current trends highlights the need for innovation in both the private and public sectors if we are to improve transportation systems. From the private sector, continued innovation in transportation technologies and business models is critical. However, our analysis suggests that technology and market forces alone will not produce change on the scale or at the rate needed to address the world's most important mobility challenges. Well-designed and timely policy actions from the public sector are needed to expand access to safe, efficient, equitable, and more environmentally sustainable mobility options. In the near- and mid-term, the largest changes are likely to come from more effective deployment and widespread adoption of existing policy mechanisms, such as congestion pricing, stricter vehicle fuel efficiency standards, subsidies for alternative fuel vehicles with complementary policies to reduce the carbon intensity of electricity production, and investments in mass transit systems. Over the longer term, policy actions could help reshape social norms surrounding vehicle ownership and use as new technologies and business models enter the market. Only through careful consideration of the multifaceted impacts of new technologies, policies, and markets will we be able to anticipate and shape a future of mobility that works better for people and for our planet.

## Afterword

# Visions for Future Mobility

This study has provided key insights into how technology, economics, policy, and consumer behavior may work together toward more sustainable future mobility. Many of these insights are based on models that use historical data, current conditions, and plausible scenarios to explore potential future outcomes. This data-driven, descriptive approach is best at identifying how various combinations of factors could realistically lead to different mobility futures, thereby helping us to demonstrate how personal mobility might benefit if it evolves out of current mobility practices and norms. What this descriptive approach lacks is a normative vision for what the future should be. Therefore, this afterword complements the summary of descriptive findings presented in Chapter 7 (Conclusion) with a series of thought pieces on what the future of mobility could or should be, as well as perspectives on the challenges that will need to be overcome.

We invited four MIT faculty involved in this study to offer their visions for the mobility of the future. While informed by extensive work in their respective disciplines, each of these visions reflects the author's personal perspective. The first two pieces focus on climate change and, to a lesser extent, local air pollution. In the first piece, Sergey Paltsev, Deputy Director of the MIT Joint Program on the Science and Policy of Global Change (the Joint Program) and a Senior Research Scientist at the MIT Energy Initiative (MITEI), and Jennifer Morris, a Research Scientist at the Joint Program, highlight the imperative of moving all sectors of the economy, including transportation, toward net-zero carbon emissions even though existing technologies and policy mechanisms are imperfect. In the second piece, Christopher Knittel, the George P. Shultz Professor of Applied Economics and Director of the MIT Center for Energy and Environmental Policy Research (CEEPR), discusses why the threat of climate change is such a difficult issue to address geopolitically. The third and fourth pieces in this afterword expand the discussion beyond climate change to consider other important aspects of mobility, including congestion, accessibility and quality of life, and the design of urban space. In the third piece, William Green, the Hoyt C. Hottel Professor of Chemical Engineering and faculty chair of this study, provides an engineer's perspective on the evolution of mobility to 2050, discussing how new technologies and services might develop in urban, rural, and suburban areas. In the fourth piece, Jinhua Zhao, the Edward and Joyce Linde Associate Professor of Transportation and City Planning, describes a multifaceted framing of mobility and its value in terms of sustainability, public health, personal identity, urban development, social justice and equity, and much more.

Each piece offers a stand-alone vision, and there are clear areas of divergence. Some experts advocate for immediate political action, even if it is imperfect, while others are wary of the potential downsides of hasty and ineffective policy. Some argue for a move to 100% zero-emission vehicles, while others see a perpetual place for (increasingly fuel-efficient) fossil fuel-powered internal combustion engine vehicles. There is also a tension between emphasizing the need for individual countries to step up as political and technological leaders and recognizing the importance of international collaboration.

Among these diverse opinions, readers will also find areas of commonality. Multiple authors agree that the transportation sector must evolve alongside other sectors of the economy, particularly the energy sector, in order to achieve a sustainable future. And all authors echo the need for bold and smart policy that is informed by considerations of technological feasibility (the realm of the engineer) and cost-benefit tradeoffs (the realm of the economist). The role of the policymaker will be to weigh the information provided by technical experts, consider remaining sources of uncertainty, proactively set reasonable and effective targets that protect the public welfare, and implement well-designed policies for achieving these targets. The targets themselves will be key in generating the buy-in from industry and the general public that will be needed in order to implement real solutions at a global scale. Finally, all the authors agree that the "mobility of the future" is ours to shape now.

*The views and opinions expressed in the pieces that follow are those of the individual authors and do not necessarily reflect the opinion of other members of the study team, the study consortium members, or the MIT Energy Initiative.*

# *Global Decarbonization*

*Sergey Paltsev[1] and Jennifer Morris[2]*

Dramatic reductions in greenhouse gas emissions and air pollutants are needed to prevent dangerous changes in the Earth's climate that threaten human life and prosperity. For many years, scientists have tried to raise awareness about the disastrous impacts of proceeding unabated down a "business-as-usual" path. We are already seeing the impacts of climate change in the form of more frequent and more intense extreme weather events, threats to agriculture and natural habitats, and effects on human health and infrastructure. These early signs are extremely disturbing. Unfortunately, because of substantial inertia in the climate system and the buildup of greenhouse gases in the atmosphere from previous emissions, impacts are expected to worsen in coming decades, regardless of near-term actions in emissions mitigation. However, near-term mitigation can still prevent more dangerous outcomes, particularly in the second half of the century. Reducing emissions is not only about climate change, but also about improving local conditions, since air pollution has severe implications for health and economic productivity.

Our future depends on regular citizens holding decision makers and industry leaders accountable for their action (or inaction) in preserving our planet while also providing economic growth and prosperity to a growing population. In 2015, 195 nations of the world decided to act, signing the Paris Agreement that paves the way for international cooperation to reduce climate risks. Reaching the goals of the agreement ultimately means achieving net-zero greenhouse gas emissions. It is clear that the road to a zero-emission future will be difficult and costly, but the cost of inaction might be catastrophic. Given that fast and large emission reductions are needed, every reduction in emissions matters.

The scenarios considered in this study show some potential trajectories for achieving emission mitigation goals at a global scale. Realizing the aggressive *Paris to 2°C* scenario would demand a substantial increase in policy development and coordination among nations in comparison to the current path of country-specific actions. However, following this trajectory may not avert some major consequences of climate change, and even more aggressive actions may be necessary, requiring a faster transition to low-emitting options than in our scenarios.

## Vehicle Electrification: A Partial but Meaningful Contributor

This report assessed several pathways that show the impacts of climate policies on personal mobility. We show that the personal transportation sector is not a major player in emission reductions. However, it would be incorrect to assume that personal transportation is not relevant for near-term mitigation actions. As mentioned, every reduction in emissions matters—from every car and inefficiently insulated house, to every coal plant. The ultimate goal of net-zero emissions means that we need to create a future in which nearly all facets of human life are indeed zero-emitting.

Based on our numerous publications, we know that climate policies need to cover all sectors. Transportation alone will not solve the problem, but it must be part of the solution. In many regions, electric vehicles (EVs) do not currently offer substantial carbon and air pollution benefits in comparison to internal combustion engine vehicles (ICEVs) because the electric grid still heavily relies on fossil fuels (see Section 4.2). However, as the world is moving to low-emitting electricity generation options, the emission

---

[1] Deputy Director of the MIT Joint Program on the Science and Policy of Global Change (the Joint Program) and a Senior Research Scientist at the MIT Energy Initiative (MITEI).

[2] Research Scientist at the Joint Program.

benefits of EVs will become more pronounced. Therefore, policymakers and stakeholders in the transportation sector must anticipate and advocate for the move toward low-emissions electricity generation if they are serious about EVs as a low-emissions mobility option.

Transportation is harder to decarbonize than power generation because power generation already has numerous low-emitting options, such as hydroelectric, wind, and solar generators; nuclear energy; and carbon capture technology, that may be deployed at a reasonable cost. Currently, the cost of low-emitting personal transportation technologies is higher than the cost of traditional options (see Section 4.4). In the absence of targeted policies, EVs and other low-carbon vehicles will continue to be at a cost disadvantage.

While it is important to continue to reduce the costs of all low-emission options for personal mobility, the competiveness of such options can also be increased by making high-emitting technologies more expensive. Policies can be introduced to make the relative cost of ownership for low-emitting vehicles more attractive than the ownership cost of ICEVs. We turn to electricity generation as an example: Although the cost of renewable power is still higher than coal-based power in many regions, renewables are rapidly expanding across the globe. The low cost of coal does not include estimates of coal's impacts on climate and air pollution. Including these impacts makes coal generation much more expensive for society, and policies can account for these impacts by imposing additional fees on coal generation or by simply not permitting unabated (i.e., without capture of carbon and other pollutants) coal use. Coal will not disappear overnight and there are countries that are still building new coal power plants, but pressure for a low-carbon future should make it harder and harder for policymakers to approve coal projects.

Just as unabated coal use does not have a sustainable future, high-polluting and carbon-emitting forms of transportation do not have a sustainable future. As coal is being pushed out of the energy system, ICEVs can be proactively pushed out of personal mobility with policies. The market will not allow for ICEVs to rapidly disappear; our projections show that ICEVs will be in the mix for a long time, with new, more efficient vehicles replacing current ones. However, local air pollution and climate change will make it increasingly difficult for policymakers to avoid taking actions for dramatic growth in zero-emitting vehicles.

In addition to the push for lower emissions, the future of EVs will be shaped by technological leadership aspirations from China. Currently, China provides substantial government support to battery and EV production and is a leader in this technology. So far, it seems that China is determined to dominate EV development into the future. Time will tell if vehicle electrification will be the primary zero-emission transportation option, but it is clear that EV development would be slower without this industrial policy from the Chinese government.

### Coming to Grips with the Cost of Policy Intervention

Ultimately, policies will be needed around the world to implement personal transportation options that are currently more expensive, but lower-emitting. Initially, these policies are unlikely to be the most economically efficient. However, if one accepts the imminent need for action to mitigate impacts of climate change and air pollution, there is no time to wait for opportunities when the most efficient policies—such as undistorted carbon pricing or economy-wide emission trading—might be politically feasible. Decision makers need to introduce policies that are currently politically feasible (e.g., standards and mandates) and constantly reassess and introduce more efficient pathways to reduce emissions (e.g., carbon pricing and emission trading) as the political context changes. Different options have different costs, and in our study we show that the costs are manageable even in settings that include less efficient policies. Still, the costs of policies are extremely important;

ultimately, public opinion about benefits and costs will affect policymakers' willingness to take substantial actions.

The costs of all competing options are important. For personal mobility, one may consider the following cost questions: What is the cost to make ICEVs more energy efficient and low polluting? How does that cost compare with the cost of electric or fuel cell electric vehicle (FCEV) options? How will the costs of infrastructure requirements for EV charging and FCEV fueling be distributed among vehicle owners, vehicle manufacturers, electricity ratepayers, and society? Would supporting EVs affect the deployment of other low-carbon options, like hydrogen fuel cells, that might provide a solution not only for personal mobility, but also for a wider range of energy needs as well? What are the likely cost-reduction trajectories for these technologies? Economic models, like those employed in this study, are important tools that can help quantify the trade-offs involved in these choices.

## The Need for Adaptable Policies in the Face of Uncertainty

Having explored the costs of different policy options, we conclude that EVs, combined with decarbonized electricity, offer a substantial opportunity to providing zero-emission personal mobility. We have also shown that EVs still require policy support into the future to make a substantial contribution. Therefore, decision makers need to continue to evaluate different options as new information becomes available to make sure the policies they adopt do not lead to a dead end. Research in all low-emission options—such as batteries, hydrogen, biofuels, and gasoline with carbon capture—is essential. Regardless of the performance of the current "winning" technology, a breakthrough in some other technology may re-focus needed actions. In addition, all viable technological solutions need to be increasingly efficient over time.

The reality might be very different from our current projections. Slower progress with batteries and charging infrastructure may substantially lower rates of EV adoption. Faster progress with hydrogen infrastructure may change the economics to favor FCEVs. Public transportation options may play a larger role than we currently envision, particularly as the world continues to urbanize. Severe air pollution may drive policymakers to ban ICEVs in major metropolitan areas. More extreme impacts of climate change may facilitate more dramatic government actions and faster adoption of low-carbon options in many sectors of the economy, including transportation. However, one thing is quite certain: A push for lower-emitting options is emerging within the public and private sectors.

Achieving substantial emissions reductions (and ultimately moving to zero emissions) in the transportation sector will require not just one technology, but an integrated system approach that includes more efficient ICEVs, a long-term switch to low-carbon and net-zero carbon fuels for transport, and increased efficiency of the transport system through digitalization, smart pricing, and multimodal integration. Shifting consumers' travel behavior from private transportation to more efficient modes, such as public transport, biking, walking, or pooled vehicle trips will also be important for reducing environmental impacts and improving quality of life. Personal mobility is at the forefront of changes, and will pave the way for decarbonization in other segments of the transportation sector, such as heavy-duty vehicles and marine and air transport.

# *Geopolitical Challenges of Decarbonization*

*Christopher Knittel*[3]

For the most part, this study asks how transportation might evolve in a carbon-constrained world. We then compare and contrast these evolution paths with a business-as-usual world (*Reference* scenario). We leave a number of important questions unanswered. For one, we do not ask the equally, if not more, important question of whether or not the transportation sector will indeed be carbon constrained. Nor do we ask the important question of how society will generate enough political support to adopt carbon-constraining policies within the transportation sector. Finally, we do not ask what specific policies will be used to constrain carbon within transportation. Here, I give one take on these questions.

## Market Forces Will Not Be Enough to Decarbonize Transportation

First consider the question of whether or not the transportation sector will be carbon constrained in the future. Our global economic and policy model simulations make it clear that in order to meet the *Paris Forever* scenario, let alone the *Paris to 2°C* scenario, carbon will have to be constrained in some way. That is, unfettered market forces will not be enough to meet most climate goals. This is an important point: The market alone is very unlikely to limit climate change impacts to any reasonable degree. Policies that *constrain* carbon emissions in many economic sectors, including transportation, are *required*.

For readers still unconvinced of this fact, notice that for market forces to limit societal carbon emissions to acceptable levels, we would need either the carbon-intensive fuels that we rely on to become more expensive or the low-carbon alternatives to become cheaper. Some of my recent work with colleagues strongly suggests neither of these is likely to occur. We discuss each of these possibilities and conclude that relative prices would need to change *a lot* (Covert, Knittel, and Greenstone 2016).

While some have claimed that fossil fuels are bound to become prohibitively expensive, these pundits ignore the fact that the price of oil is the equilibrium of a constant battle between consumption and technological progress. Technology has historically won in this battle and there is no reason to think technology will not continue to win. As an example, we calculate that global oil reserves have increased by an average of roughly 2.5% per year over the past 40 years (Covert, Knittel, and Greenstone 2016).[4] Therefore, the data are telling us that each year the world discovers new reserves and develops technologies for taking more known resources out of the ground at a pace that more than covers what we consumed in the previous year; thus, our reserves actually *grow* despite growing consumption.

Perhaps there is hope that low-carbon transportation alternatives will become cheaper than fossil-fuel based technologies. But this, too, is unlikely, at least in the near term. A number of studies suggest that batteries will have to get much cheaper before EVs are at parity with ICEVs in terms of total cost of ownership. We suggest that batteries will have to cost less than $100 per kilowatt hour (kWh) if oil prices track those suggested by New York Mercantile Exchange futures markets (Covert, Knittel, and Greenstone 2016). In Chapter 4, this study suggests that battery costs need to be $124/kWh for battery electric vehicles (BEVs) to be at cost

---

[3] The George P. Shultz Professor of Applied Economics at MIT and Director of the MIT Center for Energy and Environmental Policy Research (CEEPR).

[4] The calculations use data from BP's Annual Energy Outlook dating back to 1980, but the results hold even when considering data back to 1950.

parity with ICEVs in the U.S., a target not likely to be met until 2030. In forthcoming work, we find similar results but note that maintenance cost savings for BEVs over ICEVs have to be substantial and one must ignore the opportunity cost of charging and scrappage costs for this cost parity to be achieved (Clinton, Knittel, and Metaxoglou 2019). Furthermore, it is important to realize that ICEVs also exhibit substantial technological progress; ICEV efficiency increases roughly 2.5% per year (Knittel 2013). But if all of this technological progress was put into fuel economy as opposed to power and size, a vehicle that achieves 30 miles per gallon (MPG) today could have a fuel economy of more than 39 MPG in 2030. This implies that battery costs would have to be even lower in 2030 to compete with the ICEV.

Does the fact that we cannot rely on the market to solve climate change mean all is lost? No. As comparing the *Reference* case and the climate-goal cases suggests, policy action is required if the world is going to limit climate change damages. This shouldn't be surprising. Greenhouse gases are a classic example of what economists call an "externality"—a cost borne by someone outside the buyer–seller relationship. By definition, the market will not correct an externality, so policymakers must intervene. And policymakers have a rich history of adopting policies to fix, or at least make better, the market in the presence of externalities. This list includes negative externalities, such as pollution (e.g., acid rain and smog) and congestion, as well as positive externalities such as innovation.

## Geopolitical Inaction in the Face of Climate Change

Unfortunately, a number of features of climate change stack the deck toward inaction. For one, greenhouse gases are *global* pollutants. A ton of $CO_2$ released in the U.S. does most of its lifetime damage *outside* the U.S. And it is hard for policymakers to take action to correct an environmental externality if the people being harmed by that environmental issue are not the people who elect them (i.e., outside their constituency). This creates a *geographical* disconnect between those harmed by climate change and policymakers. I'll note that the world has come together to solve global problems that share this feature in the past (an example is the hole in the ozone layer).

A second way climate change differs from many environmental externalities is that much of the damages are in the future. This creates a *temporal* disconnect between those harmed by climate change and policymakers. Put simply, those who will be most affected by climate change are not voting for and against the policymakers who might be tasked with solving the problem; in fact, they may not yet be born. Even if current voters value the welfare of future generations, they are likely to value their own current welfare much more.

A third difference is that, while there is a clear consensus among the scientific community that humans play a significant role in climate change, these effects are unlike many other environmental issues because they are not as easily observable by the public. The link between sulfur dioxide ($SO_2$) and acid rain is clearer. So are the links between volatile organic compounds (VOCs) and smog or between particulate matter and air pollution. This feature has enabled science deniers to inject more doubt than they otherwise would be able to.

A fourth difference (at least when comparing to the hole in the ozone layer) is that with climate change, *developing* countries are quickly becoming the greatest source of $CO_2$. This is an important distinction because the marginal benefit of using an extra ton of fossil fuels is likely much larger in these countries. To put it bluntly, many people living in developing countries are more worried, rightly so, about where their next meal is coming from or how they will supply water to their family, than about how their greenhouse gas emissions are affecting climate change.

The final difference is perhaps the most important one: It will be expensive to transition away from carbon-intensive energy resources. This is especially true in the light-duty vehicle market where, even if battery costs continue to fall, a significant transition from ICEVs to BEVs will require an implicit tax on oil or alternative subsidies to make BEVs attractive to consumers in the near term. Moreover, most comparisons of total cost of ownership ignore the cost of the new charging infrastructure that would be required for widespread adoption of BEVs, as well as the question of who would be responsible for paying for it. There is also the issue of how governments will replace the gasoline and diesel tax revenue they currently collect.

When the world came together to ban ozone-destroying chlorofluorocarbons (CFCs), the gap between the price of CFCs and chemical alternatives, hydrochlorofluorocarbons (HCFCs), was not nearly as large as the existing cost differential between ICEVs and BEVs. In addition, CFCs accounted for a much smaller share of manufacturing costs for typical appliances compared to the cost of the battery as a portion of overall BEV cost. Similarly, large-scale reductions in $SO_2$ emissions in the U.S. were aided by the presence of a readily available low-sulfur coal resource in the Powder River Basin.

In other parts of the transportation sector, such as heavy-duty vehicles and shipping, the costs of shifting to low-carbon alternatives are probably even greater than in the light-duty vehicle segment. Furthermore, for electrification to be a viable low-carbon pathway for transportation, the electricity sector will also have to decarbonize—and this transition will also be expensive. Even if nuclear energy is part of the decarbonization toolbox, it is estimated that average electricity generation costs could increase from roughly \$0.08/kWh to \$0.12/kWh when average $CO_2$ emissions go from 500 grams/kWh to 1 gram/kWh (MIT Energy Initiative 2018).

## A Way Forward (from Game Theory)

What is the way out of this bleak picture I have just painted? From my perspective, it is difficult to imagine the world seriously addressing climate change without two things: (1) U.S. leadership and (2) willingness of developed countries to provide resources to developing countries.

While voicing a need for U.S. leadership seems trite, it is actually rooted in standard economic game theory. By definition, there is a strong free-riding incentive with climate change. In the parlance of game theory, climate change is a prisoner's dilemma: Everyone is better off if all of the players act compared to if no one acts, but each country is *best* off if everyone else acts and it does not. In other words, each country wants the benefits from reducing climate change, but does not want to pay for these benefits itself; each country would prefer others to foot the bill. The equilibrium of this game is that no one acts.

Escaping the prisoner's dilemma leverages the repeated nature of the game. If this game repeats over and over again in a way where the end of the game is known, then the players can overcome the incentive to free ride. In practice, the "game" of negotiating global climate change does repeat over and over again because nations interact daily, not just once. The Paris Agreement and the infrastructure it helps provide for countries to publish and update their Nationally Determined Contributions help define the repeated nature of this negotiation. This situation allows the players to threaten punishment if one of the players reverts to a strategy of inaction (i.e., the player cheats).

What might that punishment look like in the context of climate change mitigation? Punishments could take a number of forms. Other countries could place tariffs on imports from the country breaching the agreement, or they could withhold aide to the infringing nation. Given the size of U.S. imports and foreign aid, no other country has the ability to punish like the U.S., making it the prime candidate for leading any international agreement. Furthermore, the U.S. could join forces with the E.U. and leverage their combined role in other international organizations, such as the World Trade Organization (WTO), to make membership conditional on climate mitigation.

Of course, if the U.S. is not acting to mitigate its own emissions, it is difficult for the country to punish others for doing the same. Therefore, the U.S. needs to be a leader on the mitigation front so that it can be a legitimate enforcer of any climate agreement.

Why do resources need to flow from developed countries to undeveloped countries? Game theory aids us here, too. The solution to climate change involves forming what is known as a "self-enforcing international environmental agreement" (SEIEA). Under a SEIEA, countries decide to either be part of the coalition or not. Members of the coalition agree to abatement levels that maximize the welfare of the coalition (i.e., solve the prisoner's dilemma problem within the coalition). Defecting countries go off on their own and face the tariffs or other punishment mechanisms described above because those punishments are less costly than the costs associated with abatement. It is the presence of these types of countries that keeps the world from completely "solving" climate change. Shifting resources from developed countries to developing countries would grow the size of the coalition in a way that is beneficial to everyone, including those transferring the resources.

## References

Clinton, Bentley, Christopher R. Knittel, and Konstantinos Metaxoglou. 2019. "Electrifying Transportation: Challenges and Opportunities." In *Handbook on the Economics of Electricity*, edited by J.M. Glachant, P.L. Joskow, and M. Pollitt. Northampton, MA: Edward Elgar.

Covert, Thomas, Michael Greenstone, and Christopher R. Knittel. 2016. "Will We Ever Stop Using Fossil Fuels?" *Journal of Economic Perspectives*, 30, no. 1: 117-138. https://www.aeaweb.org/articles?id=10.1257/jep.30.1.117

Knittel, Christopher R. 2013. "Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector." *American Economics Review*, 100 no. 7: 3368-3399.

MIT Energy Initiative. 2018. *The Future of Nuclear Energy in a Carbon-Constrained World: An Interdisciplinary MIT Study*. Cambridge, MA: MIT Energy Initiative. http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/

# *The Year Is 2050:*
# *An Engineer's Reflections on the Past Few Decades*

*William H. Green*[5]

## From Private Car to Mass Transit in Urban Areas

Looking back from where we are now in 2050, the transition from private car to mass transit in heavily populated cities was obvious. By the end of the 20th century, the old system based primarily on individual cars was already inefficient and becoming unworkable in large dense cities because of traffic congestion and the cost of providing parking. Subways and bus rapid transit (BRT) lines provided a much more time-efficient and cost-efficient transportation solution, and the cities that built out these transportation solutions boomed, growing even more densely populated as they grew more prosperous. The development of convenient app-based bike-sharing, ride-sharing, and other vehicle-sharing options that could be picked up at transit stations made the use of the subway and BRT lines even more attractive.

Many cities in East Asia and South Asia had sufficient population density to make mass transit efficient even before 2000 and were suffering from severe congestion and smog by 2010. So by 2020, there was already public consensus supporting a major change. The fact that most residents of these cities had never owned a car and had no prospect of owning a car in the near future made the transition much less politically challenging than in some cities in more developed countries. Policymakers in these high-growth developing cities eventually had the courage to act, rejecting the car-oriented development pattern of many cities in developing countries and defining a sustainable alternative.

In many city centers, most internal combustion engine vehicles (ICEVs) are now banned except at nighttime, significantly reducing congestion and local air pollution. In other areas, high road pricing has been effective at directing many taxi and ride-share trips into "last mile" service to mass transit stations. In most dense cities, curbside parking has been all but eliminated, making it easy to devote existing road space to BRT and bicycle lanes, and making private car ownership less appealing. There was initial public resistance to the changes in land use and zoning needed to make mass transit more attractive than traveling by car. But a sequence of disasters attributed to climate change, which culminated in a particularly devastating typhoon that flooded major cities in East Asia in 2028, decisively altered public opinion around the world and gave many big-city mayors the power to push through big changes.

## Clean Electricity for Mass Transit in Urban Areas

Global population growth since 2000—almost 3 billion more people in just 50 years—has concentrated heavily in urban areas, where personal transportation is now powered more by electricity than by liquid fuels. In 2050, diesel-powered buses are rare antiques and most taxi and other on-demand vehicle fleets use battery electric vehicles (BEVs). This electrification of mass transit in large cities has had measurable health benefits, although it is still debated in the medical community whether this is mostly due to improved air quality or because urbanites are spending more time walking and less time sitting in a car. The electrification of personal transportation has also provided significant climate benefits, particularly now that very little electricity is made from coal.

At the beginning of the century, most electricity was generated by burning coal, and it was hard to imagine coal could be replaced: It was the cheapest fuel, and it was plentiful in most populous countries, so it was much less

---

[5] The Hoyt C. Hottel Professor of Chemical Engineering at MIT and Faculty Chair of the *Mobility of the Future* study.

susceptible to embargoes or blockades than oil or gas. But the transition turned out to be surprisingly straightforward. In the 2020s, the E.U. and the U.S. enacted modest matching carbon taxes, with corresponding "carbon tariffs" imposed on goods imported from countries that did not apply the same carbon tax. The carbon taxes were high enough to push out most of the remaining coal-fired power in the U.S. and the E.U. In the E.U., much of the power was replaced by new nuclear plants built in France, and by solar power from Mediterranean countries, both subsidized for political reasons. China's industries were hurt by the carbon tariffs, and the government saw the opportunity to capture carbon tax revenues for itself rather than having the U.S. collect carbon-tariff revenues on Chinese imports. With these considerations in mind, and in the aftermath of a major flood widely blamed on climate change, China also signed on to the carbon-tax/carbon-tariff regime. Since then, most of the coal plants in China have shut down, with the majority replaced by a vast number of new nuclear power plants mass-produced to the same standardized design. Today, in 2050, India is the nation that produces the most electricity from coal, but public opinion there is also turning.

## The Continued Reign of the Car in Rural and Suburban Areas

While personal transportation has changed dramatically in the large cities, the car is still king in rural areas, small cities, and in the suburbs that fringe big cities. However, the type of propulsion systems used in these cars has changed dramatically. Average MPG of gasoline-powered vehicles has doubled since 2020, driven by gradually tightening fuel economy standards. Since the emissions scandal of the 2010s, which, in addition to fines, resulted in several company officials and complicit regulators losing their jobs or even going to prison, compliance with both the spirit and the letter of emission standards has increased significantly. Most countries now have effective emissions inspection systems, and ways to get the most polluting vehicles off the road. Now most new gasoline vehicles sold are hybrid electric, while some others achieve the required fuel economy by using different combustion modes depending on the engine load. For more than a century, most of the vehicles on the road were powered by naturally-aspirated gasoline spark engines. But now these engines are no longer mass-produced, though used vehicles of this type are still plentiful in the handful of countries which do not yet enforce modern fuel economy or emissions standards. As expected, ICEVs still dominate in rural areas since they are so convenient for traveling long distances.

Prices for BEVs dropped significantly from 2015 to 2035 as production volumes skyrocketed due to Chinese mandates, and since then the total cost of ownership for a BEV has been competitive with an equivalent ICEV. BEVs are particularly popular in countries with high gasoline taxes or other governmental supports, which make them significantly cheaper to own than ICEVs. Personal BEVs are very popular in big city suburbs for practical reasons: They are permitted in downtown areas where combustion vehicles are banned, and regions near big cities tend to have a high density of convenient chargers. Another factor for BEV popularity may be that suburbanites often follow big-city trends.

Breakthroughs in battery chemistry may help BEVs finally penetrate rural markets, but we're not there yet. Some new cars use lithium sulfur batteries, which promise to be much less expensive than conventional lithium nickel manganese cobalt batteries in the long run, but it will be some years before that new technology takes over the now quite large and well-established BEV market (over 300 million BEVs have been manufactured over the past 30 years). Relatively inexpensive lithium sulfur batteries are expected to make battery swapping economically attractive, providing a fast and easy method for charging BEVs that are traveling long distances. This may be the technological advance needed to significantly reduce vehicle emissions in rural areas that are still dominated by hybrid electric vehicles or ICEVs.

## Autonomous Vehicles on Highways and in Garages

It took several decades, but autonomous vehicles (AVs) are now widely accepted. Most modern cars have an autonomous mode that can operate safely on limited-access highways, making long-distance road travel much less tiring, dangerous, and unpleasant than it was early in the century. This on-highway AV technology has also completely disrupted long-haul trucking—many long-haul trucks now operate with no humans on board, and in other cases humans sleep while the truck cruises on the highway and then the human takes control on local roads to make the delivery.

A significant market for personally-owned AVs supervised by a remote operator has appeared in developed countries, mostly among the many people who cannot drive due to old age, disabilities, or medical conditions, as well as among wealthier families, who use supervised AVs as a cheaper version of a chauffeured limousine. Supervised AVs now account for almost 25% of all vehicles in rich, aging countries like Japan and Germany, though they account for a much smaller fraction of total vehicle miles traveled. Supervised AV taxis have also been successful in some rural and low-density suburban areas, where there were not enough customers to sustain on-demand chauffeured vehicle businesses.

By contrast, AV taxis have been less successful than expected in big cities. Human drivers turn out to be much better than computers at predicting the behavior of pedestrians, bicyclists, and human-driven motor vehicles in congested dense cities, and car-makers have decided they don't want to be liable for accidents. Also, in many cities, resistance to AV taxis has emerged from politically powerful taxi and on-demand vehicle businesses and their driver unions. Others worry that increased public use of less costly AV taxis would add to congestion, and thus reduce ridership on cities' mass transit systems.

## Celebrating Progress and Confronting Remaining Challenges

Looking back, it is clear that government mandates such as California's vehicle emissions standards, China's BEV policy of the 2020s, and U.S. fuel economy standards played a key role in the timely deployment of efficient low-emission automobile technologies. The modest carbon taxes introduced so far would probably not have been effective at changing the industry, since fuel cost is a relatively small component of the total cost of owning a vehicle, and an even smaller fraction of taxi and on-demand vehicle fares. Some mandates forced (or attempted to force) the introduction of technologies to the market before they were ready; for example, cellulosic biofuels and hydrogen fuel cell vehicles. In other cases, imposing a mandate significantly increased the short-term cost to consumers in specific countries (e.g., the Chinese BEV mandate; the German feed-in-tariff for rooftop photovoltaics; and the U.S. carbon tariff that led to nuclear largely replacing coal as a source of electricity in China), but provided a long-term benefit to humankind. By driving increases in production volumes beyond the market pace, these policies helped drive down the price of important low-carbon technologies, making them much more commercially viable.

A major challenge going forward from 2050 is how to drive fossil fuel emissions from personal transportation down even more drastically while reducing associated climate damages, without significantly increasing the cost of motorized transportation, which is already unaffordable for a significant number of people. It is not clear whether these changes should be incentivized through taxes, mandates, or other instruments. Although almost everyone now believes anthropogenic climate change is a major problem, there is still a human tendency to hope that someone else will pay the cost of solving the problem.

Looking back, however, we have a lot to be proud of. During the last half-century, from 2000 to 2050, the number of people with access to motorized ground transportation has more than doubled, while this sector's greenhouse gas emissions and price-per-mile-traveled have both dropped. In most big cities around the world, transportation is more efficient than ever. Automated vehicles have improved quality of life for hundreds of millions of elderly and disabled people. Through the efforts of thousands of engineers over more than a decade, the cost to the consumer of electrified transportation options was made comparable to that of combustion-powered vehicles. This facilitates the ongoing transition from gasoline-powered to electricity-powered automobiles, which reduces local air pollution today and will reduce future climate damage. All of these changes combined have brought benefits for the environment, as well as expanded accessibility for many around the world.

Despite this progress, the outlook going forward is not all rosy. Almost half the world's population still does not have access to the efficient, affordable motorized transportation they desire, in part because transportation costs are still high relative to incomes in many poor countries. While we have made good progress in big cities, it is much more challenging to provide attractive, cost-effective, and environmentally acceptable transportation solutions in rural and low-density suburban areas. It is also growing ever more challenging to improve vehicle efficiency. We engineers still have a lot more work to do to help ensure sustainable, affordable, and equitable transportation for all.

# *Technology and Value: An Urban Agenda for Future Mobility*

*Jinhua Zhao*[6]

"Transport—maker and breaker of cities."
— Colin Clarks, 1958

Transportation is changing due to developments in technology, data, and values. Technological advancement and data analytics capture headlines and research conducted at MIT contributes to both. However, in this final vision, I step away from models and instead emphasize the changes in values that are happening—and must continue to happen—to shape the sustainable mobility of the future. Before the 1980s, transportation mostly meant solving congestion; from the 1990s, transportation started to be seen as a sustainability problem; and more and more today, transportation can be framed as a public health problem, a personal identity problem, an urban agglomeration problem, and a social justice problem. We should embrace this multifaceted framing of transportation, which enriches scholarship and demands reform of both industry practice and public policymaking.

## Behavioral Foundation of Urban Mobility

Transportation is often seen as a mundane daily chore. However, travel is also charged with emotional and social meaning. Such perceptions have substantive impacts on how we understand travel with behavioral realism, and how we change behavior with creative combinations of economic incentives, technological and service innovations, and policies.

In particular, the personal car not only fulfills instrumental functions, it also holds symbolic and affective meaning. This study shows that "car pride" significantly impacts car ownership decisions, and the magnitude of this impact is on par with the effect of income. Comparing car pride across 51 countries, developing countries have substantially higher car pride than developed countries. Desire is high but purchasing power is low in developing countries; however, when incomes grow, high pride could exacerbate global automobile growth and associated greenhouse gas emissions and energy consumption. People in many developing countries such as China and India are entering a critical stage of defining the ideal life, and how this ideal materializes in people's general consumption, work, and travel patterns will have tremendous impacts on society as a whole. If every one of the 7.7 billion human beings on the planet strives to own a car as part of a successful life and drives tens of thousands of miles per year, no technical solutions exist today that can satisfy this desire without destroying our cities (with gridlock) and our world (with emissions). While countries invest in infrastructure and services, interventions must also tackle emotional and cultural factors such as car pride.

Traffic congestion, dominated by single-occupancy vehicles, reflects not only transportation system inefficiencies and externalities, but also a sociological state of human isolation. Advances in information technology are enabling real-time ridesharing to improve efficiency by moving more people in fewer cars. Less understood, however, are the experiences of social interaction during ridesharing. On the one hand, ridesharing may enable the expression of prejudice toward passengers of different social groups, but it may also be used as a tool to foster positive human interaction. Shared rides involve the impromptu matching of an individual and a stranger in an intimate, confined space for a considerable duration. Understanding the unique, social nature of shared rides should inspire us to develop a human-centric ridesharing system that respects both network efficiency and individuals' preferences for human interaction, or lack thereof.

---

[6] The Edward and Joyce Linde Associate Professor of Transportation and City Planning at MIT.

Seen through a sociological lens, transportation can be an opportune occasion for people to encounter each other in a diverse city.

These emotional and social factors and the models and algorithms to examine and harness them broaden the traditional perspective from which transportation systems have been examined. Encompassing behavioral and sociological considerations enriches the possibility of mobility system design and highlights key challenges for policymaking in the future of urban mobility.

## Autonomous Vehicles and Public Transportation

While autonomous vehicles (AVs) represent a revolutionary future for urban mobility, there is a high degree of uncertainty in how AVs will be perceived by consumers; how they will be operated; how they will interact in multimodal, urban transportation systems; and how they will be governed under regulatory frameworks. Despite this uncertainty, planners must help shape the pathway of technological advancement toward the public good. In that spirit, I propose an urban agenda for AV deployment that combines three aspects: behavioral understanding of technology adoption (including individual risk preferences, public perceptions of safety, and time use during journeys), multimodal mobility system design, and preparation for municipal AV regulation. One particular system-level question concerns the relationship between AVs and public transit (PT). Most discussions of AVs today have either ignored their impact on PT or simply pitted vehicles as competitors to transit. However, regardless of the level of development of AV technology, PT will continue to play an irreplaceable role in large metropolitan areas with high population density and limited road resources. This is an argument based on fundamental geometry of space, in contrast to economics or preferences: Public transit, which itself can be automated, remains the only geometric form for high-throughput passenger transport that can sustain high-density urban activities.

We need to emphasize the complementary relationship between AVs and PT, identify synergistic opportunities between them, and develop a transit-oriented AV deployment framework. The possibilities include enhancing first/last mile access, repurposing low-productivity services, such as suburban bus routes, and re-optimizing transit networks based on new AV–PT options. Integration must occur in all aspects of the mobility system, including information, ticketing, fare policy, service planning and operations, business models, and regulation. Thus, transit-oriented AV deployment differs substantively from non-integrated AV operation in terms of its regulatory burden and analytic methods. But these costs would be far outweighed by the broader benefits this AV–PT integration would bring to economic productivity and quality of life in cities.

City governments must be at the forefront of this discussion—yet the AV policy discussion to date has primarily focused on national and state regulations of manufacturing, emissions, safety, and licensing. However, the impacts of AVs on cityscapes and land uses, walking and cycling environments, and traffic congestion, as well as questions of service availability and equity, are generally outside the purview of national and state governments. Cities will have to fill this role in shaping the future of urban mobility through AV policies. Cities need to go beyond the hype of framing AVs as a symbol for “innovation,” and examine AVs as a means of travel to be embedded in the urban mobility system.

## Access for All

Today’s urban transportation systems do not function adequately for many of their users. Those who take transit are frequently beset by multiple transfers, infrequent service, crowded trains, delayed buses, and inadequate coverage. Those who drive are stuck in traffic, put themselves and others at risk on unsafe roads, and pollute our environment. Those who walk or bike are confined to poorly maintained, often discontinuous, dangerous, and circuitous routes. Few receive the service that adequately meets their needs, and some are excluded from the transportation system altogether due to their inability to pay, their age, or their physical abilities.

Urban mobility is on the cusp of a technological revolution brought on by the convergence of electrification, sharing, and automation. Can this revolution fulfill the long-time ambition of the transportation profession: providing access to opportunities for all? Looking back in history, there is no guarantee that “disruption” will bring a positive outcome. Cities are shaped by successive waves of new transportation technologies. The introduction of streetcars, commuter rail, subways, automobiles, and highways has had profound impacts on congestion, pollution, land uses, and quality of life. Yet the divergent ways people use transportation in different cities suggest that technologies can be implemented in dramatically varying manners, aiding or hindering the production of desirable urban environments.

## Human Agency: Pricing, Rules, and Norms

Fundamental technology transformations rarely come alone; instead, they bring with them new behaviors, new systems, and new institutions. Therefore, achieving a future of sustainable mobility requires substantial changes in behavior, systems, and policy. A combination of pricing (market mechanisms that properly reflect the cost of travel and incentivize sustainable behavior), rules (rational government regulations that guide the development of transportation technology and mobility systems), and norms (social values encoded in community and individual practices) is necessary to realize these changes.

Technologies do not inherently have a purpose; the cities they serve give them a purpose. Planning for the future of mobility requires more than just projecting trends and responding accordingly; we must proactively consider societal goals and shape consumer preferences as well as encourage the development and integrated implementation of new technologies and services. It is the fundamental role of the policymaker to guide society and industry toward the goals of equitable, environmentally sustainable, efficient, and livable cities. The only way to do this is to focus on the human fundamentals of mobility needs when examining new technologies, and set the direction of future changes in transportation technology and value.

# Appendix A

# Global Economic and Policy Modeling

## A.1 DESCRIPTION OF THE ECONOMIC PROJECTION AND POLICY ANALYSIS MODEL

MIT's Economic Projection and Policy Analysis (EPPA) model (Paltsev, et al. 2005; Chen, et al. 2016) offers an analytic tool that includes a technology-rich representation of household transportation and its substitution with purchased modes of transportation, as documented in Karplus, et al. (2013). The model captures interactions between all sectors of the economy, accounting for changes in international trade. Data on production, consumption, intermediate inputs, international trade, energy, and taxes for the base year are from the Global Trade Analysis Project (GTAP) dataset (Aguiar, et al. 2016). The GTAP dataset is aggregated into 18 regions (Figure A.1).

The EPPA model has more than 30 sectors (Table A.1), including several advanced technology sectors that are parameterized with supplementary engineering cost data. The model accounts for carbon dioxide ($CO_2$) and non-$CO_2$ greenhouse gas (GHG) emissions, including methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$). The model includes representations of emission control technologies and calculates reductions from gas-specific control measures as well as those occurring as a byproduct of actions directed at $CO_2$. The model also tracks major air pollutants, including sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), black carbon (BC), organic carbon (OC), carbon monoxide (CO), ammonia ($NH_3$), and

**Figure A.1: EPPA model regional coverage**

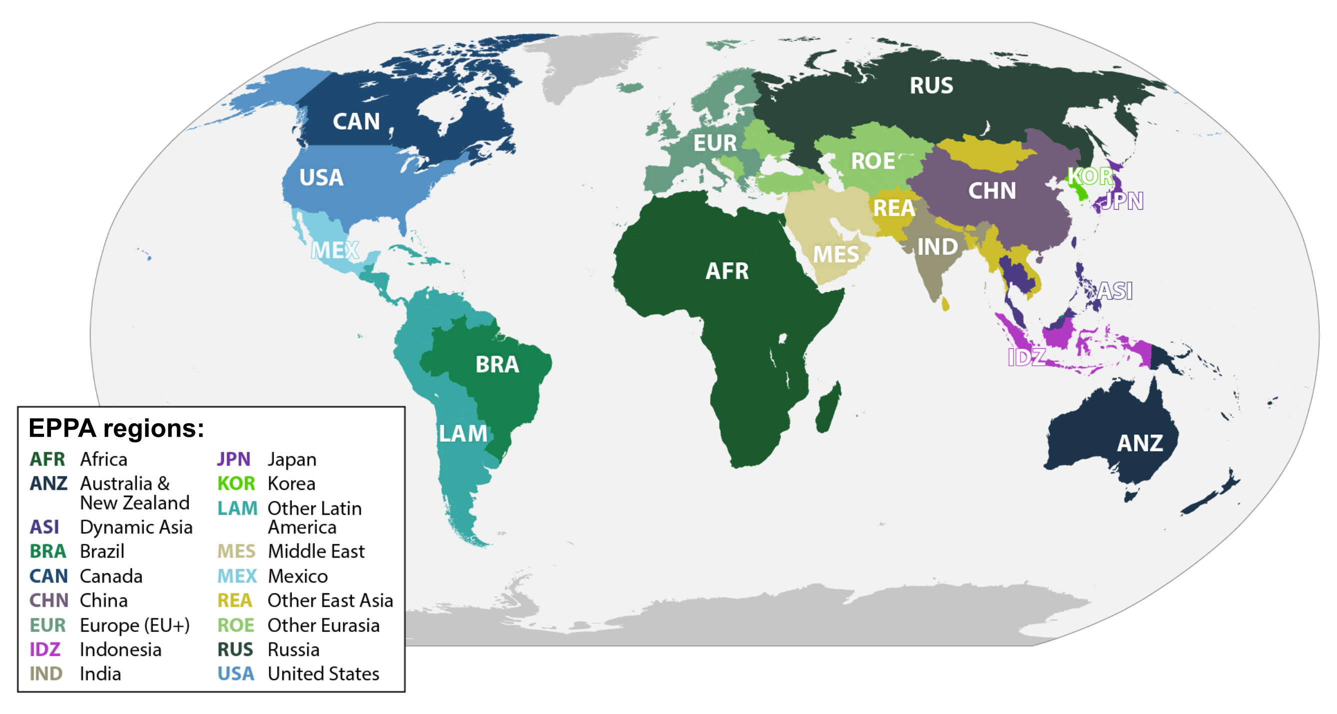


**Table A.1: Sectors in the EPPA model**

| Sectors |
|---|
| Energy-intensive industries |
| Other industries |
| Services |
| Crops |
| Livestock |
| Forestry |
| Food processing |
| Coal production |
| Oil production |
| Refining |
| Natural gas production |
| Coal electricity |
| Natural gas electricity |
| Petroleum electricity |
| Nuclear electricity |
| Hydro electricity |
| Wind electricity |
| Solar electricity |
| Biomass electricity |
| Wind combined with gas backup |
| Wind combined with biofuel backup |
| Coal with CCS |
| Natural gas with CCS |
| Advanced nuclear electricity |
| Advanced natural gas |
| **Household transportation** (by type of vehicle: internal combustion engine, plug-in hybrid, and battery electric) |
| Commercial transportation |
| First-generation biofuels |
| Advanced biofuels |
| Oil shale |
| Synthetic gas from coal |

Note: CCS = carbon capture and storage

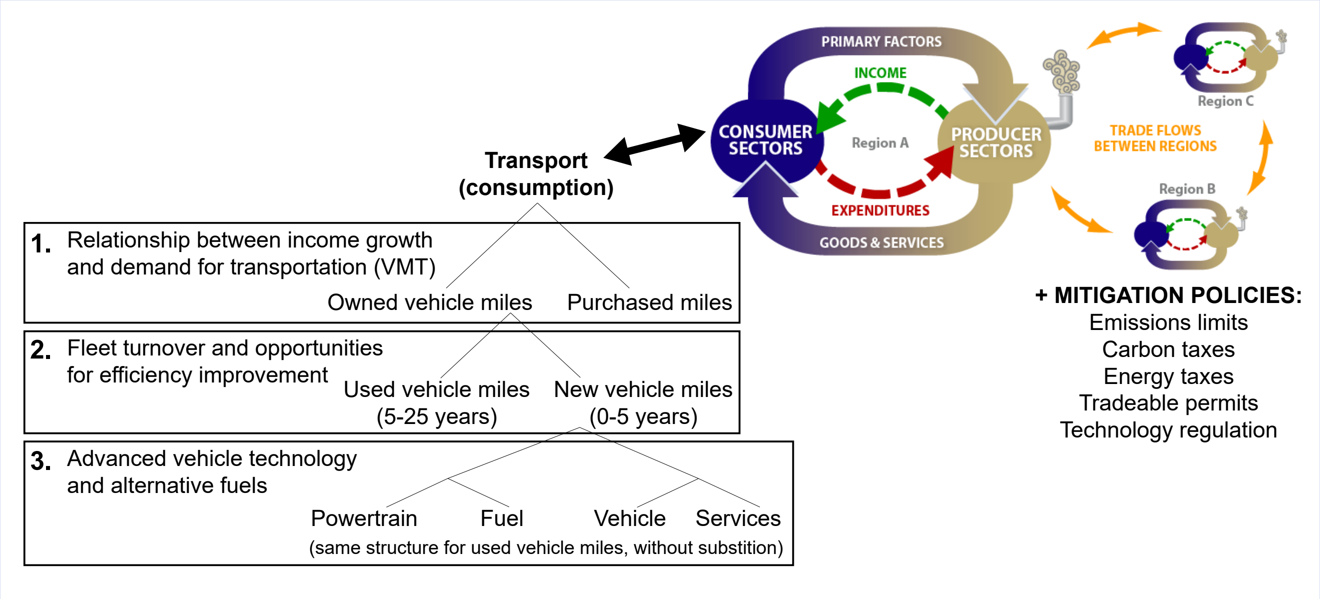
non-methane volatile organic compounds (VOCs); however, the different impacts of local air emissions in cities and rural areas are not considered. The data on GHGs and air pollutants in EPPA are documented in Waugh, et al. (2011).

From 2010 the model solves at 5-year intervals, with economic growth and energy use for 2010–2015 calibrated to data and short-term projections from the International Monetary Fund (2018) and the International Energy Agency (2017). The model includes a representation of household transportation and its substitution with purchased modes of transportation, including aviation, rail, and marine transport (Paltsev, et al. 2004). Several features were incorporated into the EPPA model to explicitly represent household transportation (Karplus, et al. 2013; Ghandi and Paltsev 2018).

These features include an empirically-based parameterization of the relationship between income growth and demand for vehicle miles traveled (VMT), a representation of fleet turnover, and opportunities for fuel use and emissions abatement, including representation of electric vehicles. Opportunities for fuel efficiency improvement are parameterized based on data from the U.S. Environmental Protection Agency (2010; 2012) as described in Karplus (2011), Karplus and Paltsev (2012), and Karplus, et al. (2010; 2013). Additional information about the details of the EPPA model can be found in Chen, et al. (2016) and Paltsev, et al. (2018).

The GTAP data, which is the source for the underlying data used in EPPA to model a base year, does not provide details on household transportation. To calibrate the EPPA model, we use additional data on stock of private light-duty vehicles; expenditures on fuel, vehicles, and services; and cost of alternative fuel vehicles, such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) for all 18 regions of the model. Figure A.2 illustrates the data requirements for modeling household transportation in EPPA, in addition to those data represented in the GTAP dataset.

**Figure A.2: Schematic overview of household transportation details and the circular flow of goods and resources in the EPPA model**



Aggregate consumer expenditures on private transportation are divided into expenditures on fuel, vehicles, and services. Energy in the EPPA model is tracked in value terms (i.e., expenditures) and in physical terms (exajoules or metric tons of oil equivalent). To represent the competitiveness of alternative fuel vehicles, the relative purchase costs of different powertrains are used together with the costs of different fuels to provide information that drives economic decisions about expanding the fleet of vehicles of different types. A description of the relative costs of different types of light-duty vehicles (LDVs) is provided in Ghandi and Paltsev (2019).

## A.2 IMPLEMENTATION OF NATIONALLY DETERMINED CONTRIBUTIONS (NDCs) UNDER THE PARIS AGREEMENT IN THE EPPA MODEL

Table A.2 provides information about how EPPA models the implementation of NDCs under the Paris Agreement at the country/region level. Many countries describe emissions reduction targets relative to an absolute (ABS) level of emissions defined by a historic base year, such as 2005. Europe and Russia continue to use 1990 as the base year. Other countries such as China and India have described targets based on emissions intensity (INT).

For countries with NDCs that are included within larger EPPA regions, we assess how achieving their GHG mitigation targets would affect emissions for the region as a whole relative to business-as-usual.

The combined effect is summarized in the next-to-final column of the table as a percentage reduction, in $CO_2$-equivalent ($CO_2e$) terms from the identified base value for each country/region, or in terms of energy intensity reductions for regions that have chosen an emissions intensity goal. The assessment of expected emission reductions in 2030 is based on Jacoby, et al. (2017).

The climate implications of achieving stated NDCs are provided in Reilly, et al. (2018). For the *Paris to 2°C* scenarios we assume a global economy-wide carbon price after 2030 (including in Russia) with emission profiles from Sokolov, et al. (2017). Corresponding emission reductions in 2050—relative to estimated emissions in 2030—are shown in the final column of Table A.2.

## A.3 CURRENT PRIVATE LDV INVENTORY

Table A.3 shows the number of private LDVs in different EPPA regions in 2015 (data taken from Ghandi and Paltsev 2019). Europe and the U.S. are currently the regions that have the largest vehicle inventory, followed by China, Japan, and Russia. However, in terms of motorization rate, China has seen the most significant growth; its vehicle stock increased by 590% between 2005 and 2015. India and Indonesia are the second and third-ranked regions in terms of growth. The global stock of privately-owned LDVs grew from about 735 million vehicles in 2005 to about 1.07 billion vehicles in 2015.

**Table A.2: Conversion of policies and measures into specific targets for regions of the EPPA model**

| Region | NDC type/base | NDC reduction | $CO_2e$ 2005 Mt or $tCO_2$/ \$1000 | Other features | Expected $CO_2e$ emissions reduction in 2030 | Additional $CO_2e$ emissions reduction in 2050 relative to 2030 |
|---|---|---|---|---|---|---|
| USA | ABS 2005 | 26-28% by 2025 | 6,220 | | 25% | 30% |
| EUR | ABS 1990 | 40% by 2030 | 5,370 (1990) | 27% renewables in electricity by 2040 | 40% | 20% |
| CAN | ABS 2005 | 30% by 2030 | 789 | Mainly land use & forestry with 18% reduction in industrial emissions | 25% | 45% |
| JPN | ABS 2005 | 25% by 2030 | 1,260 | 2.5% from land use change; assumes internationally transferred mitigation outcomes | 20% | 40% |
| ANZ | ABS 2005 | 26-28% by 2030 | 596 | | 20% | 45% |
| BRA | ABS 2005 | 37% by 2025 | 2.19 | 45% of primary energy renewable by 2030; LUCF down 41% 2005-12 | 35% | 10% |
| CHN | $CO_2$ INT 2005 | 60-65% by 2030 | 2.00 (INT) | NDC is $CO_2$ only, discount to account for other gases; $CO_2$ peak by 2030, non-fossil 20% of primary energy | 55% | 60% |
| KOR | BAU | 37% by 2030 | NA | Policies and measures on renewables and autos | 25% | 30% |
| IND | INT 2005 | 30-36% by 2030 | 1.17 (INT) | 2.5-3.0b tons $CO_2$ from forests; 40% non-fossil electric; assumes unspecified financial assistance | 30% | 27% |
| IDZ | BAU | 29% by 2030 | NA | Role of LUCF (63% of current emissions); industrial emissions increase | 30% | 5% |
| MEX | BAU | 25% by 2030 | NA | 22% of $CO_2$, 51% of BC, intensity reduction of 40% 2013-2030 | 25% | 30% |
| ASI | BAU | | NA | Malaysia 45% INT, Philippines 70% BAU, Thailand 20% BAU, Singapore ABS 36% | 10% | 45% |
| AFR | BAU | | NA | Nigeria 45% BAU, South Africa 20-80% increase (ABS), limited information on other regions | 5% | 37% |
| MES | BAU | | NA | Saudi & Kuwait actions only, Iran 15% BAU, UAE non-GHG actions | 10% | 45% |
| LAM | BAU | | NA | Argentina 15% BAU, Chile 35% INT, PERU 20% BAU, Colombia 20% BAU | 10% | 30% |
| REA | BAU | | NA | Bangladesh 5% BAU, Pakistan reduction after unspecified peak, Sri Lanka 7% BAU, Myanmar & Nepal miscellaneous actions | 10% | 25% |
| ROE | BAU | | NA | Azerbaijan 13% BAU, Kazakhstan 15% 1990, Turkey 21% BAU, Ukraine 40% BAU | 10% | 50% |

Note: BAU = business-as-usual; NA = not applicable.

**Table A.3: Stock of private LDVs in 2015 and increase in LDV stock relative to 2005 in the EPPA regions**

| EPPA region | Stock of private LDVs in 2015 (millions) | Increase in LDV stock from 2005 to 2015 (%) |
|---|---|---|
| Africa | 26.54 | |
| Australia and New Zealand | 16.78 | |
| Dynamic Asia | 30.78 | |
| Brazil | 35.47 | |
| Canada | 22.07 | |
| China | 141.48 | 590 |
| Europe (EU+) | 261.90 | 12 |
| Indonesia | 13.48 | 165 |
| India | 22.47 | 194 |
| Japan | 60.99 | 7 |
| Korea | 16.56 | |
| Other Latin America | 35.74 | |
| Middle East | 33.96 | |
| Mexico | 26.94 | |
| Other East Asia | 7.22 | |
| Other Eurasia | 33.27 | |
| Russia | 44.25 | |
| United States | 242.42 | 12 |
| **Global** | 1,072.31 | 46 |

## A.4 REFERENCES

Aguiar, Angel, Badri Narayanan, and Robert McDougall. 2016. "An Overview of the GTAP 9 Data Base." *Journal of Global Economic Analysis* 1: 181-208.

Chen, Y.-H. Henry, Sergey Paltsev, John M. Reilly, Jennifer F. Morris, and Mustafa H. Babiker. 2016. "Long-Term Economic Modeling for Climate Change Assessment." *Economic Modeling* 52, part B: 867-883. https://doi.org/10.1016/j.econmod.2015.10.023

Ghandi, Abbas, and Sergey Paltsev. 2019. *Representing a Deployment of Light-Duty Internal Combustion and Electric Vehicles in Economy-Wide Models*. Technical Note 17. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/17199

International Energy Agency (IEA). 2017. *World Energy Outlook 2017*. Paris, France: IEA.

International Monetary Fund (IMF). 2018. *World Economic Outlook 2018*. Washington, D.C.: IMF.

Jacoby, Henry D., Y.-H. Henry Chen, and Brian P. Flannery. 2017. "Informing Transparency in the Paris Agreement: The Role of Economic Models." *Climate Policy* 17: 873-890. https://doi.org/10.1080/14693062.2017.1357528

Karplus, Valerie J. 2011. *Climate and Energy Policy for U.S. Passenger Vehicles: A Technology-Rich Economic Modeling and Policy Analysis*. Ph.D. dissertation. Cambridge, MA: Massachusetts Institute of Technology.

Karplus, Valerie J., Sergey Paltsev, and John M. Reilly. 2010. "Prospects for Plug-In Hybrid Electric Vehicles in the United States and Japan: A General Equilibrium Analysis." *Transportation Research Part A: Policy and Practice* 44, no. 8: 620-641. https://doi.org/10.1016/j.tra.2010.04.004

Karplus, Valerie J. and Sergey Paltsev. 2012. "Proposed Vehicle Fuel Economy Standards in the United States for 2017 to 2025: Impacts on the Economy, Energy, and Greenhouse Gas Emissions." *Transportation Research Record*, no. 2287: 132-139. https://doi.org/10.3141/2287-16

Karplus, Valerie J., Sergey Paltsev, Mustafa F. Babiker, and John M. Reilly. 2013. "Applying Engineering and Fleet Detail to Represent Passenger Vehicle Transport in a Computable General Equilibrium Model." *Economic Modelling*, no. 30: 295-305. https://doi.org/10.1016/j.econmod.2012.08.019

Paltsev, Sergey, Y-H. Henry Chen, Valerie J. Karplus, Paul N. Kishimoto, John M. Reilly, Andreas Löschel, Kathrine von Graevenitz, and Simon Koesler. 2018. "Reducing $CO_2$ from Cars in the European Union." *Transportation* 45, no. 2: 573-595. https://doi.org/10.1007/s11116-016-9741-3

Paltsev, Sergey, Henry D. Jacoby, John M. Reilly, Laurent L. Viguier, and Mustafa F. Babiker. 2005. "Transport and Climate Policy Modeling the Transport Sector: The Role of Existing Fuel Taxes in Climate Policy." In *Energy and Environment*, edited by R. Loulou, J.-P. Waaub, and G. Zaccour, 211-238. New York, NY: Springer. https://link.springer.com/chapter/10.1007/0-387-25352-1_9

Paltsev, Sergey, Laurent L. Viguier, Mustafa Babiker, John M. Reilly, and K.-H. Tay. 2005. *Disaggregating Household Transport in the MIT-EPPA Model*. Technical Note 5. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/13870

Reilly, John M., Ronald Prinn, Y.-H. Henry Chen, Andrei Sokolov, Xiang Gao, Adam Schlosser, Jennifer F. Morris, Sergey Paltsev, and Henry Jacoby. 2018. *2018 Food, Water, Energy, and Climate Outlook*. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publications/signature/2018-food-water-energy-climate-outlook

Sokolov, Andrei, Sergey Paltsev, Y.-H. Henry Chen, Martin Haigh, Ronald Prinn, and Erwan Monier. 2017. *Climate Stabilization at 2°C and Net Zero Carbon Emissions*. Report 309. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/16629

U.S. Environmental Protection Agency (EPA) and U.S. National Highway Traffic Safety Administration (NHTSA). 2010. *Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards: Final Rule*. 75 FR 25323 Joint Technical Support Document. Washington, D.C. https://www.federalregister.gov/documents/2010/05/07/2010-8159/light-duty-vehicle-greenhouse-gas-emission-standards-and-corporate-average-fuel-economy-standards

U.S. Environmental Protection Agency (EPA). 2012. *Regulatory Impact Analysis: Final Rulemaking for 2017–2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards*. EPA-420-R-12-016. Washington, D.C. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-model-year-2017-and-later-light-duty-vehicle

Waugh, Caleb, Sergey Paltsev, Noelle Selin, John M. Reilly, Jennifer F. Morris, and Marcus Sarofim. 2011. *Emission Inventory for Non-$CO_2$ Greenhouse Gases and Air Pollutants in EPPA 5*. Technical Note 12. Cambridge, MA: MIT Joint Program for the Science and Policy of Global Change. https://globalchange.mit.edu/publication/13919

# Appendix B

# Vehicle Ownership and Usage in the U.S.

## B.1 MODELING THE IMPACT OF MILLENNIAL PREFERENCES

We used linear regression models to isolate the impact of generational preferences on vehicle ownership and use from other contributing factors. Our statistical models relate ownership and VMT to the household's generation cohort, as well as to a number of control variables. These variables, which are formally described in Knittel and Murphy (2019), include: income, household size, household composition,[1] location (urban or rural), state, education, survey year, age, sex, race, family life cycle, marital status, and number of children. Some of our model formulations use data for all household ages and some use only data for ages 18 to 37 (the current age range for millennials) to fully control for age differences between generations. The generational definitions used in this work are: the greatest generation (1901-1927), the silent generation (1928-1945), baby boomers (1946-1964), generation X (1965-1979), millennials (1980-1994), and generation Z (1995-2015).

The primary data source for this work is the U.S. Department of Transportation's National Household Travel Survey (NHTS). The NHTS is conducted every 5–7 years and elicits information from a nationally representative set of households regarding personal travel, demographics, and vehicle ownership. We utilized surveys from 1990, 1995, 2001, 2009, and 2017.[2] We also used NHTS data for our analysis of vehicle miles traveled (VMT). Here, VMT is measured at the person level rather than at the household level; it does not include all miles driven in a vehicle, rather it specifically quantifies the number of miles driven by the survey respondent.

To check the robustness of our results, we performed a set of alternative analyses. The vehicle ownership findings are consistent when running our models with data from the U.S. Census, including the American Community Survey. Additionally, we used a Oaxaca decomposition to further corroborate the findings from the linear regression models; and found in both data sets that the higher rate of vehicle ownership observed among baby boomers when they were the age of today's millennials is due primarily to differences in the socio-economic characteristics of the two cohorts (Knittel and Murphy 2019).

## B.2 MODELING HOUSEHOLD VEHICLE OWNERSHIP AND USE

Our projections of future vehicle ownership are derived from logistic regressions that relate ownership to a set of explanatory variables: the number of adults in a household, the number of children in a household, household location (urban or rural), and log-transformed household income. This analysis uses data from the NHTS for survey years 2017, 2009, and 2001. Three binary logistic models are used: the first examines the probability of owning one or more vehicles; the second examines the probability of owning two or more vehicles, conditional on owning at least one vehicle; the third examines the probability of owning three or more vehicles, conditional on owning at least two vehicles. Each of the logistic

---

[1] The NHTS data contains household composition indicators. These indicate whether the household has 1 or 2 working adults, and then either: no children, a youngest child between 0 and 5 years old, a youngest child between 6 and 15 years old, and a youngest child between 16 and 21 years old.

[2] The 2016 survey spans April 2016 through April 2017. It is referred to as the 2017 survey throughout this work.

regressions uses the following equation to calculate these probabilities. Coefficients were estimated separately for each of the three models. Estimations for the second and third models were performed only for households that own at least one and two vehicles, respectively.

$$P = \frac{1}{1 + e^{(-(\alpha+\beta_1 * ADULTS+\beta_2 * KIDS+\beta_3 * Urban+\beta_4 * INCOME))}}$$

The $R^2$ values for the three models are 0.27, 0.37, and 0.07, respectively. Values between 0.2 and 0.4 reflect a strong model fit for logistic regression (Whelan 2007). All coefficients are statistically significant at the 99% confidence level. Results from this model are displayed in Figure 3-7.

Vehicle use, expressed in VMT, was modeled using a linear regression that relates VMT to the same four explanatory variables described above for the vehicle ownership model.

$$VMT = \alpha+\beta_1 * ADULTS+\beta_2 * KIDS+\beta_3 * Urban+\beta_4 * INCOME$$

The $R^2$ value of the linear VMT regression model is 0.2, reflecting a large degree of uncertainty in the modeling results. All coefficients are significant at the 99% confidence level.

## B.3 ESTIMATING TOTAL VEHICLE STOCK AND VMT

To capture the heterogeneity of American households, we divided households into 90 categories along the four explanatory variables used in the model described above. The categories distinguish between households according to the following characteristics: the number of adults equal to one, two, or more; the number of children equal to zero, one, or more; located in an urban or rural area; and household income within one of five quintiles. We used the statistical models described above to estimate the probability of vehicle ownership and predicted VMT for each of the 90 household types. We then estimated total number of vehicles and total VMT by combining these estimates with our projections for the number of households in each category. Our estimate of the number of households in each category is derived from our projection of the total number of households (described in Chapter 3) and our estimates for the share of each type. The method used to estimate future household shares is described in the next section.

To estimate total vehicle stock and VMT in the U.S., we made an additional assumption about the share of vehicles and VMT contributed by households. Data compiled by Ghandi and Paltsev (2019) on the number of LDVs and the number of commercial and fleet vehicles, shows that vehicles owned by households comprised 90% of the total LDV stock in the U.S. in 2015. For VMT, we estimated average annual travel of roughly 21,000 vehicle miles per household from the NHTS data. Multiplying this estimate by Census data for the total number of households in 2016 and dividing by total U.S. VMT in 2016, as reported by the Bureau of Transportation Statistics (BTS, 2018a), we estimate that households contributed roughly 91% of total VMT. Total vehicle stock and VMT were then estimated assuming that the contribution from commercial vehicles grows at the same rate as that estimated for household ownership and VMT.

Model results were further calibrated against actual vehicle ownership and VMT for 2016. This was done by adjusting the constant coefficients of our statistical models to ensure that our 2016 projections match BTS data for vehicle ownership (2018b) and VMT (2018a).

## B.4 PROJECTING SHARES OF HOUSEHOLD TYPES

Future shares of different household types were estimated using prototypical sample enumeration (Whelan 2007). Here, we briefly introduce the methodology. This method uses an optimization to estimate the share of households ($s_g$) for each household type (denoted by the index $g$) so that resulting average household characteristics match our projections for each of the household characteristics (number of adults, number of children, urban status, and income) denoted by $z_t$ (where $t$ is an index referring to the four household characteristics being matched). The estimation of household shares is done by minimizing the right-hand side of the equation:

$$s_g = argmin\left[\sum_t \left(w_t * \left(z_t - \sum_g (s_g * x_{g,t})\right)^2\right) + \sum_g (s_g - f_g)^2\right]$$

In this equation, $x_{g,t}$ refers to an average household characteristic for a given household type $g$ and for a given characteristic $t$. Additionally, $f_g$ refers to the 2017 share of household group $g$. It ensures that the relative shares of different household groups, $s_g$, stay as close as possible to their historical 2017 distribution. Finally, $w_t$ are weights that refer to the importance of matching individual household characteristics; they ensure that all household characteristics are matched to our projected averages, regardless of their units. The optimization is constrained so that the household shares sum to 100%.

Results from this procedure are displayed in Figure 3.7 in the body of the report.

## B.5 REFERENCES

Ghandi, Abbas, and Sergey Paltsev. 2019. *Representing a Deployment of Light-Duty Internal Combustion and Electric Vehicles in Economy-Wide Models*. Technical Note 17. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. https://globalchange.mit.edu/publication/17199

Knittel, Christopher R. and Elizabeth Murphy. 2019. *Generational Trends in Vehicle Ownership and Use: Are Millennials Any Different?* Working Paper 25674. Cambridge, MA: National Bureau of Economic Research. http://www.nber.org/papers/w25674.pdf

U.S. Bureau of Transportation Statistics (BTS). 2018a. *U.S. Vehicle-Miles*. https://www.bts.gov/content/us-vehicle-miles

––– 2018b. *Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances*. https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances

Whelan, Gerard. 2007. “Modelling Car Ownership in Great Britain.” *Transportation Research Part A: Policy and Practice* 41, no. 3: 205–219. https://doi.org/10.1016/j.tra.2006.09.013

# Appendix C

# Urban Mobility

## C.1 PROTOTYPE CITY GENERATION AND SIMULATION

Given the infeasibility of generating specific city models for simulation, we developed a procedure for creating a representative city for each the typologies of interest. These *prototype cities* were then calibrated and validated at various levels for demand, supply, and demand–supply interactions. Using our simulator, SimMobility, we evaluated various future mobility policies in terms of their energy and performance outcomes in different city contexts (see Chapter 6). This section describes in more detail how we generated our prototype cities. The procedure can be broken down into four major steps:

1. Archetype selection
2. Population synthesis
3. Demand
4. Supply

### C.1.1 Archetype Selection

Before we created prototype cities, we first needed to select an archetype city to which we could match population characteristics and from which we could obtain a transportation network (i.e., the physical location, geometry, and capacity of roads and transit lines) and a corresponding spatial distribution of people and trips. The selection process was conducted by ranking the cities in each type by their distance from the centroid of the city type, or the average value along multiple dimensions for the given city type. This ranking was done using all nine mobility factors used in the analysis to determine city types (see Chapter 6 and Oke, et al. 2018), but particular attention was given to those factors that represent supply–demand interactions in each city type. Finally, we also evaluated the feasibility of obtaining validation data for the candidate cities. From this process, we identified Boston, Baltimore, and Singapore as archetype cities for the *Auto Innovative*, *Auto Sprawl*, and *Mass Transit Heavyweight* city types, respectively.

A critical factor in selecting archetype cities was the availability of an estimated activity-based model, which would serve as a good starting point for calibrating mobility demand to fit average values for the cities in that city type. Considering that models had already been developed for both Boston and Singapore, these cities were chosen from among the top six cities ranked by closeness to the centroid of their respective city-types. Land use data were also readily available for these cities. In the case of Baltimore, the Boston models provided a starting point, since the *Auto Sprawl* and *Auto Innovative* types have much in common.

The archetype city served as the basis for our assumptions concerning population generation and allocation, and the supply network. Activity shares, mode shares, and fares are, however, fitted to the average levels for the cities in the type.

### C.1.2 Population Synthesis

In this initial step, we produced a representative population for each archetype city using a hierarchical iterative proportional fitting (HIPF) method that sequentially expands a sample population given specified control variables at the individual and household levels. At the individual level, we controlled for age, gender and employment status. At the household level, we controlled for income and vehicle ownership. The HIPF routine produces cross-tabulated weights that are then used to generate a full synthetic population from the microdata sample. For instance, the microdata sample for *Auto Sprawl* (Baltimore) was obtained from the American

Community Survey (ACS). Validation for population attributes was performed at the Second Administrative Level (SAL): this is analogous to a "county" in U.S. metropolitan areas.

After the population was generated, we allocated locations for households, employment, and education. First, however, we gridded the entire metropolitan area into cells. For example, the *Auto Sprawl* prototype city was gridded using 350 x 350 meter cells. Based on the land use category combination in each cell, land use weights were then assigned for residential, commercial, mixed, and education use cases. Households were then allotted to each grid to fit SAL totals. The same approach was followed for employment and education locations.

A second iterative proportional fitting procedure was carried out to assign employees and students to work and school locations, respectively.

### C.1.3 Demand

Here, we used the activity-based modeling (ABM) framework to generate an activity schedule for the synthetic population. The ABM is manually calibrated to ensure a fit to the city type for the following measures:

- Activity shares (work, education, shopping, other)
- Mode shares (car, mass transit, walk, bike, other)
- Trip generation rate
- Average trip length

We also examined tour and trip distributions, along with time-of-day distributions to ensure that modeled values were acceptable. A thorough description of the prototype city generation approach, along with relevant details on the modeling and simulation procedure, can be found in Oke, et al. (2019).

## C.2 ELASTICITY ANALYSIS

Elasticity analysis enabled us to (a) validate our demand models and (b) measure the impacts of critical input factors on major outcomes. The input factors of interest are fuel cost and fares for autonomous mobility-on-demand (AMOD) services.

First, we calibrated each city's demand model to match fuel cost elasticities in the literature. The fuel cost elasticity gives the percentage change in the number of trips demanded for a one percent change in the cost of fuel. Reference values for the fuel cost elasticities are provided in Table C.1.

The elasticity of demand by mode is given for all prototype cities in Table C.2. Across all modes, the fuel cost elasticities are about -0.01 in all cities, as expected. However, we see that *Mass Transit Heavyweight* has the greatest elasticity (by magnitude) for private car demand. This means that car trip demand is most sensitive to fuel cost changes in *Mass Transit Heavyweight* cities compared to the other two city types. Inelastic car demand in the *Auto* cities with respect to fuel cost highlights this city type's dependence on cars for passenger mobility. Similarly, *Mass Transit Heavyweight* cities have the most elastic demand for mass transit, while mass transit demand is most inelastic in *Auto Sprawl* cities. This outcome underscores the attractiveness and availability of mass transit in *Mass Transit Heavyweight* cities (and to some degree, in *Auto Innovative* cities) compared to *Auto Sprawl* cities.

Having validated fuel cost elasticities, we then computed the AMOD fare elasticity for each prototype city. The AMOD fare elasticity gives the percentage change in number of trips demanded for a corresponding one percent change in the AMOD fare. We observe that the AMOD fare elasticity of trip demand is more inelastic in *Auto Sprawl* cities than in *Auto Innovative* cities. Values for AMOD fare elasticity by mode are shown in Figure C.1. Demand for AMOD modes (exclusive trip versus pooled trip) is most sensitive to fare changes in the *Auto Innovative* prototype, which suggests that pricing will have a greater impact on service adoption in cities of this type. Relatively greater elasticity for private car demand in the *Mass Transit Heavyweight* prototype city indicates a greater tendency to switch to this mode (i.e. greater carpooling) when AMOD fares increase.

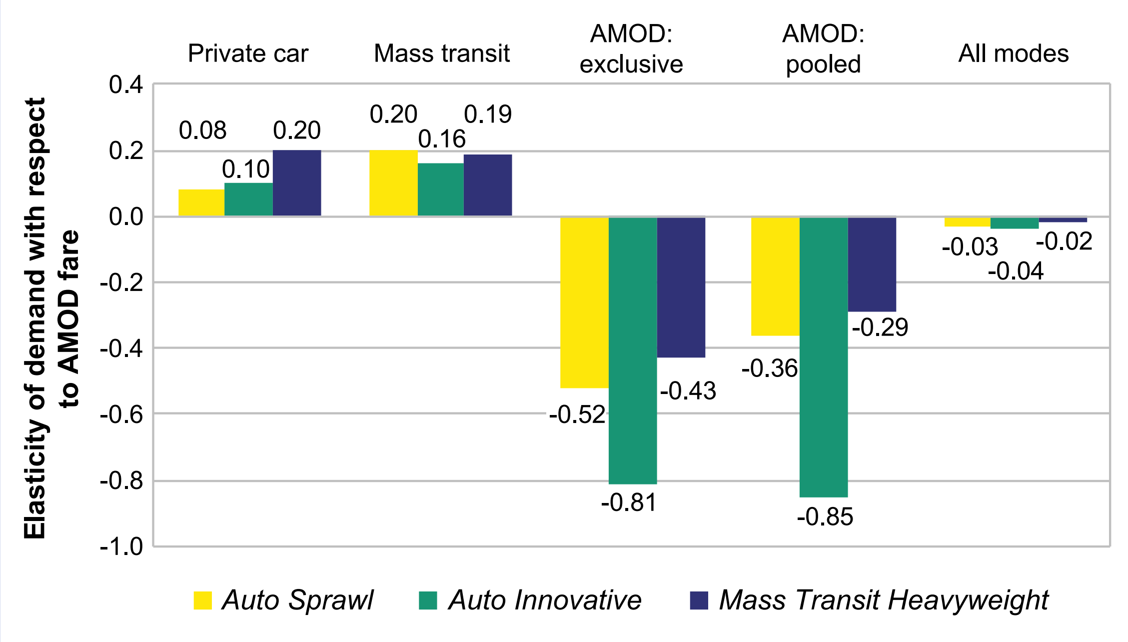
**Table C.1: Sources for fuel cost elasticities**

| Study | Scope | Short-term fuel price elasticity |
|---|---|---|
| Goodwin, Dargay, and Hanly (2004) | 1929 to 1991; North America and Europe | -0.10 (car) |
| Small and van Dender (2007) | 1997 to 2001; U.S. | -0.03 (car) |
| Dong, et al. (2012) | Europe | -0.18 (car)<br>+0.13 (mass transit)<br>+0.07 (walk/bike) |

**Table C.2: Fuel cost elasticities of demand in the *Base Case* for three prototype cities**

| Mode | *Auto Sprawl* | *Auto Innovative* | *Mass Transit Heavyweight* |
|---|---|---|---|
| Private car | -0.04 | -0.03 | -0.15 |
| Mass transit | +0.01 | +0.06 | +0.09 |
| Walk | +0.04 | +0.01 | +0.06 |
| Bike | +0.07 | *+0.08* | *+0.05* |
| All | -0.006 | *-0.005* | *-0.007* |

**Figure C.1: Elasticities of demand by mode with respect to AMOD fare**



## C.3 REFERENCES

Dong, Jing, Diane Davidson, Frank Southworth, and Tim Reuscher. 2012. *Analysis of Automobile Travel Demand Elasticities with Respect to Travel Cost*. Washington, D.C.: Federal Highway Administration. https://www.fhwa.dot.gov/policyinformation/pubs/hpl-15-014/TCElasticities.pdf

Goodwin, Phil, Joyce Dargay, and Mark Hanly. 2004. “Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review.” *Transport Reviews* 24, no. 3: 275-292. https://doi.org/10.1080/0144164042000181725

Oke, Jimi B, Youssef M. Aboutaleb, Arun Akkinepally, Carlos Lima Azevedo, Yafei Han, P. Christopher Zegras, Joseph Ferreira, and Moshe E. Ben-Akiva. 2018. “A Novel Global Urban Typology Framework for Sustainable Mobility Futures.” *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab22c7

Oke, Jimi B., Arun Akkinepally, Siyu Chen, Yifei Xie, Youssef M. Aboutaleb, Carlos Lima Azevedo, P. Christopher Zegras, Joseph Ferreira, and Moshe E. Ben-Akiva. 2019. "Evaluating Systemic Effects of Automated On-Demand Services through Large-Scale, Agent-Based Simulation of Auto-Dependent, Prototype Cities." [working paper]

Small, Kenneth A. and Kurt van Dender. 2007. *Long Run Trends in Transport Demand, Fuel Price Elasticities and Implications of the Oil Outlook for Transport Policy*. Discussion Paper No. 2017-16. Paris, France: OECD/ITF Joint Transport Research Center. https://doi.org/10.1787/234582117245

**MAILING ADDRESS**

MIT Energy Initiative
77 Massachusetts Avenue, E319-307
Cambridge, MA 02139

**energy.mit.edu**

MITei
MIT Energy Initiative