Designing Fuel-Economy Standards in Light of Electric Vehicles*

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Abstract

Electric vehicles are declining in cost so rapidly that they may claim a large share of the vehicle market by 2030. This paper examines a set of practical regulatory design considerations for fuel-economy standards or greenhouse-gas standards in the context of highly uncertain electric vehicle costs in the next decade. The analysis takes a cost-effectiveness approach and uses analytical modeling and simulation to develop insight. I show that counting electric vehicles under a standard with a multiplier or assuming zero upstream emissions can reduce electric vehicle market share by weakening the standards. Further, there are tradeoffs from implementing a backstop conventional vehicle standard along with a second standard that also includes electric vehicles, but such a backstop offers the possibility of ensuring that low-cost conventional vehicle technologies are exploited.

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"The period from 2025-2035 could bring the most fundamental transformation in the 100-plus year history of the automobile" - Page S-1 in National Academies (2021)

1 Introduction

In the United States, regulations on the fuel economy or carbon dioxide emission rate of light-duty vehicles are the most prominent policies used to address greenhouse gas emissions from the transportation sector, which generates nearly a third of U.S. greenhouse gas emissions.[1] The regulations were first promulgated as corporate average fuel-economy standards in 1975 by the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA). In addition, in 2012, the U.S. Environmental Protection Agency (EPA) began regulating vehicle greenhouse gas emissions under emissions standards.[2] The regulations are complicated and governed by multiple statues. But they were not designed for the massive transition that appears to be occurring in the automotive sector.

In the past decade, electric vehicles have gone from a curiosity to a widely-recognized alternative to conventional internal combustion engine vehicles, with as many as 100 new electric vehicle models coming to showrooms by 2025.[3] Lithium-ion battery packs, which store the energy use for propulsion of electric vehicles, have dropped in price from over $1,000 per kilowatt hour (kWh) in 2010 to roughly $125/kWh today, and are estimated to drop to $65-$80/kWh by 2030. Such a dramatic decline in battery prices could mean that electric vehicles achieve cost-parity in upfront costs by 2030 (National Academies 2021). And some analysts even forecast a faster decline in battery costs (BNEF 2021).

Electric vehicles also tend to be much less expensive to operate, with the cost of electricity usually well below the cost of gasoline or diesel for comparable vehicles. Furthermore, the maintenance costs of electric vehicles are much lower than for conventional vehicles due to far fewer engine parts that can break. In addition, electric vehicles have superb low-speed torque and acceleration. For example, the New York Times states: "Even the New Shelby GT500–history's mightiest Mustang, with 760 horsepower–won't equal the 3.5-second 0-60

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[1] See `https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions`.

[2] Vehicle fuel economy can be directly converted to a carbon dioxide emission rate, so fuel-economy standards and greenhouse-gas standards are very closely related and this paper will refer generally to 'standards' except where they differ.

[3] The term 'electric vehicles' is occasionally used to refer to both dedicated electric vehicles that have only an electric power source and plug-in hybrid electric vehicles (PHEV) that can run on both gasoline and electricity. This paper uses the term 'electric vehicle' to refer to dedicated electric vehicles because automakers appear to be moving strongly in the direction of this class of electric vehicles due to the additional costs of having both a gasoline and electric supply chain. Source for the '100 new models' is: `https://www.nytimes.com/2021/04/22/business/electric-suvs-ford-volkswagen-volvo.html?action=click&module=In%20Other%20News&pgtype=Homepage`.

m.p.h. blast of this summer's Mach-E GT Performance version" (Ulrich 2021). Indeed, many analysts have forecasted extremely rapid growth in electric vehicle sales over the next decade with battery cost declines and build-out of charging infrastructure (e.g., BNEF (2020)).

This study examines the tradeoffs inherent in several major decisions relating to the design of standards regulating vehicle fuel economy or carbon dioxide emissions in light of a potential transition from a dominantly conventional vehicle fleet to a mostly electric vehicle fleet over the coming decade. What are the ramifications of more generously crediting electric vehicles under the standards, either through a multiplier or by ignoring all upstream emissions from the generation of electricity used to power the electric vehicles? What are the effects of a combined standard that includes electric vehicles and conventional vehicles rather than a separate standard for each vehicle technology? Because policymakers must decide today how to design standards when faced with uncertain developments in electric vehicle costs, I consider the effects of policy decisions in the context of uncertainty about future battery costs and electric vehicle uptake.

The analysis in this study is based on analytical models and illustrative simulations to provide a conceptual understanding of the forces at work. My first major set of findings relates to generous crediting. One clear result is that if electric vehicles receive generous crediting under the standards, either through a multiplier or by ignoring upstream emissions, selling more electric vehicles will allow less-efficient conventional vehicles to be sold. This can be thought of as an example of "leakage" of emissions from electric vehicles to conventional vehicles, analogous to the leakage that might occur if subnational actors, such as California, implement their own more-stringent standard at the same time as a binding national standard (Goulder et al. 2011).[4]

Further, while one might expect more generous crediting to act as an incentive for electric vehicles, I find that it is more likely to actually *reduce* the incentive for automakers to sell electric vehicles. The intuition for this result is that the multipliers weaken the standard sufficiently that fewer electric vehicles are needed to enable the automakers to meet the standard while selling the (currently) more profitable conventional vehicles. This counter-intuitive finding appears to hold under reasonable assumptions, and can even hold if induced innovation in electric vehicle technology is considered.

But the counter-intuitive finding does not necessarily hold all the time. When electric vehicles are a nascent technology and are very far from competitive with conventional vehicles in terms of the profits they generate for automakers or have extremely strong innovation potential, then the standard may be more tightly binding on conventional vehicles and the

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[4] This leakage result from electric vehicles is also discussed in Jenn et al. (2016) using a different analytical and numerical framework.

generous crediting could beneficial enough to lead to greater electric vehicle market share. But as soon as electric vehicles are even remotely close to competitive with conventional vehicles, more generous electric vehicle crediting appears to lead to reductions in electric vehicle market share. This is a useful finding because electric vehicle deployment is a stated policy goal of the Biden Administration (White House 2021).

For broader context, these findings imply that even if generous crediting increases the market share of electric vehicles, it could still increase overall carbon dioxide emissions in the short run by allowing less-efficient conventional vehicles to be sold. But even in this (less likely) case, there is a long-run tradeoff: more electric vehicles could reduce emissions as the electricity system is decarbonized, but this will have to outweigh the increased short run emissions. Clearly, if overall carbon dioxide emissions increase on net, then including the generous crediting will unequivocally not be a cost-effective approach for emission reductions. Moreover, even if overall emissions decline over both periods, the generous crediting may still be a costly approach to reduce emissions because the direct emission reductions from the electric vehicles would be offset by increased emissions from conventional vehicles. Stepping back, if policymakers want to assure that generous crediting increases electric vehicle market share and/or reduces emissions, one logical approach would be to tighten the standard when implementing the generous crediting to offset the standard-weakening effect of the generous crediting.

The second major set of findings of this study relate to uncertainty in regulation design. There is substantial uncertainty about future electric vehicle costs and this uncertainty means that ex ante policy can deviate even more from what would have been the ex post optimal policy than is usual for standards. With greater uncertainty about future technology costs than usual, it will be especially difficult to set a standard in advance, as is required by law. I show that if electric vehicles become inexpensive, but there is still at least some demand for conventional vehicles, then averaging in the numerous electric vehicles into the sales-weighted average used for compliance will allow automakers to sell more inefficient conventional vehicles. This may leave low-cost emission reductions in the conventional fleet untapped.

With low-cost emission reductions in mind, I examine a standard that includes electric vehicles and conventional vehicles combined with a separate "backstop conventional vehicle standard." Such a complementary backstop standard could be non-binding in expectation for most automakers and would only play an important role if electric vehicles become very inexpensive. In the context of very inexpensive electric vehicles, I find that adding this backstop standard could lead to substantially more deployment of electric vehicles. It also would likely improve the cost-effectiveness of the policy in reducing emissions, with the caveat that this depends on the true costs of conventional vehicles emission-reduction technologies. On the downside, if the decline of electric vehicle costs is not quite as dramatic, adding the separate backstop standard could modestly reduce electric vehicle deployment and increase emissions. It also adds further complexity to an already complicated regulation. However, the statutory basis for these complementary standards appears to be strong.

This study focuses on real-world policymaker objectives, such as incentivizing greater electric vehicle deployment and achieving emission reductions cost-effectively. It examines policy-relevant metrics such as emissions and costs. While unquestionably important, analyzing the full welfare effects of standards is outside of the scope of this paper. Overall welfare effects depend on a wide variety of issues, including new vehicle purchasing decisions, the cost of new vehicle technologies, automaker vehicle design decisions, automaker long-run research and development investment decisions, strategic pricing decisions and other interactions, equilibrium in the used vehicle market, decisions about how much to drive more efficient vehicles, and even the scrappage of old vehicles. Among these numerous issues, perhaps the most important is whether consumers fully internalize the operating costs or if there are features of consumer behavior that lead to an undervaluation of future fuel savings in the new vehicle purchase decisions (Bento et al. 2018).

There are also other details that are important for standards-setting that are outside the scope of this study, such as allowing or limiting trading between automakers, designating standards based on the ‘footprint’ (a rough measure of vehicle size calculated as the wheelbase times track length) of new vehicles (Gillingham 2013, Ito & Sallee 2018), or offering credits for alternative fuel vehicles (Anderson & Sallee 2011). By focusing on cost-effectiveness and simplifying from some of these details, I aim to provide concise conceptual guidance to policymakers on the tradeoffs inherent in different approaches to designing standards in light of uncertain electric vehicle uptake in the coming decade.

The paper is organized as follows. The next section provides some brief background placing this work in the policy context. Section 3 examines the implications of generous crediting of electric vehicles under the standards. Section 4 explores how uncertainty in electric vehicle costs influence the effects of difference standards designs. Section 5 provides a concluding discussion of the policy and legal issues raised by the analysis in this study.

2 Policy Background

Fuel-economy standards originate with the Energy Policy and Conservation Act of 1975, and have been updated several times since, most notably by the Energy Independence and Security Act of 2007. The statutory authority for regulating fuel economy under these laws is assigned to NHTSA. Specifically, NHTSA is required to set "maximum feasible" fuel-economy standards that regulate the sales-weighted averaged fuel economy for each automaker's passenger car and light truck fleet. Automakers can comply with the standards by achieving the target fuel economy, paying a fine, or using crediting approaches (e.g., trading credits across fleets or automakers). However, NHTSA argues that it cannot consider compliance credits in setting the standards, so if trading occurs between automakers that lowers the cost of the regulation, the lower costs cannot be accounted for in setting the standards. In addition, NHTSA also argues that it cannot consider alternative-fuel vehicles, such as electric vehicles, in setting the standards, but is required to average in electric vehicles for compliance with the standards based on a 'petroleum-equivalence factor' set by the U.S. Department of Energy.[5] There is a limit to the number of credits that can be traded across automakers under NHTSA's authority, although most automakers do not appear to hit this limit (National Academies 2021).

Vehicle greenhouse-gas standards regulate tailpipe carbon dioxide emissions from vehicles. In 2007, the Supreme Court ruled that EPA must determine if greenhouse gas emissions from vehicles are required to be regulated under Section 202 of the Clean Air Act of 1970 (updated in 1990). EPA determined affirmatively. Because fuel economy can be mapped quite closely to carbon dioxide emissions, as mentioned above, EPA and NHTSA have been aligning their standards as closely as possible under the statutes starting with vehicle model year 2012. EPA faces fewer constraints in using the Clean Air Act than NHTSA faces under its statutory authority. EPA is permitted to allow for greater compliance flexibilities, such as flex-fuel credits or credits for less-polluting air conditioning materials, and has no limits on trading between fleets and automakers. EPA is also permitted to consider alternative-fuel vehicles in setting its standards and has substantial flexibility in how the standards are designed. These differences in the statutory authority of EPA and NHTSA add to the complexity of developing standards with a higher market share of electric vehicles in the fleet.

For historical perspective, Figure 1 shows the U.S. fleet-wide fuel-economy standard, achieved fuel economy in miles per gallon (MPG), and percent improvement in vehicle energy efficiency from 1975 levels. Prior to the standards for model year 2012, there was a

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[5] NHTSA points to a 1994 technical amendment passed by Congress that states that in developing fuel-economy standards, the Secretary of Transportation "may not consider the fuel economy of dedicated automobiles," where dedicated automobiles refer to any automobiles using only a fuel other than gasoline or diesel fuel. There is a similar clause for dual-fueled automobiles. See Page 317 in Public Law 103-272 for further details (Congress 1994). As well, on page 319 of the same law, it states "If a manufacturer manufactures an electric vehicle, the Administrator shall include in the calculation of average fuel economy... equivalent petroleum based fuel economy values determined by the Secretary of Energy for various classes of electric vehicles." The statute also goes on to describe the factors that the Secretary of Energy needs to use to determine the 'petroleum-equivalence factor.' This factor greatly increases the number of compliance credits given to automakers for electric vehicles sold.

separate standard for the passenger vehicle and light truck fleets. Starting with the model year 2012 standards, EPA and NHTSA converted to a system with separate standards for predetermined footprint bins in each of the passenger vehicle and light truck fleets, so that larger vehicles face a less-stringent standard. Credits for over-complying in one fleet's footprint can be applied to permit under-compliance in other footprints or fleets.

The most-recent standards set by EPA and NHTSA were developed in the Trump Administration's Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule, which set standards for the model years 2021-2026. The rule has standards increasing by 1.5 percent per year through 2026. This is a substantial rollback from the Obama Administration's model year 2017-2025 standards, which had the standards rising by 5 percent per year over the same set of model years (National Academies 2021). The Biden Administration has already indicated that it plans to reassess the SAFE Rule, and will likely promulgate a new set of more-stringent standards than the SAFE Rule in the next year (Davenport 2021).

3 Effects of Generous Crediting Electric Vehicles

Under the current standards, a conventional vehicle enters into the sales-weighted average used to determine automaker compliance as a single vehicle. Under NHTSA's fuel-economy standards, electric vehicles are treated the same as conventional vehicles with the miles-per-gallon-equivalent of the electric vehicle averaged in. Thus, adding electric vehicles is a compliance strategy for automakers, allowing them to meet the standards while under-complying on conventional vehicles.[6]

Under EPA's greenhouse-gas standards, electric vehicles enter into the sales-weighted average emission rate with an rate of zero grams per mile, corresponding to zero tailpipe emissions. This ignores upstream emissions from the generation of electricity. In addition, in 2012, EPA used its authority to temporarily incentivize electric vehicles through a "credit multiplier" under which each electric vehicle is counted more than once in the average.[7]. This multiplier was 2.0 for model years 2017-2019 and it dropped to 1.75 in 2020 and 1.5 in 2021. In the SAFE Rule, the Trump Administration discontinued the multiplier for all electric vehicles, returning it to 1.0 (but increased the multiplier to 2.0 for dedicated natural gas vehicles for model years 2022-2026).[8] It remains to be seen how the Biden Administration will handle the crediting.

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[6] NHTSA allows electric vehicles to be used for *compliance with* the standards, but they cannot be used in *setting* the standards.

[7] The multiplier also applied to fuel cell vehicles, and a lesser multiplier applies to PHEVs and dedicated natural gas vehicles

[8] For details, see `https://www.govinfo.gov/content/pkg/FR-2020-04-23/pdf/2020-07098.pdf`.

The vision behind the generous crediting for electric vehicles under EPA's greenhouse gas standard is that it would encourage automakers to develop and sell electric vehicles. Jenn et al. (2016) note that because the standards fix the sales-weighted average greenhouse gas emissions for each footprint and there is trading by automakers within their fleet and across fleets, the generous crediting serves to weaken the standards and can lead to additional emissions by allowing automakers to sell some less-efficient vehicles. Jenn et al. (2016) hold the number of electric vehicles in the fleet fixed, but the stated policy goal of including the generous crediting is to induce innovation in electric vehicles and incentivize automakers to sell more of the nascent technology. Thus, a key unanswered question for policymakers is how the generous crediting from the credit multipliers and the ignoring of upstream emissions affects electric vehicle deployment and overall emissions.

The focus of my analysis is on EPA's greenhouse-gas standards, but the insights also apply if generous crediting of electric vehicles is permitted under NHSTA's fuel-economy standards through very high petroleum-equivalent fuel economy values assumed for electric vehicles. In the following subsections, I build intuition by considering the automaker's profit maximization problem first in a single period model and then in a two-period model to allow for the dynamic effects of innovation.

3.1 Static Modeling of the Effects of Generous Crediting

Consider an automaker's decision problem when faced with the choice of how much to invest in developing and selling electric vehicles to maximize profits while still complying with the standards. There are many possible margins of adjustment to comply with the standard, including improving the fuel economy of new conventional vehicles, selling more electric vehicles, selling more efficient electric vehicles, and changing the relative prices of new vehicles based on their fuel economy. To provide insight on the research questions at hand, I model automakers choosing their sales of electric vehicles, represented by the market share, s_{EV}, and the average carbon dioxide emission rate for conventional vehicles, e_C. The electric vehicle market share and conventional vehicle emission rate will come about from a numerous pricing and research investment decisions, but focusing on the net result of these decisions as the choice variables allows for greater transparency and clarity in the analysis.

3.1.1 Intuition from the standard itself

Under the current crediting approach used by EPA, the electric vehicle credit multiplier is applied such that each electric vehicle counts as some multiple of a vehicle in both the calculation of the achieved average emission rate used for compliance and the target standard itself. This implies that the multiplier makes electric vehicles more attractive by averaging in more electric vehicles than there actually are (with a currently assumed zero emission rate), but also directly adjusts the stringency of the standard itself. Specifically, for the passenger vehicle and light truck fleets separately, carbon dioxide credits are calculated based on a sales-weighted average of the targets and a sales-weighted average of the assumed emission rates. This implies that the standard can be understood as the following, where the left-hand side is the sales-weighted average used for compliance and the right-hand side is the sales-weighted average target standard:[9]

$$\frac{\sum_{i\in\mathcal{C}} e_{C,i}V_i + \sum_{i\in\mathcal{EV}} e_{EV,i}V_iM}{\sum_{i\in\mathcal{C}} V_i + \sum_{i\in\mathcal{EV}} V_iM} \leq \frac{\sum_{i\in\mathcal{C}} S_{GHG,i}V_i + \sum_{i\in\mathcal{EV}} S_{GHG,i}V_iM}{\sum_{i\in\mathcal{C}} V_i + \sum_{i\in\mathcal{EV}} V_iM}. \tag{1}$$

Here $\mathcal{C}$ is the set of conventional vehicle offerings, $\mathcal{EV}$ is the set of electric vehicle offerings, $e_{C,i}$ is the emission rate for conventional vehicle type i, $e_{EV,i}$ is the emission rate for electric vehicle type i, V_i are the sales of vehicle i, $S_{GHG,i}$ is the standard facing vehicle i, and M is the multiplier. Note that M is on both the left-hand side and right-hand side. On the left-hand side, if the assumed emission rate for electric vehicles is zero, as is the current practice, the term in the numerator that includes M drops out and the multiplier only affects the denominator (and right-hand side of course).

To analyze the consequences of adding the multiplier, I simplify by using the average emission rate for conventional vehicles (e_C) and electric vehicles (e_{EV}), and assume a single combined standard (S_{GHG}). A single combined standard is consistent with full trading across fleets and is also consistent with the EPA greenhouse gas standard (additional statutory authority would have to be given NHTSA for a combined CAFE standard). After some rearranging, the sales volumes drop out, and I can rewrite (1) in terms of the market share of electric vehicles (s_{EV}) as follows (see Appendix subsection A.1 for details):

$$s_{EV}e_{EV}M + (1 - s_{EV})e_C \leq S_{GHG}(1 + (M - 1)s_{EV}) \tag{2}$$

The left-hand side here is the sales-weighted average emission rate adjusted by the multiplier and the right-hand side is the target standard adjusted by the multiplier. This inequality immediately suggests some of the tradeoffs inherent in including a multiplier greater than one. Specifically, $M > 1$ helps automakers with compliance on the left-hand side (providing an incentive to sell more electric vehicles), but also directly relaxes the standard on the right-hand side. This can be seen most easily if one assumes that $e_{EV} = 0$ as EPA does. Then

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[9] For details, see `https://www.govinfo.gov/content/pkg/FR-2020-04-23/pdf/2020-07098.pdf`. Technically, the actual calculation of the carbon dioxide credits is the difference between the left-hand side and right-hand side below multiplied by the number of miles the vehicles are expected to be driven and total production (also adjusted for the multiplier) and normalized to be in the appropriate units.

we can focus on the right-hand side and observe that $M > 1$ implies that $(M-1)s_{EV} > 0$, so the carbon dioxide grams/mile emission rate required is higher, which is a more relaxed standard.

Thus, a first finding of this study is the following:

Finding 1. An electric vehicle credit multiplier greater than one relaxes the standard when the assumed emission rate for electric vehicles is zero, as it is currently.

There is an analogous finding to this one in Jenn et al. (2016), although the formulation is different here. One takeaway from (2) is that if $e_{EV} = 0$ and the standard is tightened by $(M-1)s_{EV}$ (i.e., there is a new S'_{GHG} that is equal to $S_{GHG} - (M-1)s_{EV})$), then the direct effect in relaxing the standard could be mitigated. In other words, policymakers could simultaneously tighten the standard at the same time as introducing a credit multiplier greater than one to assure that the effective stringency of the policy remains the same.

If the assumed emission rate for electric vehicles is greater than zero, so $e_{EV} > 0$, then increasing $M > 1$ increases the left-hand side, which makes compliance more difficult, and thus serves to effectively tighten the standard. This would have to be weighed against the relaxing of the standard from the inclusion of $M > 1$ on the right-hand side, so the net effect may be ambiguous. Increasing the assumed emission rate (e_{EV}), with s_{EV} and M held constant, will make compliance more difficult by averaging in a higher emission rate.

To build intuition on how the choice of credit multiplier and e_{EV} affect automaker incentives to sell electric vehicles and choose the emission rate of conventional vehicles, we now turn to the automaker's profit maximization problem.

3.1.2 Automaker profit maximization

Let the per-vehicle profits from electric vehicles and conventional vehicles be given by π_{EV} and $\pi_C(e_C)$ respectively, where it is assumed that today $\pi_{EV} < \pi_C(e_C)$, so there is an opportunity cost for the automaker to develop and sell more EVs rather than conventional vehicles. Thus selling more EVs reduces the automaker profits in the short run, although this may change in the future.[10] For simplicity, I assume away competitive interactions between automakers, allowing me to focus on a single representative automaker. Similarly, I also assume that the choice of how many electric vehicles to sell does not influence the total

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[10] This approach assumes that the electric vehicle profits are constant with the electric vehicle share. One could imagine profits from electric vehicles decreasing with electric vehicle sales if it requires more marketing or manufacturer discounts to sell more electric vehicles. Profits from conventional vehicles could even be affected as well. Exploring these details would be interesting for future work.

number of vehicles sold on the market, V.

I write the representative automaker's stylized profit maximization problem as the weighted average per-vehicle profits across electric vehicles and conventional vehicles times the total vehicles sold by the automaker, subject to the constraint of the greenhouse gas standard:

$$\max_{s_{EV}, e_C} V\left[s_{EV}\pi_{EV} + (1 - s_{EV})\pi_C(e_C)\right]$$
$$\text{subject to } s_{EV}e_{EV}M + (1 - s_{EV})e_C \leq S_{GHG}(1 + (M - 1)s_{EV}).$$

This formulation immediately provides insight. As discussed above, it is clear that the constraint is relaxed if e_{EV} is reduced (e.g., upstream emissions are ignored) and M is increased (e.g., a credit multiplier greater than one is applied). Thus, if $\pi_{EV} < \pi_C(e_C)$ in the range of e_C being considered (as is likely because electric vehicles are a newer technology) and automakers make greater profits from less-efficient vehicles (i.e., $\frac{d\pi_C(e_C)}{de_C} > 0$), then one might expect reducing e_{EV} and increasing M to lead to higher emission rates for conventional vehicles (e_C) in the profit-maximizing solution. This is the basic intuition in Jenn et al. (2016), and I will show the assumptions necessary for it to hold.

Let λ denote the shadow price on the standard constraint. The first-order conditions of optimality from differentiating with respect to s_{EV} and e_C are given as follows:

$$V(\pi_C(e_C) - \pi_{EV}) + \lambda\left[e_{EV}M - e_C - S_{GHG}(M - 1)\right] = 0 \tag{3}$$
$$-V\frac{d\pi_C(e_C)}{de_C} + \lambda = 0.$$

Rearranging for λ and noting that the shadow price must be the same across the two first-order conditions, yields

$$e_C^* = e_{EV}M - S_{GHG}(M - 1) - \frac{\pi_{EV} - \pi_C(e_C^*)}{\frac{d\pi_C(e_C^*)}{de_C^*}}. \tag{4}$$

This equation implicitly defines the optimal emission rate for conventional vehicles, which is seen to be a function of the electric vehicle emission rate, credit multiplier, adjusted standard, and difference between electric vehicle and conventional vehicle profits divided by the marginal profits from a change in the conventional vehicle emission rate. Assuming a binding constraint, we can similarly rearrange the constraint for an equation that defines the optimal market share of electric vehicles as a function of the optimal emission rate of conventional vehicles, the standard, the electric vehicle emission rate, and the credit multiplier:

$$s_{EV}^* = \frac{S_{GHG} - e_C^*}{e_{EV}M - e_C^* - S_{GHG}(M-1)}. \tag{5}$$

3.1.3 Comparative statics for the conventional vehicle emission rate

To proceed, I first examine comparative statics at the optimum for the chosen conventional vehicle emission rate when the credit multiplier and assumed electric vehicle emission rate are changed. I rearrange (4) to set it equal to zero and then employ the implicit function theorem to obtain:

$$\frac{\partial e_C^*}{\partial M} = \frac{(S_{GHG} - e_{EV})\left(\frac{\partial \pi_C(e_C^*)}{\partial e_C^*}\right)^2}{(\pi_{EV} - \pi_C(e_C^*))\frac{\partial^2 \pi_C(e_C^*)}{\partial e_C^{*2}}}.$$

This comparative static shows that the optimal conventional vehicle emission rate depends on several intuitive terms. First, there is the difference between the standard and the assumed electric vehicle emission rate, which is important because it determines how much in the way of worse conventional emission rates each electric vehicle will allow. Second, it depends on the additional per-vehicle profits from increasing the conventional vehicle emission rate (squared, which perhaps emphasizes the importance of this term). Third, in the denominator, it depends on the difference in the per-vehicle profits between conventional vehicles and electric vehicles, which again is important for determining the loss from using electric vehicles to allow for less-efficient conventional vehicles. Finally, it depends on whether the convexity or concavity of the per-vehicle profit function for conventional vehicles, which indicates what the marginal gain in profits might be from adjusting the conventional vehicle emission rate to take advantage of the credit multiplier.

The first two terms (the two terms in the numerator) are both expected to be positive, as the standard (S_{GHG}) should be larger than the assumed emission rate of electric vehicles (e_{EV}) and a square term is always positive. The third term is expected to be negative, as the profits from electric vehicles are likely to be less than those from conventional vehicles in the near term. The fourth term is a little less clear. However, one might expect that profits increase with higher emission rates (and thus lower fuel economy), but do so with diminishing returns. This would suggest a concave function, so that $\frac{\partial^2 \pi_C(e_C^*)}{\partial e_C^{*2}} < 0$.

Making these reasonable assumptions implies that the $\frac{\partial e_C^*}{\partial M} > 0$, so that the optimal emission rate for conventional vehicles is increasing with the credit multiplier. Put simply, the automakers will have an incentive to sell less-efficient vehicles with a higher electric vehicle credit multiplier.

This leads to the second analytical finding:

Finding 2. In a static setting and under the assumptions discussed above used to sign the terms of the comparative static, the emission rate for conventional vehicles will increase with the electric vehicle credit multiplier.

This finding points to the "leakage" effect from using a credit multiplier to incentivize electric vehicles–it will likely lead to less-efficient conventional vehicles on the road.

There is a similar finding for how the emission rate of conventional vehicles changes with the assumed emission rate for electric vehicles. The assumed emission rate for electric vehicles is currently zero in current regulations, but would increase if upsteam emissions from electric vehicle charging are accounted for.

Using the implicit function theorem again, the comparative static is the following:

$$\frac{\partial e_C^*}{\partial e_{EV}} = \frac{M\left(\frac{\partial \pi_C(e_C^*)}{\partial e_C^*}\right)^2}{(\pi_C(e_C^*) - \pi_{EV})\frac{\partial^2 \pi_C(e_C^*)}{\partial e_C^{*2}}}.$$

There is an economic interpretation to this comparative static as well. In the first term, we observe that if the electric vehicle credit multiplier M is increased, then the assumed emission rate for electric vehicles will have a greater impact on the automaker's choice of emission rate for conventional vehicles. This is intuitive because the credit multiplier exacerbates the effect of the assumed electric vehicle emission rate in the constraint (recall (2)). In the second term in the numerator, the additional per-vehicle profits from increasing the conventional vehicle emission rate increases the effect on the conventional vehicle emission rate. This logic is the same as in the previous comparative static.

In the denominator, the difference between the conventional vehicle and electric vehicle per-vehicle profits is important because it influences how many more electric vehicles may be sold in the optimum, which affects how important the assumed electric vehicle emission rate is. Finally the concavity or convexity of the per-vehicle profit function for conventional vehicles is important, as before because it determines the added profits from changing the emission rate for conventional vehicles due to the relaxing of the standard from the electric vehicle emission rate.

Both terms in the numerator are positive. In the denominator, the per-vehicle profits for conventional vehicles should be higher than for electric vehicles in the near term, so $\pi_C(e_C^*) - \pi_{EV} > 0$. If the profit function is concave as discussed above, so that $\frac{\partial^2 \pi_C(e_C^*)}{\partial e_C^{*2}} < 0$, then the denominator is negative.

Thus, under these reasonable assumptions, $\frac{\partial e_C^*}{\partial e_{EV}} < 0$. This implies that if the assumed emission rate for electric vehicles is increased, then the automaker's optimal emission rate for conventional vehicles will decrease and conventional vehicles will become more efficient. Hence, we have the third analytical finding:

Finding 3. In a static setting and under the assumptions discussed above used to sign the terms of the comparative static, the emission rate for conventional vehicles will decrease with the assumed electric vehicle emission rate.

The intuition for this finding is that if electric vehicles become less beneficial towards meeting the standards due to the assumed electric vehicle emission rate increasing, then conventional vehicles will have to make up the slack and become more efficient.

3.1.4 Comparative statics for the electric vehicle market share

I now turn to exploring how the market share of electric vehicles is affected. For this analysis, I rely directly on the solution for the optimal electric vehicle market share as function of the optimal conventional vehicle emission rate given in (5). Differentiating with respect to the credit multiplier M yields the following comparative static:

$$\frac{\partial s_{EV}^*}{\partial M} = \frac{\frac{\partial e_C^*}{\partial M}}{e_{EV}M - e_C^* - S_{GHG}(M-1)} - \frac{(S_{GHG} - e_C^*)(e_{EV} - \frac{\partial e_C^*}{\partial M} - S_{GHG})}{(e_{EV}M - e_C^* - S_{GHG}(M-1))^2}.$$

This equation is somewhat long, but has some economic intuition. Whether electric vehicle market share increases with the credit multiplier depends on several factors. First, it depends on how the optimal conventional vehicle emission rate changes with the credit multiplier because this influences how stringent the standard is going to be. We showed above in Finding 2 that under reasonable assumptions, this should be positive. In the denominator of the first term, we see that the comparative static also depends on the assumed emission rate of electric vehicles relative to the adjusted standard (i.e., $S_{GHG}(M-1)$) and the conventional vehicle emission rate. If the assumed $e_{EV} = 0$, as is current practice, this denominator will definitely be negative. But it is very likely to be negative even if $e_{EV} > 0$ because the electric vehicle emission rate should be smaller than either the standard or the conventional vehicle emission rate.

In the numerator of the second term, we observe that the comparative static depends on the difference between the standard and the conventional vehicle emission rate. The intuition here is that if the conventional vehicle emission rate is far off, increasing the credit multiplier is more important. This difference should always be (weakly) negative because the optimal conventional vehicle emission rate will be at or above the standard due to the electric vehicles allowing for less-efficient conventional vehicles. This difference is multiplied by the difference between the electric vehicle emission rate and the optimal conventional vehicle emission rate changes with the credit multiplier plus the the standard itself. The intuition here is more difficult to discern, but it appears to be capturing how the electric vehicle emissions rate compares to the conventional vehicle emission rate changes and the standard. If $e_{EV} = 0$, this simplifies further and makes it easier to sign. Based on Finding 2, the derivative is positive, and the standard itself is positive, so $-\frac{\partial e_C^*}{\partial M} - S_{GHG} < 0$.

Because the electric vehicle emission rate is likely to be small, is is also very reasonable to assume that $e_{EV} - \frac{\partial e_C^*}{\partial M} - S_{GHG} < 0$. The denominator is the square of the assumed electric vehicle emission rate relative to the adjusted standard and conventional vehicle emission rate, just as before. Because it is squared, it must be positive.

Signing each of the terms suggests that as long as the reasonable assumptions $e_{EV} \leq \frac{\partial e_C^*}{\partial M} + S_{GHG}$ and $e_{EV}M - e_C^* - S_{GHG}(M-1) < 0$ hold, then the overall comparative static $\frac{\partial s_{EV}^*}{\partial M}$ is negative. This implies that the market share of electric vehicles will be decreasing with increases in the credit multiplier, which provides our first analytical finding focusing on electric vehicles:

Finding 4. In a static setting and under the reasonable assumptions described above, the electric vehicle market share will decline with an increase in the credit multiplier.

This finding indicates that instead of incentivizing electric vehicles, the credit multiplier may actually reduce the market share of electric vehicles. The core intuition is that while the credit multiplier may make it more advantageous for the automakers to sell electric vehicles to meet the standard, the credit multiplier also relaxes the standard, and this relaxing force appears to dominate under reasonable assumptions.

This finding, while based on reasonable assumptions, may not hold all the time. For example, if the reasonable assumptions suggesting that $\frac{\partial e_C^*}{\partial M} > 0$ do not hold, then one could find that electric vehicle market share increases along with the credit multiplier. Other combinations of parameters are possible too. In the illustrative simulation, I explore circumstances when this result does not appear to hold.

I next examine the comparative static showing how the electric vehicle market share changes with the assumed electric vehicle emission rate. Differentiating (5) with respect to e_{EV} gives the following:

$$\frac{\partial s^*_{EV}}{\partial e_{EV}} = \frac{(e^*_C - S_{GHG})(M - \frac{\partial e^*_C}{\partial e_{EV}})}{(e_{EV}M - e^*_C - S_{GHG}(M-1))^2} - \frac{\frac{\partial e^*_C}{\partial e_{EV}}}{e_{EV}M - e^*_C - S_{GHG}(M-1)}.$$

This comparative static is somewhat more difficult to interpret and sign. It shows that whether the electric vehicle market share increases or decreases with the emission rate depends on several factors. First is the difference between the optimal conventional vehicle emission rate and the standard (to capture the stringency on conventional vehicles and thus need for electric vehicles). Second, the difference between the credit multiplier and derivative of the conventional emission rate with respect to the electric vehicle emission rate (again capturing how electric vehicles are needed). Third, the relative difference between the adjusted electric vehicle emission rate and the conventional vehicle emission rate and adjusted standard. Finally, the derivative of the conventional emission rate with respect to the electric vehicle emission rate also comes in separately.

Since we showed above that $\frac{\partial e^*_C}{\partial e_{EV}}$ is most likely negative, following the same assumptions made before, the first of the two large terms on the right-hand side is going to be positive. The second, is also going to be positive, but is being subtracted off, leaving the sign of the comparative static ambiguous. It is difficult to sign the two terms without parameterization, but it seems quite possible that the first term is larger because the terms in the numerator are likely to be much larger than the derivative (although they are divided by a square in the denominator). Thus, the next finding is the following:

Finding 5. In a static setting, electric vehicle market share *may* be increasing with the assumed electric vehicle emission rate.

Put differently, this finding states that ignoring upstream emissions from electric vehicles when calculating the fleet-wide average greenhouse gas emissions rate for compliance with the EPA greenhouse gas standard could reduce electric vehicle market share, counter to the intention. This counter-intuitive result holds when $\frac{(e^*_C - S_{GHG})(M - \frac{\partial e^*_C}{\partial e_{EV}})}{(e_{EV}M - e^*_C - S_{GHG}(M-1))^2} > \frac{\frac{\partial e*_C}{\partial e_{EV}}}{e_{EV}M - e^*_C - S_{GHG}(M-1)}$.

For some intuition, we can see that the result is more likely to occur when the optimal emission rate for conventional vehicles is substantially above the standard (S_{GHG}), so that the automaker is far from meeting the standard based on their conventional vehicle fleet alone. Thus, the finding would be less likely hold in the very early stages of electric vehicle penetration when compliance is largely possible based on the emission rate of the conventional vehicle fleet on its own.

These two findings on electric vehicles point to possible unintended consequence of regulatory design features that were expected to promote electric vehicles but instead can weaken the standards sufficiently that they reduce the incentive to sell electric vehicles.

3.2 Effects of Generous Crediting Allowing for Innovation

The analysis so far has been a static analysis, but at least part of the policy rationale for the generous crediting may have been to induce innovation in electric vehicles, to bring down their costs. I extend the static model above to a two-period setting, in which the profits from electric vehicles in the second period are a function of the market share of electric vehicles in the first period. Under this framework, it is also possible to allow the conventional vehicle profits to depend on the market share of conventional vehicles or the emission rate of conventional vehicles in the first period. For example, if automakers invest heavily in reducing the emission rate in the first period, this may influence the cost of emission rate reductions in the second period. I allow for this by writing the second period profits from conventional vehicles as a function of first-period outcomes, but focus on the induced innovation channel for electric vehicles because they are the newer technology with the most scope for innovation.

For this analysis, I assume that automakers have perfect foresight and optimize over both periods. To simplify notation, I set up the problem ignoring any discounting of the second period. With a slight addition to the notation to refer to period 1 and period 2 in subscripts, this extended profit maximization problem can be written as follows:

$$\begin{aligned}
\max_{s_{EV,t}, e_{C,t} \forall t \in \{1,2\}} \; & V_1 \left[s_{EV,1} \pi_{EV,1} + (1 - s_{EV,1}) \pi_{C,1}(e_{C,1}) \right] + & (6) \\
& V_2 \left[s_{EV,2} \pi_{EV,2}(s_{EV,1}) + (1 - s_{EV,2}) \pi_{C,2}(1 - s_{C,1}, e_{C,1}, e_{C,2}) \right] & (7) \\
\text{subject to } & s_{EV,1} e_{EV,1} M_1 + (1 - s_{EV,1}) e_{C,1} \leq S_{GHG,1}(1 + (M_1 - 1) s_{EV,1}) \\
& s_{EV,2} e_{EV,2} M_2 + (1 - s_{EV,2}) e_{C,2} \leq S_{GHG,2}(1 + (M_2 - 1) s_{EV,2})
\end{aligned}$$

By adding the link between the two time periods, the automaker has an incentive to sell more electric vehicles in the first period to raise the profits from selling electric vehicles in the second period as long as $\frac{d\pi_{EV,2}}{ds_{EV,1}} \geq 0$, as would be expected.

The first-order conditions described in the previous subsection are identical for $s_{EV,2}$ and $e_{C,2}$, but in the first period, the first-order conditions will contain a new term that captures the incentive to sell more electric vehicles in the first period. Thus, the first-order condition from differentiating with respect to $s_{EV,1}$ is:

$$V_1\left[\pi_{C,1}-\pi_{EV,1}\right]-V_2 s_{EV,2}\frac{d\pi_{EV,2}}{ds_{EV,1}}+\lambda_1\left[e_{EV,1}M_1-e_{C,1}-S_{GHG,1}(M_1-1)\right]=0$$

Comparing this to (3), we observe a new middle term. $V_2 \geq 0$, $s_{EV,2} \geq 0$, and $\frac{d\pi_{EV,2}}{ds_{EV,1}} \geq 0$ (the latter due to lowered costs from additional experience), so the first-order condition subtracts off a positive term. Accordingly, the addition of this term to the first-order condition implies that the automaker will sell more electric vehicles in the first period than without the term. The intuition is straightforward: there are additional profits to be had in the second period if the automaker sells more electric vehicles in the first period to bring down the costs.

A straightforward rearrangement of the first-order condition also suggests that, all else equal, the shadow price on the constraint decreases due to the addition of the new term. In other words, the choice to sell more electric vehicles makes it easier to meet the standard. This also then implies that the automakers can raise the vehicle emission rate of their conventional vehicles in the first period.

Of course, if more electric vehicles are sold in the first period, automakers can sell more inefficient conventional vehicles while still meeting the standard, which would diminish any emission reductions in that first period. This may or may not affect innovation in conventional vehicles that affects the second period, depending on how reduced numbers of conventional vehicles (which are also less-efficient conventional vehicles) affect profits for conventional vehicles in the second period. It is possible that with fewer conventional vehicles being sold that are less efficient, the profits from selling conventional vehicles will be lower in the second period (due to less innovation and higher costs). If the automakers recognize this "deferred innovation" effect, they may choose to reduce the emission intensity of conventional vehicles or sell more conventional vehicles in the first period, perhaps offsetting the electric vehicle innovation effect.

The research question at hand, however, is whether generous crediting of electric vehicles in the first period can be beneficial when there is an electric vehicle innovation effect and automakers are forward-looking. It turns out that the assumptions that lead to the relatively clean findings in the static setting may still hold, but are slightly less likely to hold. This is stated in the following:

Finding 6: In a dynamic setting with perfect foresight where electric vehicle innovation can be induced by electric vehicle sales today, electric vehicle market share in the first period may increase or decrease when the first-period credit multiplier is increased or the first-period emission rate assumed for electric vehicles in ascertaining compliance with the standards is decreased.

This finding comes about because the assumptions underlying the previous findings are somewhat less likely to hold. The intuition for this result is that in a dynamic setting with induced innovation in electric vehicles, there is greater value to sales of electric vehicles in the first time period due to the benefits in the second time period. Thus, at low levels of electric vehicle market share, the more generous crediting can make electric vehicles worth selling for the automaker even if they are less profitable in the short-run, while not substantially affecting compliance with the standards by conventional vehicles. Note that this phenomenon may also occur in the static setting, but that the assumptions required are less likely without the added innovation benefit in the second period from the first period's electric vehicle sales.

In short, this analysis suggests that at very low levels of electric vehicle market share (which can be somewhat higher as the innovation effect for electric vehicles is strengthened), the generous crediting in the EPA greenhouse-gas standards can increase electric vehicle market share by making some additional electric vehicles worth selling. But at higher levels of electric vehicle market share, the weakening of the standard dominates and the generous crediting decreases the electric vehicle market share. The next section provides simulation results to illustrate this relationship.

There is a corollary here to carbon dioxide emissions as well. More generous crediting would only reduce emissions if the innovation effect is strong and the second-period upstream emissions from electricity generation to power the electric vehicles do not appreciably weaken the standards and allow for less-efficient vehicles. This will depend on the emission rates, strength of the innovation effect, the exact specifications of profits, and the level of the standard itself. A simulation approach is well-suited for exploring this.

3.3 Simulation Results

This section develops a simple simulation to illustrate how these effects may play out in a transparent setting. While this simulation is stylized to build intuition, the building blocks here could readily be implemented in a carefully parameterized modeling framework by EPA and NHSTA. For example, NHTSA could run their Volpe CAFE model that is used for rulemakings with different crediting approaches for electric vehicles to see which effects dominate. The goal of this exercise is to use parameterizations that are reasonable and can provide insight across a broader range of parameter values than could be readily implemented in a much more complex model.

For the primary simulation results presented here, I implement a two-period model with perfect foresight. Just as in (6), automakers choose the electric vehicle market share and emission rate of conventional vehicles in both periods to maximize the sum of profits over the two periods while meeting the standards in each period. The model allows for an electric vehicle induced innovation effect, although if this effect is removed, the model reduces to two separate static models.

I assume that the per-vehicle profits for conventional vehicles are a fixed value minus a concave function of the difference between a starting or baseline emission rate and the chosen emission rate. If this difference is larger, then the automakers have invested more to reduce the emission rate (either directly in technologies or indirectly through opportunity costs of reduced levels of other valued attributes), thus lowering the per-vehicle profit. The per-vehicle profit for electric vehicles is an assumed constant in the first period and is a linear function of the first period electric vehicle sales in the second period. The constraint in each period is just the weighted average emission rate across the fleet.

I choose parameterizations to give values for outcome variables that are at least generally realistic, and the details of these, along with the exact equations used, are given in Appendix B.1. The greenhouse gas standard in the first period is assumed to be 165 grams/mile, which is a modest decrease from today's standard. The greenhouse gas standard for the second period is assumed to be 100 grams/mile, which is an ambitious standard that goes well beyond the Obama-era standards. It may be a possible standard for 2028 or 2030 though. For calculating total emissions, I assume this representative automaker sells 500,000 vehicles per year. I solve the model using a nonlinear solver with different values of the electric vehicle credit multiplier and emission intensity assumed for electric vehicles for compliance with the standards.[11]

Figure 2 shows the first-period share of electric vehicles–a key policy objective–over different values of the electric vehicle credit multiplier (x-axis) and assumed electric vehicle emission intensity (the three different lines). This figure uses the baseline values, which assume that electric vehicles are modestly less profitable than conventional vehicles (an average profit per vehicle of $4,000 rather than just over $5,000). This is what we might expect to be the case in the next few years, although is likely to be optimistic today. Note that the market share of electric vehicles at the 1.6 multiplier and zero assumed emission rate for electric vehicles is about 8%, which is above the 2% market share of electric vehicles in the United States in 2020 (Statistica 2021), likely because the profits per vehicle for electric vehicles are less than for conventional vehicles by a larger margin today (James-Armand 2021). This is projected to change in the upcoming years by many industry analysts (BNEF

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[11] I use GRG Nonlinear solver in Excel for most of the results, but confirm several in Matlab using fmincon.

2020).

In Figure 2, we observe that the market share of electric vehicles is lower with higher electric vehicle credit multipliers. Similarly, the market share of electric vehicles is also declining with lower emission rates assumed for electric vehicles for compliance with the standards. Indeed, the lowest electric vehicle market share is with a high credit multiplier and zero emission intensity. These results correspond quite closely with the analytical findings above.

What do they imply for emissions? Panel (a) in Figure 3 shows the first-period tailpipe emissions from the overall vehicle fleet and Panel (b) of Figure 3 shows the first-period total emissions, assuming a true upstream emission rate for electric vehicles of 100 grams/mile in the first period. The results are clear: carbon dioxide emissions are higher with higher credit multipliers and with lower assumed electric vehicle emission intensity. These results come about primarily from the reduced electric vehicle market share. The optimal emission rate for conventional vehicles does change very slightly across the scenarios due to the constraint being slightly relaxed with more electric vehicles, but this effect is very modest (less than 1% in these simulations).

Automaker profits are slightly affected as well. Figure 4 shows that automaker profits in the first period increase with the electric vehicle credit multiplier. This is mostly because it allows them to sell more higher-profit conventional vehicles. Automaker profits are also higher with a lower assumed electric vehicle emission rate, with the highest profits at a zero emission rate, which relaxes the constraint the most. These simulation results are illustrative, but they provide suggestive evidence for why most automakers have not been opposed to generous electric vehicle credits.

The analytical results suggested that generous crediting could increase the market share of electric vehicles when the electric vehicle market share is very low and there is substantial induced innovation. The simulation results so far allow for induced innovation, but assume that electric vehicles are at least somewhat close to being as profitable as conventional vehicles in the first period. I adjust the assumed profitability of electric vehicles downward, reducing it to \$1,000 per vehicle in the first period. This may even be more realistic today (although some Tesla models could be quite profitable). This change alone dramatically affects the results.

Panel (a) of Figure 5 shows the share of electric vehicles with this lower profitability of electric vehicles in the first period. We observe that the overall market shares, regardless of the values of crediting or emission intensity, are less than half of those in Figure 2, as would be expected if electric vehicles are much less profitable. Notably, there is overall an increase in the electric vehicle market share with higher credit multipliers. Along the same lines, there is also an increase in electric vehicle market share as the emission rate decreases, with the zero assumed emission rate having the highest electric vehicle market share for most values of the credit multiplier.

The intuition for these results is that when electric vehicles are so much less profitable than conventional vehicles, the credit multipliers or zero assumed emission rate can mean that additional electric vehicles sold provide for greater profits from selling less-efficient conventional vehicles, providing an incentive for electric vehicles. This appears to be what the policymakers had in mind when including the multipliers and zero assumed emission rate. However, total first-period emissions increase with the higher electric vehicle credit multiplier and lower emission rate, so this boost to electric vehicle sales comes at a cost in terms of emissions in the first period. This can be seen in Panel (b) of Figure 5. Thus, the electric vehicle innovation effect must be sufficiently strong to lead to reductions in the second period (which it can be depending on the parameterization) for the generous crediting to be overall emission-reducing.[12]

The key takeaway from this simulation analysis is that when electric vehicles are a nascent unprofitable technology, generous crediting under the standards for electric vehicles can serve to increase the electric vehicle market share, but as soon as electric vehicles become even close to competitive with conventional vehicles, generous crediting is likely to decrease the electric vehicle market share. Furthermore, even if generous crediting increases the share of electric vehicles, it will increase period one emissions and could even increase overall carbon dioxide emissions. If overall emissions increase over both periods, then including the generous crediting in the regulatory design will clearly not be a cost-effective approach to reduce carbon dioxide emissions. But even if overall emissions decline over both periods, the generous crediting may be a costly approach to reduce emissions because the direct emission reductions from the electric vehicles would be offset by increased emissions from conventional vehicles.

These findings provide clear guidance to policymakers on the factors at work in the generous crediting of electric vehicles and show how timing matters for the cost-effectiveness of the regulatory design approach.

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[12] In additional simulations, I find that increasing the strength of the electric vehicle innovation effect makes it slightly more likely that generous crediting will increase the share of electric vehicles in the first period, but the effect appears to be modest, even with a substantial innovation effect. These results are available upon request.

4 Standards with Uncertain Electric Vehicle Costs

Vehicle standards are always set with uncertainty about future technology improvements. But before electric vehicles, this uncertainty was at least somewhat constained. Conventional vehicle technologies are relatively mature and the standards are typically only set for five years (by statute, NHTSA can only set fuel-economy standards for five years). Thus, the list of technologies and approaches to improve conventional vehicle fuel economy and reduce greenhouse gas emissions can be developed in advance and used in standard-setting.

In contrast to the costs of conventional vehicle technologies, there is substantial uncertainty about electric vehicle technology costs even five years from today. Some analysts foresee costs remaining high and only a modest market share for electric vehicles (EIA 2021). Others are much more optimistic and forecast electric vehicles rapidly declining in price over the next several years and reaching a relatively sizable market share by 2030 and nearly half of the market or more by 2035 (e.g., BNEF (2020)). It is likely that the next standards being set under the Biden Administration will cover much of this period of highly uncertain, but potentially rapid, development of electric vehicles.

A potential concern with having only a single combined standard is that if electric vehicles become very low cost, this will lead many to be sold, but will enable automakers to sell highly inefficient conventional vehicles while still meeting the standard. Indeed, in this case, the conventional vehicles could even have lower fuel economy on average than the current vehicles on the road today, which are constrained by today's standards. Thus, emissions from conventional vehicles could remain constant or even increase with the standard, offsetting some of the emission reductions from the increased electric vehicles.

If the policymaker goal is to reduce emissions, then having emissions from conventional vehicles increasing would be counterproductive. This depends of course on whether consumers gain or lose welfare from less-efficient conventional vehicles. If either the Trump Administration or the Obama Administration's rulemakings on standards are correct, then year-over-year improvements in conventional fuel economy have positive net benefits and thus are social welfare improving.[13] Thus, having conventional vehicle fuel economy and emissions backslide and become worse than today's would leave cost-effective emission reductions on the table.

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[13] The automakers also have supported year-over-year increases in conventional vehicle fuel economy, although generally they have only supported small increases. The economic rationale for the positive net benefits when we do not see consumers buying the more efficient vehicles in the market is that consumers undervalue future fuel savings from fuel-economy improvements by overweighting upfront costs. Several recent papers have suggested undervaluation (Allcott & Wozny 2014, Leard et al. 2018, Gillingham et al. 2021), while others cannot reject perfect valuation (Busse et al. 2013, Sallee et al. 2016, Grigolon et al. 2018) of fuel economy.

How can policymakers ensure cost-effective improvements for conventional vehicles? It would not be possible under a combined standard alone. Another component to the regulatory design would have to be added. One possibility is a “backstop” standard for conventional vehicles that is designed to be non-binding unless electric vehicles quickly become quite inexpensive. This could be a weak conventional vehicle standard that requires only modest year-over-year improvements. For example, it could require the automakers to add new low-cost conventional vehicle technologies. And it could be implemented in concert with an ambitious combined standard that accounts for electric vehicles in the setting of the standard. No trading would be allowed between this backstop standard and the combined standard.

The automakers would not have to worry about this conventional vehicle standard under most circumstances, so the additional regulatory burden would only occur if inexpensive electric vehicles render the combined standard largely non-binding and allow for highly inefficient conventional vehicles to be sold. These two standards should be permitted under existing statutes. For example, EPA has the flexibility to set a backstop vehicle greenhouse gas standard alone. Alternatively, with a tweak to the statutes that NHTSA is working under to remove the requirement that electric vehicles apply towards standard compliance (with the petroleum equivalence factor), the NHSTA fuel-economy standard could serve as the conventional backstop and EPA’s greenhouse-gas standards could serve as the more ambitious combined standard. Such a tweak would of course require Congressional action. It may also be possible to set the petroleum-equivalence factor for electric vehicles so that electric vehicles do not apply towards compliance with an argument that the statute requires the Secretary of Energy to set the factor based on ‘the need of the United States to conserve all forms of energy and the relative scarcity and value to the United States of all fuel used to generate electricity’ (see page 317 of (Congress 1994)).

An analytical treatment of the two standards looks similar to the analytical modeling in the previous section, and adding uncertainty–while very possible to do–adds complexity without much additional intuition. Thus, I turn directly to a simulation to consider ex ante regulatory design under uncertainty.

4.1 Simulation Results

The simulation analysis focuses on three scenarios of electric vehicle costs: high, medium, and low. The high cost scenario assumes that the profits from electric vehicles remain well below the profits from conventional vehicles, even in the second period. The medium cost scenario assumes higher profits for electric vehicles, but profits that are still below those for conventional vehicles. The low cost scenario assumes that the profits for electric vehicles approach those for conventional vehicles.

For all three of these scenarios, I first explore what the scenarios would imply under a combined standard that covers conventional and electric vehicles, with a stronger standard in the second period than the first. The basic framework is the two-period framework discussed above, only I use different assumptions about the profitability of electric vehicles. For realism, I assume that the electric vehicle credit multiplier is 1.6 in the first period and 1 in the second period, and that electric vehicles are assumed to have zero emissions when calculating compliance with the standards. Changing these assumptions changes the exact quantitative estimates, but does not alter the qualitative findings.

For the standards in this illustrative scenario, I assume a combined standard of 160 g/mi in the first period and 100 g/mi in the second period. When a backstop conventional standard is added, I assume this standard is set at 150 g/mi in the second period (with no backstop in the first period). The parameterizations of each of the three scenarios are laid out in Appendix B.2.

Figure 7 clearly illustrates how the two standards influence electric vehicle market share. Panel (a) shows the results for the first period and Panel (b) shows the results for the second period. In the high electric vehicle cost scenario, automakers have to improve conventional vehicle technology anyway to meet the binding combined standard, so the backstop conventional vehicle standard has no effect. In the medium cost scenario, more electric vehicles come on the road anyway, but somewhat fewer are required to enable the automaker to meet the standard when there is a conventional vehicle backstop standard forcing improvements in the emission rate of conventional vehicles anyway. In the low cost scenario, the addition of the backstop conventional vehicle standard considerably increases the electric vehicle market share because conventional vehicles are more efficient and thus less profitable, so it is profit-maximizing to switch over more quickly and completely to electric vehicles. These are the high-level findings and examining the full suite of results helps to clarify the mechanisms at work.

I thus present Table 1, which includes all of the main results to enable a more complete explanation for the findings. Column 1 shows the results under high electric vehicle costs, column 2 under medium costs, and column 3 under low costs. Panel A shows the results with a single combined standard, while Panel B shows the results with both a combined standard and a backstop. It is useful to look both across the panels and across the electric vehicle cost scenarios.

With high costs under the single standard (Column 1 in Panel A), the electric vehicle market share is very small in the first period and increases in the second period due to the need for electric vehicles to meet an ambitious standard, just as in Figure 7. The conventional vehicle emission factors are substantially above the standard in both periods because the electric vehicles are averaged in. Emissions decline in the second period due to the tighter standard, and correspondingly, automaker profits are reduced. When the profit maximization is performed with the backstop conventional standard as an additional constraint, the results are identical, as can be seen in Panel B. This is because the backstop conventional standard is not binding, and thus the representative automaker will effectively ignore it.

With medium costs under the single standard (column 2 in Panel A), the electric vehicle market share is slightly larger than with high costs, again as in Figure 7. The market share increases in the second period, just as in the high cost scenario. The conventional vehicle emission rate is also substantially above the standard in both period because the electric vehicles are averaged in, just as under high costs. Emissions again decline in the second period, although they are even higher than in the high cost scenario. Automaker profits are lower in the second period than the first, although higher in the second period than under the high cost scenario.

When the backstop conventional standard is added under the medium costs scenario, this standard is binding in the second period, so the conventional vehicle emission rate in the second period is exactly equal to 150 g/mi. This occurs because the increased electric vehicles allow for more less-efficient conventional vehicles that the backstop conventional standard binds. With this binding backstop standard in the second period, total emissions do not go increase as much relative to the high cost scenario as they did with a single combined standard. But profits do not increase as much. The electric vehicle market share is also slightly lower in both periods when the backstop conventional standard is also in place. This is true in the second period because the automaker is required to improve the conventional vehicle emission rate to meet the backstop standard, so fewer electric vehicles are required. This effect in the second period also influences the first period through the electric vehicle innovation effect.

With low electric vehicle costs under the single standard (column 3 in Panel A), the electric vehicle market share is notably higher, just as was seen in Figure 7. However, this higher electric vehicle market share enables automakers to sell less-efficient conventional vehicles in both periods, so the conventional vehicle emission rate increases substantially in both. This means that total emissions do not substantially decrease in period 1 and actually increase in period 2. However, note that a 100 g/mi emission rate is assumed for upstream electricity generation in both periods. If electricity is substantially decarbonized by the second period, total emissions could decline in this scenario relative to the medium or high cost scenarios.

The backstop conventional standard binds even more strongly when electric vehicle costs are low (column 3 in Panel B). Specifically, the conventional emission rate in the second period in Panel A is 189 g/mi, which is substantially above the backstop standard of 150 g/mi. With that standard included, we observe a relatively extreme result: the automaker switches entirely to electric vehicles. Electric vehicles are similarly profitable to conventional vehicles and the 150 g/mi conventional vehicle standard is difficult to meet, so the profit-maximizing approach simply leads to all electric vehicles. The automaker profits are also higher and total emissions are much lower. I describe this as a relatively extreme result because there may be heterogeneity in consumers and certain vehicle types may be more more expensive to shift to electric vehicles, so an average analysis, such as this one, would miss the tails. But the insight from the illustrative simulation is clear: adding the backstop conventional vehicle standard can lead to a much higher market share of electric vehicles under the low cost scenario.

These simulation findings underscore that a combined standard along with a backstop conventional standard set with small year-over-year increases in fuel economy has the potential to substatially increase electric vehicle uptake and reduce carbon dioxide emissions if electric vehicle technology continues to progress very rapidly. The tradeoff is that if electric vehicle costs align more closely with the medium cost decline scenario, then electric vehicle uptake could slightly decrease and carbon dioxide emissions slightly increase. If electric vehicle costs remain much higher than conventional vehicle costs, the backstop conventional standard is entirely non-binding and thus does not impact automaker decisions.

One possible caveat is the potential for the conventional vehicle standard to induce some innovation in conventional vehicle technology. In theory, if this effect is very strong, it could lead to more profitable conventional vehicles in the second period, and reduced electric vehicle market share and emissions reductions in both periods. However, conventional vehicles are a quite mature technology and the backstop conventional vehicle standard would be set with small year-over-year increases or no increases at all. This suggests such a conventional induced innovation effect may not appreciably affect the key findings.

5 Concluding Discussion

This study analyzes key aspects of ex-ante policy design for standards that regulate the fuel economy or greenhouse gas emissions of light-duty vehicles. The technology pathway for the light duty vehicle fleet appears to be at a crossroads, with many analysts forecasting much higher electric vehicle market share in the upcoming decade. However, this is highly uncertain and policymakers face challenging questions about how to design the regulation to meet policy objectives. One stated policy objective of the Biden Administration is to encourage electric vehicle deployment.[14] Design details of standards have been leveraged in the recent past to try to encourage electric vehicles and there are open questions about how to encourage them cost-effectively going forward.

The first major result of this study points to tradeoffs inherent in generous crediting of electric vehicles as part of the standard. When electric vehicles are a niche technology that is far from being profitable, generous crediting can serve to increase electric vehicle market share because automakers will find selling more unprofitable electric vehicle worth it to allow them to see more profitable inefficient conventional vehicles. However, as electric vehicles become even remotely close to being profitable, generous crediting can quickly serve to relax the constraint imposed by the standard sufficiently that it reduces electric vehicle market share.

Furthermore, by relaxing the standard, the generous crediting can lead to less-efficient conventional vehicles and higher overall emissions from light duty transportation. These basic findings hold both with and without induced innovation for electric vehicles based on the first period market share, but induced innovation makes it more likely that electric vehicle market share will increase. Thus, policymakers may wish to be cautious in extending generous crediting for electric vehicles if the policy goals are to increase electric vehicle market share and reduce emissions. Indeed, by allowing for less-efficient conventional vehicles, the generous crediting is not likely to be a cost-effective approach to reducing emissions once electric vehicles are a competitive technology with conventional vehicles. Policymakers could of course tighten the standard at the same time as allowing generous crediting, which would ensure that the effective stringency of the standard remains the same.

This study also explores the tradeoffs from implementing a weak backstop conventional vehicle standard in concert with a more ambitious standard that covers both electric vehicles and conventional vehicles. This approach with two standards appears possible under existing statutes, with one possibility being that EPA develops both standards under the Clean Air Act. Another possibility might be that the NHTSA CAFE standard serves as the backstop conventional vehicle standard and the EPA greenhouse gas regulation serves as the combined standard. This second possibility would certainly be enabled with only a minor tweak to language by Congress. The backstop standard will not be binding if electric vehicle costs remain high, so it is possible that that it will not affect automaker decisions.

In a world with inexpensive electric vehicles, more electric vehicles will be sold perhaps

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[14] For example, see the White House Fact Sheet on advancing electric vehicle charging on April 22, 2021 (White House 2021).

leading the combined standard to become non-binding. Thus, the backstop standard serves to prevent automakers from selling highly inefficient conventional vehicles. This would imply that somewhat fewer electric vehicles will be sold than without the backstop, but emissions will be lower on net. In addition, as long as there continue to be low-cost emissions reductions possible from the conventional fleet with steadily improving technology, the backstop standard ensures that these cost-effective emissions reductions occur, leading to greater overall cost-effectiveness of the regulation. With much lower electric vehicle costs that bring electric vehicles close to upfront cost parity with conventional vehicles, the backstop will mean that automakers are better off switching entirely to electric vehicles, leading to much larger emissions reductions (and higher profits for the automakers). Thus, under uncertainty, there are tradeoffs in implementing a secondary backstop standard that depend on the exact path of electric vehicle technology costs.

The results of this study are illustrated for a representative automaker, but there will be heterogeneity in automakers and classes of vehicles. For example, General Motors has already indicated that they plan to sell only electric vehicles by 2035 (Boudette & Davenport 2021), perhaps consistent with a corporate belief that electric vehicles will become inexpensive and highly profitable. In contrast, the management of Toyota has expressed much more skepticism about electric vehicles and plans on retaining conventional vehicles and explore hydrogen vehicles much more. Such heterogeneity will likely prevent 100% market share of electric vehicles in the entire new vehicle fleet in the next decade, but it would not change the core insights of this paper. NHTSA and EPA could readily draw upon the intuition laid out in this paper to perform more detailed modeling of the light duty fleet to trace out exactly when each of the findings will hold, allowing for regulatory development to meet policymaker objectives as cost-effectively as possible.

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Figures and Tables

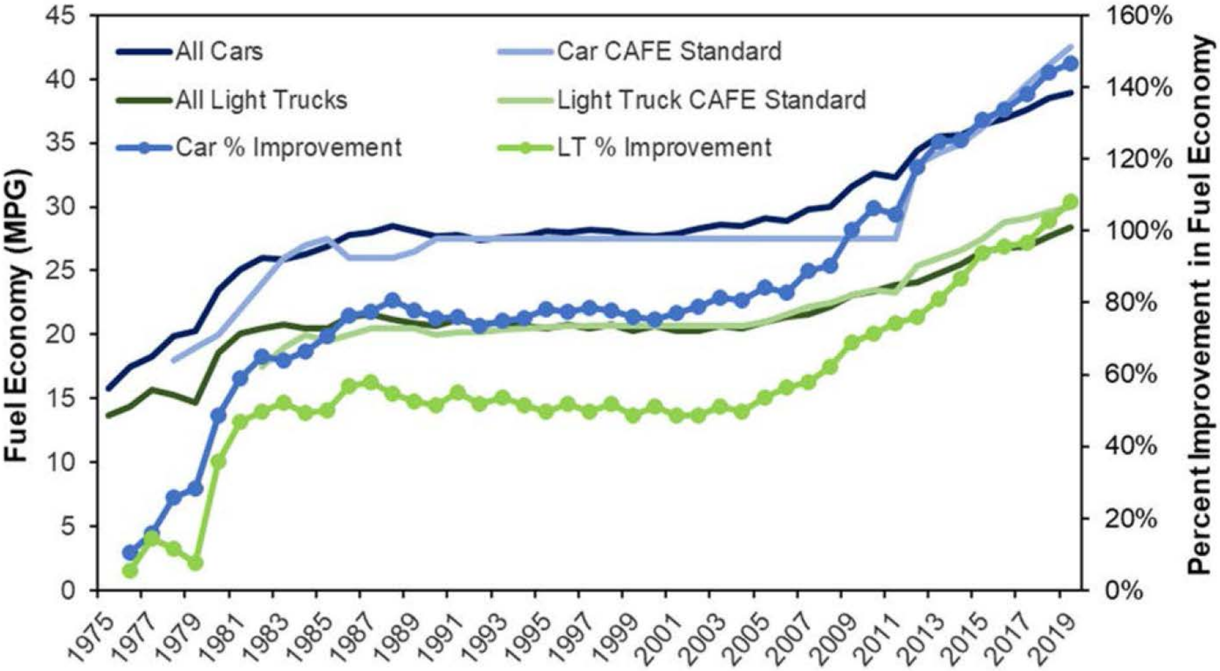


Figure 1: Historical data from 1975-2018 showing fuel-economy standards, achieved fuel economy in miles per gallon (MPG) and percent improvement from 1975 levels. Source: (National Academies 2021)

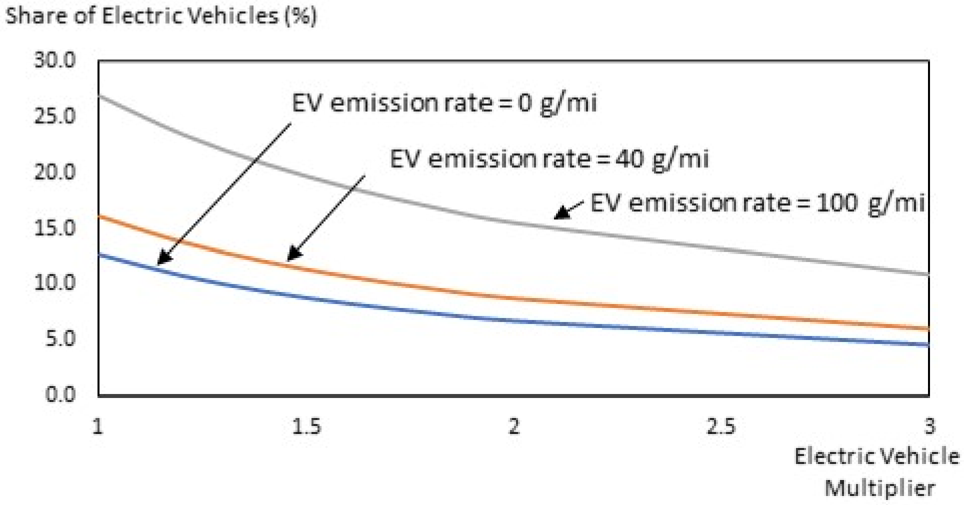
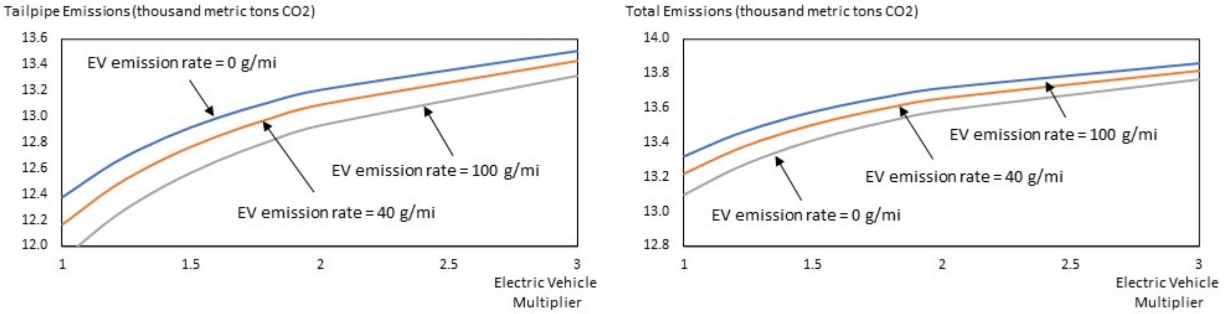


Figure 2: Period 1 electric vehicle (EV) market share with different assumed EV emission rates and credit multipliers



(a) Tailpipe emissions **(b)** Total emissions

Figure 3: Period 1 tailpipe emissions (Panel (a)) and total emissions (Panel (b)) with different assumed electric vehicle (EV) emission rates and credit multipliers.

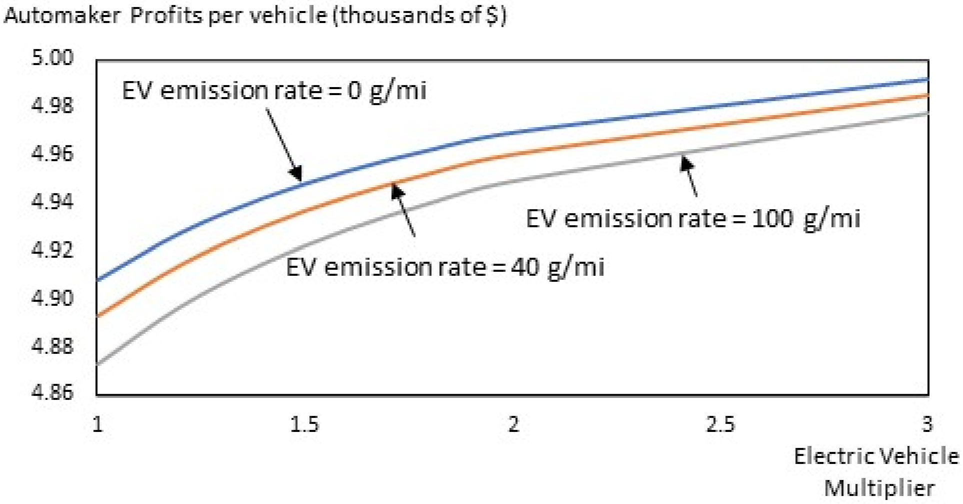
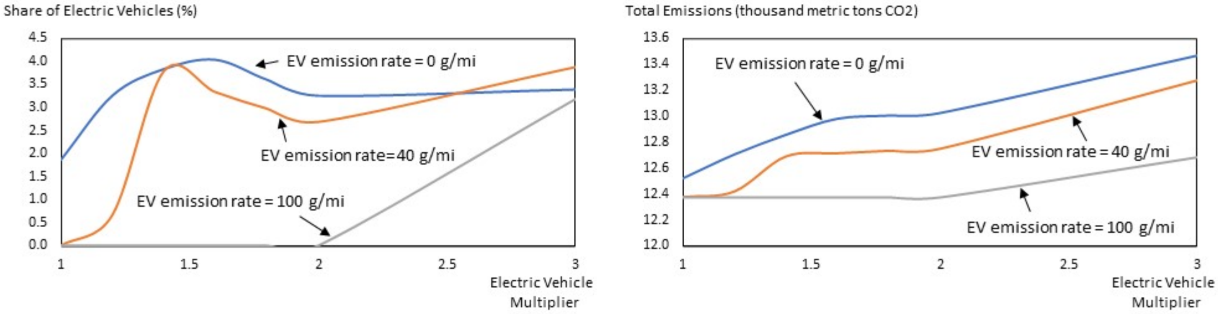


Figure 4: Period 1 profits per vehicle for the representative automaker with different assumed electric vehicle (EV) emission rates and credit multipliers.



(a) Electric vehicle market share **(b)** Total emissions

Figure 5: Period 1 electric vehicle (EV) market share (Panel (a)) and total emissions (Panel (b)) with different assumed EV emission rates and credit multipliers when electric vehicles are very far from cost-competitive with conventional vehicles.

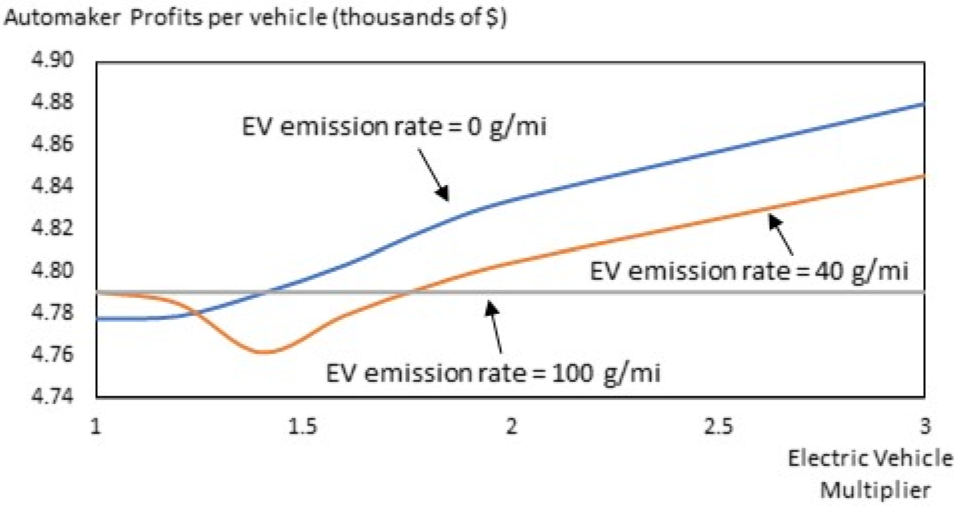
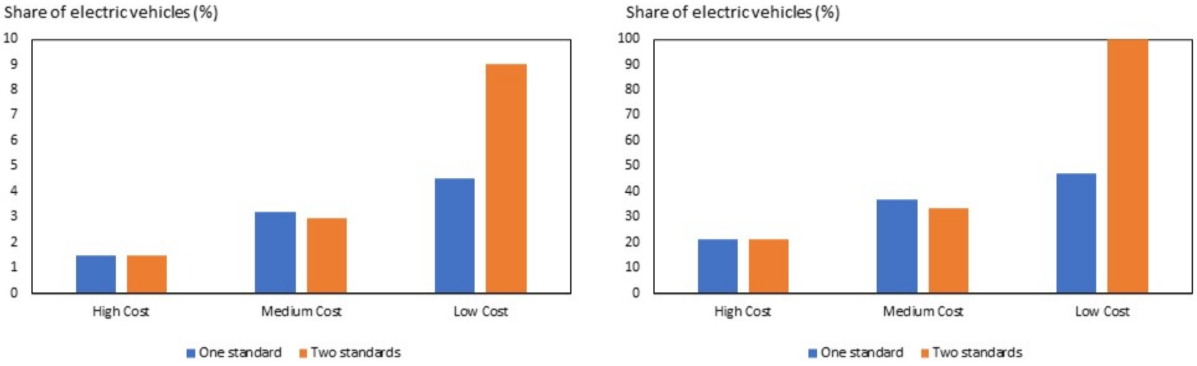


Figure 6: Period 1 profits per vehicle for the representative automaker with different assumed electric vehicle (EV) emission rates and credit multipliers when electric vehicles are very far from cost-competitive with conventional vehicles.



(a) Period 1

(b) Period 2

Figure 7: Market share of electric vehicles under the three scenarios of electric vehicle cost with a single standard covering electric vehicles and conventional vehicles or two standards, which would consist of the single standard plus a backstop conventional vehicle standard. Note the very different y-axis scales in Panel (a), which shows the results for the first period, and Panel (b), which shows the results for the second period.

Table 1: Simulation Results

	(1) High EV Cost	(2) Medium EV Cost	(3) Low EV Cost
Panel A: Single standard			
Period 1 EV Market Share (%)	1.5	3.2	4.5
Period 2 EV Market Share (%)	21.3	36.8	47.0
Period 1 Conventional Emission Rate (g/mi)	169	174	172
Period 2 Conventional Emission Rate (g/mi)	127	158	189
Period 1 Tailpipe Emissions (1000s t CO2)	12.5	12.6	12.3
Period 2 Tailpipe Emissions (1000s t CO2)	7.5	7.5	7.5
Period 1 Total Emissions (1000s t CO2)	12.6	12.9	12.7
Period 2 Total Emissions (1000s t CO2)	7.8	8.1	8.2
Period 1 Profits per vehicle (1000s $)	4.8	4.8	4.7
Period 2 Profits per vehicle (1000s $)	2.1	3.2	5.0
Panel B: Two standards			
Period 1 EV Market Share (%)	1.5	3.0	9.0
Period 2 EV Market Share (%)	21.3	33.3	100.0
Period 1 Conventional Emission Rate (g/mi)	169	173	185
Period 2 Conventional Emission Rate (g/mi)	127	150	150
Period 1 Tailpipe Emissions (1000s t CO2)	12.5	12.6	12.7
Period 2 Tailpipe Emissions (1000s t CO2)	7.5	7.5	0.0
Period 1 Total Emissions (1000s t CO2)	12.6	12.8	13.3
Period 2 Total Emissions (1000s t CO2)	7.8	8.0	1.5
Period 1 Profits per vehicle (1000s $)	4.8	4.8	4.6
Period 2 Profits per vehicle (1000s $)	2.1	3.1	5.1

The results in this table are from the illustrative simulation showing how the automaker profit-maximizing solution changes depending on whether electric vehicle (EV) costs are high, medium, or low. High costs are a situation where electric are very far from profitable relative to conventional vehicles; medium costs are when electric vehicles are still less profitable than conventional vehicles but are still somewhat profitable; and low costs are when electric vehicles are nearly as profitable as conventional vehicles.

APPENDIX

A Mathematical Details on the Effects of Generous Crediting in a Static Model

A.1 Rewriting the Standard

This short appendix section explains how we can obtain the version of the standard in (2), which illustrates how including a multiplier greater than 1 can directly influence the standard. Recall, we begin with (1), which I rewrite here for completeness:

$$\frac{\sum_{i\in\mathcal{C}} e_{C,i}V_i + \sum_{i\in\mathcal{EV}} e_{EV,i}V_iM}{\sum_{i\in\mathcal{C}} V_i + \sum_{i\in\mathcal{EV}} V_iM} \leq \frac{\sum_{i\in\mathcal{C}} S_{GHG,i}V_i + \sum_{i\in\mathcal{EV}} S_{GHG,i}V_iM}{\sum_{i\in\mathcal{C}} V_i + \sum_{i\in\mathcal{EV}} V_iM},$$

We can first note that the denominator is identical on both sides of the inequality, so it can be rewritten as:

$$\sum_{i\in\mathcal{C}} e_{C,i}V_i + \sum_{i\in\mathcal{EV}} e_{EV,i}V_iM \leq \sum_{i\in\mathcal{C}} e_C V_i + \sum_{i\in\mathcal{EV}} e_{EV}V_iM,$$

We can then note that $\sum_{i\in\mathcal{C}} e_{C,i}V_i = V(1-s_{EV})e_C$, where V is the total number of vehicles sold, so $V(1-s_{EV})$ is the number of conventional vehicles sold. This equality follows simply from the definition of an average for e_C. We can similarly replace the other summations, using the average for $S_{GHG,i}$ for the two on the right-hand side. This leads to the following inequality:

$$V(1-s_{EV})e_C + Vs_{EV}Me_{EV} \leq V(1-s_{EV})S_{GHG} + Vs_{EV}MS_{GHG}.$$

This much more compact equation is useful for providing quick intuition and provides the groundwork for the remainder of the analysis. We can divide both sides by V and rearrange to obtain:

$$(1-s_{EV})e_C + s_{EV}Me_{EV} \leq S_{GHG}(1+(M-1)s_{EV})$$

This provides first intuition about how a multiplier greater than one serves to directly relax the standard, because $(M-1)s_{EV}$ is positive, so a higher grams/mile emission rate is permitted if $M > 1$.

B Details of the Simulation

B.1 Details for Generous Crediting Analysis

This appendix subsection describes further details of the illustrative simulation analysis. The basic framework of the simulation uses the same profit maximization approach laid out in the main text and I solve for the model explicitly using constrained optimization (rather than the first-order conditions, although using those would not change the result). I will describe the two-period model equations, as those are the ones used in the simulation results presented.

The choice variables for the model are the electric vehicle share and conventional vehicle emission rate. For both there is a period one and period two value, for a total of four choice variables. There also are several exogenous variables: the emission rate of electric vehicles in both periods, the credit multiplier in both periods, and the greenhouse gas standard itself in both periods.

I solve the maximization problem with values of the period one emission rate of electric vehicles in the following set: $\{0, 40, 100\}$. The units of these values are grams of carbon dioxide per mile. I fix the period two emission rate at zero, commensurate with a deep decarbonization of the electricity system. I solve the maximization problem with values of the period one credit multiplier in the set: $\{1, 1.2, 1.4, 1.6, 1.8, 2, 3\}$. I fix the period two credit multiplier at 1, so that electric vehicles and conventional vehicles will be treated the same in the second period. I set the period one greenhouse gas standard at 165 grams/mile and the period two standard at 100 grams per mile. These are both extremely ambitious relative to values today, which are on the order of 400 grams/mile on average in 2018.[15] They should be considered illustrative examples in a future year with better technology. In that future year, I assume that the baseline no-standard average emission rate is 200 grams per mile.

I calculate several variables of interest. Most simply, the market share of conventional vehicles is just one minus the market share of electric vehicles. I fix the per-vehicle profit for electric vehicles in the first period at $4,000 in my baseline runs. This can the thought of as an expected profit for all electric vehicles over a several year period. Given that several automakers have announced a plan to go fully electric by 2035, clearly some automakers believe that they will be making profits from selling electric vehicles. Moreover, Tesla today is already earning a profit on each vehicle sold. In the second period, I model profits from selling electric vehicles as a function of the electric vehicle sales in the first period: $\pi_{EV,2} =$

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[15] See `https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle`.

$4000 + \gamma s_{EV,1}$. Here γ models the strength of the innovation effect. My baseline estimate for γ is 2,000. This leads to an electric vehicle profit that is higher in the second period than the first.

I model the conventional vehicle profits as a quadratic and concave function of the difference between the baseline average emission rate and the conventional vehicle emission rate. My baseline parametrization for period one is $\pi_{C,1} = 5000 + 8(\eta - e_{C,1}) - 0.4(\eta - e_{C,1})^2$. Here η is the baseline parametrization (200 grams per mile). This equation gives a conventional vehicle profit on the order of \$5,000 per vehicle in the first period. The period two parametrization for conventional vehicles is identical, only based on $e_{C,2}$. In side sensitivity runs, I also explored adding induced technological change to conventional vehicles as well, but do not include these in the primary results, as it is unclear how strong this induced innovation effect is (or even whether it exists at all).

I also constrain profits to be nonnegative and the electric vehicle shares to be between zero and one. The objective function and constraints are identical to those in the main paper. For calculating emissions and profits, I assume the automaker sells 500,000 vehicles a year, which are driven 150,000 miles over their full lifetimes. The assumed upstream emission rate from charging electric vehicles is 100 grams per mile in period one and 20 grams per mile in period two.

B.2 Details for the Uncertainty Analysis with a Backstop

For the analysis with uncertainty, I develop parameterizations for the high electric vehicle cost, medium cost, and low cost scenarios. The basic approach used is otherwise identical to that used for the crediting analysis, with exactly the same objective function and constraints.

Table A.1 shows the full set of parameterizations used across the three scenarios in the baseline results presented in the main text. $S_{C,t}$ refers to the level of the conventional vehicle backstop standard in period t. The equations for the conventional vehicle profits ($\pi_{C,1}$ and $\pi_{C,2}$) are identical to those used in the generous crediting analysis described above. The equation for the per-vehicle profits in period two is $pi_{EV,2} = \nu + \gamma s_{EV,1}$, and I show the values for ν and γ in the table.

Table A.1: Uncertainty Simulation Parameterizations

	(1) High EV Cost	(2) Medium EV Cost	(3) Low EV Cost
$e_{EV,1}$	0	0	0
$e_{EV,2}$	0	0	0
M_1	1.6	1.6	1.6
M_2	1	1	1
$S_{GHG,1}$	165	165	165
$S_{GHG,2}$	100	100	100
$S_{C,1}$	170	170	170
$S_{C,2}$	150	150	150
$pi_{EV,1}$	-500	-100	0
ν for $pi_{EV,2}$	-3000	500	4760
γ for $pi_{EV,2}$	4000	4000	4000