

Integrating electric vehicles within U.S. and European efficiency regulations

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I. Introduction

Battery technology advances, automaker announcements, market developments, and policy statements all suggest that the prospects for electric vehicles are on the rise. Yet there is uncertainty about how quickly a transition could happen, and which policies are most critical to smartly navigate the transition. Factoring in this uncertainty is important for vehicle efficiency regulations. Efficiency and carbon dioxide (CO₂) regulations are developed to reduce vehicle emissions and energy use, but they have been developed for internal combustion vehicles, which have dominated the automobile industry for over a century.

Over the last several decades, regulatory authorities have sought to integrate alternative fuel technologies in vehicle policies with mixed results. Various alternatives such as methanol, ethanol, natural gas, hydrogen, and electricity have all gone through cycles of hype and then disappointment, with multi-year spurts of new research, policy, and incentives (e.g., see Melton et al, 2016). Policymakers have struggled in their attempts to make efficiency regulations consistently

and objectively account for full environmental impacts of alternative fuel vehicles. Efficiency regulations have typically included temporary incentives and preferential emission accounting to promote emerging technologies such as electric vehicles. In addition, efficiency regulations are generally set with short time frames that make consideration of long-term technology transitions difficult.

Due to the potential for much greater electric vehicle deployment in the next two decades, combined with consideration of 2025 standards in the United States and Europe, it is an ideal time for a deeper analysis of how best to integrate electric vehicles within the standards. With over 2 million electric vehicles sold globally in six years, electric vehicle technology has progressed further and faster in the market than other alternative fuel vehicle introductions. Essentially every automaker has committed billion-dollar investments, and production volume and supplier competition are expected to continue to lower costs (Slowik et al, 2016).

Life-cycle accounting methods and data on electric grid emissions have greatly improved and allow for a

complete assessment of electric vehicles' benefits versus those of conventional combustion vehicles (e.g., see EPRI and NRDC, 2015a,b; Nealer et al., 2015). Including the most recent trends—away from coal and toward more renewable power—result in greater environmental benefits for electric vehicles, as compared with conventional vehicles (Reichmuth, 2017). Based on such analyses, governments in many major automobile markets have committed to the technology as part of their long-term climate goals (Lutsey, 2015; Creutzig et al, 2015). Even though electric vehicles have lower emissions, artificial incentives in the regulations can partially undermine the overall short-term benefits of the standards (e.g., see Lutsey and Sperling, 2012; Irvine, 2017). This underscores the importance of more detailed analysis into how electric vehicles are integrated within the regulations over the long term.

This paper assesses several key questions related to how efficiency regulations integrate electric vehicles, specifically analyzing the United States' and European Union's CO₂ regulations. The U.S. and EU automobile markets

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are among the largest globally, with approximately 14-17 million annual sales each. These two markets also have relatively high deployment of advanced technologies (U.S. EPA, 2016a; Mock, 2016), and have major regulations that are commonly viewed as benchmarks for other governments developing their own regulations.

How can electric vehicles optimally be integrated within vehicle regulations in the 2025 to 2030 time frame? To answer this, my assessment below includes an evaluation of future electric vehicle penetration under three regulatory approaches: life-cycle accounting, tailpipe accounting (i.e., electric vehicles are counted as zero), and the use of multipliers or super-credits (i.e., electric vehicles get counted multiple times) to increase electric vehicle production. I examine the impacts of these three regulatory scenarios for their impact on energy efficiency improvements of combustion vehicles and on fleet-wide CO₂ emission reductions. In addition, to further understand how these regulatory approaches for electric vehicles are seen from the perspective of automaker compliance, I assess their cost-effectiveness versus other technology options. The results are presented throughout the paper in the conventionally used metrics in each market, namely grams of CO₂ per mile (g/mi) and fuel economy miles per gallon (mpg) for the United States and grams of CO₂ per kilometer (g/km) for Europe.

II. Integrating electric vehicles into U.S. regulation

This section includes an analysis of the regulatory treatment of electric vehicles under U.S. federal regulation and at the state level in California, including basic background for the existing regulatory structure for CO₂ standards and the associated electric vehicle policy mechanisms. Fuel-cycle CO₂

emissions of electric vehicles, based on recent electric grid data, are applied to evaluate the cost-effectiveness and environmental impact of various electric vehicle regulatory mechanisms.

EXISTING POLICY

The U.S. regulatory structure for promoting vehicle efficiency in new vehicles involves three regulatory agencies: the U.S. Environmental Protection Agency (U.S. EPA), the U.S. Department of Transportation (U.S. DOT), and California Air Resources Board (CARB). Each agency holds unique regulatory authority based on various legislation and court rulings over the past decades. The three agencies coordinate in developing their rulemakings such that each auto company can simultaneously comply with all three regulations. The standards are measured in CO₂ for U.S. EPA and CARB, and in miles per gallon for U.S. DOT.

Compliance with the CO₂ targets through model year 2025 is projected to achieve approximately 173 grams per mile (g/mile) in the United States and 165 g/mile in California (U.S. EPA, 2016c; CARB, 2017a). The technical stringency of the CO₂ targets for the United States and California are identical, but the projected future emission levels are different due to the fleet mix in California having more cars than light trucks, and its vehicles having somewhat smaller footprint on average than in the national fleet. The CO₂ standards are reduced by approximately 4.5% per year from 2016 to 2025; excluding the air conditioning credits, the CO₂ emission levels drop by 3.7% annually over that period. California's latest regulatory review indicates that electric vehicles would amount to about 8% of new vehicles in model year 2025 to meet the requirements of the Zero Emission Vehicle (ZEV) regulation (CARB, 2017a). The latest joint three-agency document, the Draft

Technology Assessment Report in late 2016 (U.S. EPA et al, 2016), indicates that in model year 2025, a new U.S. vehicle fleet of which approximately 5% of vehicles are plug-in electric would satisfy the federal and California regulations. California's climate change mitigation plans rely on post-2025 standards that continue to reduce CO₂ emissions by 4-5% per year and increased ZEV requirements (CARB, 2017b, 2017c).

Electric vehicles receive several explicit incentives within the CO₂ accounting of the U.S. regulations, including being counted as zero grams CO₂ per mile until higher volumes are reached. From 2022 to 2025, zero g/mile is allowed for up to 200,000 per-company cumulative electric vehicles—or up to 600,000 electric vehicle sales for companies that sell a total of 300,000 electric vehicles within model years 2019-2021. Fully battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs) are counted within these provisions. PHEVs only receive 0 gram/mile, accounting for the estimated fraction of their driving that is from electric grid power. PHEVs with about 20 miles in electric range are weighted at about 40% electric, and PHEVs with 40 miles in electric range are weighted at about 63% electric, based on SAE J2841 (see SAE International, 2010). Also, as another regulatory incentive, multipliers count electric vehicles as multiple vehicles in the calculation of average emissions. Multipliers start with 2.0 in model year 2017 and phase down to 1.3 in 2021.

U.S. EPA incorporates a shift toward more true CO₂ performance standards by including upstream electricity-related emissions for electric vehicles in later years. After manufacturers reach the allotted cumulative-electric vehicle incentive thresholds, U.S. EPA's fuel cycle accounting is used

in the CO₂ regulations. The U.S. EPA provisions use electric vehicle test cycle kWh per mile, grid average CO₂ per kWh emissions, grid transmission and distribution losses (6.5%), and charging losses (incorporated directly by measuring electricity at the power outlet). Instead of shifting the entire regulatory accounting to a life-cycle basis, the U.S. regulatory accounting makes an additional adjustment for electric vehicles to ensure the electric and gasoline technologies' relative gram per mile difference is accurately counted. An additional "credit" is subtracted from the electric vehicles' upstream CO₂ emission rating, to reflect how an electric vehicle removes the equivalent gasoline vehicle's upstream oil (e.g., extraction, transport, refining) emissions.

ELECTRIC VEHICLE CO₂ EMISSIONS

Analysis of existing CO₂ emissions from conventional and electric vehicles, including tailpipe and upstream, provides further context for the 2025–2030 scenarios below. Figure 1 shows how electric vehicles and conventional vehicles compare in CO₂ emissions based on recent data. The estimated average model year 2016 passenger car, with a test cycle fuel economy of 37 mpg (real world approximately 29 mpg), is shown (U.S. EPA, 2016a). For context, the most efficient hybrid vehicle, the 2016 Toyota Prius Eco, with 81 mpg test (56 mpg real-world) is also shown. Consistent with the U.S. EPA regulation accounting, gasoline's upstream emissions of 22% of the full fuel cycle are included for petroleum extraction, refining, and distribution to make for a rigorous comparison here with upstream electricity production (see U.S. EPA et al, 2016; CARB, 2016). The equivalent test cycle emissions for an electric vehicle with 0.2 kWh/mile (0.3 kWh/

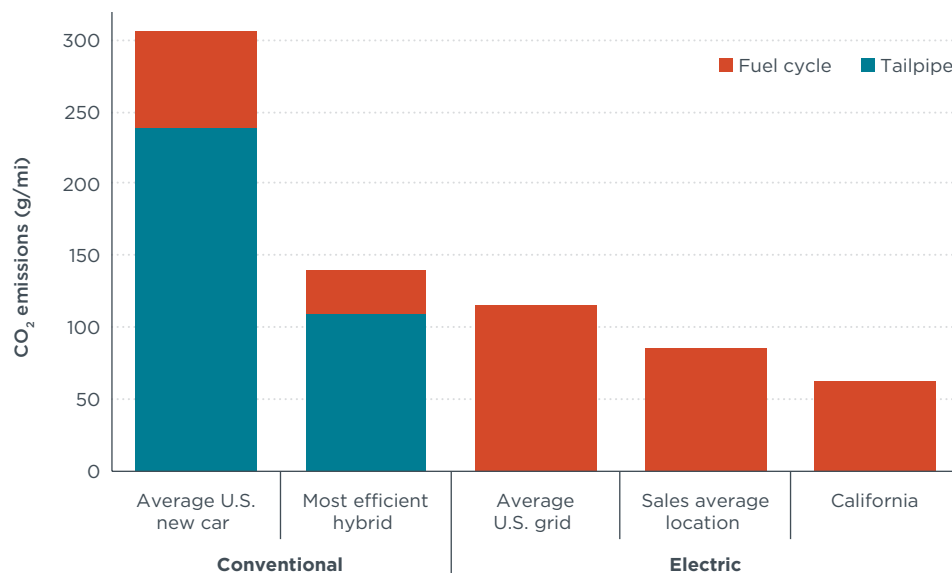


Figure 1. Electric and conventional vehicle test-cycle and upstream fuel cycle emissions in the U.S.

mile real world), based on the average of the latest Nissan Leaf, Chevrolet Bolt, and Hyundai Ioniq models, and fuel cycle losses and feedstock emissions throughout the fuel cycle are shown under three grid assumptions: the average U.S. grid, average grid emissions weighted according to each state's electric vehicle sales, and California's grid. Under the three scenarios shown, electric vehicles have 62–80% lower CO₂ emissions than average U.S. cars in 2016. The electricity generation data are for calendar year 2014, the latest year for detailed U.S. grid data with geographic resolution (U.S. EPA, 2016b). Also shown, electric vehicles offer a 17–55% CO₂ benefit as compared to the most efficient combustion hybrid vehicle.

Several other electricity market trends will impact analyses like those above. U.S. grid sources have been shifting from coal to lower-carbon energy sources quite rapidly, even since the 2014 grid data above. The U.S. grid has shifted from about 39% coal in 2014 to about 30% coal in 2016 (U.S. EIA, 2017a). The average U.S. grid's

emissions, measured in grams of CO₂ per kWh, are estimated to reduce by about 2% per year over 2015–2030. This is because over that period, coal is projected to fall from 35% to 25% of U.S. electricity generation, while renewable sources increase from 13% to 25%, between 2015 and 2030 (U.S. EIA, 2017b). Based on this trend to a cleaner grid, electric vehicles, as they age, continue to extend their CO₂ emission benefit versus gasoline vehicles of the same model year.

ANALYSIS OF POLICY MECHANISMS

In this section, I evaluate the policy mechanisms of emission accounting of upstream electric vehicle grid emissions, tailpipe-only emission accounting (i.e., electric vehicles are counted as zero), and the use of multipliers (i.e., electric vehicles are counted multiple times). This includes analysis of how these policy mechanisms impact the cost-effectiveness of deploying electric vehicles, relative to other technology options and the potential impacts of the electric vehicle incentive mechanisms

on combustion vehicle efficiency and on CO₂ emission benefits.

Cost-effectiveness. The crux of CO₂ policy is typically the analysis of available efficiency technologies and the associated costs of those technologies. Industry compliance with the regulations relies on increasing deployment of the most cost-effective technologies to meet the CO₂ requirements over time. For more stringent long-term regulations in the 2025-2030 time frame, companies would incrementally need to apply advanced engine technology, lightweighting, hybridization, and electric vehicle technologies. As introduced above, the U.S. EPA's analysis indicated that the automobile industry would apply electric vehicle technology up to a 5% share of new vehicles in 2025 to jointly comply with the federal CO₂ standards and the California ZEV regulation.

Figure 2 summarizes the cost-effectiveness analysis of efficiency technologies to contribute to 2025 compliance with the U.S. CO₂ standards. For this analysis of the relative cost-effectiveness of deploying electric vehicles as part of the compliance, technology and cost data from Lutsey et al. (2017) are applied for a C-class passenger car, with a baseline in-line four-cylinder engine with an average curb weight of approximately 3,266 lbs. Four gasoline efficiency technology packages are shown. An incremental vehicle technology improvement that is similar to some technology packages in the fleet in model 2015 is the first step shown. After that, three advanced gasoline efficiency technologies are shown, all with 47 to 58 mpg real-world consumer label fuel economy. The figure shows the average cost-effectiveness value for each full vehicle technology package (i.e., they are not the marginal impact of the final technology added). Details on the technologies included and the technology package costs are included

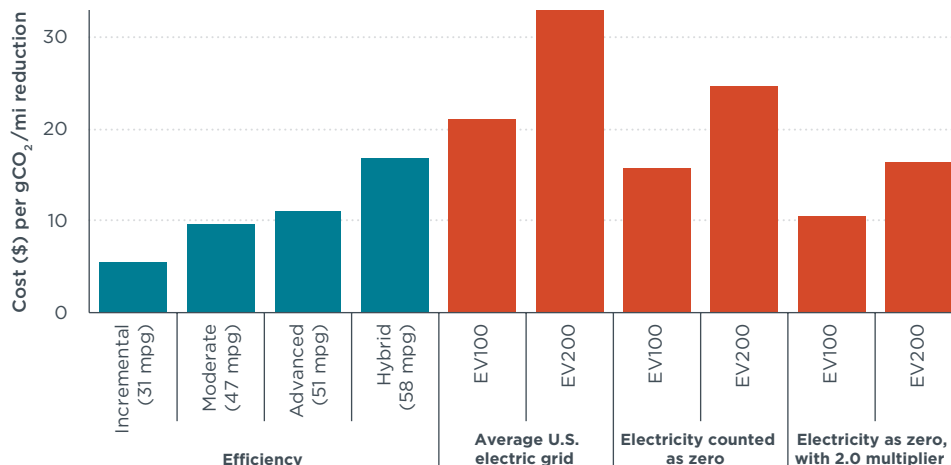


Figure 2. CO₂ reduction cost effectiveness of gasoline efficiency and electric vehicle packages under various electric vehicle accounting mechanisms in the U.S.

in the Annex. These technologies are compared against electric vehicles with real-world 100-mile range (EV100) and 200-mile range (EV200) under three emissions accounting cases. Relatively short-range and long-range electric vehicles are applied in the cost-effectiveness analysis to reflect the likelihood that each will have a place for cost-conscious and range-conscious consumers, respectively.

As shown in Figure 2, applying scientifically appropriate grid-average accounting of electric vehicle grid emissions would result in the two electric vehicle packages being less cost-effective than the most advanced hybrid. However, with the use of zero g/mi accounting, the lower-cost 100-mile electric vehicle becomes more cost-effective than hybrid technology. The use of zero g/mi accounting reduces the cost per CO₂ reduction of electric vehicles by 23%. With zero g/mile and a multiplier of 2.0, both electric vehicles are more cost-effective than the hybrid; the EV100 would have cost-effectiveness that approaches the moderate technology package and the EV200 would be more cost-effective than the hybrid. The use of the multiplier plus zero g/mi accounting

reduces the cost per CO₂ reduction of electric vehicles by 49%, as compared with accurate electric grid accounting without multipliers.

Combustion vehicle efficiency. The use of preferential incentives carries a potential risk: that the overall benefits from regulating vehicle efficiency and CO₂ levels will be undermined. In the case of electric vehicle incentives, such as counting their emissions as zero and counting each vehicle as if it were multiple vehicles, these allow the rest of the vehicle fleet to emit higher CO₂ emissions or remain at lower mpg levels. To analyze the impact of such electric vehicle regulatory incentives, I assume a fixed scenario where U.S. and California regulations continue to reduce CO₂ emissions at 6% per year for new model year 2025-2030 vehicles. Although there is uncertainty, this is a plausible hypothetical path and one for which there is relevant and analysis to draw upon. Namely, recent work (see Lutsey et al, 2017) indicates a minimum compliance cost scenario for the extended 2025-2030 standards, which includes increasing electric vehicle shares from 5% in 2025 up to 23% by 2030. The electric vehicle shares include all-electric vehicles and

plug-in hybrids, but plug-in hybrids remain a low 2% share due to all-electrics' greater cost effectiveness.

Figure 3 illustrates the impact of the increased penetration of electric vehicles (see the gray dashed line, right axis) on the CO₂ emissions of the remaining combustion vehicles in the fleet under three electric vehicle accounting scenarios. The figure shows the extent to which the conventional combustion (i.e., non-plug-in electric) portion of the vehicle fleet's emissions are impacted by the potential regulatory incentives in the 2025-2030 time frame. The blue CO₂ line is for the CO₂ target, regardless of electric vehicles, extending the adopted 2025 standards to reduce CO₂ emissions by 6% per year for 2026-2030. The blue line is based on the adopted 2025 standards, which are not linear. Moving up in the chart, the green line reflects the scientifically accurate inclusion of upstream grid emissions for electric vehicles, where combustion vehicles would reduce CO₂ by 3.1% per year for 2020-2030. The blue and green scenarios achieve the same overall CO₂ benefit (the overall benefits of the scenarios is addressed in Table 1 below).

The two additional lines in Figure 3 where greater incentives are given reflect scenarios with a key difference from the blue and green scenarios. The scenarios shown as dashed yellow and dashed red lines reflect two ways to implement the same CO₂ standards, but where the incentives result in achieving somewhat less overall CO₂ emission benefit than the blue and green scenarios. The dashed yellow line reflects counting grid emissions as zero for electric vehicles, where combustion vehicles would reduce CO₂ by about 2.9% per year. The dashed red line reflects counting grid emissions as zero and providing a 2.0 multiplier for electric vehicles. Electric vehicle uptake is constant across the three scenarios in order to isolate the

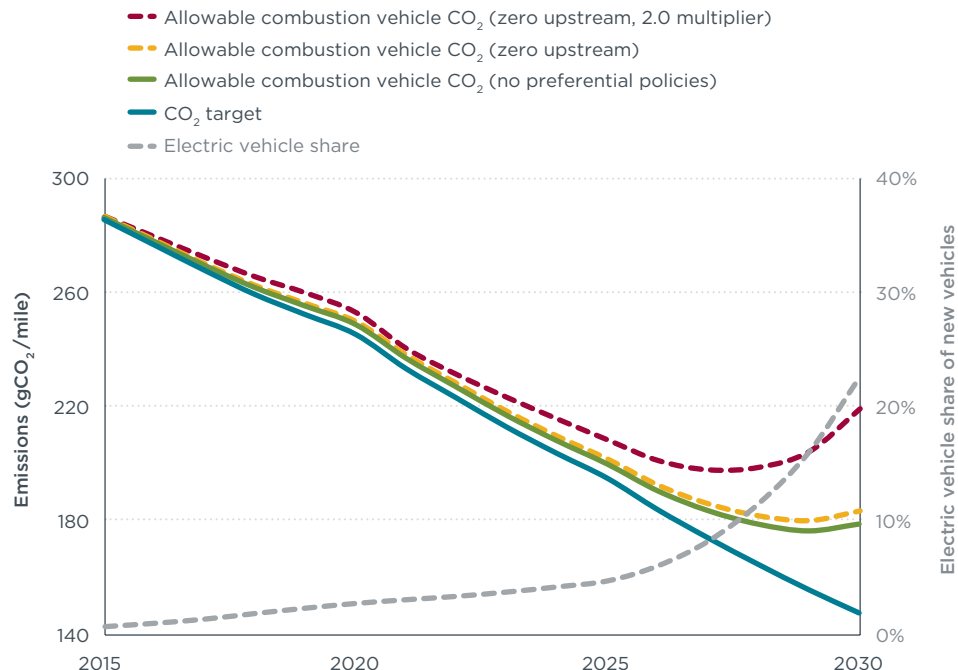


Figure 3. Impact of three electric vehicle accounting cases on combustion vehicle efficiency, for given CO₂ stringency and electric vehicle penetration through 2030 in the U.S.

effect of the three different accounting mechanisms on average CO₂ emission values of combustion vehicles. In reality, the different electric vehicle regulatory incentives (and many additional non-regulatory factors and policies) will affect electric vehicle uptake. As shown, once electric vehicles' share of the new market increases above 5%, the use of both the electric vehicle incentives results in incrementally less combustion efficiency improvement over time.

Considering the importance of the CO₂ standards in promoting vehicle efficiency, I provide additional quantification of the other 77% of the fleet that are not plug-in electric in 2030. The increasingly stringent 2030 standard, if there were no electric vehicles, would achieve 46 mpg in real-world fuel economy, up from 26 mpg in 2016. With the penetration of 23% electric vehicles, depending on the accounting method for those vehicles, the combustion vehicle fuel economy

for a 2030-compliant fleet could differ widely. With scientifically accurate inclusion of grid emissions for electric vehicles, combustion vehicles would achieve 38 mpg, whereas counting grid emissions as zero for electric vehicles results in 37 mpg in real-world fuel economy. With counting grid emissions as zero and providing a 2.0 multiplier for electric vehicles, combustion vehicles could achieve 31 mpg in real-world fuel economy, including essentially no change from 2024 to 2030.

Environmental impact. Table 1 summarizes several of the key results from above and the impact of various potential electric vehicle incentive mechanisms for new 2020-2030 vehicles in the United States, assuming adopted 2021-2025 standards and extension of the standards at 6% annual CO₂ reduction for 2026-2030, and 23% electric vehicle share of new 2030 vehicles. As shown, the cases with more regulatory incentives for electric

Table 1. Summary of 2020–2030 U.S. cases for performance standards with varying electric vehicle preferential incentives

Case	Electric vehicle Share in 2030	Internal combustion engine efficiency			Reduction in 2020–2030 CO ₂ emissions ^a (million metric tons)		Loss of CO ₂ benefits from preferential electric vehicle incentives
		Annual g/mile CO ₂ change 2020–2030	Test cycle CO ₂ in 2030 (g/mile)	Real world fuel economy in 2030 ^b (mpg)	Reduction from flat 2020+ g/mi standards	Reduction from performance standards	
Performance standard with all combustion vehicles	0%	-4.9%	92	46	2,312	0	0%
Electric vehicle penetration (no preferential policies)	23%	-3.1%	112	38	2,312	0	0%
Electric vehicle penetration (zero upstream incentive)	23%	-2.9%	114	37	2,227	85	-4%
Electric vehicle penetration (zero upstream, 2.0 multiplier incentives)	23%	-1.1%	136	31	1,711	601	-26%

^a Assume 180,000 mile average vehicle lifetime

^b Gasoline equivalent miles per gallon, based on 8,887 gCO₂ per gallon; assumes real-world fuel use 30% higher than test cycle

vehicles result in less improvement in the combustion vehicles. There is also a substantial impact of the incentive mechanisms on the overall environmental benefits from the regulations. Counting electric vehicles as having zero emissions would reduce the overall benefits from new 2020–2030 vehicles by 4%. The eroded benefits from 0 g/mi accounting remain so low because electric vehicles use increasingly lower grid carbon electricity over their lifetime. Zero-emissions accounting and including a multiplier of 2.0 for electric vehicles would result in a loss of 26% of the CO₂ benefits from all the new 2020–2030 vehicles.

III. Integrating electric vehicles into European regulation

In this section, I analyze the regulatory treatment of electric vehicles in the European context. First, I provide basic background for the existing CO₂ standards, their baseline inclusion of various electric vehicle policy mechanisms, and their fuel-cycle CO₂ emissions in Europe. Then I evaluate the implications of policy mechanisms on cost-effectiveness versus other

technologies, on combustion vehicle CO₂ emissions, and on the overall environmental impacts.

EXISTING POLICY

The European Union (EU) first introduced mandatory CO₂ standards for new passenger cars in 2009, setting a 2015 target of 130 grams per kilometer (g/km) of CO₂ for the fleet average of all manufacturers combined (Mock, 2014). Confirmed with a review in 2013, the light-duty vehicle CO₂ regulations were finalized to 2020, setting a cars' fleet target of 95 g/km (Mock, 2014). This 2020 regulation includes a phase-in provision, so that 100% compliance with the 95 g/km will be achieved only in 2021. For the time period beyond 2021, the next set of CO₂ standards is currently in preparation, and a regulatory proposal for introducing 2025/30 CO₂ standards is expected in late 2017 (European Commission, 2016).

The fleet CO₂ targets for 2021 that are set by the EU's regulation for cars can still be met by increasing the efficiency of conventional combustion engine technologies, thereby requiring zero or a very low market share of electric

vehicles (Mock, 2017). The regulation provides additional incentives for the deployment of electric vehicles though (1) neglecting any emissions caused upstream as part of the electricity or hydrogen production and (2) allowing for "super-credits." Neglecting the upstream electricity fuel cycle emissions inherently provides an advantage by making all electric vehicles zero g/km, and there are no provisions in place to phase in the counting of grid CO₂ as in the U.S. As part of the super-credits provision, every car with CO₂ emissions of less than 50 g/km (as measured in the New European Driving Cycle, or NEDC) counts more towards meeting the fleet average than cars with emissions above that cutoff. For 2020, this multiplier is set as 2.0, falling to 1.0 by 2023 (European Union, 2014). Despite these accounting provisions at the EU level, the electric vehicle markets vary greatly by member state. For example, in 2015 electric vehicles had a 9.7% share of the new-vehicle market in the Netherlands, but only a 0.7% share in Germany (Mock, 2016), illustrating the important role of fiscal and other incentives provided at the local and national levels (Tietge et al, 2016).

ELECTRIC VEHICLE CO₂ EMISSIONS

Analysis of existing CO₂ emissions from conventional and electric vehicles, including tailpipe and upstream, provides further context for the 2025-2030 scenarios below. Figure 4 shows how electric vehicles and conventional vehicles compare in CO₂ emissions based on recent data. The average model year 2015 passenger car with test cycle CO₂ emissions of 120 g/km is shown. For context on low-CO₂ combustion vehicles, the lowest CO₂ non-hybrid is the Peugeot 208 with 79 g/km. The lowest CO₂ hybrid is the Toyota Prius with 70 g/km test cycle emissions, which is shown. As above, petroleum fuel upstream emissions of 22% of the full fuel cycle are included for petroleum extraction, refining, and distribution to make for a rigorous comparison here with upstream electricity production. The equivalent test cycle emissions for an electric vehicle with 0.12 kWh/km (0.17 kWh/km real world), approximately equivalent to a 2016 Nissan Leaf, and fuel cycle losses and feedstock emissions throughout the fuel cycle are included. The figure shows electric vehicle results for the average European grid and for the five largest European electric vehicle markets, the Netherlands, Germany, United Kingdom, France, and Norway, based on 2014 grid CO₂ data (based on EEA, 2016). As shown, electric vehicles on the average Europe grid have 70% lower CO₂ emissions than the average EU car of 2015. Across the five markets electric vehicles have 51-98% lower CO₂ emissions than the average conventional car. Electric vehicles have particularly low CO₂ emissions in France and Norway due to the high share of nuclear power in France and hydropower in Norway. Also shown, electric vehicles offer a 15-97% CO₂ benefit even over the most efficient combustion vehicle.

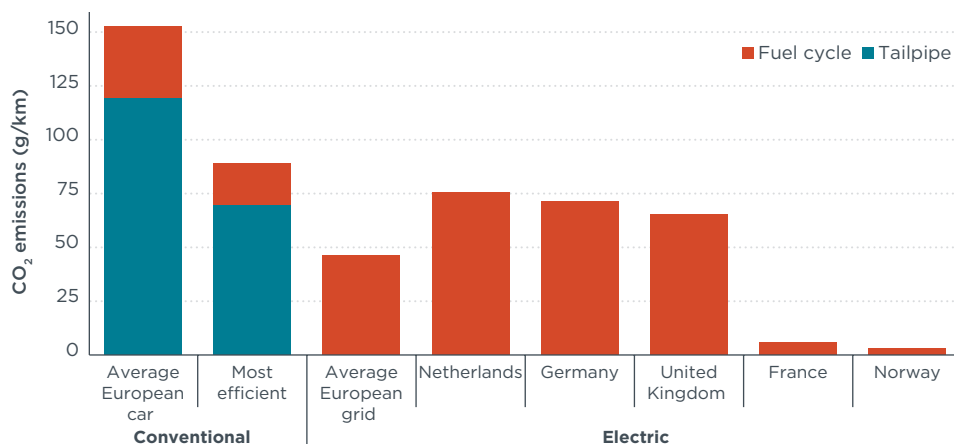


Figure 4. Electric and conventional vehicle test-cycle and upstream fuel-cycle emissions in Europe

As is the case above for the United States, Europe's electric grid continues to be gradually decarbonized. Based on the data source applied in Figure 4 (EEA, 2016) the average carbon intensity of electricity generated in Europe has fallen by 36%, or 2% per year, from 1990 to 2014. According to the three scenarios in the World Energy Outlook, Europe's grid carbon intensity will be reduced by 2% (with no new policy), 3% (with new policy), or 5% (climate stabilization 450 ppm) annually from 2013 to 2030 (IEA, 2015). In addition, there is a commitment from the power industry for carbon-neutral electricity by 2050 (Eurelectric, 2017). As a result of this trend, electric vehicles, as they age, increase their CO₂ emission benefit versus gasoline and diesel vehicles of the same model year.

ANALYSIS OF POLICY MECHANISMS

As above for the U.S., I evaluate European upstream electric vehicle grid emissions, tailpipe-only emission accounting (i.e., electric vehicles are counted as zero), and the use of multipliers (i.e., electric vehicles get counted multiple times). This includes an evaluation of the implications of such policy mechanisms on cost-effectiveness of electric vehicles versus advanced combustion technologies,

on their impact on combustion vehicle CO₂ emission rates, and on the overall cumulative CO₂ impacts.

Cost-effectiveness. As above for the U.S. analysis, I analyze technologies that auto companies can deploy to meet decreasing CO₂ levels in the 2025-2030 time frame in Europe. For the European context, I use data from Europe-based studies that analyzed a series of advanced efficiency technologies based on similar simulation modeling and teardown cost analysis (FEV, 2015; Meszler et al 2016). The underlying engine, transmission, mass reduction, aerodynamics, and tire rolling resistance technologies included within the European technology packages are the same as the United States, but applied to the European baseline vehicles according to the NEDC test procedure. A key difference is that the efficiency technology and cost data include diesel efficiency options, due to the prevalence of diesel vehicles in the Europe market.

Figure 5 summarizes the cost-effectiveness analysis of efficiency and electric vehicle technologies to contribute toward meeting CO₂ standards. These are the average cost-effectiveness values for the full vehicle technology package (i.e., they are not the marginal impact of the final

technology added). As shown, multiple efficiency technologies are examined for the C-class passenger car segment. The baseline gasoline vehicle has an in-line four-cylinder engine with a curb weight of approximately 1,370 kg (3,021 lb), and the baseline diesel vehicle has an in-line four-cylinder engine with a weight of 1,459 kg (3,259 lb). Three increasingly efficient diesel packages are shown achieving 89 g/km, down to 70 g/km, as are three similar gasoline packages achieving down to 75 g/km on the NEDC procedure. Details on the technologies included and the technology package costs are included in the Annex. These technologies are compared with electric vehicles in the ranges of NEDC 150-km (EV150) and 300-km (EV300) under three emissions accounting cases.

Several key findings result from the cost-effectiveness analysis shown in Figure 5. Applying average electric vehicle grid emissions, the 150-km electric vehicle package is approximately equivalent in its cost-effectiveness to the advanced hybrid

packages (slightly more cost effective than the diesel hybrid, less so than the gasoline hybrid), but the 300-km electric vehicle is at least double the cost per CO₂ reduction. The use of zero g/km accounting reduces the cost per CO₂ reduction of electric vehicles by 33%. With the use of zero g/km accounting, the lower cost 150-km electric vehicle becomes more cost effective than the hybrids. The use of the 2.0 multiplier plus zero g/km accounting reduces the cost per CO₂ reduction of electric vehicles by 66%, as compared with accurate electric grid accounting without multipliers. With zero g/km and a multiplier of 2.0, both electric vehicles are more cost-effective than the hybrids, and the EV150 would even have better cost-effectiveness than the advanced efficiency technology packages.

Combustion vehicle CO₂ emissions. Conventional vehicle CO₂ g/km levels through 2030 in Europe depend on whether electric vehicles are counted as having zero emissions and whether each is counted as multiple vehicles. To

analyze the impact on the fleet, a fixed scenario where Europe regulations see reduced CO₂ emissions at 6% per year for new model year 2021–2030 vehicles. To analyze this scenario a fixed scenario where Europe regulations see reduced CO₂ emissions at 6% per year for new model year 2021–2030, drawing upon the same analysis from above (i.e., Meszler et al., 2016) which examines the ability to minimize technology costs to achieve lower g/km CO₂ levels in the 2020–2030 time frame. Based on the Meszler et al. analysis of minimum compliance cost scenario for 2025–2030 standards this analysis applies a scenario for increasing electric vehicle shares from 9% in 2025 up to 28% by 2030.

Figure 6 illustrates the impact of the three electric vehicle accounting scenarios, assuming a given electric vehicle market share (see the gray hashed line, right axis) on the average CO₂ emission levels of the remaining new combustion vehicles. As above, the CO₂ emissions are based on the NEDC test procedure. As depicted in

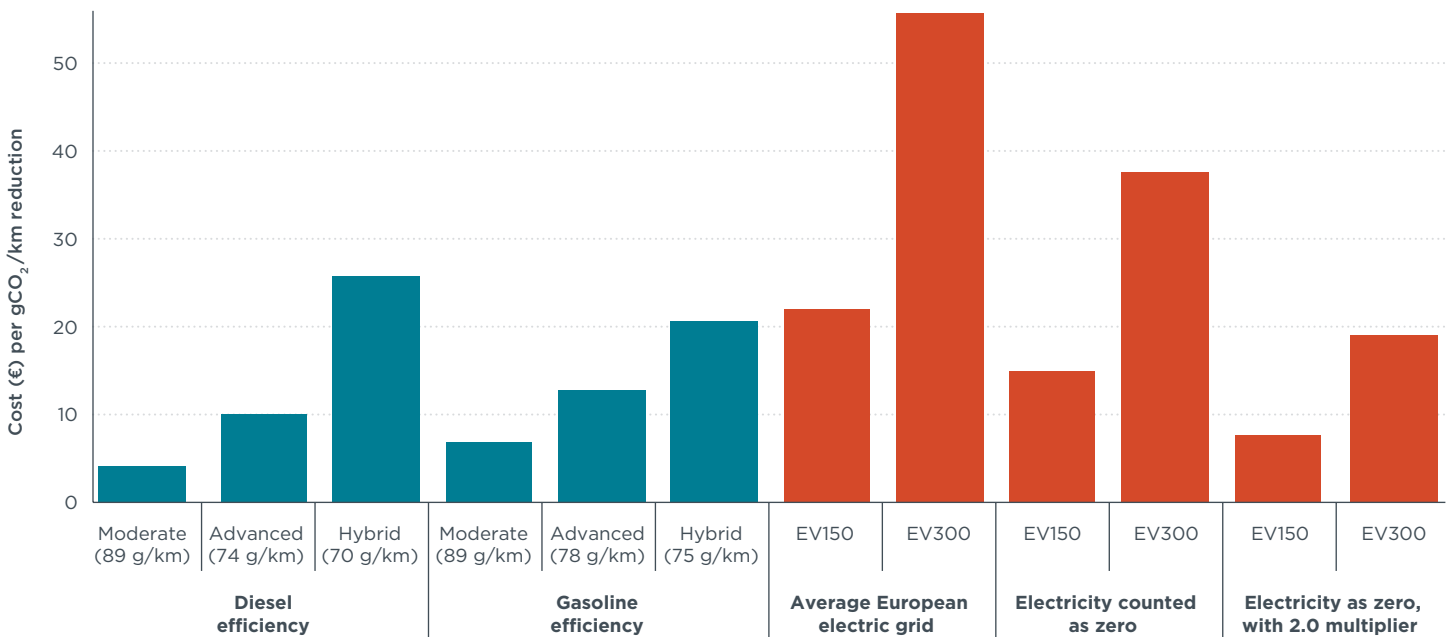


Figure 5. CO₂ reduction cost-effectiveness of gasoline efficiency and electric vehicle packages under various electric vehicle accounting mechanisms in Europe

the figure, the CO₂ levels of the conventional combustion (i.e., non-plug-in electric) portion of the vehicle fleet are greatly affected by potential regulatory incentives in the 2025-2030 time frame. The blue CO₂ line is for the CO₂ target, regardless of electric vehicles, reducing CO₂ emissions by 6% year for 2022-2030. Moving up in the chart, the green line reflects the inclusion of average upstream grid emissions for electric vehicles, where combustion vehicles would reduce CO₂ by 3.4% per year for 2020-2030. The blue and green scenarios achieve the same overall CO₂ benefit (the overall benefits of the scenarios is addressed in Table 2 below).

The two additional lines in Figure 6 where greater incentives are given reflect scenarios with a key difference from the blue and green scenarios. The scenarios shown as dashed yellow and dashed red lines reflect two ways to implement the same CO₂ standards, but where the incentives result in achieving somewhat less overall CO₂ emission benefit than the blue and green scenarios. The dashed yellow line reflects counting grid emissions

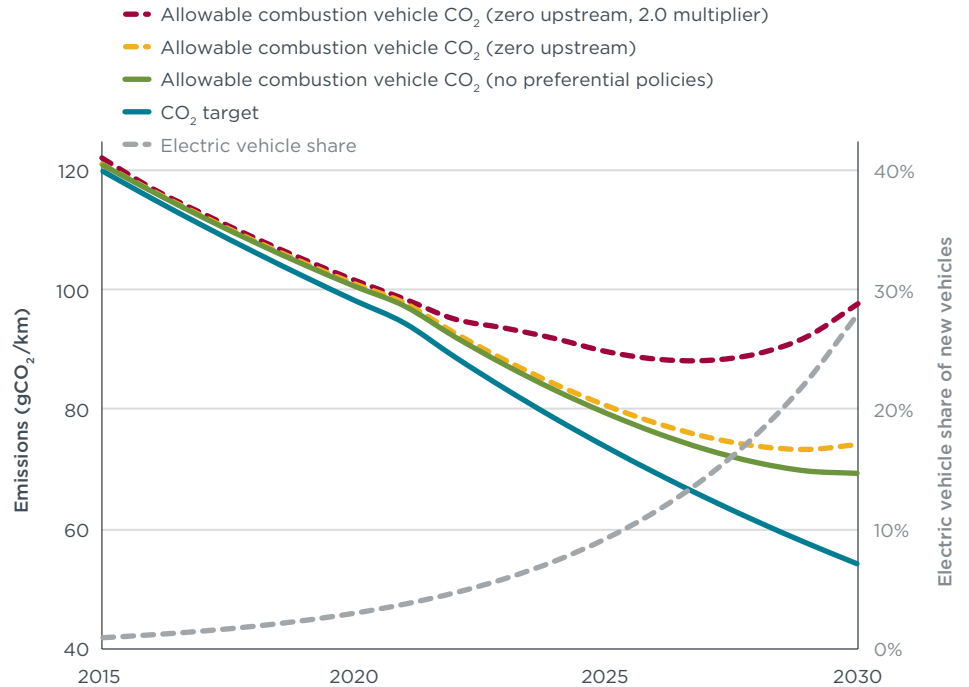


Figure 6. Impact of three electric vehicle accounting cases on combustion vehicle efficiency, for given CO₂ stringency and electric vehicle penetration through 2030 in Europe

as zero for electric vehicles, where combustion vehicles would reduce CO₂ by about 2.8% per year. The dashed red line reflects counting grid emissions as zero and providing a 2.0 multiplier for electric vehicles, where combustion vehicles would essentially be allowed to

produce about the same CO₂ emissions in 2030 as in 2021.

Considering the importance of the CO₂ standards to promote combustion vehicle efficiency, I provide additional quantification of the non-electric

Table 2. Summary of 2020-2030 Europe cases for electric vehicle regulatory incentives

Case	Electric vehicle Share in 2030	Internal combustion engine efficiency			Reduction in 2020-2030 CO ₂ emissions ^a (million metric tons)		Loss of CO ₂ benefits from preferential electric vehicle incentives
		Annual g/km CO ₂ change 2020-2030	Test cycle CO ₂ in 2030 (g/km)	Real-world fuel consumption in 2030 ^b (L/100 km)	Reduction from flat 2020+ g/km standards	Reduction from performance standards	
Performance standard with all combustion vehicles	0%	-5.8%	54	3.2	1,384	0	0%
Electric vehicle penetration (no preferential policies)	28%	-3.4%	69	4.1	1,384	0	0%
Electric vehicle penetration (zero-upstream incentive)	28%	-2.8%	74	4.4	1,295	90	6%
Electric vehicle penetration (zero-upstream, 2.0 multiplier incentives)	28%	-0.1%	98	5.8	822	562	41%

^a Assumes 180,000 kilometer average vehicle lifetime

^b Gasoline equivalent miles per gallon, based on 8,887 gCO₂ per gallon; assumes real world fuel use 40% higher than test cycle

fleet based on the scenarios analyzed above. The increasingly stringent 2030 standard, if there were no electric vehicles, would achieve 54 g/km in NEDC test-cycle CO₂ emissions, down from 120 g/km in 2015. With the penetration of 28% electric vehicles, depending on the accounting method for those electric vehicles, the average combustion vehicle CO₂ for a 2030-compliant fleet could differ very widely. With scientifically accurate inclusion of grid emissions for electric vehicles, combustion vehicles would achieve 69 g/km, whereas counting grid emissions as zero for electric vehicles results in 74 g/km in test-cycle CO₂ emissions. By counting grid emissions as zero and providing a 2.0 multiplier for electric vehicles to comply with a 2030 standard of 54 g/km, combustion vehicles would achieve 98 g/km, essentially the same as in 2020.

Environmental impact. Table 2 summarizes several of the key results from above and the impact of various potential electric vehicle incentive mechanisms for new 2020–2030 vehicles in Europe. As described, I assume the extension of the standards at 6% annual CO₂ reduction for 2022–2030, and a 28% new-vehicle market share for electric vehicles in 2030. As shown, the cases with more regulatory incentives for electric vehicles result in less improvement in the combustion vehicles. There is also a substantial impact of the incentive mechanisms on the overall environmental benefits from the regulations. Counting electric vehicles as having zero emissions would reduce the overall benefits from new 2020–2030 vehicles by 6%. The eroded benefits from zero CO₂ accounting remain so low because electric vehicle upstream grid CO₂ emissions are so much lower than average combustion vehicle lifecycle emissions and because electric vehicles use increasingly lower-carbon electricity over their lifetimes. Counting

electric vehicles as zero upstream emissions and including a multiplier of 2.0 would result in a loss of 41% of the CO₂ benefits from all the new 2020–2030 vehicles.

IV. Conclusions and discussion

This work builds upon two analyses of future efficiency and CO₂ standards—for the United States and Europe. Beginning from the existing regulations, adopted through 2025 for the United States and through 2021 for Europe, I apply hypothetical extensions of the standards, reducing new vehicle CO₂ emissions by 6% annually through 2030. Two previous studies (Lutsey et al., 2017; Meszler et al., 2016) are applied in this analysis because of their rigorous analysis of technologies, including advanced combustion and electric vehicle technologies, and their associated costs in this time frame. I conclude with a discussion of the potential implications for upcoming regulations for the United States, Europe, and elsewhere.

USING REGULATORY MULTIPLIERS AND SUPER CREDITS

The analysis indicates that the use of electric vehicle multipliers or super-credits come with a substantial environmental cost. The positive aspect of these incentives is that they greatly improve the cost-effectiveness for automakers of using electric vehicles as a compliance strategy, reducing the cost per CO₂ reduction by 45–66%, as compared to appropriate upstream grid accounting. However, as electric vehicle shares continue to increase above 5%, vehicle efficiency improvements are increasingly undermined due to the excessive preferential credit given to electric vehicles from such multipliers or super-credits.

The analysis of U.S. and European CO₂ targets through 2030 especially

illustrates that multipliers are counter-productive long-term vehicle policy. With electric vehicle penetration above 20% of the new fleet, multipliers have the perverse consequence of dramatically eroding the environmental benefits from the CO₂ standards. In the U.S. case, a 23% penetration of electric vehicles results in a 26% loss in the U.S. regulatory program's CO₂ benefits when multipliers and zero-upstream emission accounting are used for electric vehicles. The use of the multipliers on top of zero-upstream accounting essentially multiplies the eroded CO₂ benefits by a factor of seven in this U.S. case. The artificial credits also greatly diminish efficiency improvements in the rest of the fleet. In the U.S. case, fuel efficiency in 2030 could be about the same in 2024, even with continually improving efficiency standards over that period.

In the European case, the environmental and energy impacts of super-credits are more dramatic. With electric vehicle penetration at 28% of new vehicle sales in Europe, the regulation loses 41% of its intended CO₂ benefits when super credits are allowed along with zero-upstream accounting—essentially multiplying the eroded CO₂ benefits by a factor of six. The relative CO₂ losses from super-credits are greater in the European case because for its 2022–2030 standards, CO₂ levels are lower already and projected electric vehicle growth is greater. With 28% of new vehicles becoming electric with increasingly stringent 2030 CO₂ standards, a multiplier of 2.0 allows the remaining new combustion vehicles to have approximately the same CO₂ emission levels in 2030 as in 2020, and still make for a compliant fleet. Such a scenario would amount to an enormous lost opportunity to push the gasoline and diesel combustion fleet with known, cost-effective efficiency technologies. With such a significant erosion of the intended environmental benefits, it is clear that technology

super-credits for 2025 and beyond amounts to poor environmental policy.

USING ZERO GRAM PER MILE OR KILOMETER ACCOUNTING

This analysis indicates that there is a limited place for preferential incentives for electric vehicles within the efficiency and CO₂ regulations. Although multipliers provide rather excessive incentives, zero gram per mile or kilometer CO₂ accounting in regulations could provide a smart balance—substantially improving cost-effectiveness of electric vehicle deployment for automakers, with a rather limited overall societal loss. Accounting for electric vehicles as having zero CO₂ emissions improves the cost-effectiveness of the vehicles as a compliance strategy, reducing the cost per CO₂ reduction by 23–33%, as compared to more scientifically correct upstream grid accounting. This puts lower-range electric vehicles on par with advanced combustion and hybrid efficiency technology. This is a substantial enticement to automakers deliberating greater deployment of electric vehicles versus other technologies. Doing so comes at a modest environmental cost, losing approximately 4–6% of regulatory CO₂ benefits as electric vehicles are gradually deployed in the fleet through 2030. As compared to the scenarios where multipliers or super-credits erode up to 26–41% of the environmental benefits, accounting electric vehicles as zero provides a reasonable tradeoff to spur the development of the market.

A key reason that using zero CO₂ accounting minimally erodes CO₂ benefits is that electric vehicles have inherently very low CO₂ emissions due to their much greater on-vehicle efficiency and their electricity's lower carbon energy sources. Powering electric vehicles on average electric grids in 2015 already provides substantial CO₂ benefits: 50–70% lower CO₂ than average light-duty vehicles in the U.S. and Europe. The benefits

tend to be even greater where most electric vehicles are sold, for example in California and Norway. Continued grid improvements, as more renewable energy sources come on line, ensures that the electric vehicle CO₂ advantage grows further as electric vehicles age. The International Energy Agency's projected grid trajectory indicates that grid carbon intensity from 2013–2030 will be reduced by 42% in Europe and 28% in the United States due to expected new policies (IEA, 2015). As a result, zero-gram CO₂ accounting provides a reasonable incentive, until the fleet has more electric vehicles and they are integrated in a true technology-neutral performance standard.

The use of zero-emissions accounting of electric vehicles, which have known quantifiable emissions, is typically seen as debatable or objectionable to stakeholders that are interested in the environmental outcome. Nonetheless, regulatory agencies continue to see the merits in incentivizing electric vehicles, especially due to their long-term prospects to decarbonize the transport sector. There are other policies or programs, outside the regulations, that could constructively address these “ignored” upstream emissions as electric vehicles enter the fleet. For example, electric utilities and automakers have a number of programs that are working to link electric vehicle charging with renewable power that is coming on line (Hall and Lutsey, 2017). Alternatively, automakers could purchase renewable electricity credits, or purchase and retire the equivalent CO₂ credits, for the electric vehicles they sell, and then market the vehicles as carbon-neutral (Lutsey and Sperling, 2012).

ELECTRIC VEHICLES IN U.S. REGULATION

These findings have relevance for the U.S. market context, where California could, once again lead the nation by establishing the CO₂ and electric vehicle regulations by extending them

to 2030. California has long established the use of performance standards, including the accounting for the fuel cycle and grid emissions for electric vehicles, along with direct regulations for electric vehicle deployment. This remains appropriate. Especially considering uncertainty whether the national U.S. fleet could surpass a 15% electric vehicle share in the 2030 new-vehicle market, continued direct regulations to further promote electric vehicles is still important to launch the market. In the federal U.S. context, this analysis suggests that continued use of zero gram per mile with company-specific production caps (generally up to 200,000), and permanently eliminating the use of technology-specific multipliers after 2021, are warranted.

ELECTRIC VEHICLES IN EUROPE REGULATION

For Europe, there is more of a blank slate beyond 2021. There are no provisions in place for 2025 or 2030 CO₂ standards, or for the associated incentive provisions for electric vehicles for those years. Several ideas have been suggested for Europe, such as flexible compliance provisions that allow more lax CO₂ standards for companies that deploy greater percentages of electric vehicles (e.g., see Element Energy, 2016). In essence, the use of artificial credits like zero g/km does exactly that. It allows companies that produce more electric vehicles to have greater leniency with regard to improving their combustion fleets, while also compromising some amount of CO₂ benefits, to serve the long-term goal of accelerating the transition to electric drive.

Figure 7 illustrates the implications of zero g/km accounting to provide options for companies to opt for lesser or greater electric vehicle penetration to comply with the same numerical CO₂ standards. As shown, under hypothetical 6% per year CO₂ standards with zero g/km electric vehicle accounting, two

companies could take very different compliance approaches. One company (yellow in the figure) might seek to more progressively deploy electric vehicles. In 2030, this electric-focused company could ramp up to a 35% electric vehicle share, with their combustion fleet reducing CO₂ emissions by about 2% annually to reach 82 g/km to comply with the 2030 CO₂ standards. A less electric-focused company (blue in the figure) could instead deploy far less electric vehicles, up to 20% in 2030, and reduce its combustion fleet CO₂ emissions at about 4% per year to 67 g/km by 2030, to comply with the same 2030 standards.

As a result, I find that with the simple regulatory provision of continuing 0 g/km accounting, the standards will effectively allow multiple automaker compliance paths to deploy more, or less, electric vehicles according to their technical competencies. The analysis clearly illustrates the merits of continuing zero g/km to reward—but not require or overcompensate—companies to shift to electric vehicles.

ELECTRIC VEHICLES BROADLY

Beyond the United States and Europe, this analysis of the use of regulatory incentives for electric vehicles has much broader implications. The vast majority of the world’s automobile sales are subject to efficiency or CO₂ standards, and governments tend to closely watch the market and regulatory developments of the United States and Europe. Most governments are seeking to meet a combination of climate, energy dependence, and air quality goals and are also trying to shift their fleets to electric vehicles. China in particular is at a similar strategic point in its efficiency standards and electric vehicle development. Canada, Mexico, Brazil, India, and other markets are facing similar questions. The findings of this analysis, on the appropriate and limited use of regulatory incentives for

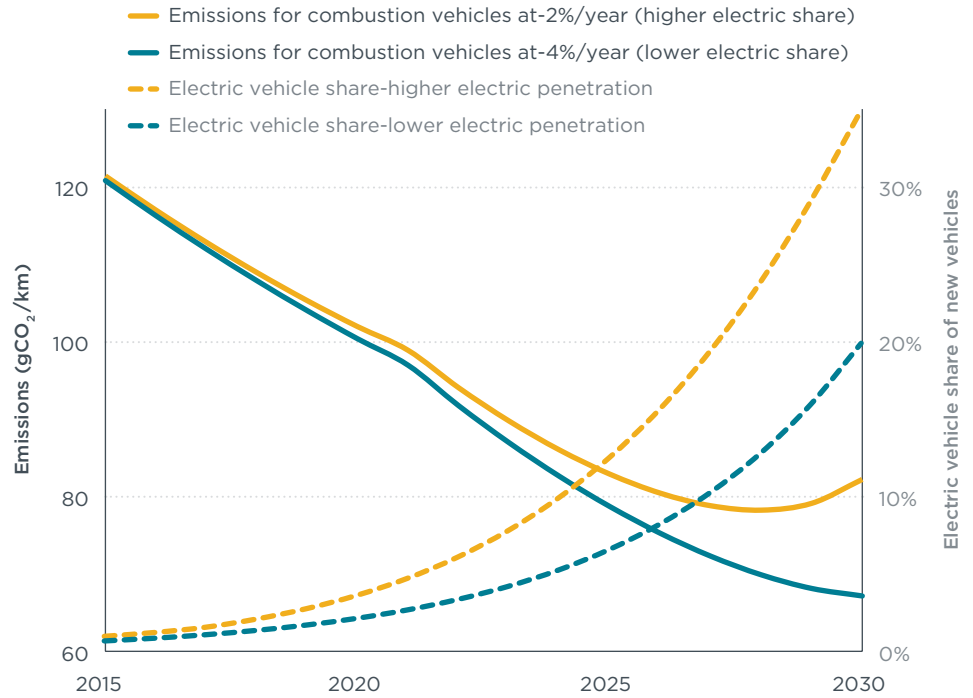


Figure 7. Illustration of higher and lower electric vehicle penetration scenarios to meet 6% per year CO₂ emission targets for 2021–2030 in Europe

electric vehicles, are applicable for all these regulations.

Although this paper is focused on a couple of smaller regulatory provisions regarding electric vehicles, there is a much broader set of policies that promote electric vehicles. Obviously, less stringent standards than discussed here will do far less to promote all high-efficiency or electric vehicle options, putting more pressure on non-regulatory actions to spur the manufacture and sale of cleaner cars. Efficiency and CO₂ regulations are not the only way to support electrification. Comprehensive policies, like those in California, China, the Netherlands, and Norway, support electric vehicles with consumer incentives, sustained education campaigns, and charging infrastructure programs (e.g., see Hall et al., 2017; Lutsey, 2015). Many of the most successful markets have more forceful mandates and local vehicle licensing restrictions. China in 2016 accounted for over half the global electric vehicle market, whereas California accounted

for half of the U.S. market; these cases underscore the major impact of direct requirements for electric vehicles, in addition to efficiency regulations and fiscal incentives. It will take a strong combination of long-term regulation, incentives, infrastructure, and education to break down prevailing barriers and spur sustained market growth for electric vehicles.

Electric vehicles offer the potential for the world to break the historical cycle in which policy and incentives have failed to pave the way for a transition to an alternative to petroleum fuels. Vehicle efficiency and CO₂ regulations around the world have always held immense potential to increase and shift industry investments in emerging technologies. Any stringent standards can help drive electric vehicles into the market. Such regulations, if developed with smart built-in incentives, clear targets for electric vehicles, and complementary consumer policies, can be highly effective in accelerating the deployment of electric vehicles.

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Annex

This section includes additional data assumptions from the analysis above. In Table A1, shows a summary of the technology packages that are included in Figure 2 (from Lutsey et al., 2017). In Table A2 summarizes the technology packages from Figure 5 (from Meszler et al., 2016). Additional data assumptions are shown for the fleet analysis of electric vehicles, and their associated grid and upstream fuel-cycle energy and CO₂ calculations are shown in Table A3.

Table A1. Technology package, CO₂ emissions, efficiency, and cost for 2025 cost-effectiveness analysis for U.S. passenger car

	Technology package	Real World fuel economy (mpg)	Test cycle Electricity efficiency (kWh/mile)	Test cycle CO ₂ (g/mile)	Technology cost (2015 USD)
Gasoline	Incremental	31	-	221	389
	Moderate	47	-	145	1,433
	Advanced	51	-	134	1,744
	Hybrid	58	-	118	2,906
Electric	EV (100 mile range)	-	0.20	0	4,594
	EV (200 mile range)	-	0.20	0	7,190

From Lutsey et al., 2017 technology packages (Vehicle type #3)

Table A2. Technology package, CO₂ emissions, efficiency, and cost for 2025 cost-effectiveness analysis for Europe C-class car

	Technology package	Real World fuel Consumption (L/100km)	Test cycle electricity (kWh/km)	Test Cycle CO ₂ (g/km)	Technology Cost (2014 Euro)
Diesel	Moderate	3.8	-	89	104
	Advanced	3.2	-	74	403
	Hybrid	3.0	-	70	1,156
Gasoline	Moderate	3.9	-	91	522
	Advanced	3.3	-	78	1,153
	Hybrid	3.2	-	75	1,961
Electric	EV (150 km range NEDC)	-	0.12	0	2,102
	EV (300 km range NEDC)	-	0.12	0	5,338

From Meszler et al., 2016 technology packages, lower bound costs (C-Class vehicle)

Table A3. Electric vehicle fleet analysis assumptions

Assumption	United States	Europe
Fleet electric vehicle efficiency, test cycle 2015	0.24 kWh/mi	0.15 kWh/km
Electric vehicle technical efficiency annual improvement	1.5%	1.5%
Transmission and distribution efficiency factor	0.935	0.935
Charging efficiency factor	0.93	0.93
Upstream feedstock emission factor for grid energy sources	1.20	1.20
Upstream feedstock emission factor for petroleum fuels	1.28	1.28
Test cycle to real-world multiplier for additional fuel use by combustion vehicles	1.30	1.40
Test cycle to real-world multiplier for additional fuel use by combustion vehicles	1.43	1.50
Gasoline CO₂ energy intensity, gasoline	8,887 gCO ₂ /gallon (vehicle) 2,478 gCO ₂ /gallon (upstream)	8,887 gCO ₂ /gallon (vehicle) 2,478 gCO ₂ /gallon (upstream)
Gasoline CO₂ energy intensity, diesel	10,180 gCO ₂ /gallon (vehicle) 2,839 gCO ₂ /gallon (upstream)	10,180 gCO ₂ /gallon (vehicle) 2,839 gCO ₂ /gallon (upstream)
Grid CO₂ intensity, 2015 (gCO₂/kWh)	522 (US) 282 (California)	276 (Europe) 425 (Germany) 451 (Netherlands) 389 (United Kingdom) 35 (France) 17 (Norway)
Average grid CO₂ intensity reduction through 2030	3% (US)	3% (Europe)
Average lifetime travel	180,000 mi	180,000 km
Percent of plug-in hybrid electric vehicle vehicle travel powered by grid power (i.e., utility factor)	0.35 (2015) 0.63 (2030)	0.35 (2015) 0.63 (2030)