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Working Paper Series

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JUNE 2020

CEEPR WP 2020-010

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Handbook on the Economics of Electricity
Electrifying Transportation: Issues and Opportunities

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June 2020

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1 Introduction

The stock of electric vehicles (EVs) worldwide increased by 65 percent between 2017 and 2018 to approximately 5 million total vehicles (IEA, 2019b). While this is a small percentage of the global stock of more than 1 billion passenger vehicles, increasing adoption rates and model availability signal the potential for EVs to become a significant component of future transportation markets. An expanding EV fleet represents a potentially large transition in energy demand from the established liquid transportation fuel supply network to the electricity system. The International Energy Agency estimates this transition could reduce oil demand by 2.5 to 4.3 million barrels per day and increase electricity demand by 640 to 1,110 terawatt-hours (IEA, 2019a).

This transition is motivated in part by increasing pressure for policy makers to deeply decarbonize both the electricity and transportation sectors—a response to warnings from atmospheric scientists that 45 percent reductions in 2010 CO_2 levels by 2030 and net zero carbon emissions by 2050 are necessary to maintain global average temperature increases below 1.5 degrees Celsius (IPCC, 2018). In this chapter, we examine the challenges and implications of decorbanizing the transportation sector.

Decarbonizing transportation is generally regarded as a more difficult undertaking than decarbonizing the electricity sector. Decarbonization of the electricity sector can be achieved via a deployment of a variety of technologies. These technologies range from nuclear to renewable power sources like wind and solar, and include advances in demand response and energy storage. Fewer options are available for transportation. In most of our discussion in this chapter, we will focus on understanding the role electrification will play in one segment of global transportation: the light-duty vehicle (LDV) sector. This sector is typically defined to include passenger automobiles and light trucks. Two leading candidates exist for a decarbonized LDV fleet: battery electric vehicles (BEVs) or hydrogen fuel cell electric vehicles (FCEVs). Each of these technologies has its own set of advantages and disadvantages. Our focus is on BEVs, as they are seen by many to have a leg up on FCEVs because of recent progress in lithium-ion battery technology. Although FCEVs may affect the demand for electricity (e.g., through the production of hydrogen for fuel cells), BEVs also provide the most direct–and potentially substantial–demand for electricity in the coming decades.

EVs have several advantages over traditional internal combustion engine vehicles (ICEVs).[1] The biggest advantage is that, provided the electric grid is decarbonized, EVs can serve to decarbonize the LDV sector. Other advantages exist, however. Electric motors are highly efficient. Synchronous motors with permanent magnets, such as those used by Nissan, BMW, and Chevrolet EVs, have peak efficiencies in excess of 95 percent (Doppelbauer and Winzer, 2017).[2] In contrast, internal combustion engines (ICEs) average only 20% efficiency and have a peak efficiency of roughly 40% (Roberts et al., 2014). Electric motors also have

[1]For the discussion that follows, we use the term "EVs" to refer to electric vehicles that rely on stored electric power. In many cases, our current EV metrics combine fully-electric (battery electric vehicles, or BEVs) and plug-in hybrid electric vehicles (PHEVs) that have a gasoline engine on board but can also be plugged directly into the grid for charging.

[2]When comparing efficiencies, one would also want to account for inefficiencies upstream. If the marginal power plant is a combined-cycle gas turbine power plant, which is roughly 60% efficient, the efficiency of the EV would be roughly 48%. Oil refineries are roughly 90% efficient bringing the efficiency of the ICE vehicles to 18%.

higher torque throughout their power cycle. This increases the utility of driving EVs through performance and towing ability. The use of electric motors and the lack of a traditional gasoline engine in BEVs also means these vehicles do not require the costly maintenance that accompanies high temperature combustion and cylinder friction (e.g., BEVs avoid engine lubrication, fuel system wear, and the associated servicing). In many cases, battery placement in EVs lowers the center of gravity of vehicles, directly improving handling characteristics.

EVs have several drawbacks, as well. Despite large reductions in the cost of batteries in recent years, EVs remain more expensive than ICEVs. Because of the cost, energy density, and added weight of batteries compared to liquid fuel systems, EVs also have more limited range compared to ICEVs. These range limits increase the frequency of recharging and may create "range anxiety" among drivers. While financial incentives and infrastructure build-outs exist in part to allay these concerns, range anxiety, battery cost, and infrastructure are primary concerns of prospective BEV buyers (Egbue and Long, 2012).

In what follows, we expand on these advantages and disadvantages and explore the opportunities and challenges of the LDV fleet electrification, highlighting the major impediments to large scale EV adoption and discussing technological trends and policy interventions aimed at overcoming these barriers. We first discuss the current state of the LDV sector, taking stock of the number of vehicles worldwide and describing the broader LDV ecosystem. We pay particular attention to fuel markets and refueling infrastructure. Having discussed the system we seek to decarbonize, we turn to EVs. We compare vehicle cost factors and investigate the break-even cost relationship between oil and battery prices. We include a discussion of policy interventions and their effectiveness. We then quantify the energy demand effects for a range of LDV electrification scenarios before turning to the emissions and fuel taxation implications of this transition. We conclude with some thoughts on electrification in other transportation sector contexts, namely, in heavy-duty freight transport, and the role EVs may have in ride sharing and autonomous vehicle networks.

2 The existing light-duty vehicle ecosystem

2.1 Vehicles on the Road

As of 2015, there were roughly 950 million passenger cars in use worldwide. The are three striking observations regarding the growth and spatial distribution of LDVs (Figure 1). First, the number of vehicles in use increased by 45 percent between 2005 and 2015. This increase occurred despite the Great Recession in the late 2000s. The negative effects of the most recent financial crisis were dwarfed by long-run global LDV growth trends. Second, the stock of passenger cars is concentrated in a few regions. The European Union (EU), US, Japan, and China represent more than half of the total vehicle stock worldwide. Third, while other regions have seen some modest growth in the vehicle market, the demand for passenger cars in China is the main driver behind the the market growth during this time. Most of this global vehicle stock is powered by ICEVs, burning either gasoline or diesel to create the mechanical power to move the vehicle and its contents (ExxonMobil, 2019). The efficiency with which these vehicles convert fuel inputs to kinetic output dictates total energy use in the sector.

The ICE efficiency has come a long way since the days of Karl Benz and Henry Ford. Knittel (2011) finds that the efficiency of the modern-day car increases by roughly 2.4 percent per year. This is a combination of efficiency improvements in engine and in other parts of the drivetrain. The efficiency of modern-day gasoline engines is roughly 30-35% (Edwards et al., 2011). That is, modern day gasoline engines, operating at ideal conditions, convert 30-35% of the British Thermal Units (BTUs) they consume into work. The rest of the BTUs escape as heat. In practice, the average efficiency of ICEVs, accounting for all other energy losses, is closer to 20% (US DOE, 2019b). Although Diesel engines are roughly 20 percent more efficient than gasoline engines, their average efficiency is approximately 40 percent (UTI, 2019; Edwards et al., 2011).

Vehicle efficiency is evaluated in terms of miles per gallon (in the US) or liters per kilometer (in most other countries). Figure 2 shows fuel efficiency trends and targets as calculated in Yang and Bandivadekar (2017). The EU and Japan are leaders in fuel efficiency, while North America lags behind. Overall, LDV efficiency is gradually increasing. Many regions have exhibited substantial fuel efficiency improvements since 2005 regardless of their initial efficiency level. The EU and US, for example, have seen improvements of approximately 20–30 percent. To maintain this course and meet increasing regulatory stringency, automakers must continue to find and implement fuel-saving technologies in their LDV model offerings.

These efficiency measures are important factors in the discussion of vehicle electrification. Decarbonization is a key motivator for policies that promote the electrification of transportation, and vehicle fuel efficiency plays a central role in determining the decarbonization benefits of an electrified vehicle fleet. In addition to fuel economy, the climate change benefits of electrification depend on vehicle usage patterns and the carbon dioxide (CO_2) emissions associated with the electricity grid. Holding fixed grid emissions intensity and total vehicle miles traveled, the climate change benefits of electrification will be largest in the Americas. As we show later in this chapter, many other regions also stand to benefit from a transition to EVs.

2.2 Fuel Price Levels and Trends

Behind depreciation costs, refueling makes up a significant portion of total vehicle ownership costs (Palmer et al., 2018). For mainstream ICEVs, the principal driver of refueling costs is the price of fuel. Globally, most ICEVs are gasoline- and diesel-powered. Market penetrations of diesel-fueled ICEVs vary greatly by country. For example, diesel vehicles represented only one percent of the passenger car fleet in the United States in 2015, compared to 52 percent in the EU-28 states (Yang and Bandivadekar, 2017). While there are some signs that this level is set to decline, including changing diesel taxation policy and proposals to ban diesel vehicles from urban areas in some European countries, the level of existing diesel vehicle stock suggests drivers may still consider a diesel option when selecting new car purchases (Tietge, 2018).

Figure 3 shows real gasoline prices (USD/liter) at the pump for various countries between 1998 and 2016. In panel (a), we plot prices in Canada, Australia, and in Asia. In panel (b), we plot US prices along with prices in Europe. The price spread between diesel and gasoline is reported in panels (c) and (d). A cursory glance at the figure makes it clear that gasoline prices in Asia and Europe are consistently higher than prices in other regions. The majority of spatial heterogeneity in prices can be attributed to spatial variation in fuel tax rates. For example, tax levels in Spain are the lowest within the group of EU countries shown, but higher than those in the US and Canada (OECD, 2018; Wappelhorst et al., 2018). Moreover, price spreads between gasoline and diesel vary widely by country. Prices in the US consistently favor gasoline as the less expensive fuel option, while the opposite is true for many European countries in the figure. In the EU countries in particular, this is likely due to lower fuel tax rates on diesel than gasoline (OECD, 2019). Finally, with respect to trends, gasoline prices in European countries tend to follow similar price patterns, while trends for other areas vary considerably. With the exception of Korea and India—where price increases occurred prior to 2006—global gasoline prices increase prior to 2012 before declining through 2016. The trends for both gasoline and diesel generally follow global crude oil price patterns.[3]

As vehicle electrification expands, electricity price trends are expected to have an effect on fuel prices in the transportation sector. Figure 4 shows a gradual increase in electricity prices over the past decade for European countries and steady prices in the US, Korea, and Canada. To facilitate a uniform comparison across fuels, Figure 5 shows travel-distance-adjusted prices for a number of countries in 2016.[4] EVs are the least expensive option in all countries, followed by diesel. As we note later in this chapter, diesel vehicles and EVs are both more fuel efficient than gasoline-powered ICEVs. The price discrepancies and efficiency levels combined produce the striking heterogeneity across fuel types. Assessed strictly on a marginal fuel cost basis, EVs hold clear advantages over existing ICEV technologies.

2.3 Vehicle Miles Traveled

Where fuel prices determine the marginal cost of LDV energy consumption, the quantity of energy consumed is determined primarily by LDV use. One key measure of LDV use is the number of vehicle miles traveled (VMT). While availability of VMT information varies by country, Figure 6a shows clearly the stark contrast between VMT levels in the US compared to other regions. More relevant to consideration of future trends for energy use in the transportation sector are global trends in vehicle use. Figure 6b shows a modest increase in VMT levels for most OECD countries, with some large markets, notably Japan, seeing a VMT decrease in recent years. These growth patterns are driven in part by macroeconomic factors, regional transportation network capacities, and evolving consumer mobility needs. In the US, for example, Leard et al. (2019) attributes a portion of this growth to changes in household-level socioeconomic factors. Since the Great Recession, VMT growth has remained relatively flat and is predicted to remain at a rate of approximately 1 percent annually (US DOT, 2019).

The steady VMT levels observed in the US are present in other markets as well. Although some predict an end to slow and steady VMT growth rates (IHS Markit, 2017), future growth trends are uncertain and depend

[3]Currently, IEA models predict flat to moderate growth in oil prices to 2040, contingent on policy scenario assumptions (IEA, 2019b).

[4]In line with this section's discussion, this figure illustrates differences in fuel prices alone. For ease of comparison, we hold vehicle efficiencies fixed by vehicle type, across countries.

on a multitude of factors. Crucially, as global vehicle use trends evolve and national economies grow, annual, individual travel distances may approach saturation levels (Ecola et al., 2014). The current trends in VMTs and predictions related to these potential upper bounds for individual mobility illustrate the challenges of employing altered vehicle use behavior as a lever for reducing emissions from the transportation sector.[5]

Another important consideration regarding LDV use—one that is unique to the transition to EVs—is the presence of consumer "range anxiety", the concern about insufficient electrical energy stored for EV trips. Several studies on consumer perceptions of EVs cite range anxiety as a barrier to adoption or a concern that is more prevalent in EVs than ICEVs (Daziano, 2013; Franke and Krems, 2013; Franke et al., 2012). Data from the US Department of Energy show average daily VMT ranges of 30–50 miles (US DOE, 2018). Analysis of driving patterns in the US and Germany indicate more than 90 percent of daily driving distances are within 100 miles–a range less than the capacity limits of most existing EV models (Gnann et al., 2012). Hence, for the majority of trips, VMT limitations are more likely perceived than a product of technical constraints. Nonetheless, the failure to address the perception of range anxiety may hinder wider adoption of EV models. One reason these range anxiety concerns are *de minimis* in the ICEV market is the wide availability of refueling locations. We turn to this component of the LDV ecosystem in the next section.

2.4 Refueling Stations

ICEV refueling relies on a wide network of supply infrastructure that covers fuel refining, blending, and distribution. After fuel blendstocks and additives are combined, trucks deliver liquid motor fuels to fueling stations that store the finished fuel in underground tanks until it is pumped into vehicles. Although gasoline and diesel have an advantage of being relatively energy dense, battery technology is improving thus narrowing this gap (Vijayagopal et al., 2016). Near-term favorability of liquid fuels also stems from the fact that the infrastructure for their distribution and storage in the transportation sector is more mature than that of electricity. In contrast, while EV energy distribution is similarly well-developed, as it relies on the existing electric grid, the final retail stage of EV fueling is less developed.

Table 1 demonstrates the heterogeneity of public EV charging infrastructure relative to a number of market metrics across countries. For example, the ratio of EVs to public EV charge locations is between 5 (Germany and Korea), and 16 (US). To put the relative maturity of liquid transportation fuel retailing and electric charging into context, we also include a calculation of EV chargers to gasoline stations. The emphasis that Norway and China place on EV deployment—multiple charge points for every gasoline station—stands out among the countries listed in this table.

Norway is a special case worth noting, and the density of charge points illustrates why. The 11 charge points per 100km of road network is due in part to a 2015 push to install fast charging stations every 50km on main roads in the country (Lorentzen et al., 2017). While Norway's high level of EV adoption is a result of numerous factors that include incentives, high ICEV taxation rates, and resident travel preferences, the robust charging infrastructure plays a role in supporting and sustaining the country's place as a leader in

[5]For a summary of the literature on the inelasticity of VMTs, see Knittel (2012).

the EV space. The availability of charging infrastructure in Norway has not yet had a significant effect on total electricity demand in the country, and full electrification is likely to have a minimal impact on energy demand overall (IEA, 2018b). At the distribution level, however, urban areas with high population density and popular, more remote travel destinations experienced some distribution disturbances (IEA, 2018b; Klingenberg, 2017).

While public EV charging availability lags behind that of ICEV refueling in many areas, the number of EV charging locations is increasing. Table 2 shows the recent expansion of EV charging stations in several European countries, the US, and China, highlighting nontrivial build-outs of EV charging infrastructure. Whether this trend of new installations will continue is likely to play a key role in sustaining EV market development. In the US, Li et al. (2017) demonstrate significant feedback effects between EV adoption and investments in public EV charging infrastructure. The authors' estimates suggest a 10 percent increase in public chargers produces an 8 percent increase in adoptions, and a 10 percent increase in adoptions results in a six percent increase in public supply points. These findings lead the authors to posit policy focused on infrastructure, rather than adoption, could produce greater overall consumer uptake of EVs. These estimates are based on observations in urban areas of the US between 2011 and 2013 and therefore represent an early period of EV availability in the US. Many consumers purchasing EVs during this period are likely to be early adopters who are less price sensitive than the general car-buying population. The extent to which these estimates scale and their applicability in other market contexts is an area that would benefit from additional empirical research.

EV owners have the capability to charge their vehicles using electrical connections at home or at their place of work, unlike ICEV owners that rely nearly exclusively on public refueling infrastructure. Another relevant consideration when assessing the future of LDV fueling infrastructure is therefore the necessity for public fuel supply and the effect EV expansion will have on existing retail fueling station owners. Already, areas such as the UK have seen significant declines in gasoline and diesel fueling locations (Campbell, 2018). This is a result of increased vehicle fuel efficiencies and will accelerate with fuel demand reductions that accompany broader EV adoption. A recent study by Boston Consulting Group indicates many fuel retailers could struggle to be profitable within the next two decades. As the traditional network of retailers confronts this challenging landscape, opportunity exists for new business models tailored to the needs of EV drivers (Rubeis et al., 2019). Beyond these implications for existing fossil fuel retailers and the liquid fuel distribution market, we also must consider the relative benefits of home and workplace charging of EVs in the context of both consumer value of refueling time and in considering the grid-based consequences of a fully electrified vehicle fleet. We turn to these and other challenges in the next section.

3 Challenges

The decision to purchase an EV is one for purchasing a durable good: it involves an intertemporal tradeoff between upfront (purchase price) and operating costs and the lifetime benefits of the vehicle. Both the costs and benefits of vehicle ownership, in general, are multidimensional. That is, vehicles are differentiated products that vary in terms of their performance and size, among other dimensions. The private costs of owning the vehicle include the upfront costs, maintenance costs, costs of refueling in terms of both fuel and time, and associated costs of the complementary products. There are also external costs in terms of emissions and congestion.

In this section, we discuss the likely impediments to large scale EV adoption. We begin by discussing the lifetime costs associated with owning EVs and ICEVs. In general, EVs have higher upfront costs, but lower future costs of ownership through a lower cost per mile and lower maintenance costs. These lower per-mile and maintenance costs are potentially counterbalanced by higher time costs associated with refueling and higher disposal costs. We discuss some efforts to overcome the higher upfront costs of EVs through policies that provide EV buyers with subsidies or other benefits. We then turn to the challenges associated with complementary products. For EVs, the challenges pertain to costs attributed to the recharging network—both the physical recharging infrastructure and the associated electricity grid-level costs—that an expanded recharging network will require.

3.1 Vehicle Costs

The biggest challenge to large-scale EV adoption is the price of batteries. Batteries represent a significant portion of the retail price premium of EVs over their ICEV counterparts (Baik et al., 2019). Current estimates suggest that the cost of batteries at the system level is roughly \$160 per kWh (BloombergNEF, 2019; Kapoor et al., 2020).[6] To put this number in perspective, the Tesla Model S requires 0.3 kWh per mile. For an average daily-trip distance of approximately 60 miles, this vehicle requires a battery of 18 kWh to operate on a single charge per day, on average.[7] At battery costs of \$160 per kWh, the battery for such a vehicle would cost \$2,880. Producing an EV with a range similar to that of an ICEV would be significantly more costly. The median range for ICEVs available in the US is approximately 400 miles (EVAdoption, 2018). An EV with this range would require a 120 kWh battery for a cost of \$19,200 at current prices. This cost is similar to the average price of a mid-size ICEV. In the remainder of this section, we assess the cost competitiveness of EVs by estimating price parity between ICEVs and EVs based on battery costs and oil price levels.

We undertake a series of calculations. We first build on the analysis in Covert, Greenstone and Knittel (2016); henceforth, CGK. CGK calculate the break-even price for oil for a range of battery costs.[8] Such an analysis requires several assumptions. An interactive tool that calculates results presented in this section is available on our website for those that would like to vary these assumptions. We then extend the CGK analysis in a number of ways.

[6] Except where otherwise noted, prices in real 2018 US dollars.

[7] This travel distance is equal to the 85th percentile of daily driving for conventional vehicles in the United States (Li et al., 2019). We use the US as a reference point to maintain consistency with the other inputs of our calculation. While we are not aware of a systematic study of travel ranges at the country level outside of the US, Plötz et al. (2017) study data from four locations (Germany; Western Sweden; Winnipeg, Canada; Seattle, US) and indicate values may be slightly lower in some other regions.

[8] In line with CGK, analysis here relies on data and assumptions for the US and is based on our analysis of the US oil-gas price relationship and existing fuel tax levels. Outside of the US context, we refer the reader to Newbery and Strbac (2016) for an exploration of cost parity calculations for the UK. Newbery and Strbac undertake noteworthy effort to account for the full social costs across delivered energy source options in their model.

Our break-even analysis requires assumptions on the mapping from oil prices to gasoline prices, the annual travel distance, the desired range, the discount rates, the efficiency levels of ICEVs and EVs, and the price of electricity. As in CGK, we assume that the vehicle travels 15,000 miles annually and the owner would like an EV range of 250 miles. We compare an EV that uses 0.3 kWh per mile to an ICEV that gets 30 miles per gallon of gasoline. As such, we are comparing, effectively, two medium-sized sedans such as the Tesla Model S and the Honda Accord.[9] We use a discount rate of 5 percent. To map oil prices to gasoline prices in the US, we use monthly data on US gasoline prices and Brent Crude prices and estimate a log-log relationship between the two series. Our gasoline prices include state and federal taxes. The federal gasoline tax is approximately 18 cents per gallon. The average state-level tax is roughly 30 cents per gallon (US EIA, 2019).[10] Finally, we assume an electricity price of 12.4 cents per kWh, which is the average residential retail price in the US in January 2017 (US EIA, 2017).

Figure 7a plots the results of this exercise. The estimated line of cost parity is represented by the solid back line. Points below the line represent oil price and battery price pairs where ICEVs are less expensive to operate than EVs. The opposite relationship holds for points above the line. To a first order, the relationship is close to a 1:1 mapping between oil prices and battery costs. This does not bode well for EVs. For example, as of this writing, the price of Brent Crude is roughly \$40 per barrel with NYMEX futures out to 2026 approaching \$50 per barrel. At an oil price of \$40, batteries need to be roughly \$44 per kWh for EVs and ICEVs to be at cost parity. At battery costs of \$160, the price of oil needs to be approximately \$140 per barrel, which exceeds peak oil prices over the past decade. These results can be used to evaluate existing battery cost goals and projections. Consider for example the US DOE goal of \$125 per kWh by 2022. At parity, oil would need to be priced at approximately \$100 per barrel.

We extend this analysis in several directions. We start with assumptions that make EVs more attractive. One advantage of EVs is that they have fewer moving parts, do not require as many system fluids, and, due to regenerative braking, may have longer-lasting brake systems. Hence EVs have lower maintenance costs than similar ICEVs (US DOE, 2019a). We repeat our calculations for four levels of annual maintenance savings, ranging from \$200 to \$500 in Figure 7b. We include the cost parity line of Figure 7a (i.e., assumed annual savings of \$0). At current oil prices of \$40 per barrel, \$100 of annual maintenance savings reduce the break-even cost of batteries by roughly \$10 per kWh. For example, if EVs save \$200 per year in maintenance costs, the break-even cost of batteries at \$40 oil is roughly \$65 per kWh, compared to \$45 per kWh if there are no maintenance cost savings. Increasing the annual maintenance cost savings to \$300 increases the break-even battery cost to \$75 per kWh. With large savings in maintenance costs, cost parity is attainable at the US DOE's target of \$125 per kWh. With maintenance savings of \$700 per year, the break-even oil price is \$43 per barrel at the US DOE's target.

The higher frequency and longer wait times associated with EV recharging counterbalance the maintenance savings associated with EVs. In our second series of calculations, we compute back-of-the-envelope costs

[9]Honda offers two engines for the 2019 Honda Accord 4-door. The combined fuel economy for the 1.5L Turbo is 33 MPG, while the combined fuel economy for the 2.0L Turbo is 27 MPG. For details, see `fueleconomy.gov`.

[10]Gasoline tax revenues typically fund road infrastructure. We return to this point in Section 4.2.

associated with the longer wait times, ignoring the more frequent recharging. Such a calculation requires two inputs: the value of time and the share of charges that take place outside of home. The latter is important because charging at home likely reduces the lost value of time. We calculate the lost value of time for values ranging from $5 per hour to $100 per hour and the outside-the-home charging share between zero and 100 percent. We assume that it takes 30 minutes to charge the EV, while it takes 5 minutes to refuel the ICEV. Table 3 shows this new set of calculations. We shade the areas to make them comparable to the assumed maintenance cost savings discussed above. The lost value of time can easily exceed the maintenance cost savings even if the value of time is as low as $15 per hour.

These calculations are biased toward EVs because they ignore the revenue generated from gasoline taxes. That is, they implicitly assume that these revenues will not be collected from EVs. There are two ways to think about this issue. On the one hand, one could argue that these taxes reflect the relative social cost of the fuels. In the US context, this is not exactly true because the state-level taxes do not vary based on the external costs associated with electricity production. However, the average federal- plus state-level gasoline tax is close an implied social cost of carbon of roughly $50 per ton. Therefore, one could argue that it is unnecessary to adjust the EV calculations for this revenue shortfall.[11] On the other hand, in the US, gasoline tax revenues largely go toward road maintenance. From this standpoint, it is possible, if not likely, that in an EV regime, electricity prices would be taxed in order to cover this revenue shortfall.[12] If we adjust the electricity prices in our calculations such that the same amount of taxes is collected, this adds a little over 5 cents per kWh to the price and increases the break even oil price from $103 per barrel at the DOE target to $127 per barrel.[13] Alternatively, one may annualize the tax revenues making them comparable to the maintenance savings discussed above. When computed this way, annual tax revenues are roughly $240 per year.

Figure 7a also includes results for a scenario in which gasoline is taxed at levels that internalize the social cost of carbon; this is represented by the dotted line in the figure. Because this additional tax increases the cost of gasoline, a given battery price requires a lower oil price for cost parity. Put another way, there is a slice of oil-battery price pairs where EVs are now less expensive to operate than ICEVs than under the baseline scenario. As expected, this has the opposite effect of the tax scenario discussed above. The fuel for EVs is more expensive and there is a larger region of prices under which the ICEV operating costs are lower than the EV costs.

We implement a similar cost parity calculation for PHEVs. This calculation adds a level of complexity as PHEVs are able to operate on both liquid fuel and electricity. We allow for "dual-fuel" operation and account for smaller battery sizes, lower efficiencies when propelled by electricity, and higher internal combustion engine efficiencies observed in today's PHEVs. We allocate a portion of travel distance to electric energy

[11]Tax rates elsewhere, especially in the EU, are higher than those in the US. This produces tax levels above the implied social cost of carbon. Accounting for this cost differential, and recognizing other potential externality costs (e.g., damages from local emissions, especially in heavily populated areas), suggests cost adjustments in other contexts may be necessary.

[12]Alternatively, policy makers could adopt mileage taxes. This would have the same effect of increasing the costs of operating an EV relative to the costs assumed above.

[13]See Figure 7a for tax adjusted values across the computed battery price range.

only and the remaining travel to an ICE mode. The resulting parity line, along with the BEV parity line, is shown in Figure 7c. PHEVs require lower oil prices at parity, which is due in large part to the smaller battery sizes in PHEVs and the resulting lower vehicle fixed costs. Using PHEV battery range along with electric and gasoline mode efficiencies equal to the average for US PHEV models in 2019, at today's battery cost of $160 per kWh, parity requires oil prices of roughly $50 per barrel. These prices are below crude prices observed prior to the April 2020 price declines. At the US DOE battery price target of $125 per kWh, break-even oil prices are approximately $47 per barrel–similar to futures prices in 2025 as of this writing. When calculated using BNEF's forecast of $100 per kWh batteries in 2023, the corresponding break-even oil price is $44. This estimate is below current oil futures prices for 2023.

The figure also illustrates points at which BEVs can be more cost effective than PHEVs and ICEVs. While these points occur at very low battery price levels, it is worth noting that such an inflection point exists at around $38 per kWh and $36 per barrel of oil. The fact that BEVs become more cost effective at low battery prices suggests that PHEVs can facilitate the transition from ICEVs to BEVs. In the presence of additional market failures, such as research and development or learning-by-doing spillovers, policy makers can incentivize the adoption of PHEVs while battery costs are above this "switch point," allowing for technology to advance either through technological progress or learning-by-doing. As battery costs continue to fall, policy makers can shift their attention to BEVs. We caution, however, that this inflection point is sensitive to assumptions about EV, ICEV, and PHEV efficiencies and predictions about future tradeoffs between PHEV-to-EV switching points would benefit from additional work understanding the interaction in efficiency gains across powertrain types.

As a last step to our extension of the CGK analysis, we examine the sensitivity of our BEV results to a set of key input parameters. Figure 8 presents battery price parity levels corresponding to specified ranges of (i) gasoline price, (ii) ICEV efficiencies (in MPG), (iii) oil prices (USD/bbl), and (iv) gasoline tax levels (USD/gallon). The main message of these calculations is that a decline in ICEV cost components requires larger reductions in EV battery prices. For example, lower gasoline prices, more fuel-efficient ICEVs, lower oil prices, and lower gasoline taxes require significant battery price reductions beyond current levels to achieve an ICEV-EV cost parity.

While our analysis indicates that cost parity for PHEVs may be on the horizon in the US, parity levels for BEVs remain out of reach at current price levels. Battery costs for BEVs have a long way to go to achieve cost parity. As noted, battery costs have fallen dramatically over the past decade; continued battery price declines coupled with steady oil price levels may produce vehicle price parity in the near future. Several papers have estimated learning-by-doing models of battery production and extrapolated these out in time. See, for example, Nykvist and Nilsson (2015), Schmidt et al. (2017), Kittner et al. (2017), Berckmans et al. (2017). These papers estimate learning rates of roughly 8-10 percent, implying an 8-10 percent drop in costs for every doubling of past production. At these learning rates, battery costs will fall below $100 per kWh by 2030 (MIT Energy Initiative, 2019).[14]

[14]These estimates are based on what MIT Energy Initiative (2019) calls a one-stage learning model. Effectively, the log of costs is regressed on the log of cumulative production, generating the learning rate. These models imply that battery costs will fall to below

3.2 Financial and Other Incentives

Many public and private entities offer incentives to promote EV adoption. For example, incentives for zero- and low-emissions vehicles are coupled with fuel economy standards to bridge the cost gap between EVs and ICEVs and promote the deployment of charging infrastructure. Incentives offered at the national, sub-national, and private level, represent notable portions of a consumer's initial outlays for an EV purchase. Fuel economy standards and mandates for clean vehicle production are driving forces in expanding the availability of more efficient and electrified LDV options.

IEA (2019a) summarizes EV-related policies for various countries. This summary is reproduced here as Table 4. All regions in the table implement some form of targets for both vehicles and recharging infrastructure. Most also offer financial incentives to prospective EV consumers to offset vehicle and charger costs. The value and availability of these incentives varies across regions and vehicle models. In general, direct vehicle incentives do not completely overcome the cost differential between ICEVs and EVs; Yang et al. (2016) show this is true for both PHEVs and BEVs only in Norway. In Sweden, Canada, and Germany, EVs may be more than 50 percent more expensive than comparable ICEVs.

An extensive body of literature investigates the effectiveness of EV incentives in stimulating new EV adoptions.[15] In general, subsidies play an important role in EV purchase decisions. In a survey of California EV owners, respondents indicated federal and state incentives played a significant role in their ultimate EV purchase decision (Jenn et al., 2020). In the EU, a survey of public and private sector experts across five countries indicated tax incentives and vehicle purchase subsidies had the potential for a strong, positive impact on EV adoption (Santos and Davies, 2019). Sierzchula et al. (2014) estimate the effect of EV adoption incentives on passenger vehicle fleet electrification. The authors examine a cross-section of 20 countries in 2012 and find a significant, positive relationship between EV incentives and EV market shares. Though the magnitude of this effect varies across countries in the study, their findings lend support to the general perception of EV subsidy effectiveness.[16]

Compared to one-time financial incentives, measuring the effectiveness of recurring and non-monetary incentives is more challenging, due in part to the difficulty in assigning consumer value to these offerings. In the US, Jin et al. (2014) monetize benefits such as carpool lane access and parking privileges and find positive correlation between incentives and EV adoptions. A review study by Hardman et al. (2018) demonstrates the potential for a wide variety of incentives that include the incentives above along with infrastructure investment, and toll, licensing, and other fee waivers, to actively promote EV adoption. Individually, each of these incentives can reduce the barriers to broader EV adoption. In some cases, multiple incentives (e.g., financial incentives and infrastructure advancement) exhibit complementaries in promoting adoption (Li

$100 per kWh by 2030 bringing them nearly to cost parity with an associated oil price of $80 per barrel. It is important to note that this calculation holds constant ICEV technology, which as noted above improves by roughly 2.4% per year. If we account for these improvements, the 30 MPG comparison vehicle will instead have a fuel economy of 39 MPG by 2030, leading to a cost-parity oil price of $124 per barrel in our base case.

[15]For a comprehensive review of existing studies, see Münzel et al. (2019).

[16]Existing work finds similar results for national (Tietge et al., 2016; Tal and Nicholas, 2016) and sub-national policies (Mersky et al., 2016; DeShazo et al., 2017; Clinton and Steinberg, 2019).

et al., 2017).

The approach to EV promotion in Norway deserves particular attention in a discussion of incentive structure and effectiveness. Norway has made a concerted effort to target EV price competitiveness with ICEVs. This is aided by the country's taxation structure. Since 2001, EVs in Norway are exempt from purchase/import taxes, the 25 percent VAT on vehicle purchases, and are charged no annual road tax (EV Norway, 2020). Additional taxes levied at the time of vehicle purchase are a function of vehicle weight and emissions, which produces significant tax penalties for gasoline and diesel vehicles. Combined, these measures ensure price competitiveness of EVs over ICEV models (Haugneland et al., 2017). The comprehensive package of incentives and other interventions that bolster EVs play an important role in driving the successes observed in the Norwegian EV market (Bjerkan et al., 2016; Zhang et al., 2016).

An important future consideration for market participants is the sustainability of the EV market in the absence of these incentives. Subsidies or tax incentives valued at a few thousand dollars per vehicle represent a significant outlay of funds, especially in the context of higher levels of EV demand. Other concerns, such as the implementation of incentive programs as a transfer from taxpayers to EV adopters, highlight the importance of evaluating incentive effectiveness and optimal phase-out (Egbue et al., 2017). Many existing EV incentive structures include phase-outs based on temporal or aggregate sales thresholds.

One alternative to incentive offerings at the time of vehicle purchase is to emphasize total cost of vehicle ownership (TCO) to EV buyers. The EV TCO exhibits a negative relationship with overall EV market share in EU member states (i.e., lower EV TCO corresponds to higher EV market share) (Lévay et al., 2017). Providing this information to consumers for consideration when purchasing a vehicle may influence their ultimate vehicle purchase. Dumortier et al. (2015) present survey respondents with TCO information for ICEV and EV models and find higher rankings for EVs in the presence of this information. It is interesting to note that this finding does not require EVs to be strictly less expensive than ICEVs; the results generally hold when EV and ICEV models were of similar TCO. An information-based intervention such as this is likely to be less costly than direct financial incentives, though its effectiveness on a broad scale remains an open question.

3.3 Vehicle Variety

While pricing is perhaps the paramount factor in consumers' decision making, manufacturers must also provide potential buyers with a mix of vehicle offerings that adequately cover the range of consumer preferences. Compared to ICEVs, the number of available BEV and PHEV models is limited. Table 5 shows the number of ICEV, EV, and PHEV models marketed in the US for 2011–2019. Although there is notable increase in the number of both BEVs and PHEVs, EVs only account for about 5 percent of total vehicle models offered in the US. IEA (2019a) reports similar data for China, Europe, and the US. The number of available PHEV models ranges from 30 to 40 in these countries. The number of BEV models differs dramatically. There are 19 BEV models offered in the US, 40 in Europe, and 122 in China.

Although available models do span vehicle segments, the majority of the BEVs and PHEVs offered today occupy the small and medium car segment. The decision to design and build vehicles in this segment is not surprising, as models of this type are typically of lower weight and therefore more efficient and less expensive than larger vehicles. However, concentrating offerings in this vehicle class leaves some untapped segments of vehicle buyers. In the US and Europe, there is a growing interest in crossovers and SUVs among consumers. This trend is expected to continue, likely at the expense of the market share of cars (Cozzi and Petropoulos, 2019).

Although the trends in overall vehicle model offerings signal a growing sector, it will be necessary to overcome challenges inherent in porting EV powertrains to larger vehicle model segments to continue moving the electrified vehicle fleet to the mainstream. Higher weights, available all-wheel-drive systems, and less advantageous aerodynamics of these vehicles often require larger and more expensive battery and drive systems. While this clearly presents a challenge to manufacturers, the crossover and SUV segment has seen the greatest increase in the number of model offerings in China, the US, and the EU (IEA, 2019a). Current product announcement schedules from leading vehicle manufacturers indicate this emphasis will continue in the near term as the portfolio of available EV models expands (Automotive News, 2018).

3.4 Electricity Grid Issues

Beyond consumer cost and vehicle performance concerns, broad EV adoption presents unique challenges to the energy supply network. Electrification of the vehicle fleet has the potential to generate a significant increase in aggregate electricity demand and alter intra-day load patterns. To maintain consistent supply, grid operators must address these challenges in the context of an evolving power system. In this section, we quantify aggregate electricity demand consequences of an electrified LDV sector. We also assess intra-day grid effects based on a set of vehicle charging scenarios. Both exercises illustrate the energy supply-side challenges of large-scale EV adoption.

To estimate aggregate EV energy demand, we combine data on electricity consumption, vehicles, and vehicle miles traveled across multiple systems. We compute the total energy demanded assuming all existing VMTs were associated with EVs. The resulting total EV energy demand is compared to current annual system energy demand by country. Results of these calculations are presented in Table 6. Based on these values and assumptions, the scale of energy consumption effects from the move to an electrified vehicle fleet range from 9 percent (in France, which has a relatively low level of annual VMT) to over 30 percent (in the UK, where existing electricity consumption is relatively low compared to other nations). Given the current state of EV adoption—where EVs make up less than 1 percent of many national LDV fleets—these loads in aggregate are not likely to challenge the existing fleet of electric power plants. That said, the long-term planning horizon for power plant construction and accelerating EV adoption trends in some areas suggest the value of more detailed insights regarding these effects of LDV electrification. The costs required for electricity suppliers to meet these levels of energy demand will depend crucially on their need and ability to expand generating capacity to address demand changes, their accuracy in properly predicting the growth rates of EV stock, and on the cost trajectories of input fuels for power generation. With respect to the first of these three elements, the aggregate annual demand is likely less important than the effect EVs have on intra-day load patterns.

While a rigorous analysis of grid implications accounting for existing load patterns, distribution grid topology, and localized consumer adoption trends is beyond the scope of this chapter, we estimate regional grid consequences of EV adoption for a range of EV penetration scenarios in the US (CAISO in California, PJM in the mid-atlantic region, and ERCOT in Texas), the EU, China, and Japan. We compute approximate energy demand based on total EV stock and fixed levels of annual VMT and vehicle energy efficiency. To estimate effects on an hourly scale, we approximate load due to EV charging using representative EV charging profiles developed by the US DOE's National Renewable Energy Laboratory and published as part of the US DOE's EVI-Pro simulation tool (Wood et al., 2017). We modify these profiles to produce four illustrative scenarios for EV charging: (i) uniform charging across all hours, (ii) a base profile directly from the EV-Pro tool, (iii) charging without the availability of workplace charging networks, and (iv) charging in the evening only.[17] The results of this exercise are presented in Table 7.

In all regions, current levels of EVs remain a small fraction of existing vehicle stock. Estimates of total generation and capacity requirements suggest current EV penetration levels are of limited magnitude at a grid-wide scale; only in California do energy and power demands reach half of one percent of existing levels. An increase in adoption rates, however, will make EV loads major players in dictating capacity expansion and grid operation patterns. EV adoptions at scale, whether split between BEVs and PHEVs or as part of a fully electrified fleet, produce a wide range of aggregate grid implications. In large systems, such as that in China, high levels of EV adoption only represent 6 to 7 percent of current energy demand and 5 to 6 percent of current system capacity. These requirements are in stark contrast to grids such as that in California, where penetrations of this size represent over 50 percent of current energy generation and approximatley 35 percent of existing capacity. While it is unlikely that fleet electrification on this scale will be realized in the near term, these calculations illustrate the magnitude of the electrification task at hand.

In a scenario similar to that of the current state of the market in Norway, where roughly 7 percent of the total passenger vehicle stock is BEVs and 4 percent is PHEVs, total energy demand reaches single digit percentages of existing energy demand and system-level capacities across the regions studied. Current annual energy demand from EVs in CAISO (1.05 TWh) is equivalent to the annual generation of one 250 MW natural-gas combined-cycle plant.[18] Adoption levels similar to those in Norway increase energy demand to levels that require 8 such plants.Beyond concerns of total energy demand, grid operators must content with the timing of EV charging events. The presence of homogeneous travel patterns, especially in urban commuting zones, means coincident EV charging events contribute to system peak load levels.[19]

The loads calculated here are for EV charging alone and do not account for other sources of load or load growth. If these peak loads were to occur in the late afternoon hours, concurrent with evening load ramps,

[17]Illustrations of these charging profile scenarios are included in Figure A1.

[18]We assume an average annual capacity factor of 0.6 percent. Source: https://www.eia.gov/todayinenergy/detail.php?id=25652

[19]These base scenarios assume charging coincides with evening demand peaks based on observed vehicle charging behavior and assumptions of the EVI-Pro model. Similar metrics for the various load scenarios are included in Table A1.

capacity margins are likely to be significantly diminished in high EV penetration scenarios. Figure 9 displays these charging profiles along with the current load profile within CAISO. The evening ramp of EV charging is predicted to coincide with the current evening increase in system-wide energy demand. Current analysis of summer capacity margins in the CAISO indicates median capacity margins of approximately 36 percent (CAISO, 2019). Applying this value to the reported system operating capacity of 70 GW indicates median capacity margin levels of 25 GW. Although near-term EV adoption levels are not likely to approach these limits, capacity constraints are likely to become binding in scenarios with high levels of EV adoption. This result is similar in PJM where current reserve margins are approximately 40 GW (PJM, 2019) and 12 GW in ERCOT (ERCOT, 2019).

Given that mechanisms exist to shift EV charging, implementation of these mechanisms would diminish the computed peak load levels. One such mechanism allows consumers or aggregators to delay or schedule charging events and alter charging durations. In the case of the Netherlands, Refa and Hubbers (2019) found peak shifting of approximately 4 hours, no longer coinciding with the evening load period. The authors estimate an increase in this shifted peak demand of approximately 13 percent and an increase in aggregate demand of approximately 23 percent over the patterns for typical charging behavior. The peak energy increases mean our estimates may be on the lower end of the spectrum if the results of the Netherlands study hold in other settings. Additional work in this space is necessary as EV penetrations increase and aggregation pilots such as those studied by Refa and Hubbers are implemented in varied settings. Importantly, load shifting to avoid coincident peaks between EV loads and non-EV loads has the potential to reduce capacity requirements and avoid possible price spikes and marginal emissions rate increases due to steep evening ramp events. We turn to implications for emissions in the next section.

4 Implications

Challenges like vehicle costs, meeting consumer demands, and ensuring sufficient electricity supply infrastructure are of primary interest when considering the potential for high levels of LDV fleet electrification. Next, we outline two important implications of such a shift in transportation fuel choice. A primary motivator for a transition to an electrified vehicle fleet is the decreased reliance on fossil fuel sources and the corresponding emissions benefits. Here, we estimate differences in average carbon dioxide (CO_2) emissions levels across fuels and across regions. We then summarize existing work that measures these implications through both simulation modeling and empirical estimates. Subsequently, we turn to the tax revenue effects of EVs and estimate the magnitude of foregone tax revenues for the current electrified fleet and compare alternate means to raise equivalent revenue from EVs.

4.1 CO_2 Emissions

The emissions benefits of LDV fleet electrification depend primarily on two items: (i) how electricity is generated, and (ii) what types of vehicles EVs displace. Specifically, emissions benefits of a switch to EVs are determined in large part by the carbon intensities of the aforementioned factors.[20] Figure 10 presents annual carbon intensities of electricity generation in grams of CO_2 per kWh for a number of national electricity grids illustrating the regional heterogeneity in these intensities. To better represent the relative emissions levels of ICEVs and energy generation, we also compute emissions intensities for vehicle categories: the LDV fleet average in each individual country, a compact car, an HEV, and a PHEV. Each of these values is based on the emissions coefficient for gasoline–19.6 lbs of CO_2 per gallon (US EIA, 2016)–and the assumed MPG value for each respective vehicle category as described in the table note. With the exception of India, average grid carbon intensities are lower than the LDV fleet average. While this figure is illustrative, it should be noted that because values in this figure are system-wide averages, they do not represent the complete system dynamics of EV charging. Specifically, realized emissions benefits will depend on the time at which the EV is drawing power from the grid and on the marginal, rather than the average, emissions intensity.[21]

A wealth of studies explores the implications that carbon intensity of grid infrastructure has on CO_2 abatement potential in the transportation sector. Woo et al. (2017) conduct a comprehensive well-to-wheels comparison of EVs and ICEVs in 70 countries. The authors aggregate emissions levels for a set of representative vehicle models. Based on median grid-level emissions factors through 2016, EVs produce lower emissions levels than gasoline or diesel ICEVs for most model types studied. This result does not consistently hold for the set of subcompact models tested, likely a result of the fuel efficiency levels of subcompact vehicles. Interestingly, repeating the calculation with maximum emissions intensities leads to mixed results, with EVs producing higher levels of emissions than ICEVs under this assumption. This again illustrates the importance of understanding the timing of vehicle charging and corresponding power system operation.

Work by Jochem et al. (2015) reinforces this conclusion with a study of EV charging and emissions consequences in Germany. The authors employ an energy system model and estimate EV emissions levels in a hypothetical market with 6 million EVs, or approximately 15 percent vehicle market share. Emissions are higher with marginal electricity mix in the presence of EV loads than their counterparts assuming on average emissions rates in the system. This result holds only in the case of uncontrolled charging (i.e., vehicles charge immediately when connected to the grid). Controlled charging (i.e., vehicle charging can be optimally scheduled) produces a 30 percent reduction in emissions levels.

Graff Zivin et al. (2014) use data from various US regions to demonstrate the difference between average and marginal emissions rates and the importance of accounting for the time of day during which an EV is charged. The authors estimate marginal intensities as much as 44 percent under, and 54 percent over, the computed average emissions intensity. Based on marginal rates for each hour of the day and different parts of the country, the ratio of intra-day maximum-to-minimum marginal emissions rates is as high as 2.4. That

[20]For the remainder of this section we focus on emissions for BEVs. Assessment of marginal PHEV emissions is complicated by the fuel switching nature of PHEVs. As BEVs rely solely on electricity for power, the marginal emissions factor of the electricity grid plays a more significant role in determining the emissions from BEVs than PHEVs. For a discussion of BEV and PHEV emissions effects, see for example McLaren et al. (2016).

[21]The average carbon intensity is defined to be total emissions from power generation divided by aggregate energy production. Marginal carbon intensity metrics instead measure the change in emissions intensity for an additional unit of power demand. As it is this additional demand that alters system power flows and subsequently modifies emissions levels, it is more accurate to focus on marginal emissions levels when considering the effect of charging additional EVs.

is, depending on when an EV is plugged in, its marginal contribution to CO_2 emissions could be 2.4 times higher than if the EV were plugged in during the lowest carbon-intensity hour. Holland et al. (2016) couple the analysis of Graff Zivin et al. with a model of emissions damages and calculate the optimal subsidy (tax) for foregone emissions benefits (costs) of EVs. The heterogeneity of grid infrastructure carries through to this result, indicating a spatially differentiated optimal intervention regime for consumers to fully internalize costs of emissions from LDV use.

While these studies offer valuable insights into the link between marginal energy demand and marginal emissions, it is important to note the limitations of such studies in drawing conclusions about long-run implications of EVs. With the exception of the Jochem et al. study, the analyses mentioned here are based on observed generation data and therefore measure grid effects only within the bounds of the study data. They therefore provide general clues about potential carbon implications only in so much as the future grid represents current grid conditions. While this may be a reasonable assumption in the near term, expansion of renewable sources (e.g., solar and wind), unit retirements (e.g., coal), or development of grid-level storage capacity are likely to alter these results. In the presence of a trend toward decarbonization in the electricity system, long run grid emissions factors have the potential to produce significant emissions reductions (Hawkes, 2014).

It is also important to understand the substitution patterns of EV purchases when evaluating the comparative emissions benefits of EVs. The emissions benefits of EVs are much higher if they replace a fuel inefficient vehicle (usually an older, larger, more powerful ICEV) than a more efficient vehicle (i.e., a newer, smaller, less powerful ICEV). Xing et al. (2019) find that households purchasing EVs also prefer more fuel efficient vehicles. Hence, the counterfactual to an EV purchase is more accurately specified by an efficient ICEV or hybrid. Revisiting Figure 10, this finding suggests other grids, such as those in Australia and China, may require additional grid decarbonization efforts to bring EV emissions levels below those of existing ICEV options.

4.2 Tax Revenues

A primary consequence of the increased reliance on electric powertrains in the LDV fleet is declining demand for gasoline as a transport fuel. In many regions, excise taxes on gasoline are important revenue sources for funding transportation infrastructure. As this revenue stream decreases, national and sub-national entities will need to revisit these revenue-raising instruments.

We follow Davis and Sallee (2019) to estimate foregone fuel tax revenue due to EVs for a number of countries. Davis and Sallee estimate annual foregone fuel tax revenues as a function of fuel excise taxes, travel distances, ICEV efficiency, and the total stock of EVs in the US. Using existing national excise tax levels for gasoline and country-wide averages of vehicle fleet attributes, we provide estimates of foregone annual tax revenue. The results of our calculations are presented in the first panel of Table 8. Revenue shortfalls from EVs are largest in the US, where low fuel tax levels are offset by low ICEV efficiency, high annual VMTs and a relatively large number of EVs. Canada's revenue value is much lower than any of the other countries in the table, though the similarity of market characteristics with the US indicates this number would likely rise in line with that of the US as EV penetration increased.

There are a variety of methods for recovering these lost revenues. Here, we explore two: a per-kWh excise tax on electricity for EV charging and an annual fee for EV drivers.[22] Both have precedent in the ICEV market in the form of the aforementioned gasoline excise tax and existing annual fees for ICEV owners–often called ownership or circulation taxes. Calculated per-kWh taxes and annual fees are presented in panel (b) of Table 8. The table also shows current residential electricity taxes and ICEV annual ownership fees. These estimates reveal two important insights. First, imposing an additional energy charge on EV drivers to recoup ICEV fuel tax revenue would require an increase in residential EV charging prices on the order of 5–10 percent. While these changes are nontrivial, research in the fossil-fueled transport space indicates vehicle efficiency, annual travel distance, and individual trip elasticities are relatively low (Litman, 2019; Antweiler and Gulati, 2019; Dong et al., 2012). Though more research is needed to understand the response of EV drivers, existing work suggests these revenues are likely to be recouped and not significantly displaced by changes in consumption. Second, regarding the imposition of an annual EV use fee, the full value of the fee is significant when compared to existing ownership tax rates. In fact, the smallest estimated change is in Japan, where annual fees would double from approximately \$300 to \$600. This result suggests that such a policy prescription should be regarded with caution, especially as EVs currently face concerns about cost competitiveness with ICEVs.

The results of our calculations require a set of simplifying assumptions that have implications for the level of displaced excise tax revenues and level of alternative revenue generation methods. The three primary determinants of these values are the existing excise taxes, and the efficiencies of ICEVs and EVs. Taken individually, higher excise taxes and lower ICEV efficiencies (MPG) both contribute to higher equivalent annual fees. Additional per-kWh charges are also affected by the efficiency level of EVs. Specifically, higher EV efficiencies (kWh/mile) require higher equivalent electricity excise tax levels. As an example of the magnitude of these effects, we include three EV efficiency levels in Table 8b; efficiency improvements from 0.3 kWh/mile to 0.1 kWh/mile results in a tripling of the equivalent excise tax rates.

5 The next frontiers for electrification

The LDV sector is not the only segment of transportation with its eye toward an electrified future. Commercial trucking, rail, ship, and airborne operators are all weighing the costs and benefits of switching fuel sources. To reach climate goals outlined by IPCC (2018), all of these sectors must undergo dramatic efforts to reduce carbon consumption and electrification is an important route to this end. There is an expansive, and rapidly growing, body of literature that addresses the full spectrum of transport sector electrification. In this section, discuss the electrification opportunities that are most closely related to our preceding discussion of LDV electrification: electrification of medium- and heavy-duty vehicles, and EV implications for ride-hailing

[22] In our hypothetical example, the per-kWh tax is levied for electricity for EVs only and would therefore require separate metering for vehicle charging. For the purposes of this calculation, we assume zero cost and full compliance with this requirement.

services and autonomous vehicles (AVs).

5.1 Medium- and heavy-duty transportation

LDVs represent one segment of the global on-road vehicle market. Oil consumption by LDVs represents approximately 60 percent of transportation energy use in the US and approximately 50 percent worldwide (US EIA, 2020; IPCC, 2014). In what follows, we discuss the prospects for electrification of the medium- and heavy-duty sectors. We split our discussion into medium-duty trucks and delivery vehicles, heavy-duty trucks (e.g., class 8 trucks), and buses. The US Federal Highway Administrations classifies medium-duty vehicles as having a gross vehicle weight between 10,000 and 26,000 pounds (classes 3 through 6), while heavy-duty vehicles exceed 26,000 pounds (classes 7 and 8).[23] For comparison, a large walk-in delivery truck, similar to those that UPS and FedEx use for home delivery in the US, would be at the low-end of medium-duty vehicles, a school bus would typically be at the high-end of medium-duty vehicles, a city-transit bus tends to be at the low-end of the heavy duty spectrum, while the "18 wheeler" tractors we typically think of would be class 8 trucks.[24]

Electric versions of medium- and heavy-duty vehicles currently exist and are being inserted into company fleets. For example, UPS recently ordered 950 EV delivery trucks, above their initial order of 50 for testing purposes.[25] China has put into the market over 400,000 electric transit buses.[26]

One characteristic of the markets that medium- and heavy-duty vehicles operate in that might make electrification more attractive compared in the light-duty market is that these larger vehicles tend to operate more. For example, the average class 8 truck drives nearly 70,000 miles per year, and the average transit bus drives 35,000 miles per year.[27] This increases the relative importance of the lower operating costs associated with EVs as well as any maintenance benefits that might also exist.

A second characteristic of the medium- and heavy-duty sector that lends itself to electrification is that many of the vehicles operate over set routes, thus saving on recharging infrastructure needs. For example, medium-duty delivery vehicles that support last-mile service operate out of central hubs on regular schedules or heavy-duty vehicles that predominantly operate across interstate highways. Operators of these vehicles could centralize infrastructure investments and charge vehicle batteries between daily shifts or establish charging infrastructure along the highway system. Buses traveling on established routes and out of a network of depots have similar advantages. Electrification of long-haul, heavy-duty freight transport will require extensive work to ensure sufficient geographic distribution and local charging capacity. Regardless of use, all modes of commercial trucking will have significant consequences for the electricity grid when deployed at scale. To illustrate the implications of commercial truck charging, consider first the relative energy quantities required for electric trucks. Commercial truck models currently proposed or in production include battery

[23] https://afdc.energy.gov/data/10380
[24] https://jalopnik.com/truck-sizes-classification-explained-from-tacomas-to-1613958192
[25] https://www.trucks.com/2018/06/14/ups-order-950-workhorse-electric-delivery-trucks/
[26] https://www.wired.com/story/electric-buses-havent-taken-over-world/
[27] https://afdc.energy.gov/data/10309

capacities of 200 to 300 kWh, approximately 5 times the capacity of typical LDVs.[28] Daily energy demand of 3 MWh for a fleet of 10 vehicles translates to a power demand of up to 1.5 MW for simultaneous DC fast charging.[29] In the case of overnight charging, these charge events may be coordinated to lessen the aggregate power requirements, but long-haul trucking–that represents 74 percent of the commercial trucking sector with respect to ton-miles–may require new approaches to incentivize temporal and geographic distribution of charging events.[30]

As with the LDV sector, range requirements for the heavy-duty, and to a lesser extent medium-duty, sector are a major hurdle. The typical class 8 truck has a fuel capacity of 200–300 gallons (Truckload Indexes, 2020). A recent survey of fuel economy finds a median fuel economy of 6.5 MPG, implying a range of 1300 to 1950 miles. In principle, this is overkill, or option value for when the truck is towing heavy loads, as drivers are constrained to drive only 11 hours per day; at 60 MPH and average fuel consumption, this would require roughly 100 gallons of fuel.[31] For electric buses, the required battery capacity is likely to be much lower.

How much battery capacity would be required for a range of roughly 660 miles per day is somewhat controversial. Tesla has announced that the Tesla Semi will consume less than 2 kWh per mile, fully loaded, prompting some skepticism by those in the industry.[32] However, calculations based on theory suggest the claims are feasible, if not likely (see, Sripad and Viswanathan (2017) and MacKenzie (2018)). Taking the mean consumption value from Sripad and Viswanathan (2017) of 1.9 kWh per mile, a class 8 truck with a 660 mile range would require, roughly, a 1,250 kWh battery. At battery costs of $200 ($100) per kWh, the cost of the battery exceeds $250,000 ($125,000). At both of these battery cost levels, the total battery cost is greater than the average price of a class 8 truck,[33] but of course there are significant fuel-cost savings. While we do not perform similar cost-parity calculations as above for the LDV market, we provide a simple comparison at current prices. As of this draft, the average price of diesel in the US is $3.07 per gallon. Assuming a truck is driven 70,000 miles per year, the annual fuel savings from an EV class 8 truck would be over $16,500. Over a 10-year period, using a discount rate of 5 percent, the fuel savings, alone, exceed $130,000, just under the battery cost at $200 per kWh and well under the $100 kWh figure.[34]

We can perform similar calculations for electric buses. The average transit bus gets roughly 3.3 miles per gallon,[35] while the "E-bus" version requires roughly 2.5 kWh per mile.[36] At $3.07 a gallon for diesel fuel

[28] https://theicct.org/blog/staff/benchmarking-growth-zero-emissions-trucking; Renault Zoe 41kWh, Nissan Leaf 40kWh.

[29] https://www.volvogroup.com/en-en/news/2018/apr/news-2879838.html

[30] Long-haul trucking defined as trips over 250 miles. Trucking sector ton-miles distribution based on US observations and calculated from data provided by the US Bureau of Transportation Statistics, "Value, Tonnage, and Ton-Miles of Freight by Distance Band," https://www.bts.gov/value-tonnage-and-ton-miles-freight-distance-band.

[31] Long-haul truckers often idle at night to provide electricity to the cabin. This consumes roughly one gallon of fuel per hour.

[32] See, for example, https://ww.electrek.co/2018/02/21/tesla-semi-defies-laws-physic-daimlers/.

[33] In the US, the average selling price of a new Class 8 truck was $117,426 in 2018 (American Truck Dealers, 2018).

[34] While class 8 truck are often on the road for longer than 10 years, we would not expect the battery last beyond 10 years and therefore perform the calculation over this time interval. The typical ICE-based class 8 truck engine is rebuilt twice within time frame (US EPA, 1995).

[35] See, for example, https://afdc.energy.gov/data/.

[36] See Zhou et al. (2016), Gallet et al. (2018), and https://www.proterra.com/vehicles/catalyst-electric-bus/

and 12.2 cents per kWh for electricity, the E-bus saves roughly 87 cents per mile driven. If a bus were to be driven the average annual of 35,000 miles, the annual savings would be over $30,000. Sizing the battery to be able to travel roughly 100 miles per day would require 250 kWh of energy. At battery costs of $200 ($100) per kWh battery, the battery would cost $50,000 ($25,000), implying a payback period of just over (just under) a year. In practice, E-bus companies appear to be using batteries much larger than 250 kWh. For example, Proterra offers transit buses with battery capacities of 440 and 660 kWh. The battery cost of these models would be $88,000 and $132,000 at a battery cost of $200 per kWh, respectively. Even at these capacity levels, the payback period is short. These calculations only account for the battery costs. A number of sources suggest that the added upfront costs for an electric bus is $300,000.[37] These might reflect other costs associated with making an electric bus or market power that may subside as the industry thickens. Here, the payback period would be 10 years, and discounting the fuel savings would obviously imply the EV bus is more expensive over a 10-year period.

These simple calculations ignore a number of important factors. In favor of EVs, we are not accounting for maintenance savings, crediting for cheaper drivetrain costs, and, of course, external costs associated with diesel consumption. In favor of the ICEs, we are not accounting for the recharging infrastructure costs associated with EVs, which given the size of the batteries and desired recharging times are likely to be substantial. We also do not include estimates of differences in vehicle payload attributable to the weight and volume of vehicle batteries.[38] Although more real world data are needed for a comprehensive estimate of these savings, an analysis of the New York City bus fleet estimates total lifetime savings for electric buses over diesel-powered buses of approximately $168,000, or 12.5 percent (Aber, 2016).

In all, these numbers suggest that at battery costs of $100 per kWh, electrification of the medium- and heavy-duty sectors has real potential; perhaps, more potential that in the LDV sector.

5.2 Ride sharing and autonomous vehicles

Two emerging trends in the transport space are (i) the expanded availability of ride sharing services, provided by transportation network companies (TNCs), and (ii) the development, testing, and preliminary deployment of autonomous vehicles (AVs). TNCs compete with traditional ride-hailing services and convert consumer LDVs to dual-use vehicles (i.e., used for both personal and ride-hailing trips). AVs allocate a portion of driving tasks to the vehicles' computerized systems. As a result, both TNCs and AVs have the potential to alter traditional use patterns for LDVs and represent sources of disruption for transportation markets in the future.

AVs and TNCs interact with an electrified LDV fleet in multiple ways. Efforts to reduce congestion and

range/.

[37]See Blynn (2018) and https://www.forbes.com/sites/sebastianblanco/2018/08/31/84-million-electric-buses.

[38]For example, estimates from Couch et al. (2019) suggest currently-available electric Class 8 trucks weigh more than 7,000 lbs more than typical diesel vehicles. The authors point out that increases in tractor curb weight decrease maximum payload limits by a 2:1 ratio, indicating payload capacity penalties for EVs could be substantial.

emissions in city centers pose opportunities for a combined transition that includes TNC services and vehicle electrification. In the US, legislation in California (SB 1014) will require TNC operators to transition to zero-emission vehicles. This legislation is aimed at meeting California's state-wide ZEV targets and at decreasing per-passenger-mile GHG emissions in the state. Elsewhere, London is implementing plans to mandate all private hire vehicles to be "zero emission capable" by 2023, and Shenzhen, China, where the city's bus fleet is already fully electrified, has now made EVs the only vehicles eligbile for ride-hailing licenses.

Compared to typical drivers, TNC drivers tend to have higher average daily driving distances. Coupled with increased vehicle stock from TNC EV mandates, these two factors combined drive up local electricity demand, which may affect electricity supply infrastructure and, at sufficiently high levels, electricity pricing. Further, TNC drivers are more likely to rely on fast charging to minimize time when they are ineligible to pick up new fares. An increased reliance on fast charging creates larger peak power demands than an equivalent frequency of charge events using lower voltage chargers and also has implications for battery life and vehicle resale value.

With respect to electrified vehicle technology, AVs draw a significantly higher electric load than traditional vehicle systems. This fact has implications for the battery size—and, hence, vehicle cost and maximum range—of the AV. As these are key attributes that consumers weigh when considering an EV purchase, AVs will need to overcome these hurdles to make electric AVs an attractive purchase option. That said, AV technology will also allow users to send vehicles off to charge independently when their energy storage levels are low. This has advantages in allowing more centralized charging locations, reducing costs for infrastructure installation.

The most significant parameter to consider for both innovations, however, is the effect each will have on total vehicle miles traveled. AVs and TNCs alike may increase the number of deadhead trips (driver-only trips for TNCs and passenger-free trips for AVs), which in turn can increase congestion and contribute to greater energy use (Taiebat et al., 2019; Wadud et al., 2016). These concerns could be reduced with implementation of centralized ownership models and optimized driving, passenger load, and charging activities. Additionally, the extent to which these new transportation approaches allow for right-sizing of vehicles (i.e., more efficiently matching vehicle size and capacity with vehicle trip usage) represent opportunities for energy demand reductions.

Recent work by MIT researchers hypothesizes that AVs are likely to be prohibitively expensive in their early availability and considers a business case for so-called robotaxis, where AVs are owned by firms and hired out for consumer use (MIT Energy Initiative, 2019). Should this scenario become reality, it is likely well-suited for EV deployment, as electrification infrastrucutre and flexible vehicle scheduling could be centralized. This model would also make revenue collection for infrastructure costs easier and more direct, as aggregate vehicle travel distances could be more easily tracked without raising individual privacy concerns. Lastly, with regard to carbon intensity considerations, an AV taxi fleet represent a potential avenue to reducing LDV emissions (Greenblatt and Saxena, 2015).

Each of these innovations represents a potentially significant disruption to the existing transportation paradigm. A simultaneous push for electrification is likely to play a role in dictating their future trajectories. The relationship among these innovations is not likely to be uni-directional and additional simulation and empirical analysis is necessary to understand the interactions between and among the transportation infrastructure and use cases of the future.

6 Conclusion

Electric drivetrains are emerging again as viable options in many segments of the transportation sector. This is motivated in part by a move to reduce reliance on fossil fuels and decrease the emissions consequences of energy use. While calls for full electrification of the vehicle fleet are widespread, a transition of this magnitude is a significant undertaking and is not likely to happen rapidly. In this chapter, we set out to provide context for a discussion of the future of electrified transportation and to consider the challenges and issues on the road ahead. As we assess the likely future trajectory of transportation electrification, three important observations merit consideration.

First, the barriers to full electrification are nontrivial. Areas such as Norway, China, and the state of California in the US, offer valuable case studies in overcoming early hurdles in building a market for EVs. At the time of this writing, no nation has demonstrated a shift to an electrified vehicle fleet without significant market intervention. This may change with continued technological progress, manufacturing improvements, and future movements in fuel prices. However, in the near term we anticipate the push for a fully-electrified vehicle fleet to remain an aspirational goal in the absence of intervention. As these interventions are likely to come with significant economic costs, rigorous and targeted analysis of policy effectiveness and efficiency is needed.

Second, any move to increase the role electricity plays in transportation networks is likely to produce benefits in the form of carbon emissions reductions, especially in the presence of routines for optimized vehicle charging. The linking of transportation emissions and emissions from electricity generation will require careful planning and analysis to fully account for marginal vehicle emissions. This consolidation of energy supply sources will also amplify the need for continued decarbonization progress for electricity suppliers.

Finally, the nature of current infrastructure and transportation support mechanisms requires scrutiny. As these elements of the transportation system grew in a world of ICEVs, some attributes are not currently designed to accommodate an electrified fleet. Strategic thinking must guide investments that influence how, when, and where EV drivers refuel their vehicles. Moreover, existing structures for public funding of transportation-related expenditures need to be revisited and updated accordingly.

Although fleet electrification is likely to be a gradual process, there are important near-term considerations. On a per-mile basis, electricity is significantly less expensive than either gasoline or diesel as a result of differences in fuel prices and vehicle energy efficiencies. This illustrates that one of the main economic barriers to broader EV adoption is the additional fixed cost of an EV, specifically the battery cost. As our cost parity calculation demonstrates, significant battery cost reductions are necessary if oil prices remain at or near current levels. This is further complicated by the ongoing debate around the achievable lower bound to battery costs based on technological limits and the markets for battery manufacturing inputs. Our analysis indicates PHEV-ICEV cost parity is potentially achievable in the near term. As PHEVs compare favorably to BEVs with respect to obstacles for consumer adoption (e.g., shorter battery charge times, extended ranges, optional charging) they represent a potential off-ramp from the current ICEV-dominated vehicle fleet.

Meeting climate goals set forth by the IPCC requires sweeping changes to existing markets. These changes in the transportation sector likely manifest in a move toward sector-wide electrification, at least in the horizon laid out by the IPCC. Such a move poses challenges, but near-term opportunities exist to move toward a low-carbon, electrified future. Ultimately, the feasibility of such a future will require a break from the status quo on the part of all transportation sector participants on both the supply and demand sides of the market.

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7 Tables

Table 1: Relative coverage of electric vehicle fueling infrastructure

	Charge points (CP)			EVs			CP per 100km of	EVs	Ratio of CPs to
	Fast	Slow	Total	BEVs	PHEVs	Total	road network	per CP	fuel stations
Canada	673	5,168	5,841	23,620	22,330	45,950	0.6	7.9	0.5
China	83,395	130,508	213,903	951,190	276,580	1,227,770	4.4	5.7	2.1
France	1,571	14,407	15,978	92,950	25,820	118,770	1.7	7.4	1.4
Germany	2,076	22,213	24,289	59,090	50,470	109,560	3.8	4.5	1.7
Japan	7,372	21,507	28,879	104,490	100,860	205,350	2.4	7.1	0.8
Korea	2,531	3,081	5,612	24,070	1,840	25,910	5.1	4.6	0.5
Norway	2,058	8,292	10,350	116,129	60,181	176,310	11.0	17.0	6.6
UK	2,037	11,497	13,534	45,010	88,660	133,670	3.4	9.9	1.6
US	6,267	39,601	45,868	401,550	360,510	762,060	0.7	16.6	0.4

Notes: The table shows the number of normal (3.7-22 kW) and fast power (AC 43KW chargers, DC chargers, inductive and Tesla superchargers) of publicly accessible charging points. The data on BEVs and PHEVs and electric charging stock are from the European Alternative Fuel Observatory and the IEA Global EV Outlook. All other data are from https://www.gocompare.com.

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Table 2: Stock of electric vehicle fueling infrastructure

Year	EU	France	Germany	Italy	UK	Spain	US	China
2012	13,350	809	1,518	1,351	2,840	406	13,392	17,900
2013	23,541	1,802	2,447	1,356	5,691	891	19,410	21,200
2014	34,448	1,834	2,941	1,363	7,912	918	25,602	23,000
2015	59,200	10,665	5,571	1,749	9,837	1,663	30,945	49,600
2016	119,615	20,439	25,240	2,741	14,256	4,974	42,029	140,000
2017	126,503	22,011	25,373	2,885	16,553	5,089	50,627	213,900
2018	143,589	24,850	27,459	3,562	19,076	5,209	61,067	299,800

Notes: For Europe, we report the total number of normal and fast public charging points from the European Alternative Fuel Observatory. For the US, we report electric fueling stations from the Alternative Fuel Data Center of the Department of Energy. For China, we report the number of public and dedicated fleet EV charging posts from Figure 5 in Hove and Sandalow (2019).

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Table 3: Estimates of lost value of time resulting from electric vehicle charge duration

	Share of charges away from home																				
Value of Time ($ / hour)	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
5	-21	-15	-8	-2	4	10	17	23	29	35	42	48	54	60	67	73	79	85	92	98	104
10	-42	-29	-17	-4	8	21	33	46	58	71	83	96	108	121	133	146	158	171	183	196	208
15	-62	-44	-25	-6	13	31	50	69	88	106	125	144	163	181	200	219	238	256	275	294	312
20	-83	-58	-33	-8	17	42	67	92	117	142	167	192	217	242	267	292	317	342	367	392	417
25	-104	-73	-42	-10	21	52	83	115	146	177	208	240	271	302	333	365	396	427	458	490	521
30	-125	-87	-50	-12	25	63	100	138	175	212	250	288	325	362	400	438	475	513	550	588	625
35	-146	-102	-58	-15	29	73	117	160	204	248	292	335	379	423	467	510	554	598	642	685	729
40	-167	-117	-67	-17	33	83	133	183	233	283	333	383	433	483	533	583	633	683	733	783	833
45	-187	-131	-75	-19	38	94	150	206	262	319	375	431	488	544	600	656	712	769	825	881	938
50	-208	-146	-83	-21	42	104	167	229	292	354	417	479	542	604	667	729	792	854	917	979	1,042
55	-229	-160	-92	-23	46	115	183	252	321	390	458	527	596	665	733	802	871	940	1,008	1,077	1,146
60	-250	-175	-100	-25	50	125	200	275	350	425	500	575	650	725	800	875	950	1,025	1,100	1,175	1,250
65	-271	-190	-108	-27	54	135	217	298	379	460	542	623	704	785	867	948	1,029	1,110	1,192	1,273	1,354
70	-292	-204	-117	-29	58	146	233	321	408	496	583	671	758	846	933	1,021	1,108	1,196	1,283	1,371	1,458
75	-312	-219	-125	-31	63	156	250	344	438	531	625	719	813	906	1,000	1,094	1,188	1,281	1,375	1,469	1,562
80	-333	-233	-133	-33	67	167	267	367	467	567	667	767	867	967	1,067	1,167	1,267	1,367	1,467	1,567	1,667
85	-354	-248	-142	-35	71	177	283	390	496	602	708	815	921	1,027	1,133	1,240	1,346	1,452	1,558	1,665	1,771
90	-375	-262	-150	-37	75	188	300	413	525	638	750	863	975	1,088	1,200	1,312	1,425	1,538	1,650	1,762	1,875
95	-396	-277	-158	-40	79	198	317	435	554	673	792	910	1,029	1,148	1,267	1,385	1,504	1,623	1,742	1,860	1,979
100	-417	-292	-167	-42	83	208	333	458	583	708	833	958	1,083	1,208	1,333	1,458	1,583	1,708	1,833	1,958	2,083

Notes: The table shading is based on savings thresholds as discussed in the main text: $(\infty, \$500]$ = dark blue; $(\$500, \$400]$ = light blue; $(\$400, \$300]$ = dark green; $(\$300, \$200]$ = light green. All reported dollar values are in nominal terms. The lost value of time assumes 15,000 annual VMT, 50 refueling events per year, and refueling times of 30 minutes (EV) and 5 minutes (ICEV).

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Table 4: Electric vehicle policy landscape for selected countries

			Canada	China	EU	India	Japan	US
Vehicles	Regulations	ZEV mandate	✓*	✓				✓*
		Fuel economy standards	✓	✓	✓	✓	✓	✓
	Incentives	Fiscal incentives	✓	✓	✓	✓		✓
	Targets		✓	✓	✓	✓	✓	✓*
Chargers	Regulations	Hardware standards**	✓	✓	✓	✓	✓	✓
		Building regulations	✓*	✓*	✓	✓		✓*
	Incentives	Fiscal incentives	✓	✓	✓		✓	✓*
	Targets		✓	✓	✓	✓	✓	✓*
Industrial policies		Subsidies	✓	✓			✓	

Notes: Reproduced from IEA (2019a), Table 1. (✓) indicates that the policy is set at national level, (✓*) denotes policies that are implemented at a state/province/local level only, ** indicates that standards for chargers are a fundamental prerequisite for the development of EV supply equipment. ZEV denotes zero-emissions vehicles. All regions have developed standards for chargers. Some (China, European Union, India) are mandating specific standards as a minimum requirement; others (Canada, Japan, United States) are not. Building regulations refer to an obligation to install chargers (or conduits to facilitate their future installation) in new and renovated buildings. Incentives for chargers include direct investment and purchase incentives for both public and private charging.

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Table 5: Number of vehicle models

		EVs			EVs as Percent
Year	ICEVs	BEVs	PHEVs	Total	of Vehicles
2019	1,255	36	31	67	5.1
2018	1,287	24	34	58	4.3
2017	1,245	30	19	49	3.8
2016	1,214	31	18	49	3.9
2015	1,255	18	12	30	2.3
2014	1,201	15	10	25	2.0
2013	1,167	15	2	17	1.4
2012	1,143	7	3	10	0.9
2011	1,133	4	1	5	0.4

Notes: The numbers reported are based on the authors' calculations using data from https://fueleconomy.gov/. The rightmost column indicates the percent of all vehicle models that electric vehicles (BEVs and PHEVs) account for.

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Table 6: Electricity grid implications

	Year	VMT (million)	EV kWh per mile	EV kWh (million)	System kWh (million)	Pct of system-wide total
Canada	2009	206,562	0.3	61,969	508,601	12.2
France	2017	129,693	0.3	38,908	415,300	9.4
Germany	2009	434,401	0.3	130,320	549,100	23.7
Japan	2017	454,932	0.3	136,480	960,000	14.2
UK	2017	327,104	0.3	98,131	309,000	31.8
US	2017	3,216,084	0.3	964,825	3,844,220	25.1

Notes: Miles are total road motor vehicle traffic from OECD. The data for electricity consumption are from the EIA International Energy Statistics. The efficiency (kWh/mile) is average combined from https://fueleconomy.gov/ for 2017.

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Table 7: Energy and capacity effects of electric vehicles

	CAISO (US)		PJM (US)		ERCOT (US)		EU-28		China		Japan	
	Level	%	Level	%	Level	%	Level	%	Level	%	Level	%
Vehicle stock (thousands)												
Total	29,652		55,631		18,905		267,834		189,303		62,026	
BEVs	204	0.7	43	0.1	12	0.1	536	0.2	1,767	0.9	131	0.2
PHEVs	136	0.5	38	0.1	10	0.1	268	0.1	539	0.3	124	0.2
Energy (GWh)												
Annual generation	193,078		803,064		379,643		3,070,057		6,266,000		935,000	
Current EV share	1,046	0.5	247	0.03	75	0.02	1,679	0.1	5,123	0.1	457	0.05
7% BEV, 4% PHEV	10,131	5.2	19,153	2.4	7,136	1.9	61,157	2.0	44,992	0.7	12,548	1.3
30% BEV, 70% PHEV	85,422	44.2	161,486	20.1	60,164	15.8	515,637	16.8	379,341	6.1	105,794	11.3
100% BEV	99,328	51.4	187,775	23.4	69,958	18.4	599,578	19.5	441,095	7.0	123,016	13.2
Power (MW)												
System capacity	70,341		204,289		107,609		1,010,998		1,794,000		313,000	
Current EV share	262	0.4	62	0.03	19	0.02	421	0.04	1,285	0.1	115	0.04
7% BEV, 4% PHEV	2,541	3.6	4,803	2.4	1,789	1.7	15,337	1.5	11,283	0.6	3,147	1.0
30% BEV, 70% PHEV	21,422	30.5	40,498	19.8	15,088	14.0	129,311	12.8	95,131	5.3	26,531	8.5
100% BEV	24,909	35.4	47,090	23.1	17,544	16.3	150,362	14.9	110,618	6.2	30,850	9.9

Notes: The values in percent columns are percentages of section headings (e.g., BEVs are a percent of total vehicle stock). The calculations assume energy intensities of 0.3 kWh/mile (BEV) and 0.4 kWh/mile (PHEV), and a PHEV electric mile factor of 0.6 (Smart et al., 2014). Annual VMT levels vary by region; US regions are vehicle-stock weighted VMT averages across states. The EV shares of 7 (BEV) and 4 (PHEV) percent represent approximate shares in Norway in 2018 (from total vehicle inventory data: `https://ofv.no/kjoretoybestanden/`). Due to vehicle mile accounting and aggregate generation source differences, totals may not exactly match Table 6. The charging profiles for hourly max load are scaled from the charging profile of the US DOE's EVI-Pro market simulation. The US regional vehicle stock is estimated based on region-wide population levels and state-level per capita EV ownership in 2017. Annual US generation and system capacity are from SNL Financial. The EU-28 Vehicle stock for 2018 is from the ACEA Vehicles in Use database. Annual generation and capacity from Eurostat. The vehicle stock for China is from the China Statistical Yearbook 2019. The vehicle stock for Japan is from the Motor Vehicle Statistics of Japan (2019).

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Table 8: Tax revenue effects of an electrified vehicle fleet

(a) Foregone revenue levels for current fleet

	Excise tax (USD/gallon)	Total EVs	Avg annual VMT	Fleet avg MPG	Foregone tax revenue (million USD/year)
Canada	0.74	45,950	9,548	25.6	12.7
France	2.77	118,770	8,076	45.2	58.8
Germany	2.79	109,560	8,766	39.2	68.4
Japan	1.91	205,350	6,611	37.9	68.3
UK	2.82	133,670	8,188	40.6	76.1
US	0.56	762,060	11,112	25.8	182.0

(b) Alternative revenue generation options

	Equiv elec excise tax (USD/kWh)†			Residential elec price	Equivalent annual fee	Existing ownership tax
	0.3	0.2	0.1	(USD/kWh)	(USD)	(USD/year)
Canada	0.10	0.15	0.29	0.96	277.33	62.77
France	0.20	0.31	0.61	1.72	495.32	0.00
Germany	0.24	0.36	0.71	3.05	624.14	30.51
Japan	0.17	0.25	0.50	2.16	332.40	324.32
UK	0.23	0.35	0.70	1.82	569.68	140.57
US	0.07	0.11	0.21	1.14	238.88	44.57

Notes: †Subheadings for this column grouping represent assumed EV efficiencies in kWh/mile. Existing gasoline excise tax rates (USD/gallon in 2017 dollars) are from OECD (2018). The number of EVs is the stock of BEVs and PHEVs from IEA (2017). The data on vehicle miles traveled (VMT) are from the ODYSSEE-MURE project (Europe) for 2015, US DOT (2017) for the US, Figure 11 in the Summary Report of the 2009 Canadian Vehicle Survey for Canada, and Japan 2050 Low Carbon Navigator for Japan in 2010. The data on fuel efficiency (MPG) are from GFEI (2017).

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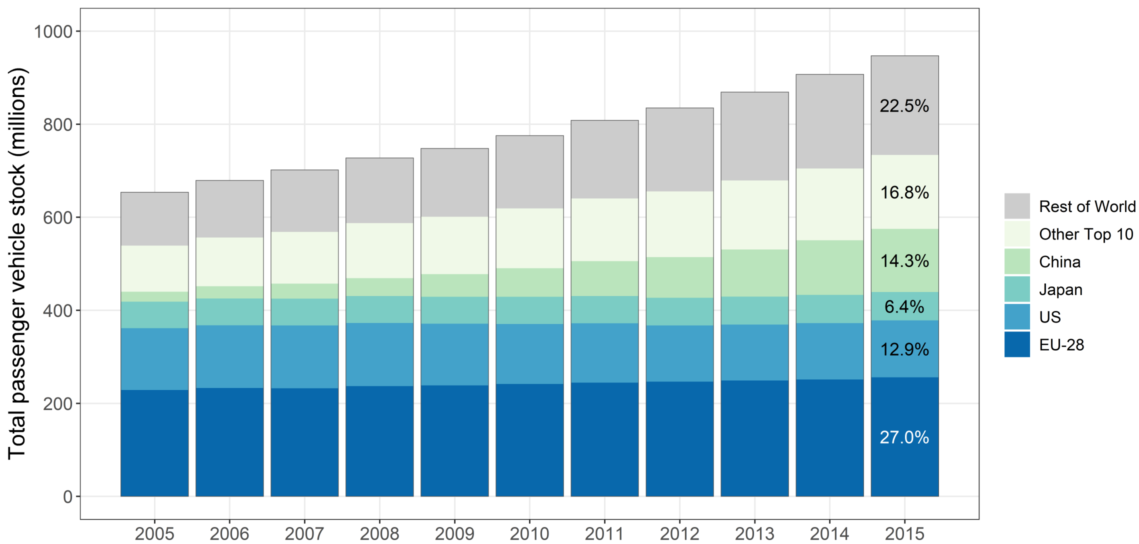
8 Figures

Figure 1: Global count of passenger cars in use



Notes: The figure is constructed using data from the International Organization of Motor Vehicle Manufacturers (OICA), Vehicles in Use database, available at `http://www.oica.net/category/vehicles-in-use/`, accessed November 2019.

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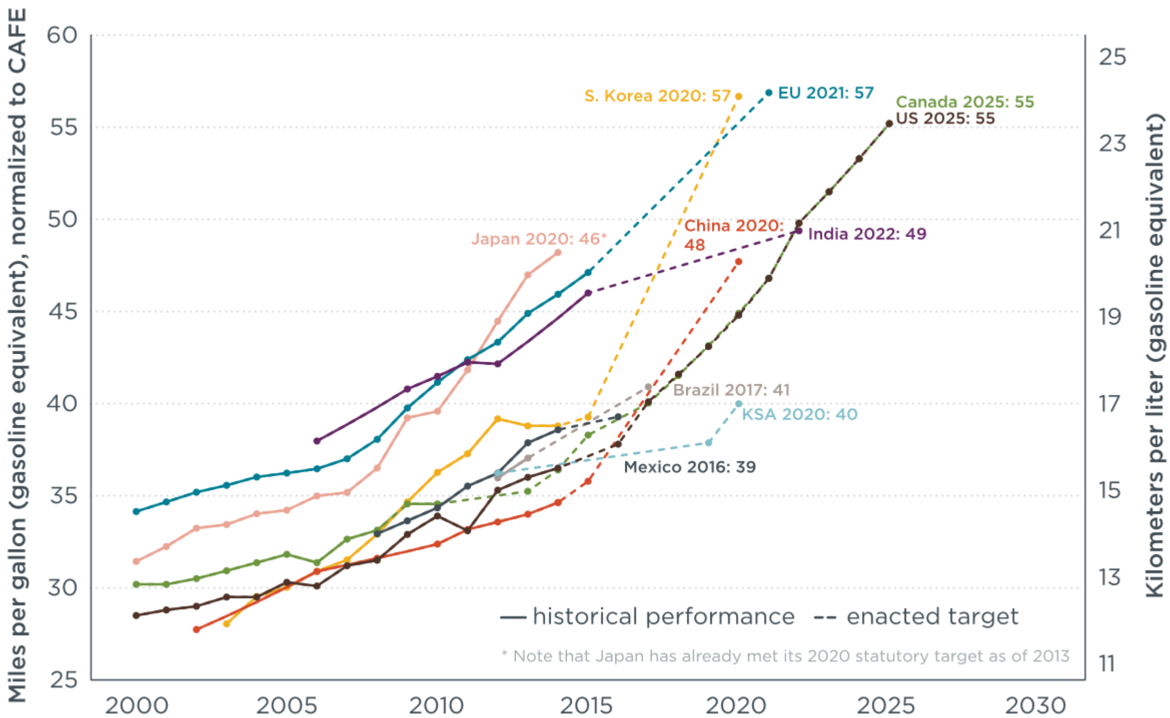
Figure 2: Historical fleet fuel efficiency and current standards for passenger cars (miles per gallon normalized to United States test cycles)



Notes: Reproduced from Yang and Bandivadekar (2017), Figure 4.

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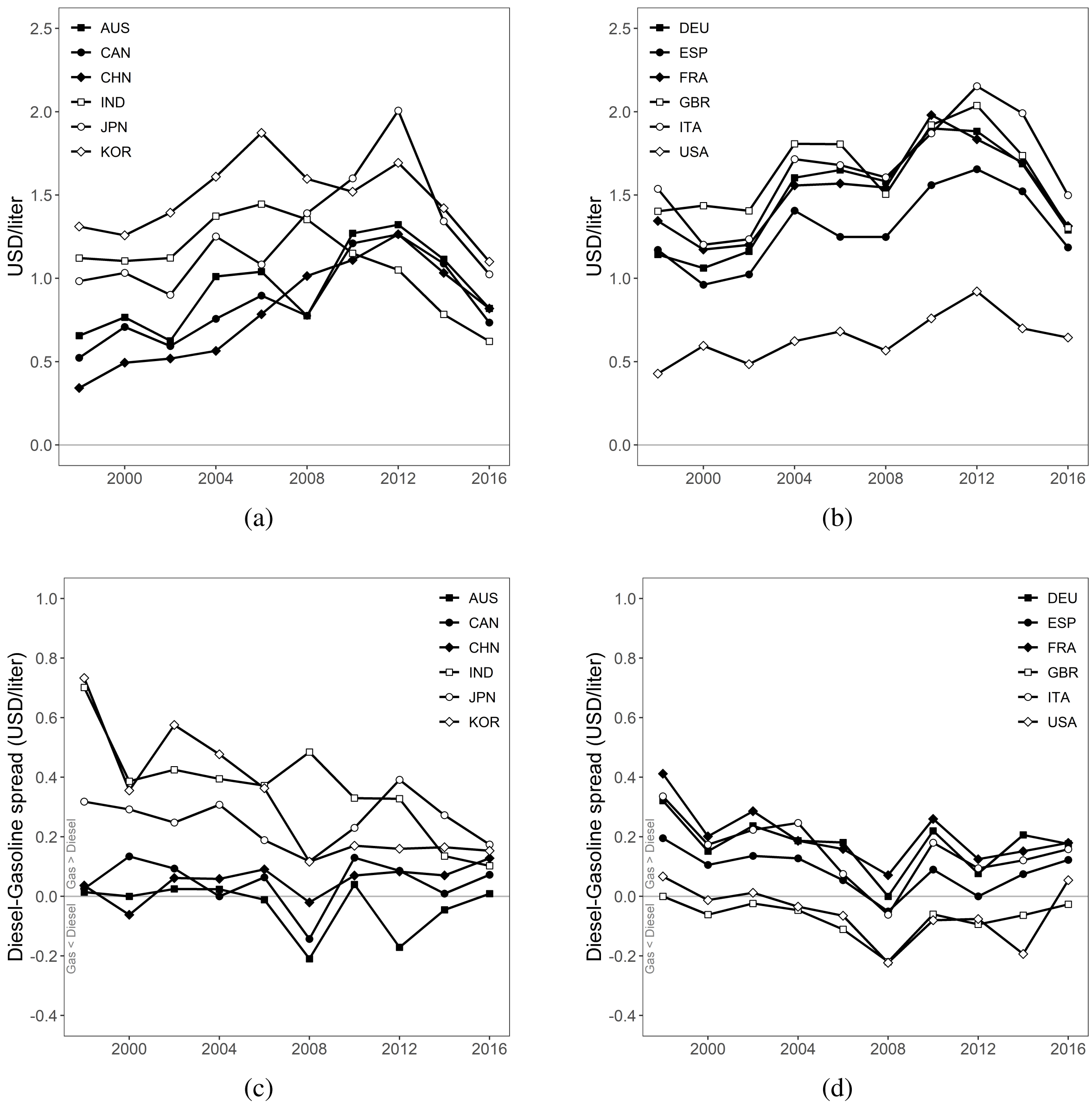
Figure 3: Transportation fuel price trends



Notes: Panels (a) and (b) report pump prices for gasoline in USD/liter by country. Panels (c) and (d) display the spread between pump prices of retail gasoline and diesel (negative spreads denote gasoline is less expensive than diesel). The prices are expressed in real 2010 dollars, adjusted based on the Consumer Price Index. Price levels and spreads are reported biennially and are based on data from the World Bank, World Development Indicators, available at https://datacatalog.worldbank.org/dataset/world-development-indicators, accessed November 2019.

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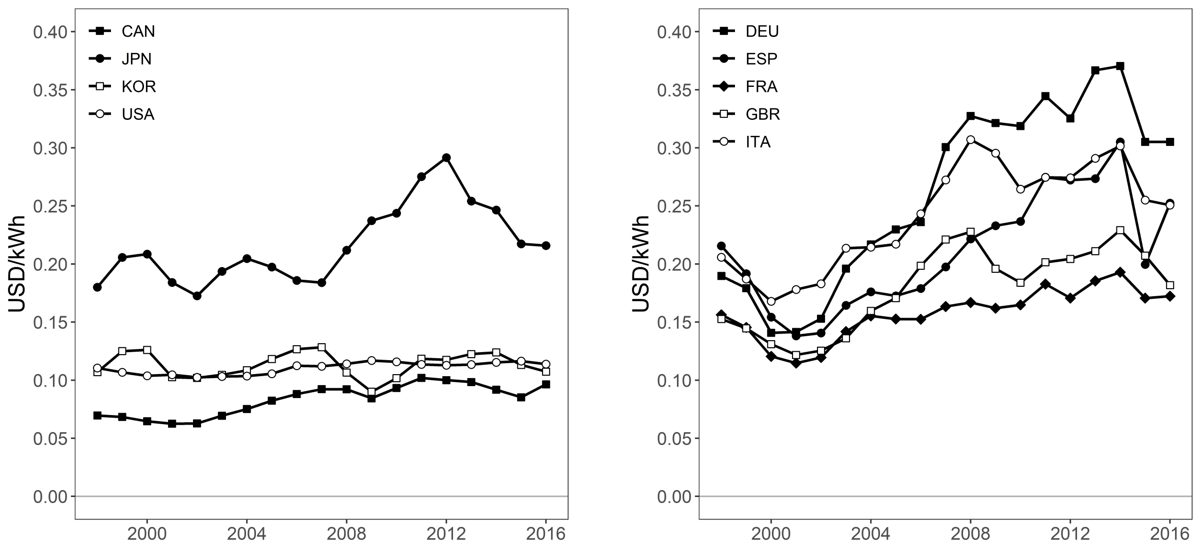
Figure 4: Household electricity prices



(a) (b)

Notes: We report tax-inclusive household electricity price in USD per kWh. The prices are expressed in real terms, adjusted based on the Consumer Price Index (2010 base year). Electricity prices from "End-use prices: Economic indicators (Edition 2018)," IEA Energy Prices and Taxes Statistics (database), https://doi.org/10.1787/d087d8da-en accessed November 2019.

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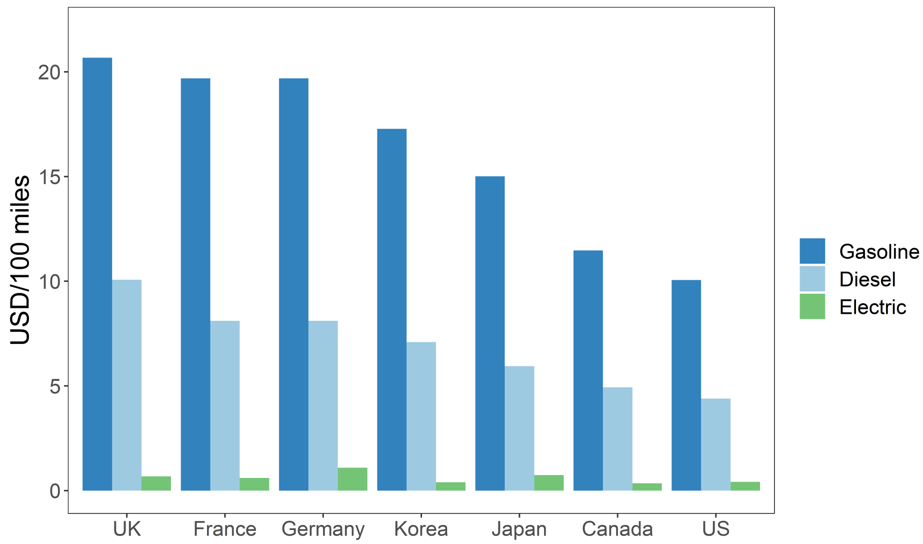
Figure 5: Normalized travel cost comparison



Notes: Travel cost based on standardized fuel efficiency levels across countries: gasoline (26.7 MPG), diesel (56.0 MPG), and electric (0.3 kWh/mile). Fuel prices differ by country and are based on 2016 levels. For sources, see notes for Figure 3 (gasoline and diesel) and Figure 4 (electricity).

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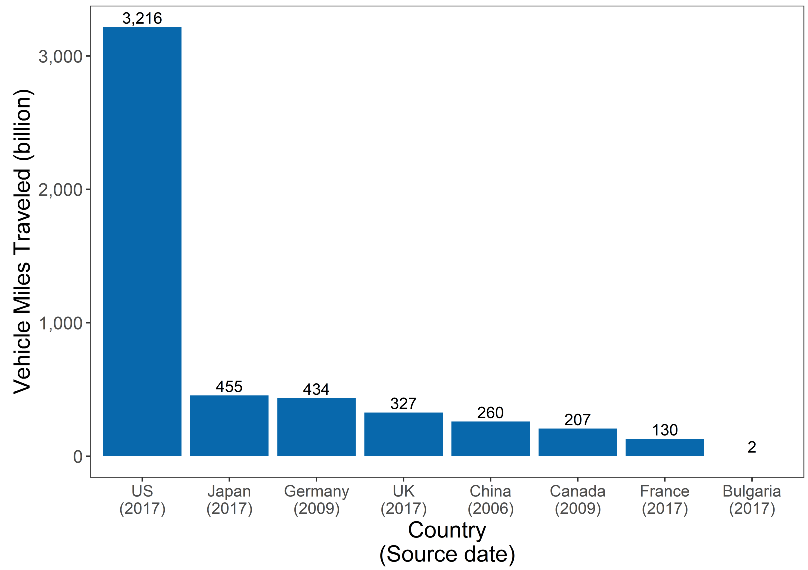
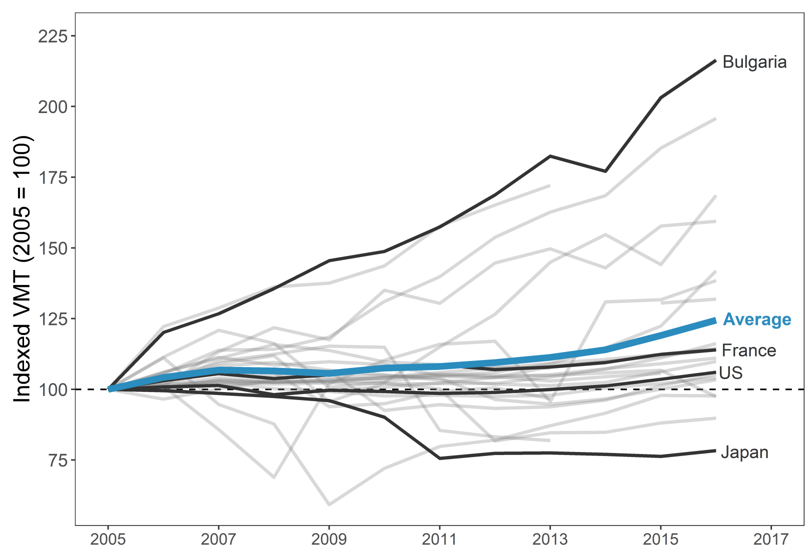
Figure 6: Trends in vehicle miles traveled for OECD countries



(a)



(b)

Notes: Panel (a) shows VMT levels for selected countries. Panel (b) shows VMT trends for OECD countries. The OECD data are from the "Total Road Motor Vehicle Traffic" database, available at https://stats.oecd.org/.

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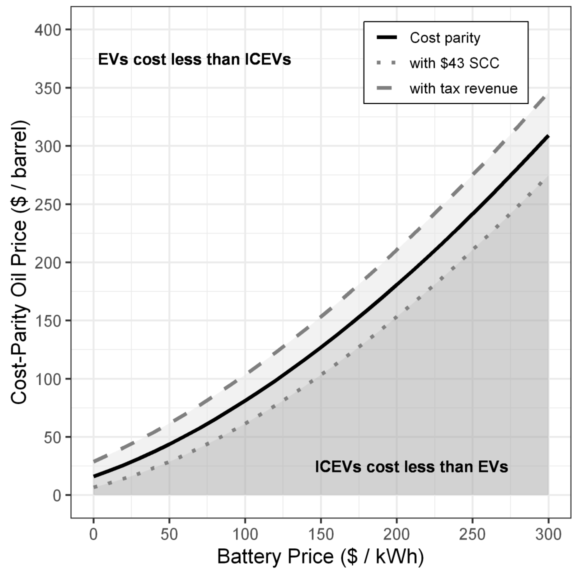
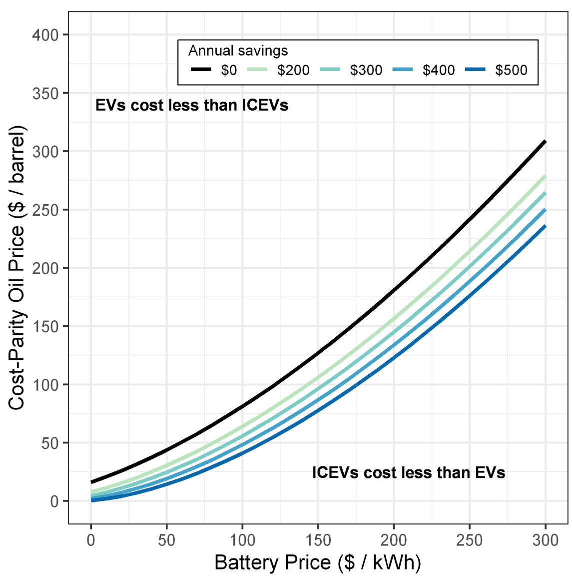
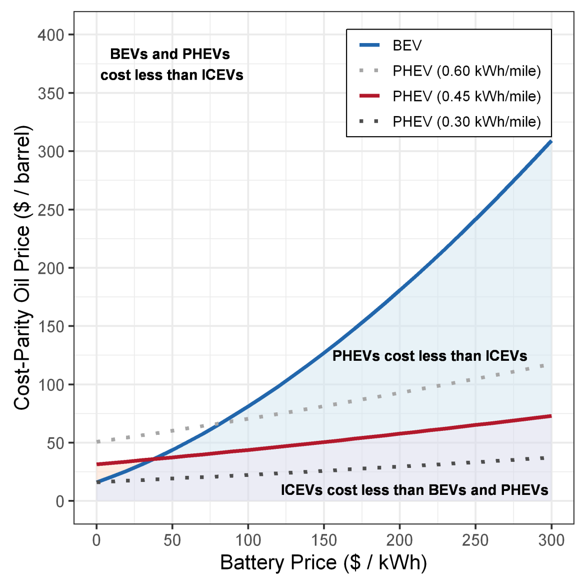
Figure 7: Electric vehicle battery/oil price cost parity analysis



(a)



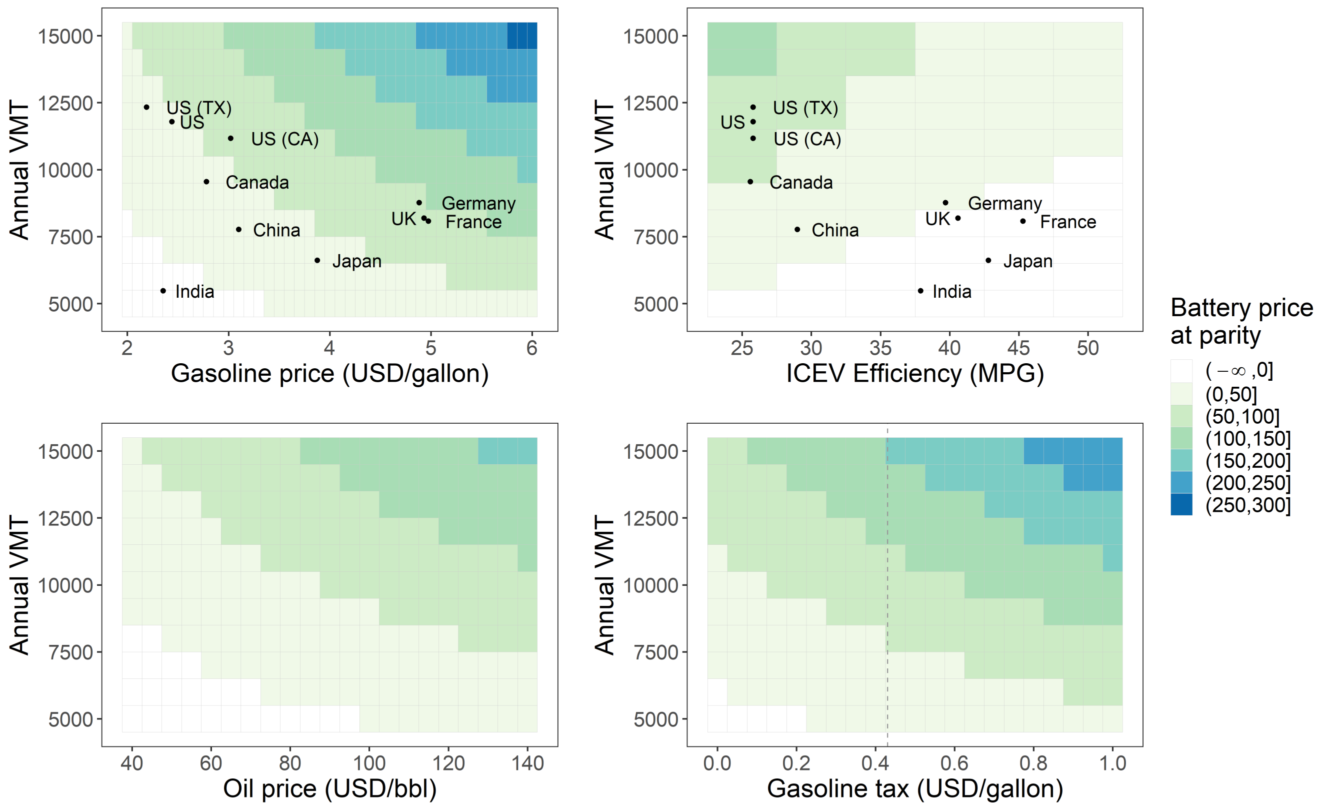
(b)



(c)

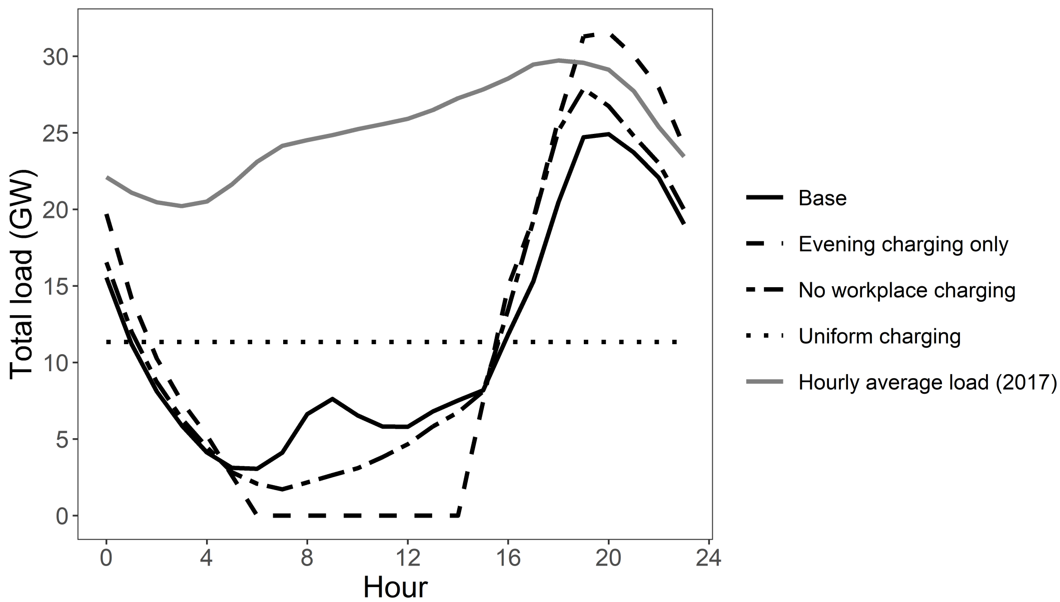
Notes: Panel (a) presents results of an analysis of the EV battery/oil price cost parity frontier. Panel (b) includes results of alternative scenarios based on specified savings thresholds. Panel (c) incorporates assumptions for PHEVs. Prices in 2018 dollars. In panel (a), a social cost of carbon of $43 in 2007 dollars equates to approximately $51 in real 2018 terms (US EPA, 2016). Dashed lines in panel (c) represent PHEV cost parity results for alternative PHEV electric efficiency levels. For additional detail, see Section 3.1.

Figure 8: Battery price cost parity sensitivities



Notes: Shading represents battery costs at EV-ICEV cost parity. Each panel varies one input (e.g., gasoline price) relative to annual VMT levels and leaves all other values at their baseline levels, as outlined in Section 3.1. For example, in the upper left panel, holding all inputs fixed, an increase in gasoline price produces higher break-even battery prices. Gasoline tax levels are additional taxes above existing rates, as gasoline prices for the fuel price regression analysis are tax-inclusive. The baseline tax level assumes the full value of tax revenues go to transportation-related funding. The vertical line in the the gasoline tax plot (lower right) represents a social cost of carbon of USD 0.43, and hence can be used to recenter calculations with carbon tax revenue (i.e., all values to the right of this vertical line contribute to transport expenditures).

Figure 9: Estimated load profiles and average hourly demand (CAISO)



Notes: Black lines represent aggregate energy for charging profiles derived from CAISO 100 percent EV penetration scenario. The average hourly load (gray line) is 2017 annual average load by hour computed from CAISO hourly data. The charging scenarios are based on DOE's EVI-Pro charging simulation. See Figure A1 for charging profiles and derivation.

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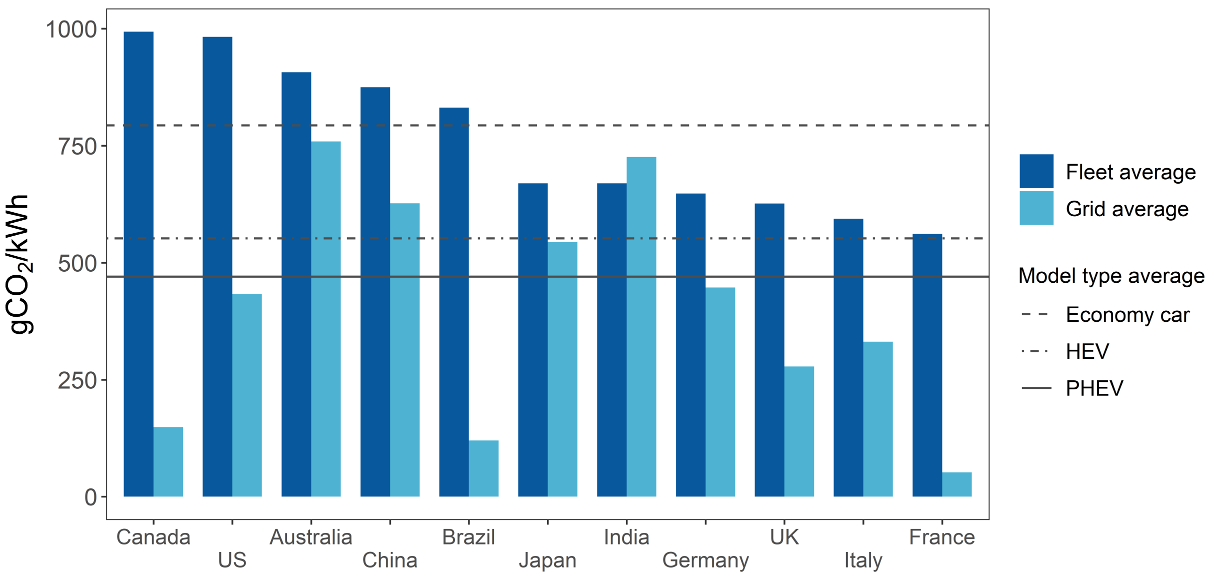
Figure 10: Relative carbon intensities of light-duty vehicle and electricity sectors



Notes: The grid-level average emissions rates are from IEA (2018a). The light-duty (LD) fleet average emissions for each country are based on average fleet fuel economy in Table A2. The vehicle-level carbon intensities are computed based on the following fuel economies (representative vehicle): economy car, 32 mpg (Toyota Corolla/Honda Civic average); HEV, 46 mpg (Toyota Prius C), PHEV, 54 mpg (Toyota Prius Prime). Vehicle calculations assume 19.6 lbs CO_2 per gallon of gasoline (US EIA, 2016).

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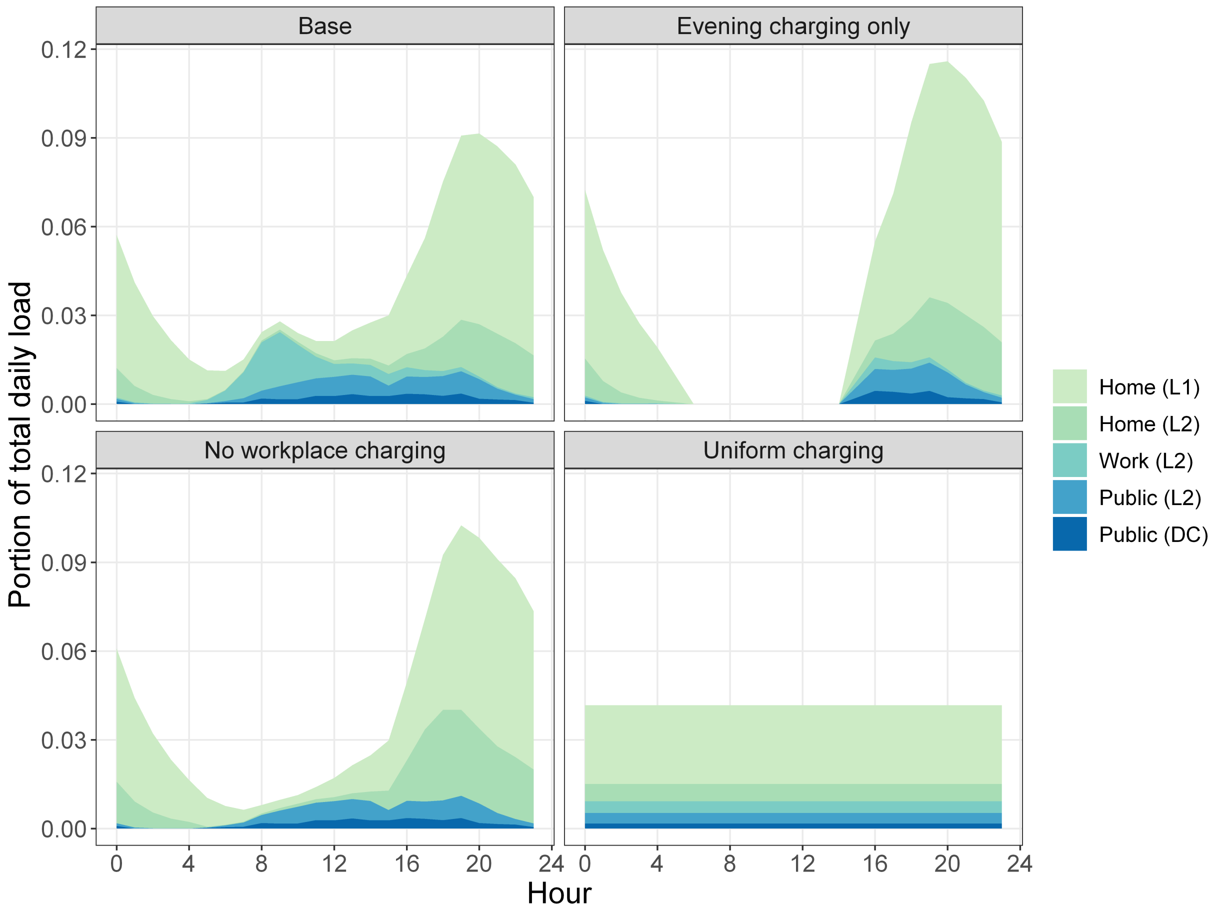
9 Appendix

Figure A1: Vehicle charging scenarios



Notes: Charge patterns derived from US DOE EVI-Pro simulations. Source: Wood et al. (2017) and authors' calculations. EVI-Pro tool available at `https://maps.nrel.gov/cec/`.

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Table A1: Projected electric vehicle loads by charging scenario

	CAISO (US)		PJM (US)		ERCOT (US)		EU-28		China		Japan	
	MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Scenario: Current EV share												
Base case	262	0.4	62	0.03	19	0.02	421	0.04	1,285	0.1	115	0.04
Uniform	119	0.2	28	0.01	9	0.01	192	0.02	585	0.03	52	0.02
No workplace	294	0.4	69	0.03	21	0.02	471	0.05	1,438	0.1	128	0.04
Evening only	332	0.5	78	0.04	24	0.02	533	0.1	1,627	0.1	145	0.05
Scenario: 7% BEV, 4% PHEV												
Base case	2,541	3.6	4,803	2.4	1,789	1.7	15,337	1.5	11,283	0.6	3,147	1.0
Uniform	1,157	1.6	2,186	1.1	815	0.8	6,981	0.7	5,136	0.3	1,432	0.5
No workplace	2,845	4.0	5,378	2.6	2,004	1.9	17,173	1.7	12,634	0.7	3,523	1.1
Evening only	3,217	4.6	6,082	3.0	2,266	2.1	19,421	1.9	14,288	0.8	3,985	1.3
Scenario: 30% BEV, 70% PHEV												
Base case	21,422	30.5	40,498	19.8	15,088	14.0	129,311	12.8	95,131	5.3	26,531	8.5
Uniform	9,751	13.9	18,435	9.0	6,868	6.4	58,863	5.8	43,304	2.4	12,077	3.9
No workplace	23,987	34.1	45,345	22.2	16,894	15.7	144,791	14.3	106,519	5.9	29,707	9.5
Evening only	27,127	38.6	51,282	25.1	19,106	17.8	163,746	16.2	120,464	6.7	33,596	10.7
Scenario: 100% BEV												
Base case	24,909	35.4	47,090	23.1	17,544	16.3	150,362	14.9	110,618	6.2	30,850	9.9
Uniform	11,339	16.1	21,435	10.5	7,986	7.4	68,445	6.8	50,353	2.8	14,043	4.5
No workplace	27,891	39.7	52,727	25.8	19,644	18.3	168,362	16.7	123,860	6.9	34,543	11.0
Evening only	31,543	44.8	59,630	29.2	22,216	20.6	190,402	18.8	140,074	7.8	39,065	12.5

Notes: Percentage values are percent of system capacity. The data sources and assumptions, including system capacity, are described in Table 7. The charging profiles for hourly maximum load are scaled from the charging profile of the US DOE's EVI-Pro market simulation. See Figure A1 for source information and profile illustrations.

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Table A2: Trends in new light-duty vehicle fuel economy (miles per gallon)

	2012	2013	2014	2015	Mean
France	45.2	47.0	43.6	45.2	45.3
Italy	42.8	44.4	41.3	42.8	42.8
Japan	45.2	48.0	39.9	37.9	42.8
UK	42.0	43.6	39.9	40.6	41.5
Germany	39.9	41.3	38.6	39.2	39.7
India	41.3	41.3	37.9	37.9	39.6
Brazil	33.6	34.1	29.8	30.5	32.0
China	30.9	31.4	28.3	29.0	29.9
Australia	28.3	29.4	27.7	28.0	28.4
Canada	27.0	27.4	25.6	25.6	26.4
US	25.6	26.1	25.8	25.8	25.8

Notes: Reported values are average fuel economy for new LDVs and are normalized to the Worldwide harmonized Light Vehicle Test Cycle. The data for 2012-2013 are from GFEI (2014); the data for 2014-2015 are from GFEI (2017).

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