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INSIGHTS INTO FUTURE MOBILITY

EXECUTIVE SUMMARY

A report from the Mobility of the Future study

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A report from the Mobility of the Future study

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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.

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).

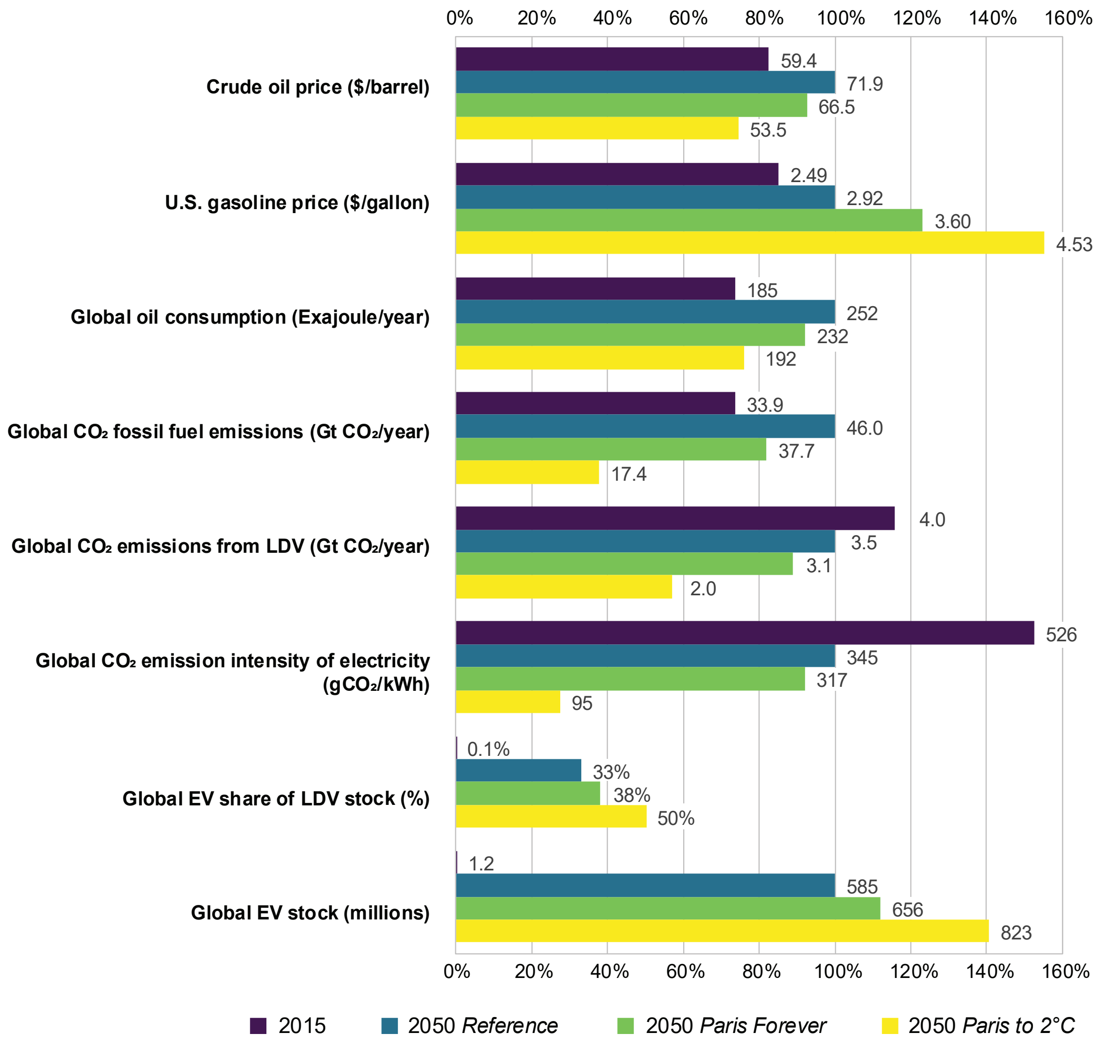
The remainder of this summary highlights our main findings in each of these areas.

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.

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