

The Plug-in Electric Vehicle System from Technologies to Consumers

K. John Holmes¹, Ellen Mantus¹, John Kassakian², Elizabeth Zeitler³

¹ The National Academies of Sciences, Engineering, and Medicine, 500 5th Street NW,
Washington, DC 20001; e-mail: jholmes@nas.edu

² Massachusetts Institute of Technology

³ Millennium Challenge Corporation

Summary

This paper discusses the recent National Academies' study *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*. The study committee concluded that, if policy makers continue to pursue PEV deployment, continuing federal funding for battery research and purchase tax credits is important to reduce vehicle cost. The committee also considered federal investments in deploying charging infrastructure. It recommended further study to understand the relationship between infrastructure and vehicle deployment and use before additional direct federal investment in charging infrastructure installation.

Keywords: BEV (battery electric vehicle), PHEV (plug in hybrid electric vehicle), charging, business model, consumers.

1. Introduction and Study Description

Technologies for plug-in electric vehicles (PEVs) have rapidly improved over the past decade. The development of battery systems, computer controls, electric motors, power electronics, and other components for light-duty vehicles (LDVs) has enabled plug-in hybrid electric vehicles (PHEVs) and pure battery electric vehicles (BEVs) in the commercial vehicle market to increase from zero in 2010 to hundreds of thousands in 2015. With the ongoing introduction of BEVs without practical range limitation, PEV deployment issues have moved from technological capabilities to whole system capabilities, including value proposition, consumer attitudes, supporting infrastructure, and regulatory requirements/incentives. The future for PEVs depends not only on the level of technological improvements but also on convincing consumers who buy, dealers who sell, and the support network that recharges and repairs PEVs that these vehicles offer economic and performance advantages over petroleum-fueled vehicles.

This paper discusses the results of a recent National Academies' study that reviewed barriers to PEV adoption. The study committee that authored this report was composed of members with backgrounds in technology, policy, business, and consumer affairs related to electric vehicles.¹ The study, *Overcoming Barriers to Deployment of Plug-in Electric Vehicles* [1], was requested by the U.S. Congress after hundreds of millions of dollars were spent on electric vehicle research and infrastructure deployment under the American Recovery and Reinvestment Act (ARRA) and the ongoing EV Project. ARRA included about \$130 million to provide incentives for the purchase of thousands of PEVs, to install about 19,000 chargers, and to collect and analyze charging behaviors [2]. Congress, in its appropriations for fiscal year 2012 for the Department of Energy (DOE), rejected the Administration's request for \$200 million for additional PEV deployment activities, including \$150 million for charging infrastructure. Instead it directed the DOE, as part of its broader efforts on PEV deployment, to fund this study to identify the market barriers slowing the purchase and hindering the deployment of supporting infrastructure. The study covered an array of topics including vehicle and charging technologies; cost and performance of vehicle batteries; classes of PEVs and relationships between PEV classes and charging infrastructure needs; the consumer purchase and market development process; and possible roles for the federal government to reduce deployment barriers.

The objective of the study was ultimately *not* to address whether increased PEV adoption is a desirable policy—the committee considered that a decision for policy makers. That made it possible to develop consensus among the varied perspectives held by committee members on the best ways to improve fuel economy and reduce greenhouse gas emissions. The committee's task was to identify the major barriers to increased deployment and to suggest possible solutions to address such barriers. The committee concluded that the task embodied two basic premises: (1) an increased fraction of electric vehicle miles traveled (eVMT) would reduce petroleum use and air pollutant emissions; and (2) the goal for reducing barriers is not simply to sustain technology-savvy early adopters but to move the market to mainstream consumers. The committee adopted increasing electric vehicle miles traveled as the relevant policy success metric to consider BEVs and PHEVs consistently.

2. Technologies and Classes of PEVs

Although electric vehicles were part of the technology mix at the turn of the 20th century, they essentially disappeared from the new vehicle market by the 1920s. Attempts at deployment by a major automobile manufacturer did not occur again until the leasing of almost 1,000 EV1s by General Motors from 1996 to 1999 in response to the California Zero Emissions Vehicle (ZEV) Mandate. The ZEV program was promulgated by the California Air Resources Board to help address air quality issues in the state. However, the EV1s disappeared from the road by 2002. The current era of PEV deployment in the United States began with the introduction of the Tesla Roadster in 2008, followed by the release of the Nissan Leaf and the General Motors Volt in 2010. Over the past 5 years, the market has seen a variety of PEV models introduced with varying characteristics of all-electric range (AER) with many more to come. Consumer adoption and charging needs are determined by the AER of the vehicles and whether the electric drive is supplemented by a gasoline engine. The committee used these two characteristics to distinguish four PEV classes (Table 1).

¹ This paper is derived from the report authored by the National Academies' Committee on Overcoming Barriers to Electric Vehicle Deployment. Committee members were John Kassakian (chair), David Bodde, Jeff Doyle, Gerald Gabrielse, Roland Hwang, Peter Isard, Linos Jacovides, Ulric Kwan, Rebecca Lindland, Ralph Masiello, Jakki Mohr, Melissa Schilling, Richard Tabors, and Thomas Turrentine.

Table 1: Four classes of plug-in electric vehicles, separated by their AER and the level of hybridization (all-electric or gasoline-electric hybrid)

PEV Classes	Description	Example (Range ^a)
Long-range BEV	Can travel hundreds of miles on a single battery charge and then be refueled in a time that is much shorter than the additional driving time that the refueling allows.	2014 Tesla Model S (AER = 265 miles)
Limited-range BEV	Is made more affordable than the long-range BEV by reducing the size of the high-energy battery. Its limited range can more than suffice for many commuters, but it is impractical for long trips.	2014 Nissan Leaf (AER = 84 miles) 2014 Ford Focus Electric (AER = 76 miles)
Range-extended PHEV	Typically, operates as a zero-emission vehicle until its battery is depleted, whereupon an ICE turns on to extend its range.	2014 Chevrolet Volt (AER = 38 miles; total range = 380 miles)
Minimal PHEV	Its small battery can be charged from the grid, but its AER is much less than the average daily U.S. driving distance.	2014 Toyota Plug-in Prius (AER = 6-11 miles; total range = 540 miles)

^a The AERs noted are average values estimated by the U.S. Environmental Protection Agency. Total ranges are provided for PHEVs; the AER is the total range for BEVs.

The classes of PEVs (Table 1) and the characteristics of daily travel (Fig. 1) can be used to assess the current capabilities of PEVs and charging infrastructure to meet consumer requirements. The Tesla Model S demonstrates the existence of a long-range BEV that provides the consumer amenities of a luxury vehicle. More importantly, limited-range BEVs are the only type of PEV that has a substantial range limitation. This realization contrasts with the public's belief that PEVs generally suffer from range limitations. Furthermore, both the range-limited BEVs and the range-extended PHEVs have typical AERs that are comparable to or larger than a majority of the average daily miles traveled. The committee also noted that minimal PHEVs function for regulatory compliance rather than to substantially increase electric drive performance and eVMT. The committee noted that these vehicle classes will evolve over time as battery capabilities improve and costs decrease, and some of these classes may disappear.

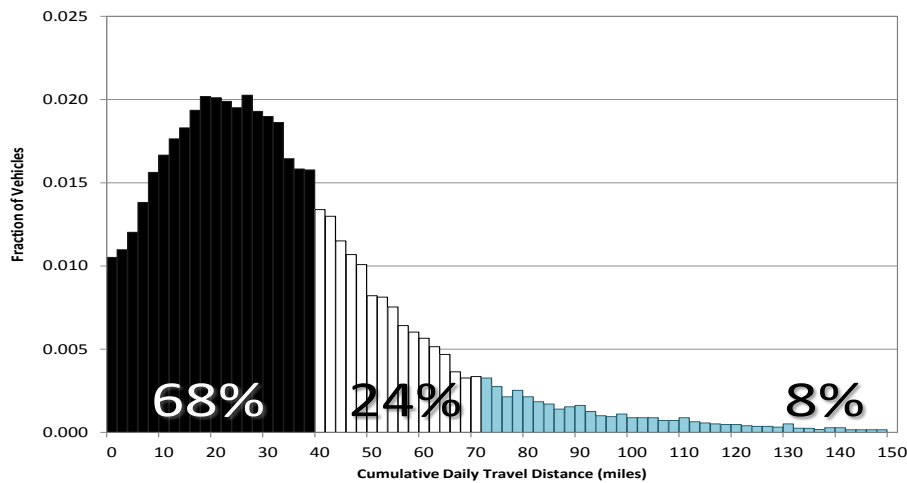


Figure 1: Distribution of daily travel distances per vehicle in 2009 [3]. Each bar represents the fraction of vehicles that traveled a given distance in a day. Colored ranges are marked at 40 and 73 miles.

Improvements in the battery system will largely determine how the range, performance, and initial cost of PEVs will compare with those of hybrid and conventional powertrains. Through its discussion with battery manufacturers, other suppliers, vehicle manufacturers, and independent analysts, the committee found strong evidence for continued increases in energy density and decreases in battery costs. By about 2023, the energy density of batteries should double, and the costs for battery packs should decline from approximately \$500/kWh to \$250/kWh. The committee also found significant potential for reducing non-battery costs, such as those of the electric motor, inverters, and other components needed to connect, cool, and monitor the battery cells. However, even with those reductions, battery system costs will still be an impediment to PEV adoption. Besides the overall costs of the battery system, the other major concern expressed by the committee was the long-term durability of batteries.

3. PEV Technologies and Infrastructure Needs

A significant component of the Academies' study was its analysis of the charging infrastructure needed to support PEV deployment. The infrastructure for charging PEVs is fundamentally different from the well-developed infrastructure for fueling gasoline-powered vehicles. Vehicle charging can be done in a wider variety of venues, including a PEV owner's residence or workplace, parking lots at commercial and other public locations, and stand-alone charging stations. Only the stand-alone charging station bears a resemblance to a traditional gas station, though the similarities do not extend to the overall business model. Further, a variety of charging options is available, from AC level 1 chargers that use the electric service present in almost every building to DC fast chargers that require higher levels of voltage not found everywhere. These charging options mean that there is variation in charging rates as well as in capital and maintenance costs. Charging with AC level 1 can add 3-5 miles per hour of charge and might cost a homeowner \$0 to \$1,000 to install, while a commercial fast-charging station might cost \$100,000 or more and provide 70 to 170 miles of range for a 30-minute charge.

To understand infrastructure barriers to PEV deployment, the committee used Fig. 2 to help consider the vehicle characteristics, infrastructure requirements, and groups that might have the incentive to deploy infrastructure in an integrated manner. As noted in this figure, various entities might have an incentive to install

or operate charging infrastructure; they include vehicle owners, workplaces, retailers, charging providers, utilities, vehicle manufacturers, and the government. Their motivations might include meeting their own demands, generating revenue, improving air quality, selling more electricity, or selling more PEVs.

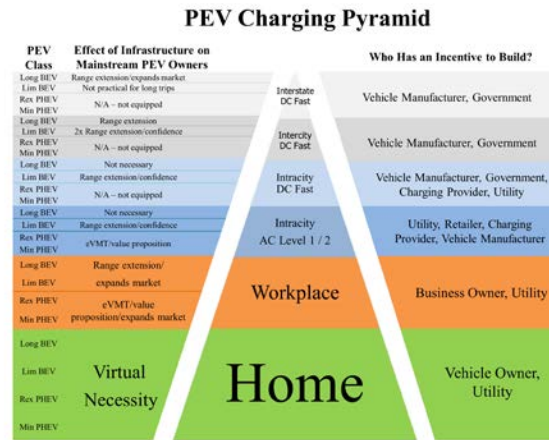


Figure 2: Integrated framework for vehicle characteristics, charging infrastructure requirements, and deployment entities. The bottom of the pyramid was considered by the committee to be most critical to mainstream market adoption.

The distribution of vehicle locations during the week, which is shown in Fig. 3, is critical for understanding charging possibilities. The figure shows why the committee considered home charging a virtual necessity for widespread adoption of PEVs. It indicates the U.S. vehicle fleet spends about 80% of its time parked at home, with 50% of that time occurring during weekday work hours. The potential for long charging times at residences allows for lower power requirements and lower costs for chargers. This means that the most critical location for infrastructure, the home, is both the least costly and least logistically complicated. However, this conclusion is only true for single-family residences and residences that have dedicated parking spots, as multi-family housing units without dedicate parking are problematic for providing PEV charging.

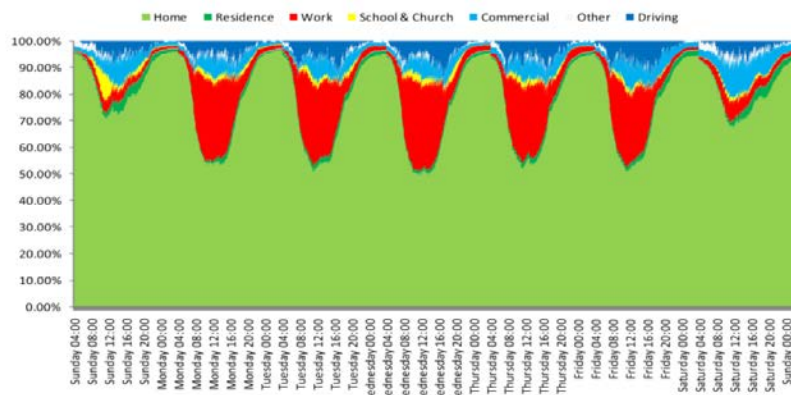


Figure 3: Distribution of vehicle locations throughout the week on the basis of data from the 2001 National Household Travel Survey. The greatest time by far is spent at home, followed by at work. Reprinted with permission from SAE paper 2009-01-1311 Copyright ©2009 SAE International [4].

Fig. 3 also shows the potential for workplace charging to increase eVMT, as the amount of time parked at work is the second longest that vehicles are parked during the week. Given the length of time vehicles are parked at the workplace, there is less need for more expensive fast-charging infrastructure. Recent data on a large sample of Leafs and Volts from the Idaho National Laboratory (Fig. 4) showed that early-adopters of both vehicles drove more eVMT with access to workplace charging [5]. DOE has spearheaded efforts to encourage and disseminate information on workplace charging.

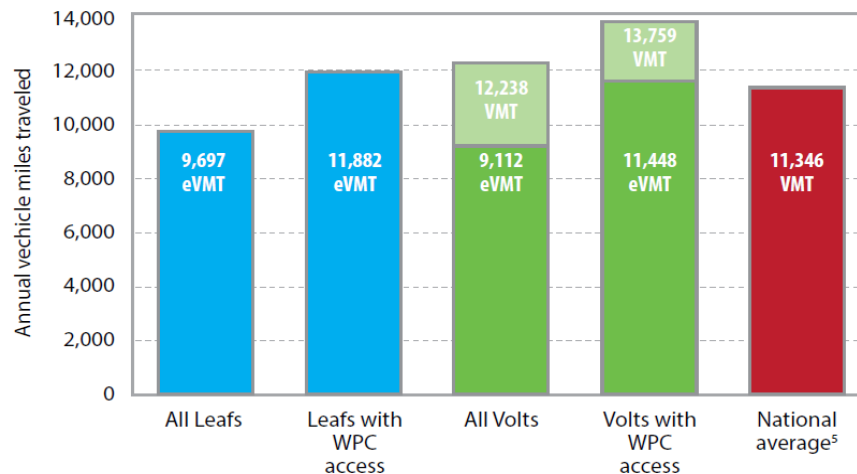


Figure 4: Impact of workplace charging (WPC) on eVMT. In a study of a large sample of Leafs and Volts, drivers with access to workplace charging drove more miles than those without access to workplace charging. Volts also increased their fraction of miles fueled with electricity rather than gasoline [5].

Although there are still issues around expanding charging availability at multi-family residences and workplaces, the development of public charging is the most vexing infrastructure question. A study of BEV drivers in Japan shows that the mere presence of public charging can greatly encourage additional eVMT [6]. However, the Academies' committee found that the impacts of the current federal investment in infrastructure on PEV deployment are not understood. Much public charging is time constrained, which requires fast charging with higher costs and power service requirements. The committee considered private sector solutions to the deployment and operation of public charging stations. But the commodity being sold, electricity, is relatively cheap and takes a comparatively long time to dispense, making private sector business cases challenging, especially the traditional gas station model. The committee recognized several models that could potentially justify the investment in the capital equipment and operating costs required for public charging. Utilities that can capture the entire residential electricity consumption of PEV owners and earn a rate of return on capital investments in charging infrastructure appear to have a business model for investing in public charging infrastructure. Initiatives undertaken by Tesla and Nissan suggest that vehicle manufacturers perceive a business case for investing in extensive networks of DC fast-charging stations. Apart from BEV manufacturers and utilities, the committee did not identify any private sector entities that have an attractive business case for absorbing the full capital costs of investments in public charging infrastructure. The federal government might decide that providing public charging infrastructure serves a public good when others do not have a business case or other incentive to do so. And various other possible models exist, such as retail

destinations that use charging sites to increase sales, subscription-based models that do not depend solely on pay-as-you-go revenues, or hybrid public-private solutions.

4. Consumers, Regulatory Incentives, and Regional Adoption

The final element of the PEV system is the consumer and the network of dealers, service support, and others who interact with the owner and vehicle. Consumer perception, knowledge, and behaviors loom large for the adoption by mainstream consumers. Unseating incumbent technologies, such as gasoline-powered vehicles, requires new technologies to offer advantages and benefits sufficient to offset price differentials and perceived risks and uncertainties of pursuing an innovation [7]. Using the adopter categories of Moore [8] and the current number of PEV consumers, PEV adoption is in the innovators/early adopter segment of the market and far from the mainstream consumer segment. Innovators/early adopters are technology enthusiasts willing to put up with deployment issues, such as those associated with infrastructure uncertainties. This contrasts with mainstream market consumers who place emphasis on the economic value proposition. As noted above, the committee's analysis focused on the barriers and possible solutions to move PEVs into the pragmatic mainstream consumer part of the market.

The National Academies' committee found mainstream consumers somewhat unaware of and disinterested in PEVs. It examined a series of issues that a consumer might face when considering a PEV, including the limited variety and availability of PEVs, the difficulties in determining individual charging needs and in installing the charging infrastructure, and the complexities in estimating purchase price and operating costs of PEVs compared with traditional vehicles. Purchasers face indifferent or uninformed dealers as well as unclear regulatory requirements and incentives. These barriers make the purchase process more complex, typically requiring the consumer to have more visits to the dealership and more background research than for a traditional vehicle. Dealers in some locations, especially in CA, have personnel specifically trained in selling PEVs to help the customer overcome these barriers.

There are an array of federal, state, and local incentives for consumers to reduce their initial costs and provide other incentives and information sources. The committee's report contains a table (Table 7-2) that shows the diversity of the incentives available for PEVs as of 2014 [1]. As noted in the introduction, federal investment in infrastructure was the issue that inspired Congress to request this study. The federal tax credit for purchasing a PEV, which ranges from \$2,500 for a PHEV10 to \$7,500 for an extended range PHEV or pure BEV, is the most important direct federal incentive because it substantially improves the economics of purchasing a PEV. The DOE also supports a broad portfolio of activities related to addressing barriers to PEV deployment. Its support includes funding basic and applied research on batteries as well as supporting local initiatives by private, governmental, and community organizations to cut petroleum use in transportation by such programs as workplace charging. States have also provided direct financial incentives, such as tax credits, rebates, and access to high occupancy vehicle (HOV) lanes. Local incentives are also important and include education, promotion, and installation of charging infrastructure. It should be noted that the committee considered state imposition of special fees on PEVs to recover lost revenue from the gasoline tax to be a potential barrier. PEV owners pay fees other than fuel taxes that support transportation budgets, and the fiscal impact from PEVs is much smaller than the increasing fuel economy of conventional vehicles. Thus, the committee recommended that PEVs remain free from special roadway or registration surcharges for a limited time to encourage their adoption.

One characteristic of PEV adoption in the United States is its strong regional distribution. The regional distribution is characterized by higher adoption on the west and east coasts, and little adoption in some states in the Midwest. Much of the regional distribution is due to the California ZEV program and other states that have

opted into the California LDV standards. The ZEV program is part California's long tradition of leading the country in the regulation of light-duty vehicle emissions, a role that California is given through the Clean Air Act [9] [10]. The Academies' committee noted that the regional distribution reflects key factors such as high fuel prices, favorable demographics and norms, and regulatory incentives. The committee found that such locally-concentrated "beachheads" were important for establishing PEV technologies and learning about infrastructure and other requirements. Moore [8] argues that finding a narrow market segment where a new technology offers consumers a compelling reason to buy and using the momentum gained from this initial beachhead to better drive sales in related, adjacent segments is an effective way to deploy new technologies.

5. Current Status of PEVs and Recent Trends

The deployment of PEVs continues to be impacted by a variety of factors since the committee completed its work. An important trend has been lower gasoline prices that directly affect the value proposition for PEVs to consumers. The national average price for regular gasoline fell below \$3/gal in the first week of Nov 2014, then fell below \$2/gal in the last week of Nov 2015, where they remain as of March 2016 [11]. Such low fuel prices negatively impact an array of fuel economy technologies, including hybrids and PEVs. Interestingly, recent sales data do not show a large loss of market share for PEVs even as the mix of vehicles moves to less fuel efficient ones. Instead, most of the market share loss for electrified transportation occurred in the HEV category, which declined from a high of 3.19% of the market for new LDV sales in 2013 to 2.21% of the market in 2015 according to purchase data from hybridcars.com [12] [13]. During that same period, PEV shares went from 0.62% of the market in 2013 to 0.73% in 2014 to 0.66% in 2015 [12] [13] [14]. The sales trends for PEVs indicate that the committee's conclusions of the PEV market being dominated by the innovators/early adopter segment are still correct. Indeed, despite the negative pressures from gas prices, some automakers are continuing to introduce new models, including long range, lower cost vehicles from General Motors and Tesla. Ford Motor Company's CEO Mark Fields also recently said its long term plans include increases in penetrations of electrification [15]. And, if public comments from General Motors on the cost of battery cells being \$145/kWh for its Bolt are accurate, battery costs have dropped more quickly than the committee thought would occur [16] [17].

Further, some regions in the United States and other countries continue to show strong growth in PEV sales. For example, San Diego Gas and Electric reported the number of PEVs in their service territory increased from just over 8,000 in May 2014 to 19,000 in November 2015 [18]. Similarly, Norway reported the number of PEVs in the country increasing from just under 17,000 to almost 58,000 over the same period [19]. Norway also has the highest fraction of new vehicle sales as PEVs at 23% in 2015, and its most popular selling vehicle overall is a PEV (VW Electric Golf). Both California, with the ZEV mandate, and Norway, with its tax policies, have strong incentives for PEV deployment.

The level of deployment in places such as CA and Norway are bringing attention to public charging and other infrastructure needs. There are many press accounts of congestion at charging stations during peak hours and calls for charging etiquette and other solutions such a financial penalties for not moving a vehicle after charging is complete. Similar to what happened to HEV access to high occupancy vehicle lanes in the United States, Norway has started to limit the incentive of PEV access to some bus-only lanes. In response to increased demands for public charging, electric utilities, automakers like Tesla and Nissan, and other private entities have increased investment in charging infrastructure. Both San Diego Gas and Electric and Southern California Edison have received permission from the California Public Utilities Commission to invest \$22 million (SCE) and \$45 million (SDG&E) in charging infrastructure and other programs. Though these are relatively small investments at this point, SCE plans a second phase of vehicle electrification investments of about \$330 million and another California utility, Pacific Gas and Electric, has a request for \$625 million on hold from CPUC. The map of charging stations also shows how Tesla has connected many interstate and cross-county corridors with

charging stations, simplifying cross-country travel [20]. These efforts and others have resulted in a large growth in public charging just since the committee completed its work. According to the DOE Alternative Fuels Database, there were nearly 8,700 AC level 2 public chargers and more than 800 public fast-charging stations in April 2015 [21]. As of March 2016, the number of AC level 2 chargers had grown to 11,300 and the number of fast chargers to 1,600 [20].

6. Conclusions and Context for National Academies' Report

The study committee concluded that, if policy makers continue to pursue PEV deployment, continuing federal funding for battery research and purchase tax credits is important to reduce vehicle cost. Both are essential for expanding the deployment of PEVs. Such investments have helped over 400,000 PEVs be sold or leased into the U.S. vehicle fleet, with increases over the past three years at about 100,000 per year. The committee also considered federal investments in deploying charging infrastructure. It recommended further study to understand the relationship between infrastructure and vehicle deployment and use before any additional direct federal investment in charging infrastructure installation.

It is important to understand the context of these recommendations as PEV deployment continues. Given that there were basically no PEVs being sold in 2010, the presence of 400,000 vehicles on the road is a substantial increase even if it is less than half of the Obama Administration's goal of having 1 million PEVs by 2015. Deployment of hundreds of thousands of vehicles increases PEV experiences for consumers, vehicle manufacturers/suppliers, regulators, and other groups. The experience gained from deployment of these vehicles can also be used to address a critical need identified by the Academies' committee: the relationship between the availability of charging infrastructure and PEV adoption and use. The Academies' committee recommended a limited federal role in public charging until this was better understood and recognized the need to see how other infrastructure deployment models might meet charging needs. As discussed above, there is an emerging need in some locations and various actors are working to meet this need. The next 5-10 years will be critical for understanding how various regulatory and market factors will affect the barriers identified by the National Academies' committee. PEVs have clearly established a presence, albeit small, in the new LDV market. What remains to be seen is how this proven technology will play out in a dynamic market affected not only by energy and technology costs but also by human behaviors including those related to location of housing, vehicle ownership, and willingness to drive.

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Authors

K. John Holmes is the associate director/scholar with the National Academies' Board on Energy and Environmental Systems. He was the co-director of the study that produced *Overcoming Barriers to Deployment of Plug-in Electric Vehicles* and director of the study that produced *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. He is currently involved in a broad set of activities at the Academies related to the electricity grid and Smart Grid technologies. Dr. Holmes has published on a range of topics including vehicle technologies and mobile source emissions, renewable electricity, climate change, air quality management, stratospheric ozone depletion, emissions trading, and the history of climate change and natural resources management. Dr. Holmes received a Ph.D. from The Johns Hopkins University.

Ellen Mantus is a Scholar and Director of Risk Assessment on the Board on Environmental Studies and Toxicology at the National Academies of Sciences, Engineering, and Medicine. She has served as the study director on projects that have ranged from assessing the health implications of various chemicals to developing decision-making frameworks for federal agencies. Recently, she served as the co-director for the study that produced *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*. Dr. Mantus received a Ph.D. in chemistry from Cornell University in Ithaca, NY.

John Kassakian is a professor of electrical engineering and former director of the Massachusetts Institute of Technology (MIT) Laboratory for Electromagnetic and Electronic Systems. He was the chair of the committee that authored *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*. His expertise is in the use of electronics for the control and conversion of electric energy, utility applications of power electronics, electronic manufacturing technologies, and automotive electronic systems. He has served on many National Academies' committees, including the Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, the Committee on Review of the 21st Century Truck Partnership Phase 2, and the Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles. He is currently the chair of the Committee on Assessment of Solid State Lighting, Phase 2. Dr. Kassakian is a member of the National Academy of Engineering. He has an Sc.D. in electrical engineering from the Massachusetts Institute of Technology.

Elizabeth Zeitler is a transportation advisor and open data advocate at the Millennium Challenge Corporation's Division of Monitoring and Evaluation. As a AAAS science and technology policy fellow, Dr. Zeitler works to expand MCC's internal knowledge of and external contributions to understanding about development projects. She examines the impact of roads investments on lives of people in low- and lower-middle-income countries. She engages with the public, particularly people in MCC's partner countries, to increase quantity, quality and access to open data. Dr. Zeitler previously worked at the National Academies' Board on Energy and Environmental Systems supporting studies of vehicle energy technologies and leading a study of energy resource potential on Department of Energy lands. Dr. Zeitler received a Ph.D. in Chemistry from Princeton University.