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THE ECONOMICS OF ELECTRIC VEHICLES

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ABSTRACT

We examine the private and public economics of electric vehicles (EVs) and discuss when market forces will produce the optimal path of EV adoption. Privately, consumer cost savings from EVs vary. Some experience net benefits from choosing gasoline cars, even after accounting for EV subsidies. Publicly, we survey the literature documenting the external costs and benefits of EVs and highlight several themes for optimal policy design including, 1) promoting regional variation in EV policies that align private incentives with social benefits, 2) pursuing a time-path of policies that reflect changing marginal benefits, and 3) rationalizing electricity and gasoline prices to reflect their social marginal cost. On the extensive margin, purchase incentives should ramp-down as learning-by-doing and network externalities (to the extent that they exist) diminish; on the intensive margin, gasoline should become relatively more expensive over time than electricity (per mile traveled) to reflect cleaner marginal emissions from electricity generation.

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1 Introduction

Electrification of the vehicle fleet is a central element to addressing major environmental, transportation and energy policy challenges. States and countries around the world have set ambitious long-run goals to transition away from internal combustion engines (ICEs), with targets for large-scale electric vehicle (EV) adoption[1] or timelines to phase out ICEs entirely.[2] However, EVs are not yet universally superior to ICEs, either economically or environmentally, leading to a complicated landscape of optimal policy.

This paper examines the economic rationale and policy implications of the suite of policies that currently affect EVs. Our goals are to clarify three aspects of the economics of EVs. First, we evaluate the private rationale for EV adoption by consumers, highlighting when the operational savings of EVs offset the higher upfront price of an EV. Second, we consider external benefits of EVs that policymakers offer as a rationale for intervention in the EV market. Potential social benefits of EV subsidies include a reduction in global and local pollution externalities, industrial learning-by-doing (LBD), network externalities relating to charging infrastructure, and enhanced energy security. We evaluate the relevance and potential magnitude of these claimed benefits through the lens of economic theory and, when available, empirical evidence. Third, we discuss what the private and public economics of EVs imply about optimal EV policy. Using efficiency as a benchmark, we assess the current landscape of EV policy.

The paper offers several lessons for optimal EV policy:

1. Some market failures have external costs or benefits that are similar across locations in the U.S. These included production spillovers, energy security and global climate change mitigation. When equating marginal costs and marginal benefits on these dimensions, a policy that is uniform across locations will be superior.
2. Other market failures vary by geography, such as externalities arising from local pollution or network effects relating to density of local charging station infrastructure. To address these concerns, location-specific policy can better equate benefits and costs.
3. The local and global externalities of EVs will change over time and may lead optimal subsidy policy to increase or decrease over time. On one hand, policy might front-load

[1] For example, Germany aims to have 6 million EVs on the road by 2030. California has also set ambitious targets: 1.5 million EVs on the road by 2025 and 5 million by 2030.

[2] Recent pledges to phase out ICEs include France and the United Kingdom (by 2040), Norway (by 2025), China (2035) and India (by 2030). Holland et al. (2021) evaluates the welfare losses associated with gasoline vehicle production bans.

stimulus to capture the dynamic benefits of production spillovers and indirect network externalities associated with charging infrastructure. But, the pollution reduction benefits from driving EVs rather than ICEs will likely grow, as electricity grids shed coal and add renewables, particularly in locations where coal remains an important source of electricity like the midwestern U.S. If environmental objectives are paramount, then optimal subsidies should increase as electric grids become cleaner.

4. Current subsidy levels are difficult to justify based on the cumulative external benefits of environmental, energy security and network externalities relating to charging infrastructure. Economic justification for EV subsidies at recent levels relies on the presence of substantial non-appropriable learning by firms. Unfortunately, it is difficult to estimate the true extent of learning-by-doing, let alone determine the extent of non-appropriability.

In what follows, readers may notice that the order of subsection topics (e.g. discussion of the intensive versus extensive margin) is not symmetric across sections. We begin each section by discussing the most salient or important topics. That the order changes between sections reflects a misalignment between the externalities (which mostly occur on the intensive margin) and existing EV policies (which mostly seek to influence the extensive margin). In Section 2 we discuss the (private) incentives buyers face when considering an EV. We then turn our focus to several potential externalities that relate to the production and use of EVs (Section 3), followed by a discussion of what these considerations collectively imply about optimal EV policy (Section 4). Section 5 concludes.

2 Private Economics of Electric Vehicles

Conventional wisdom holds that EVs are more expensive to buy and less expensive to operate than ICEs. The reality is more complex. Presently, EVs face a manufacturing cost disadvantage. Although battery costs have fallen by over 85% over the past decade, the upfront costs of EVs remain higher than ICEs. This gap continues to close with National Academy (2021) projecting cost parity later this decade at battery costs of roughly $90 per kWh. For first-time owners, an EV purchase may also entail other costs such as the cost of installing a home charger and the potential cost of switching electricity tariffs.

In exchange for higher upfront costs, the electric powertrain of EVs offer a different driving experience. EVs offer superior torque and acceleration, do so more smoothly (no gears) and quietly (no combustion engine). Battery technology creates both flexibility and constraints. Although batteries allow owners to “refuel” at home, the range of most EVs is lower than comparable ICEs and batteries take more time to refill. At present, the constraints on range and charging may force drivers to adjust driving and parking patterns.

Moreover, EVs tend to have lower operational costs. Yet, these savings can vary substantially across locations and over time, depending on the electricity and gasoline prices faced by a prospective EV buyer. Retail electricity prices differ by utility district, depending on the utility’s underlying costs and the state regulator’s appetite to recover utility fixed costs through fixed or variable fees. Differences can be considerable. For instance, the top marginal retail electricity price for residential consumers in Pacific Gas and Electric’s (PGE) service territory (which covers West Sacramento) was 40 cents per kWh, almost four times higher than the 11.4 cents per kWh rate for a residential household living in the Sacramento Municipal Utility District service territory (which serves the rest of the city).

Gasoline prices also vary over time and across states. Over time, the price of gasoline follows global crude oil prices - since 2005, the nationwide weekly average gasoline price fluctuated between $1.63/gal in December 2008 to $4.31/gal in March 2022. Gasoline prices also vary cross-sectionally due to state-level regulations, excise taxes and proximity to refining capacity. Nationally, tax-inclusive gasoline prices averaged $3.10 per gallon in 2021, but varied from a low of roughly $2.75 per gallon along the Gulf Coast to a high of $4.10 per gallon in California.

Due to regional differences in electricity and gasoline prices, variation in the operation cost savings offered by EVs is considerable. Using data from 2016 as a snapshot, Figure 1 highlights the state-level variation in annual fuel cost savings from driving a Nissan Leaf rather than a Nissan Versa (its gasoline equivalent), shading states by fuel cost savings quantile. EVs reduce operational costs by roughly $400 - $500 per year in the Pacific Northwest, where abundant hydropower provides the lowest residential electricity rates in the country. Annual savings are much lower in locations with higher residential electricity rates. In New England, annual savings are less than $200 per year.[3] And although gasoline prices in California are amongst the highest in the nation, high electricity prices reduce the potential savings from driving an EV.

[3] The savings for New England are likely lower in practice, as EV fuel efficiency declines in colder locations.

Figure 2 further illustrates how the savings from driving a Leaf rather an Versa change with gasoline and electricity prices The horizontal axis reflects the electricity price paid by the Leaf driver, while the vertical axis reflects her relative fuel cost savings. The diagonal lines illustrate the savings enjoyed by the Leaf driver at gasoline prices of $2, $3 and $4/gallon. A $1/gallon increase in the gasoline price (roughly the change in average gasoline prices from June 2020 to June 2021) translates to $300/year in savings from switching to an EV. For reference, the figure plots the savings enjoyed by the Leaf driver in 2014, 2016 and 2018, if they had faced the average gasoline prices and electricity prices in either Los Angeles (Southern California Edison) or Sacramento. Notably, with recent gasoline prices exceeding $4.00 per gallon, driving a Leaf implies cost savings over the entire range of U.S. utility electricity prices. But, the extent of saving vary considerably depending on both gasoline and electricity prices. Comparing the electricity prices in Los Angeles and Sacramento, the savings vary by roughly $700 per year depending on the electricity price tier faced by the driver. This is roughly the difference in operational costs between a Nissan Versa and a Ford F150 pickup truck. To the extent that consumers integrate these savings into their purchase decisions (see e.g., Busse et al. (2013), Allcott and Wozny (2014)), differences in operating costs impact adoption.

Finally, EV motors have fewer moving parts than internal combustion engines, and conventional wisdom holds that EVs enjoy lower maintenance costs than ICEs. Although both EVs and ICEs require insurance, tire replacement and other common maintenance costs, the electric powertrain eliminates the need for some engine maintenance such as oil changes and replacement of ignition system components (e.g., spark plugs).[4] A recent DOE study[5] examining the operations costs of the federal vehicle fleet concluded that the ongoing maintenance costs of a fully electric powertrain are roughly 60 percent of the ongoing maintenance costs of a vehicle that either fully or partially relies on burning fuel. Yet, the absolute maintenance cost savings are generally low. In the 2018 Consumer Expenditure Survey, maintenance costs over the first five years of ownership of an ICE vehicle average just $200 per year.

The relatively short history of EV ownership makes it hard to know maintenance costs for older EVs, particularly those associated with battery degradation and replacement. In 2020, the

[4] While most maintenance is likely comparable, EVs are heavier than comparable conventional vehicles, increasing the frequency of tire maintenance.

[5] https://www.osti.gov/biblio/1780970-comprehensive-total-cost-ownership-quantification-vehicles-different-size-classes-powertrains

average battery costs were roughly $137 per kWh.[6] At this price, a 30-kwh capacity battery (roughly the size of a Nissan Leaf battery) would cost $4,000, and a 75-kwh Tesla Model 3 battery would cost roughly $10,275. Although battery costs are projected to continue to decline, replacing a future battery may still be costly and possibly comparable in magnitude to the cost of ICE transmission replacement, which range from $1,100 to $3,400.[7]

3 Market Failures in Electric Vehicles

Externalities arise when decision-makers do not internalize the full social costs (or benefits) of the decisions they make. The presence of externalities (both positive and negative) are regularly offered as justification for government intervention in the EV market. In this section, we describe the main externalities, grouping them into those created by the operation of EVs (the "intensive" margin) and those arising from the production or stock of EVs on the road (the "extensive" margin).

3.1 Usage-based ("Intensive Margin") Externalities

3.1.1 Carbon emissions

Each gallon of gasoline burned generates approximately 20 lbs of carbon dioxide. In contrast, greenhouse gas (GHG) emissions from electricity generation vary based on timing and location of electricity demand.

The electricity generation sector is comprised of many different technologies: wind, solar, hydro (run-of-river and dammed), nuclear, and various fossil fuel technologies such as coal, natural gas (combined-cycle gas turbines, combustion turbines) and petroleum "peakers". The emissions impact associated with charging an EV (or any other source of load) depends on which generator "turns on" or ramps-up production when demand increases. It cannot be the case that the marginal supply comes from a technology that would be producing electricity irrespective of whether the EV is plugged in. The marginal supply must be "dispatchable"; that is, it can be turned on or off depending on market conditions. Typically, this rules out intermittent sources of renewable supply such as wind (which produces when the wind is blowing, irrespective of

[6] https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

[7] https://www.transmissionrepaircostguide.com/

demand conditions) or solar (which produces when the sun is shining, irrespective of demand conditions).

For EVs, Graff Zivin et al. (2014), Archsmith et al. (2015), and Holland et al. (2016) all use variants of a methodology that estimates the emissions profile of generators “on the margin”. Archsmith et al. (2015) extends that methodology to allow renewables (such as dammed hydro) to be part of the marginal supply mix. They also include upstream (“life cycle”) emissions that are associated with the extraction and transportation of inputs, and impacts of ambient temperatures on EV electricity use and charging efficiency (Tamayao et al. (2015)).[8] The GHG profile of ICEs depends mainly on features of the car and driving patterns, but there is less heterogeneity in fuel source. Life cycle emissions of gasoline have been studied extensively and vary primarily based on the location and extraction technology of the crude oil inputs.

The conclusions of the above studies are qualitatively similar. EVs tend to provide some GHG savings relative to ICEs in areas where natural gas is on the electricity generation margin, but tend to be more GHG-intense if coal is on the margin and temperatures are cold. Archsmith et al. (2015) estimate that a Nissan Leaf generates roughly $425 worth of life cycle GHG savings when driven in California instead of the Nissan Versa. That’s a 20 percent life cycle GHG savings in California, compared to 5 percent nationwide and -10 percent (!) in the midwest, each of which is consistent with results from Graff Zivin et al. (2014), Tamayao et al. (2015), and Holland et al. (2016). As the electricity generation sector moves away from coal and towards renewables (potentially with storage) and natural gas, the GHG profile of electricity supply will improve and the expected GHG damages over an EVs lifetime will decline.

3.1.2 Local emissions

When fossil fuels are the marginal electricity source, charging EVs generates local pollutants that impact human health, the built infrastructure, crop yields and the ecosystem. Human exposure is the primary channel of damages. Two main factors affect the extent of local pollutant damage: the quantity and type of fuel combusted and its proximity to population centers in relation to wind patterns. These factors suggest considerable differences in the local emissions

[8] While natural gas is the cleanest fuel at the point of combustion, it has a much higher upstream emissions factor than coal or gasoline. Coal, by comparison, is often extracted very close to its point of use, and is transported quite efficiently from a GHG perspective.

impacts of EVs as compared to ICEs. Gasoline combustion occurs when and where the car is driven, exposing people nearby to pollutants. In contrast, local pollution from EVs occurs around power plants that supply the grid when the EV is charging.

As with carbon emissions, the local pollution associated with charging an EV depends on the emissions of the marginal generating unit.[9] Typically, in the United States the marginal generator will be coal or natural gas due to the ability to expand production on demand. In 2020, the Energy Information Administration reports that roughly 60 percent of electricity in the United States was generated from either coal or natural gas, down from 70 percent in 2014. To the extent EV-induced fossil generation occurs near population centers, the damages may exceed those from driving ICEs. But, due to the spatial integration of electricity markets, the marginal generating unit may be far away from the EV. Pollution benefits from driving an EV (relative to ICE) will be greatest when the EV is driven in an already-polluted and densely populated area, but charged by a marginal source of electricity that is either clean (e.g. dammed hydro or natural gas) or located far from population centers.

This intuition is reflected in Holland et al. (2016), which assesses the local environmental benefits of EVs relative to ICEs. Large benefits accrue to driving EVs in cities where the ambient air quality is poor and where electricity is relatively clean (e.g. Los Angeles, California). Where coal is likely to be on the electricity generation margin and is upwind of population centers, driving EVs can actually increase net local pollution (e.g. the entire U.S. midwest).

Pollution has also been linked to many potential channels of social harm, including decreased labor productivity (Graff Zivin and Neidell (2012) and Chang et al. (2016)) and impaired cognitive performance (Archsmith et al. (2018)). Recent estimates suggest local pollution from electricity production is declining (Holland et al. (2020)), and, as the electricity grid continues to become cleaner, EVs will as well. Local pollutant benefits of EVs are greatest in dense urban centers where the electric grid is clean, such as Los Angeles and other cities in the western U.S. In contrast, in locations where the marginal unit of electricity comes from coal that is upwind of major urban areas, local pollution benefits are typically negative (Holland et al. (2016)). Of course, as coal is replaced, these damages will decrease.

[9] As the fleet of EVs grows and EV load becomes part of the baseline, the marginal emissions factor will become less reflective of true EV emissions. Exploring the nuances of this topic is beyond the scope of this paper. However, we view the marginal emissions factor as far superior to average emissions today based on the low fraction of generated electricity that serves EV load.

3.1.3 Congestion and Accidents

The extent of externalities from congestion and accidents is underappreciated. These are the largest market failures related to driving, exceeding GHG and local pollutant damages (Parry et al. (2014)). Congestion externalities are magnified in heavily trafficked routes during congested periods, and the externalities imposed by a driver are positively correlated with the weight of the vehicle driven.[10] Replacing an EV with an ICE should have little overall impact on the externality; however, some policies designed to encourage EV adoption, such as single-occupancy access to HOV (carpool) lanes, might impose externalities by reducing the utility of these lanes.

EVs increase accident externalities through two channels. First, EVs are heavier than ICEs, which increases the fatality risk from collisions (Shaffer et al 2021). There is also growing evidence of portfolio effects within households (Archsmith et al. (2020)) that may cause EVs households to purchase larger vehicles in an attempt to diversify the portfolio of vehicles owned. Again, increases in vehicle weight lead to higher accident externalities.

3.1.4 Energy Security

We follow Metcalf (2014) by defining energy security as “the ability of U.S. households and businesses to accommodate disruptions of supply in energy markets.” Much of the global crude oil supply comes from countries with geopolitical interests that are in conflict, or poorly aligned, with U.S. interests. Concerns arise from the idea that U.S. oil purchases enrich these potential adversaries. Also, in the event of a global conflict, the U.S. may not have control over valuable key energy inputs, and therefore would be practically or strategically impaired by supply disruptions. Yet these concerns are tempered by the recent increase in U.S. oil and gas production. In 2020, U.S. energy production was roughly 103 percent of domestic energy consumption, and net U.S. energy imports are rapidly declining (EIA). Widespread substitution away from gasoline-powered vehicles towards EVs would reduce reliance on crude oil in favor of electricity and, by extension, the inputs that generate electricity. This will create both level and compositional pressures in the market. A decline in domestic demand will cause the U.S. to

[10] Anderson and Auffhammer (2013), Jacobsen (2013), and Bento et al. (2017).

import less and export more, placing downward pressure on the global oil price. This highlights the contrasting effects on energy security proponents (who would applaud such a shift) and owners of domestic crude oil reserves (whose assets are less valuable in such a scenario). Falling oil prices might also have impacts on other oil-rich countries. If oil-rich countries experience a significant decline in their financial resources, it may inhibit their ability to pursue interests that conflict with those of the U.S. On the other hand, the wealth derived from oil resources has facilitated political stability within petro-states. In a counterfactual world with lower oil prices, these countries may find it more difficult to meet the expectations of their citizens, potentially planting seeds of civil unrest along the lines of what led to the Arab Spring, where economic factors (e.g. high unemployment, food-price inflation and low wages) played an important role.

3.2 Stock Based ("Extensive Margin") Externalities

Under certain conditions, the stock of EVs or charging stations might generate external benefits, such as learning-by-doing (LBD), knowledge spillovers in production, or network effects related to charging infrastructure. These types of benefits are notoriously hard to separate from economies of scale that arise from contemporaneous production or models of gradual technological diffusion without meaningful externalities. Yet, economics provides some guidance as to the conditions under which they are likely to be relevant for EV policy. We focus our attention on two channels by which production volumes might generate impacts: (1) LBD, and (2) network effects related to charging infrastructure.

3.2.1 Learning-by-Doing

LBD occurs when the firm's cumulative production experience reduces future production costs, which can arise from refinements in the firm's production process, worker skill accumulation, or gradual development of expertise in managing inputs.[11] LBD is distinct from economies of scale (the gains from which are internal to firms), whereby a firm's production costs decline with contemporaneous output, and empirically distinguishing the two is challenging. Falling costs are often accompanied by both increasing contemporaneous production and increasing cumulative

[11] We focus on process-based learning, as distinct from scientific advancements. The latter, while important, are best supported via direct funding for basic scientific research, and less so by EV-related policies.

production.

When LBD is present, it is not a market failure if benefits accrue internally to the firm. If a firm's cumulative experience increases, it often reaps the benefits of lower costs. In such cases, there are no (external) benefits that are left uncaptured by the firm making production decisions. If the firm has sufficient liquidity, and there are no other market failures that prevent the firm from capturing the benefits, LBD is not a market failure.[12] However, when LBD benefits spill over to other firms (are "non-appropriable"), a market failure may arise.

To our knowledge, no one has empirically quantified the extent of LBD for EV or battery manufacturers, let alone the appropriability of LBD gains. LBD has been documented in other manufacturing industries, most notably in aircraft manufacturing by Benkard (2000) and in Liberty production by Thornton and Thompson (2001). However, in these settings benefits of labor specialization are large, and relevance to EV production is unclear. Meaningful spillovers may also plausibly arise from either innovation or "external economies of scale", as described by Bartelme et al. (2018) for shared technologies, such as batteries. Battery production and use spurred by deployment in EVs may plausibly foster innovation in battery chemistry, characteristics, or costs. These innovations might increase the value of batteries for EV manufacturers or for manufacturers that use rechargeable batteries for other uses, such as consumer electronics. If battery producers capitalize on innovation through intellectual property, they face efficient incentives to engage in research and development. If the capture of benefits is incomplete, policymakers should consider the optimal remedy. Is offering incentives for EV adoption the most cost-effective strategy for stimulating battery (or other technological) innovation? In the realm of LBD, current research offers more questions than answers.

3.2.2 Network Effects in Charging Infrastructure

Network effects arise when increases in the existing stock of a good lead to an increase in the value of the good to prospective consumers. Network effects may be "direct" or "indirect". In the context of EVs, direct network effects exist if the marginal utility of an EV owner is increasing in the number of other EV owners, whereas indirect network effects might arise through the

[12] A parallel logic about economies of scale has long been accepted by economists (e.g. Stigler (1983) in the context of antitrust).

availability of an important complementary good: charging infrastructure.[13]

Charging infrastructure takes two forms. Level 2 chargers supply 220V and can allow for charging at a rate of up to nearly 20kW, though most Level 2 charging stations max out at a third of that level. The fixed cost associated with installing these stations is modest (on the order of several thousand dollars), as are distribution utility requirements to update transformer and delivery infrastructure. Level 2 chargers are already commonplace – e.g., roughly 57,000 level 2 charging stations have been built in California. They are typically constructed in parking lots, commercial and retail locations and multi-unit apartment buildings. In contrast, fast-charging (or Level 3) stations supply the fastest recharge available today. They cost in the range of $100,000 and can provide a nearly full charge in under 30 minutes. Fast charging stations are more likely to be built along highways to facilitate longer-distance trips between cities.

It is unclear whether market failures arise in this context. As in the case of LBD, network effects do not inherently imply a market failure. Just as firms might appropriate the benefits of LBD, benefits of network effects may also be captured by firms. For example, Microsoft benefited from enormous network effects, but the market failure that arose was due to market power, not the inability of Microsoft to internalize the benefits of the network effects. In the EV setting, Tesla's network for fast-charging stations provides a unique benefit to buyers of Tesla vehicles, and as such, Tesla has every incentive to build out the charging station network. In fact, as Li (2019) highlights, firms with incompatible networks may "overbuild" the network relative to the social optimum by creating duplicative investments.

Yet, potential market failure concerns in charging often focus on the case in which too few stations are built if network externalities arise when multiple technology platforms exist (such as the different charging standards used by EV automakers), or if market participants are unable to internalize the benefits that arise from the network effects. In the case of the former, there are currently three "standards" for fast-charging connectors adopted by EV automakers: CHAdeMO, Combined Charging System (CCS) and Tesla.[14] To the extent that standards are incompatible, governments have long played a regulatory role in aligning standards.[15] Yet, in some cases, market forces create strong incentives to achieve compatibility and obviate the need for

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13 Although charging stations are the most commonly discussed source of indirect network effects for EVs, a similar argument could be made for complementary EV-specific repair and maintenance services.

14 Broadly, Asian automakers have used CHAdeMO and U.S. legacy and European automakers have used CCS.

15 Classic examples include voltage regulation and infrastructure standards for electric utilities.

government intervention. For EVs, automakers want to design vehicles that are either compatible with a prevailing standard or offer adapters to allow their vehicles to be use across charging platforms. As one such example, the version of the Tesla Model 3 sold in Europe is built with a CCS connector allowing owners to take advantage of the existing fast-charging network.

Market participants can be expected to internalize some, but not all, of the benefits of network effects so long as there are low barriers to entry and firms are able to achieve sufficient scale. Consider the case of a firm owning a single fast-charging station along an interstate. The number of EVs (and the profits of that charging station) depend on the density of the broader network, and specifically, on whether there are other firms that build fast-charging stations along the same interstate. Here, a network externality exists with the most direct spillovers arising from nearby fast-charging stations. With low barriers to entry and sufficient capitalization, market forces create a strong incentive for an entrant to build the string of fast charging stations due to the network externalities that exist, even if the entrant does not internalize the network externalities the string of stations might link more distant markets. Market forces will strongly push towards the latter outcome – e.g. Tesla's supercharger network.

However, there may well be multiple equilibria in this industry, which has implications for efficiency. Consider the discussion in the previous paragraph as being local (in an equilibrium sense) to current supply and demand conditions. An alternative equilibrium may exist with a far higher level of both EV adoption and charging infrastructure. A market failure exists if welfare is higher at the alternative equilibrium and if a hurdle exists that inhibits the market from reaching that alternative. We can't reject whether such a high EV, high charging equilibrium exists; and indeed, it very well may. However, there is little empirical guidance to inform us whether welfare is higher or lower in such an equilibrium. The environmental benefits would likely be high, but the cost to build out the charging network and transform the electric grid will also be high. The relative magnitude of these costs and benefits is uncertain.

4 Current Policies and Economic Efficiency

In this section, we discuss how the interconnected transportation, environmental and energy policy landscapes relate to the private and public economics of EVs. We begin by discussing what the market failures from the previous section would imply for optimal policy. We then provide an overview of the current policies in place and highlight how the suite of existing policies spur, or in some cases hinder, EV adoption and affect the economic efficiency of outcomes. We also discuss distributional objectives, although they fall outside of the purview of economic efficiency.

As described above, externalities arise when decision makers do not internalize the full social costs or benefits of the decisions they make. Before discussing the role that taxes and subsidies might play in addressing potential externalities, we highlight three themes common across the externalities described in the previous section. First, an externality only arises when the benefits of an agent's decision accrue to other parties. If the agent is the residual claimant on the benefits of deploying an additional EV, there is no externality-based market failure and no justification for a production or sales subsidy. For example, if learning-by-doing or economies of scale in production accrue entirely within the boundaries of the firm, then a forward-looking firm will fully-internalize the benefits from production, and no justification for a subsidy exists. In contrast, subsidies might play a role in addressing benefits that accrue outside of a firm's boundaries, arising, for example from learning spillovers or industry-wide intellectual capital. Network externalities may create similar spillovers if the private economics of a consumer's decision fail to capture the broader benefits from a growing EV fleet or if a firm's investment creates benefits for other firms.

Second, the externalities described above vary with regards to their spatial scope. Where the externality is uniform, a one-size-fits-all approach to policy might be appropriate. One such example might be spillovers created by general knowledge accumulation. However, many externalities related to EVs vary by location. Pollution externalities depend on the regional electricity generation mix and the proximity of facilities to population centers. Network externalities depend on the local confluence of EVs and charging stations. In both cases, location-specific policies will better address local externalities created by EV fleet expansion.

Finally, some of the externalities above will change over time, and optimal policy will adjust as well. For externalities likely to exhibit diminishing marginal returns, such as network externalities and production spillovers, this suggests front-loading subsidies.[16] But, for externalities related to local or global pollution, where present-day benefits of EVs are modest

[16] Benkard (2000) and Thornton and Thompson (2001) document diminishing marginal returns in aircraft and shipbuilding manufacturing to experiential learning. Similarly, early adoption of EVs might spur charging station investment (and vice versa as suggested by Li (2019) and Springel (2021)), but the marginal external benefits decline as fleet size increases or charging stations become pervasive.

(or negative), policies should become more generous over time as the pollution intensity of the electricity grid falls.

We now turn our attention to U.S. policies that promote supply and demand in the EV market. These policies pursue a wide range of goals. State and federal tax credits (in concert with non-monetary incentives) encourage consumer adoption. California's Zero-Emission-Vehicle (ZEV) Mandate and CAFE standards create incentives to promote supply. Indirect network effects associated with charging infrastructure investments are addressed through direct subsidies for construction of charging stations. We discuss this policy landscape briefly with the goal of identifying the stated rationale when possible, and ascertaining the extent to which those stated or presumed rationale can be justified by market failure. A general principle in what follow is that policies that are not justified by a market failure cause costly distortions and are inadvisable. The same environmental and market outcomes could be achieved at a lower cost. In our view, the aspiration to cost-minimize ought to be central to any environmental policy that policymakers wish to scale or see replicated elsewhere.

4.1 EV Purchase Incentives

State and federal tax credits are motivated by the fact that, both currently and for the anticipated future, the upfront cost to purchase an EV is higher than the upfront cost to purchase a comparably sized ICE. State and federal subsidy programs are the primary policies aimed at influencing the consumer purchase decision. Federal subsidies of up to $7,500 per new EV were made available as part of the American Clean Energy and Security Act of 2009. These subsidies are tied to battery capacity and were initially capped at the manufacturer level, with up to $1.5 billion in tax credits available for consumers of each manufacturer, phasing-out after an automaker sells 200,000 EVs. A wide array of state and local incentives have been available, with the most typical being rebates or tax credits, high-occupancy vehicle lane access, and/or free or subsidized charging (more on this in the next subsection).

State governments have also set up financial incentives for EV adoptions. By 2014, over half of the states had some sort of EV incentives in place. These ranged from point-of-sale subsidies to high-occupancy vehicle (HOV) lane stickers, sales tax waivers, registration fees (waivers or taxes), parking preferences, charging infrastructure subsidies and more. The largest state program in the U.S. is the California Clean Vehicle Rebate Project (CVRP), which currently offers new EV buyers $1,000 – 4,500 depending on income and vehicle. Although initially available to all buyers in California, means-testing and a sticker-price eligibility limit were introduced in 2016 (and subsequently revised downwards) to target subsidies towards lower-income households. In addition, some funds generated by the low carbon fuel standard (LCFS) are redirected to California electric utilities to subsidize EVs.

Subsidies address two potential sources of market failure on the “extensive” margin: stock-based externalities arising from network effects or LBD and (potentially) the present discount value of usage externalities if buyers are not forward-looking with regards to future energy expenses. Notwithstanding concerns of economic efficiency, empirical research finds that subsidies can be effective at stimulating demand for alternative fuel vehicles. Gallagher and Muehlegger (2011) show that demand for hybrid vehicles was dramatically increased by the presence of sales tax waivers. In low- and middle-income subpopulations, subsidies appear to be effective as well (Muehlegger and Rapson (2018)). These results are consistent with estimates of the EV demand elasticity, which exceed -1 (Li et al. (2017), Li (2019) and Springel (2021)).

Upfront subsidies may also play a role in addressing externalities on the “intensive” margin in two cases. First, it may be infeasible to set Pigouvian taxes on gasoline and electricity. In this case, the savings offered by an EV may not reflect the social benefits of driving an EV. Second, as noted in Allcott et al. (2014), if consumers undervalue future energy cost savings, buyers facing Pigouvian taxes on electricity or gasoline will under-adopt EVs relative to the social optimum. In this case, an upfront subsidy equal to the net present value of the stream of unincorporated externalities of use is justified.

The extent to which subsidies induce “additional” EV purchases is an important determinant of cost-effectiveness and welfare effects of a subsidy policy. In the case of most EV subsidy programs, both subsidy-induced EVs and those that would have been purchased irrespective of the presence of a subsidy are subsidy-eligible. There is no way to reliably target subsidies only to marginal buyers for whom the subsidy is the determining factor in the purchase decision. Due to this information asymmetry, the cost per additional (subsidy-induced) vehicle depends on the size of the market that would have been realized in a subsidy-free world, which is unobservable. The demand elasticity summarizes much of what is needed to predict what would have happened in this alternate, subsidy-free world. On one hand, a high demand elasticity induces more EV purchases for a given amount of subsidy, thereby implying a higher degree of additionality than if demand were less elastic. On the other hand, as the proportion of subsidy-induced vehicles grows, the implication is that in a subsidy-free world the size of the EV market would have been that much smaller. To the extent subsidies are larger than socially optimal, a subsidy-induced expansion of demand reduces welfare.

To demonstrate these points, we consider the implied proportion of EVs sold under the existing federal and California subsidy regimes that is additional.[17] Table 1 present these estimates. In Panel A we report the implied fraction of battery EVs (BEVs) that were "additional" under different assumptions about the demand elasticity. Consistent with intuition, more elastic demand corresponds to a higher fraction of the market that is subsidy induced. An elasticity of -1.5 implies that the vast majority of BEVs would have been purchased even had the subsidies not been present. This is particularly true for Teslas. At the higher end of the elasticity range, -3.5, it still appears that most Teslas were likely not subsidy-induced purchases; but 64-77 percent of non-Teslas were. One can also calculate the implied subsidy per induced BEV, which decreases as demand becomes more elastic (moving left to right in the table). If most BEVs would have been purchased without subsidies, the implied subsidy cost per subsidy-induced purchase must be large. If 80 percent of Teslas in California would have been purchased without subsidies (and assuming 100 percent subsidy uptake), then the average subsidy expense per subsidy-induced Tesla would be over $50,000. Even at higher elasticities, the effective cost per subsidy-induced BEV substantially exceeds the face value of the subsidy itself.

Setting aside efficiency considerations, many policymakers and industry enthusiasts are interested in how to achieve various EV adoption goals (e.g. 5 million EVs on the road in California by 2030). Archsmith et al. (2021) estimates the relative importance of up-front purchase prices versus non-monetary EV attributes, such as battery range, the availability of EV pickup trucks, and charging station density. They conclude that EV market share in 2035 will be determined more by non-monetary factors than by subsidies. In their analysis, the first $500 billion in cumulative nationwide EV subsidies is associated with a 7-10 percent increase in EV market share in 2035, an effect that diminishes as subsidies increase. For those aspiring to

[17] The main elements of this calculation are data on actual EV purchase prices, California, federal EV subsidy amounts (which we assume to be $2,500 and $7,500 for California and federal subsidies, respectively), and data on the number of EV sales. We perform the calculations separately for Teslas to acknowledge the fact that Teslas are much more expensive than the vast majority of other EVs sold during the period of our data (before the end of 2018).

achieve upwards of 50 percent EV market share by that time, subsidies may help but will likely play a secondary role to non-monetary determinants of demand.

4.2 Policies Affecting Intensity of Use

EV miles traveled (eVMT) is a measure of the utility that drivers of EVs receive and speaks directly to the potential environment benefits provided by EVs. Yet, there is an active debate about how much EVs are driven, due to the lack of direct measurement. On one hand, surveys from California produce eVMT estimates similar to VMT from ICEs (Hardman et al. (2018)). But, responses from the 2017 National Household Travel Survey indicate that EVs are driven half as much as ICEs (Davis (2019)). This result is consistent with eVMT estimates from Burlig et al. (2021) that use household-level electricity billing data and account for away-from-home charging and estimate eVMT of roughly 6,700 miles per year for Northern California over 2014-2017. Whether observed use patterns are reflective of early adopters, range limitations, geographic variation or the role EVs play in a household's portfolio is an active area of research. Efficiency on the intensive margin requires setting Pigouvian taxes equal to the marginal external costs of gasoline and electricity, so that, on a per-mile basis, the private savings from operating an EV would equal the marginal external benefits of an EV relative to an ICE. Figure 3 plots state-level per-mile fuel cost savings against the environmental benefits or costs calculated from Holland et al. (2016) for the Ford Focus Electric with Ford Focus ICE. Pigouvian taxes would imply equality between the private savings per mile and the relative environmental benefits. Yet, the points in Figure 3 illustrate that private savings depart from those that would induce efficient usage. As an example, the private savings for EV drivers in California are lower than the private savings for EV drivers in North Dakota, despite the fact that using an EV rather than a conventional vehicle generates environmental benefits in the former and environmental costs in the latter.

The per-mile savings of driving an EV are strongly influenced by regulated electricity prices and gasoline taxes, neither of which are typically set by policymakers to reflect external costs. Gasoline taxes, to the extent they are influenced by the government, are set primarily with an eye towards funding transportation infrastructure, rather than addressing externalities from gasoline. In light of current and anticipated shortfalls from declining gasoline consumption, some states are considering raising EV registration fees or levying mileage taxes.

In contrast, electricity prices are typically set through a complicated regulatory process. A vast literature exists already describing efficient electricity pricing, and we will not revisit it all here. However, some aspects of that discussion are relevant to understanding why the cost of operating EVs differs dramatically across locations, as noted earlier in Figure 1. Differences exist because electricity prices are set through a regulated rate-setting process that balances the recovery of a utility's capital costs, consumer welfare and environmental goals. These oft-competing priorities have different implications for retail electric prices. Where (variable) retail prices are high, it is typically because fixed costs are being recovered via volumetric charges, which shifts burdens towards high-consumption households.[18] Other regulators allow utilities to recover costs primarily through fixed monthly fee irrespective of consumption. In these cases, the price per kilowatt-hour is closer to reflecting the wholesale costs of generating and delivering electricity. These differences lead to dramatic variation in how much it costs to charge an EV battery (Borenstein and Bushnell (2018)). As the efficient price reflects the entirety of upstream economic considerations and downstream externalities, charging different prices for different end uses of electricity is inefficient. Yet, this observation is at odds with the apparent preference that regulators exhibit charging prices that seek to further environmental objectives. Households with solar PV face a different electricity rate than no-solar households. Owners of EVs often have access to lower electricity rates. If EV owners are allowed to consume cheaper electricity than other consumers, there will either be over-consumption of EV miles-traveled or under-consumption of other electricity-powered goods.

4.3 Supply-Side Incentives

There are two main supply-side incentives for EVs in the U.S.: the Zero Emission Vehicle (ZEV) and Corporate Average Fuel Economy (CAFE) standards. The ZEV mandate was adopted in 1990 by the California Air Resources Board to set manufacturer-level targets for ZEV sales. Over time, the mandate was adjusted to accommodate cost realities and technical challenges, reflecting a desire to stimulate commercialization on the margin. CAFE standards were first enacted in the U.S. in 1975, shortly after the OPEC oil embargo. Initially they sought to reduce dependence on foreign oil, reflecting aspirations to improve energy security. In the 2012 CAFE

[18] One such example is increasing block prices used in California.

rules, EVs are assigned credits according to their MPG-equivalent rating, allowing electric fuel economy to be compared to that of ICEs. In the 2016 rules, EVs began to earn multipliers in the CAFE formula.

Over time, these policies were aimed at achieving emissions abatement, although the stated justification also alludes to potential market failures on the supply side and poor decisions by consumers. Both supply-side incentives have the effect of reducing the consumer price of EVs and increasing that of ICEs. These policies have one key advantage over up-front subsidies: they are designed to be self-funded and therefore don't require public funds. However, the incentives that they create deviate from an optimal Pigouvian tax. The optimal tax reduces miles travelled and the number/type of cars on the road, and gives automakers the proper incentive to invest in vehicle efficiency. Present supply-side incentives do nothing to align private and social costs on the intensive margin, nor do they yield the optimal number of cars on the extensive margin. As such, the economic justification for these policies relies on mis-optimizing consumers and the existence of market failures in production and innovation. Policymakers often appeal to similar arguments of "future domestic competitiveness" as justification for supply-side incentives or other EV-related industrial policy, but these motivations seem less economic than political.

4.4 Charging Infrastructure Incentives

The vision to extend EV ownership to all confronts the obstacle of access to EV charging for people without driveways and garages, and for drivers needing to take trips whose distance exceeds the battery range. Significant resources are being deployed to stimulate construction of EV charging infrastructure. These incentives again range from tax exemptions to subsidies. Volkswagen is directly and indirectly (via the diesel scandal settlement) funding significant investments in charging infrastructure. The largest portion of these is being allocated to California. In California, these funds supplement funds from the settlement agreement between NRG Energy and California related to the California energy crisis.

Because network externalities are likely to exist in some areas of the charging station market, private investment alone will likely lead to an under-provision of charging infrastructure. Subsidies for charging infrastructure may thus play a dual role: first by correcting for network externalities that exist, and second to the extent that they are more cost-effective at stimulating EV adoption than direct purchase subsidies. On the latter point, several economics papers have attempted to quantify the effect of charging infrastructure on EV demand. This is a challenging empirical problem due to two possible directions of causality: dense charging infrastructure may stimulate EV adoption, but a high market share (or anticipated market share) of EVs might induce investment in charging infrastructure. The best evidence to date (Li et al. (2017), Springel (2021), and Li (2019)) attempts to disentangle these effects using grocery stores, EV subsidies and government-sponsored infrastructure subsidies as instruments. These papers have been highly influential in guiding EV policy, as they find large impacts of charging station density on adoption, and stimulating adoption tends to be a primary objective of policymakers at present. However, more research is needed. The exclusion assumption in these papers – that these instruments are uncorrelated with unobservable determinants of EV demand – is unlikely to hold. Moreover, these papers analyze the EV industry during its earliest stages, and conditions change.

Our view is that there remains a high marginal benefit of designing future charging station rollouts in ways that facilitate ex-post evaluation. This will help to identify the causal effect of charging stations on EV adoption in the current environment, and to quantify the extent of network externalities. We suspect that the case for subsidizing fast-chargers on efficiency grounds is far stronger than the case for subsidizing level 2 chargers. Installing level 2 chargers at retail locations, for example, may benefit the retail establishments (either via virtue signaling or increased customer traffic), but is unlikely to yield high external benefits. In such cases, subsidies will either be wasteful or a transfer to private parties, and therefore are not a good use of public funds. Charging subsidy programs should be designed to target settings where genuine public benefits exist and where market incentives are unlikely to reflect the full social benefit.

5 Conclusion

The multi-faceted EV policy landscape reflects the complexity of the transportation and energy sectors in the economy. EV policies are often crafted to pursue a wide array of social and environmental objectives. In this paper we review the economic intuition behind various market failures and policy objectives, and explore how these align with the articulated goals of existing policies. What we find is a mixed bag. Many market failures are location- and time-specific and addressing them with a one-size-fits-all policy (such as the federal EV subsidy) is unlikely to create efficient incentives for EV adoption, use, or environmental benefits.

Benefits from EV-induced pollution reductions exhibit substantial spatial heterogeneity based on regional differences in electricity grid composition. These benefits are thus likely to increase over time, in step with grid decarbonization. A clear implication is that EV subsidies cannot be justified based on environmental benefits in regions where coal electricity generation persists. Over time, as electricity is decarbonized, the net benefits of EVs will change, and a sensible time-profile would reflect these realities. To the extent the electricity sector is transitioning at a pace that is meaningful over the life cycle of an EV, the expected value of external damages avoided is the relevant measure for efficient policy.[19]

Extensive margin externalities also vary over time and space. Non-internalized LBD in production or (non-internalized) network effects relating to charging infrastructure may justify policy intervention in the early stages of EV market development; but intervention based on these market failures will optimally diminish over time.[20] On the margin, this would imply that near-term subsidies are sensible where current network externalities might be significant. However, at the time of this writing, the level of apparent conviction about the need to subsidize charging infrastructure in general seems out of step with theory and evidence. This observation offers a note of caution for policymakers considering the promotion of investments in irreversible infrastructure.

Finally, the growing prominence of social and environmental justice goals in environmental policy is noteworthy. While these authors admit a preference for more equitable outcomes in the economy, cost-efficacy is also an important consideration. Artificially stimulating demand for EVs in an area where the private benefits are low creates a distortion that is disproportionately large relative to alternatives. Those EV owners would be better off if they were to receive the cash equivalent of the EV subsidy, rather than the subsidy itself. In an economy with scarce resources and a vast array of policy objectives, policymakers should seek to identify ways to deploy public resources that maximize net benefits, which requires avoiding the creation of conflicting incentives.

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[19] Uncertainty about the near-term future path of electricity sector emissions may lead to considerations along the lines of Weitzman (1974).

[20] See Acemoglu et al. (2012)

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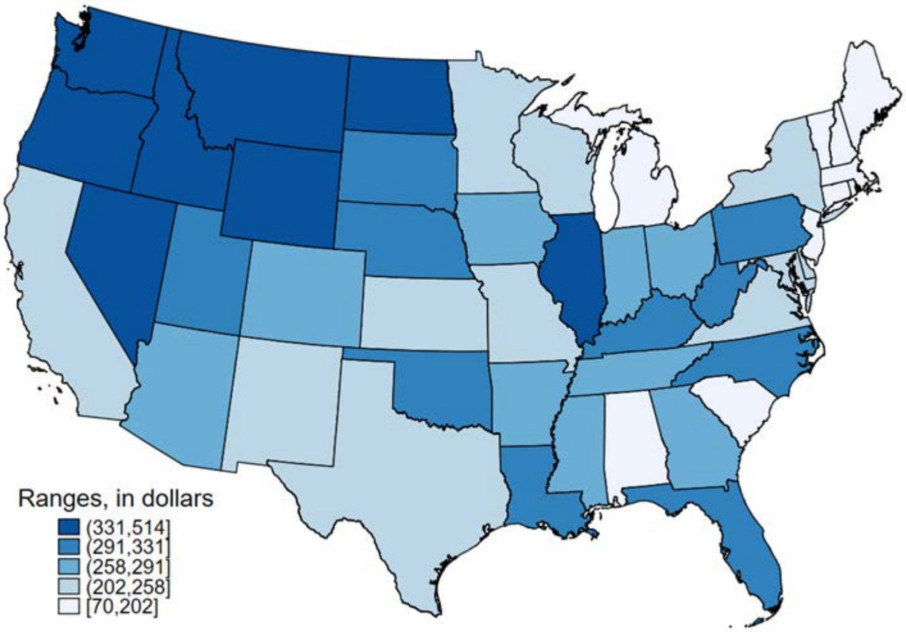
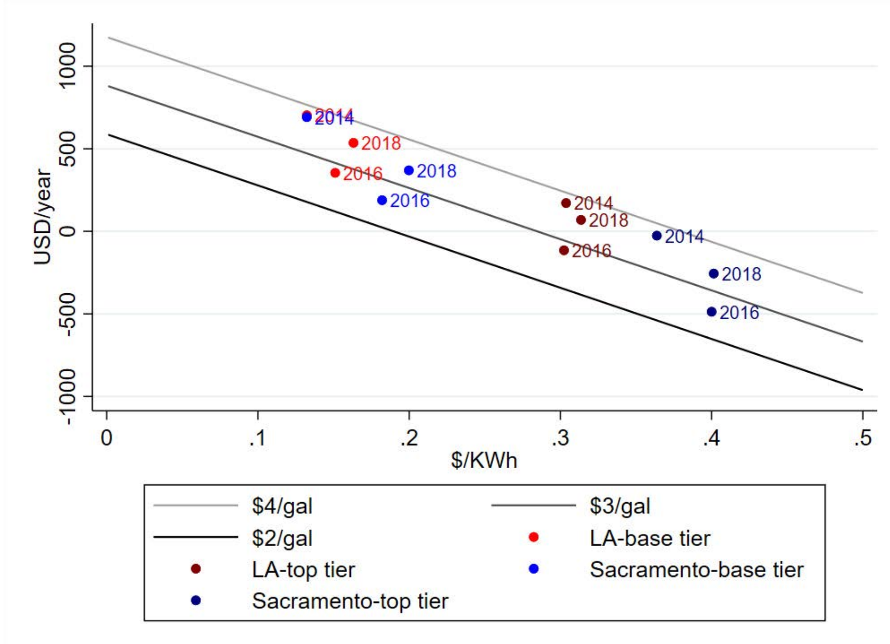
Figure 1: Implicit Variable Cost Savings Per Mile for EV Relative to ICE



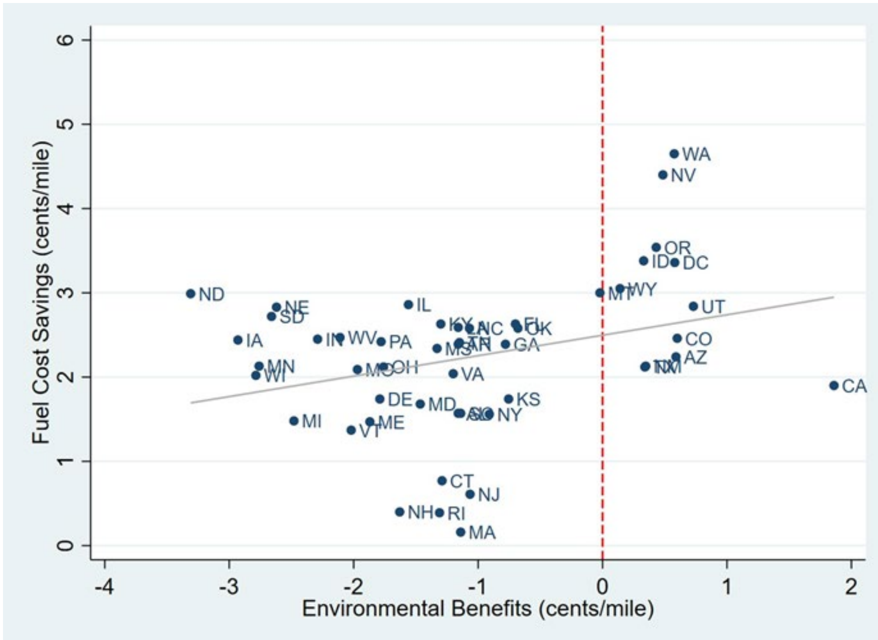
The graph compares the annual fuel savings associated with driving a 2019 Nissan Leaf (62 kWh battery) relative to a 2019 Nissan under the assumption that both vehicles are driven 10,000 miles. The Nissan Leaf runs 100 miles on 31kWh and the selected Nissan Versa earns 34 MPG according to the official estimates by the U.S. Department of Energy. State-level marginal electricity prices were calculated using the estimates from Borenstein and Bushnell (2018) using total sales at the ZIP code level as weights. Retail gasoline prices (Regular) were calculated from monthly averages posted by AAA. No adjustment is made for weather-related impacts to battery efficiency.

Figure 2: Annual Fuel Saving by Nissan Leaf: California Utilities



The graph compares the annual fuel cost of the 2019 Nissan Versa (ICE) to that of contemporary Nissan Leaf (62 kWh battery) under the assumption that both vehicles are driven 10,000 miles per year. The Nissan Leaf runs 100 miles on 31kWh, and the selected Nissan Versa earns 34 MPG, according to the official estimates by the U.S. Department of Energy. Dots represent savings by year for a driver living in LA, buying electricity from Southern California Edison and a driver living in Sacramento, buying electricity from Sacramento Municipal Utility District.

Figure 3: Private Fuel Cost Savings vs. Environmental Benefits



The scatter plots compare the per-mile fuel cost savings and per-mile pollution benefits or damages for a Ford Focus Electric and Ford Focus ICE. Per-mile fuel cost savings calculated by authors based on state-level marginal electricity prices from Borenstein and Bushnell (2018) weighted by total sales at the ZIP code level, and retail regular-grade tax-inclusive gasoline prices posted by AAA. Pollution damages are calculated based on estimates from Holland et al. (2016).

Table 1: Subsidy Additionality

		Price Elasticity of Demand		
		-1.5	-2.5	-3.5
Panel A: Fraction BEVs Subsidy-Induced				
Tesla:	California	0.19	0.30	0.39
	Rest of U.S.	0.15	0.23	0.31
Non-Tesla:	California	0.46	0.65	0.77
	Rest of U.S.	0.36	0.52	0.64
Panel B: Implied Subsidy per Induced BEV				
Tesla:	California	$ 51,727	$ 33,227	$ 25,365
	Rest of U.S.	$ 68,355	$ 43,153	$ 32,402
Non-Tesla:	California	$ 21,509	$ 15,448	$ 13,028
	Rest of U.S.	$ 27,945	$ 19,156	$ 15,522

Note: Calculations assume a) $7,500 in federal new BEV subsidies, b) $2,500 in California new BEV subsidies, and c) that all subsidy-eligible purchases receive the subsidy.