CLEAN TRUCKS, BIG BUCKS

California Energy Policy Simulator evaluation of the proposed Advanced Clean Trucks Rule

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Cover photo credit

Chesky W/Getty Images: The image shows a hybrid electric truck being charging at charging station - stock photo.

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EXECUTIVE SUMMARY

The California Air Resources Board (CARB) has proposed new zero-emission vehicle (ZEV) requirements through its Advanced Clean Trucks (ACT) proceeding. Under the revised proposal released April 28, 2020, the regulation would require about 60 percent of new medium- and heavy-duty trucks sold in California to be ZEVs by 2035.

This report evaluates the proposed rule using the California Energy Policy Simulator (EPS). First, we provide an independent check of the conclusions reached in CARB's regulatory analysis. We modify key variables in the California EPS, drawing on the evidence CARB has collected and find that the effects of the proposed rule are similar to those found in CARB's analysis. Local and global air pollution benefits are almost indistinguishable, as shown in Table ES-1. The California EPS finds the proposed rule saves $7.3 billion through 2040 compared to the $6.0 billion CARB estimates; variations in how the models treat vehicle cost largely explain this difference.[1] Importantly, savings will continue to accrue beyond 2040, so these findings should be viewed as conservative.

This research also investigates the effects of a lower battery cost assumption than that underlying CARB's analysis. Battery costs have plunged 87 percent since 2010, and forecasts point to continuing cost reductions (Henze 2019). Battery cost explains most of the cost difference between electric and internal combustion engine vehicles, so it is an important input assumption. CARB's modeling projects that batteries for medium- and heavy-duty trucks will cost more than batteries for passenger vehicles. We identify research indicating that future truck battery prices are unlikely to be as high as expected in CARB's analysis. When the proposed rule is evaluated using lower battery cost assumptions, the California EPS finds total savings increase by $5 billion to more than $12 billion through 2040.

EMISSIONS ANALYSIS

Cleaner air and public health benefits for Californians suffering from some of the nation's worst air quality are the primary goals of the rule. The truck rule is also an important step in the evolution of California's climate strategy. Table ES-1 shows similar reductions in nitrogen oxides (NOx) emissions as well as carbon pollution, i.e., carbon dioxide equivalent (CO_2e), in results found by the California EPS and CARB.

Table ES-1. Air quality and climate benefits from the proposed rule through 2040

	CARB's analysis	California EPS
NOx emissions reductions	58,000 tons	60,000 tons
CO_2e emissions reductions	17.3 MMT of CO_2e	17.6 MMT of CO_2e

Source: California EPS and CARB (2020c)

[1] All monetary results are calculated in 2018 dollars.

Air quality improvements from the proposed rule are projected to deliver $8.9 billion in public health benefits, including 943 premature deaths avoided through 2040.[2]

ECONOMIC OPPORTUNITY

Evaluation using the California EPS finds the proposed ACT rule generates more than $7 billion in savings, a figure roughly $1 billion higher than CARB's estimate. The difference is largely due to CARB's inclusion of the financing costs associated with vehicle purchases. The California EPS does not include financing charges, instead representing vehicle costs as lump sum purchases in the year in which they take place.

CARB's analysis assumes there will be a five-year delay in translating reductions in passenger car battery costs to the truck battery market. This report discusses research suggesting that the larger battery packs needed for medium- and heavy-duty trucks could offer a cost advantage over the smaller batteries needed for passenger vehicles, making it likely that battery prices for trucks will more closely track those for cars. To evaluate the implications, we develop an alternative forecast for truck battery costs based on a two-year delay, with associated results labeled "lower battery costs" in Table ES-2 and throughout this report.

Table ES-2. Total savings from the proposed ACT rule through 2040

	CARB assessment	EPS results	EPS results (lower battery costs)
Total savings (2018 $s)	$5.9 billion	$7.3 billion	$12 billion

Source: California EPS and CARB (2020c)

Figure ES-1 shows the progression of direct impacts with costs shown below and savings above the $0 line.[3] Savings on fuel and maintenance plus Low Carbon Fuel Standard (LCFS) revenue far exceed higher manufacturing costs (for new vehicles) and infrastructure costs (for charging). Fuel savings are attributable to the lower cost of powering zero-emission trucks with electricity compared to diesel, while LCFS revenue represents the value stream available to electric trucks owners.

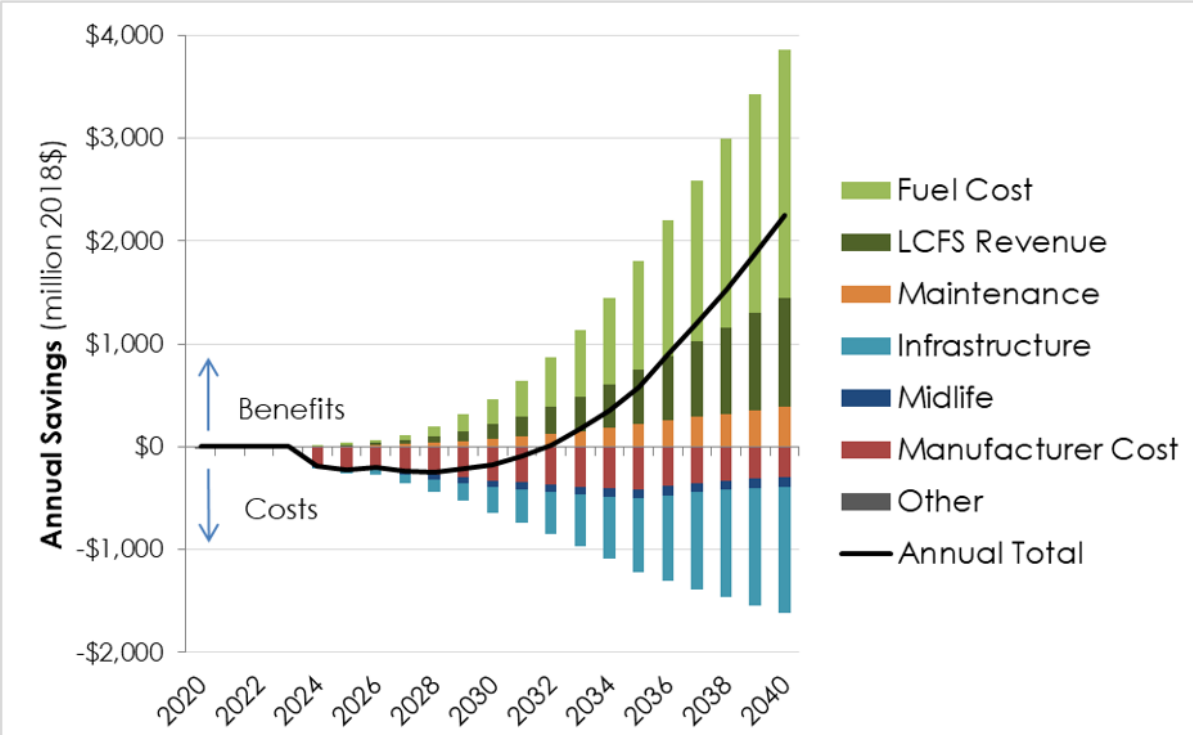
Figure ES-1 provides results in undiscounted terms, as saving and cost results are reported in CARB's analysis. We also provide results in terms of net present value, using the 5 percent rate that CARB employs in evaluating effects on a total cost of ownership basis.[4] CARB intends this method of valuation to be representative of the method a fleet owner would use in comparing different technology options.

[2] See Table II-2 in CARB 2020c.

[3] The figure is formatted to parallel Figure IV-4: Total Estimated Direct Costs of Proposed Updates Relative to the BAU Baseline (CARB 2020c).

[4] The total cost of ownership analysis is found in Appendix H (CARB 2019b).

Figure ES-1. Benefit and cost effects by year through 2040



Source: California EPS

Table ES-3 presents undiscounted and discounted perspectives and adds a new metric to results: average cost per avoided ton of CO_2e. We calculate average cost as total savings through 2040 divided by emissions reductions expected from the proposed rule through 2040.

Table ES-3. Total savings calculated as average cost and present value (2018 $s)

	EPS results with CARB battery costs		EPS results with lower battery costs	
	Total savings	Average savings per avoided ton of CO_2e*	Total savings	Average savings per avoided ton of CO_2e*
Undiscounted	$7.3 billion	$414 per metric ton	$12.4 billion	$708 per metric ton
Discounted (5%)	$6.3 billion	$358 per metric ton	$10.7 billion	$612 per metric ton

Source: California EPS and CARB (2020c)

While trends indicate that electric trucks ultimately will become less expensive to purchase than their conventional counterparts, electric trucks will have an additional upfront purchase cost in the earlier years of the proposed rule's implementation. While these costs will be more than offset over the lifetime of the vehicle by the fuel savings electric trucks provide, policymakers should develop new financing options to counterbalance the upfront cost difference and encourage broad uptake, particularly for small businesses without access to attractive financing terms. Fuel savings and other lower operating costs create an opportunity to arrange loan payback terms that align well with normal fleet business operations.

The value of good lung health looms especially large at this moment, as humanity battles a global pandemic with higher death rates in regions with more air pollution. The California EPS finds the proposed rule would eliminate significant quantities of smog-causing pollution, while also offering cost-effective reductions in climate pollution. Californians are particularly aware of the importance of climate change mitigation, having endured increasing dislocation and damage from wildfires supercharged by global warming. This research presents notable evidence of economic opportunity created by faster ZEV adoption. Technological innovation has opened up new opportunities for policy to achieve progress on multiple environmental and economic goals at the same time.

INTRODUCTION

This report provides an independent evaluation of the California Air Resources Board's (CARB) proposed Advanced Clean Trucks (ACT) rule, which would institute zero-emission vehicle (ZEV) requirements for medium- and heavy-duty trucks starting in 2024.

First and foremost, the proposed rule is a public health measure. Californians suffer from some of the nation's worst air pollution. Residents of Los Angeles are burdened with the country's worst smog, and seven of the ten nation's smoggiest cities are in California (American Lung Association 2020). Medium- and heavy-duty trucks are a major source of smog. Electric trucks, the leading advanced technology, also reduce the carbon pollution that causes climate change. The energy efficiency advantage of electric vehicles (EVs) and the relatively light carbon footprint of the state's electricity supply mean grid-connected EVs emit 75 percent fewer heat-trapping gases than diesel trucks today. These benefits will grow over time as the state converts to a zero-emission electricity grid by 2040 as required by Senate Bill 100.

To carry out the research for this report, we developed a customized version of the California Energy Policy Simulator (EPS), an open-source, quantitative model for policy analysis.[5] Two research questions motivated the analysis.

> **Research question #1:** How do the impact estimates obtained from the California EPS compare to CARB's findings when inputs are modified to parallel the evidentiary record developed through the ACT process?

To answer the first research question, we draw on a significant body of evidence, including new research that CARB conducted to support effective policy design. The regulatory analysis assumes a five-year lag before declines evident in the light-duty vehicle battery market are translated to the battery market for medium- or heavy-duty trucks. We consider it likely that battery-electric storage will be more affordable than is assumed in CARB's regulatory analysis, forming the basis for the second research question.

> **Research question #2:** How would results change if the cost of battery-electric storage for trucks is assumed to be closer to the cost of batteries in the light-duty market, specifically if a two-year delay as compared to the light-duty vehicle market is assumed rather than a five-year delay?

Comparing California EPS and CARB results, findings on emissions benefits are essentially indistinguishable and monetary saving estimates are also similar. Therefore, on the first research question, our research validates the regulatory analysis. California EPS results demonstrate that the analytical inputs developed to support the regulatory proceeding produce the depicted effects when tested through a separate modeling framework. On the second research question,

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[5] The web address for the California EPS homepage is: https://california.energypolicy.solutions/. Additional documentation regarding the model is available in our initial report (Busch and Orvis 2020).

when results are re-evaluated using lower battery costs, total savings amount to more than $12 billion through 2040, an increase in total savings of about $5 billion.

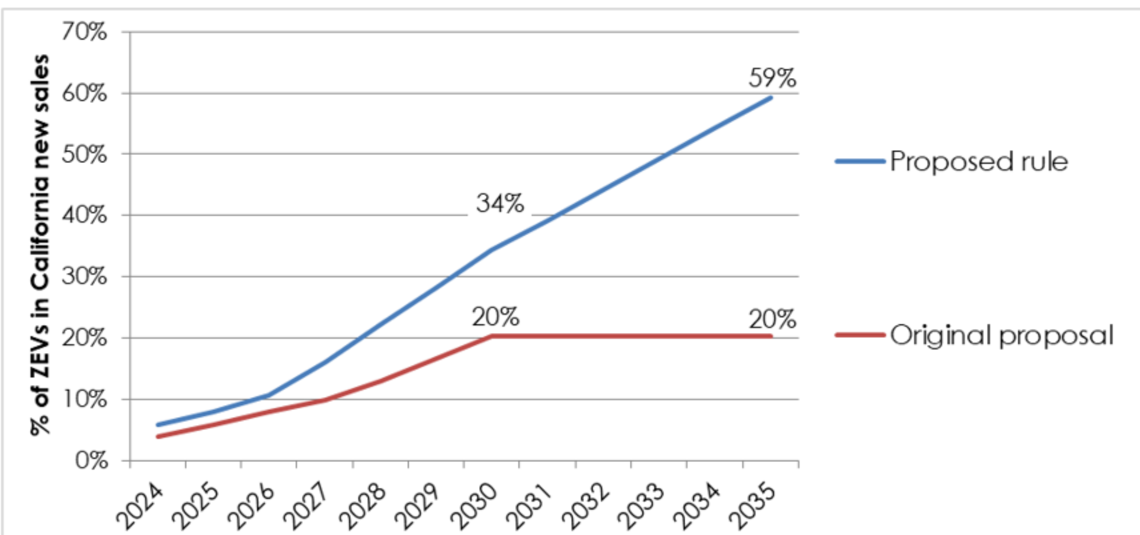
REQUIREMENTS OF THE PROPOSED RULE

The proposed rule seeks to "accelerate the widespread adoption of [ZEVs] in the medium- and heavy-duty truck sector."[6] The core compliance mechanism is a minimum performance standard for ZEVs as a percentage of each major truck manufacturer's new sales in California.

CARB's original ACT proposal was released in October 2019. A Lawrence Berkeley National Laboratory analysis concluded that the anticipated savings and the requirements of the statewide goal of carbon neutrality by 2045 call for consideration of more ambitious standards (McCall and Phadke 2019).

The revised rule currently under consideration, released on April 28, 2020, and referred to in this report simply as the "proposed rule," sets stronger standards. The original proposal would have ended the program in 2030, while the proposal rule extends the schedule while also ramping up the targeted rate of improvement, as illustrated in Figure 1.

Figure 1. Zero emission requirements for trucks, proposed rule and original proposal



Source: CARB (2019a, 2020a)

Figure 1 reflects an assumption that vehicle sales occur as in the sales forecast in CARB's regulatory analysis.[7] Some assumptions must be made to calculate the overall market requirement in any given year because the proposed rule would set different requirements for different types of trucks.

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[6] Quoting from page ES-1 of the *Initial Statement of Reasons* (CARB 2019a).

[7] The initial staff proposal (CARB 2019a, Table IX-2) gives annual sales by vehicle category from 2024 to 2030. To calculate the weighted average ZEV requirements, we found the average share of sales for each class over the 2024-2030 period and assumed these are the shares each year from 2024 to 2035.

Rule requirements are based on different classes of trucks and their relative readiness for the transition to ZEVs. Table 1 lists ZEV performance requirements in the proposed rule.

Table 1. Annual requirements in the proposed rule

	Zero emission performance thresholds		
Model year	Class 2b-3	Class 4-8	Class 7-8 tractors
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	45%
2034	50%	70%	50%
2035	55%	75%	55%

Source: CARB (2020a)

To model the policy in the California EPS, we translated the three principal groupings of truck types in CARB's analysis, those listed in Table 1, into the medium- and heavy-duty types of freight trucks designated in the California EPS. Table 2 provides details[8] of the reclassification, defining heavy-duty trucks as equal to CARB's "class 7-8 tractor" group and including all others in the medium-duty category.

Table 2: CARB truck types mapped to EPS truck types[8]

Trucks in CARB's modeling	Trucks in California EPS modeling
Class 2b-3	Medium-duty truck
Class 4-8	Medium-duty truck
Class 7-8 tractor	Heavy-duty truck

Several flexibility mechanisms are embedded in program design to encourage cost-effectiveness. One example is that the rule's requirements automatically adjust to market conditions depending on the distribution of new sales across different types of trucks. Another example is the credit trading market envisioned to work in a manner similar to the existing light-duty vehicle mandate. Manufacturers that exceed minimum requirements earn surplus credits they can bank

[8] For closer alignment with terminology familiar to policymakers and participants in the ACT proceeding, this report uses the term "medium-duty trucks" for what EPS terminology normally refers to as "light duty vehicle – freight" conveyances. School buses and two of the other bus categories covered by the proposed rule are included in the medium-duty vehicle category. Typically, buses are tracked separately in the EPS framework.

for future use or sell to other manufacturers. The possibility of accruing the valuable commodity of surplus credits encourages manufacturers with the most competitive technology to go beyond minimum requirements.

BATTERY COST EXPECTATIONS

EVs have long been recognized as much more energy efficient than vehicles with internal combustion engines. In times past, higher upfront purchase costs overwhelmed this fuel economy advantage of EVs. Despite recent cost declines and performance advances, batteries still account for most of the cost difference between electric and conventional vehicles.

Battery cost has dropped by 87 percent in real terms since 2010, to $156/kilowatt-hour (kWh) (Henze 2019). Most technology analysts expect that battery costs will continue to fall due to continued learning by doing, economies of scale with existing technologies, and development of new chemistries. For example, in the run-up to publication of this report, reports surfaced that Tesla and partners would soon announce the crossing of a new affordability threshold, thanks to an innovative cobalt-free lithium iron phosphate battery, suggesting that battery packs at a cost below $80 per kWh may soon be available (Shirouzu and Lienert 2020).

Because of these battery trends, the cost to purchase electric cars is expected to fall and reach cost parity with the purchase price of conventional passenger vehicles over the next few years. By 2028 at the latest, ICCT expects all electric passenger vehicles to cost less to purchase than their fossil-fueled equivalents in the United States.[9] On a total cost of ownership basis, EVs already cost less under some circumstances.[10]

CARB's regulatory analysis assumes that the cost of batteries for trucks will be higher than for cars or SUVs, i.e., the light-duty vehicle market. Specifically, future prices are expected to follow the same trend as observed in the light-duty vehicle market using Bloomberg New Energy Finance (BNEF) cost analysis and projections, except on a five-year delay. So, the 2020 price would be expected to equal the light-duty vehicle price from 2015. In 2021, the price of battery packs for trucks would equal the light-duty price from 2016, and so on. Other than the indication that this assumption was suggested by industry stakeholders, we see no basis for taking this analytical approach.[11]

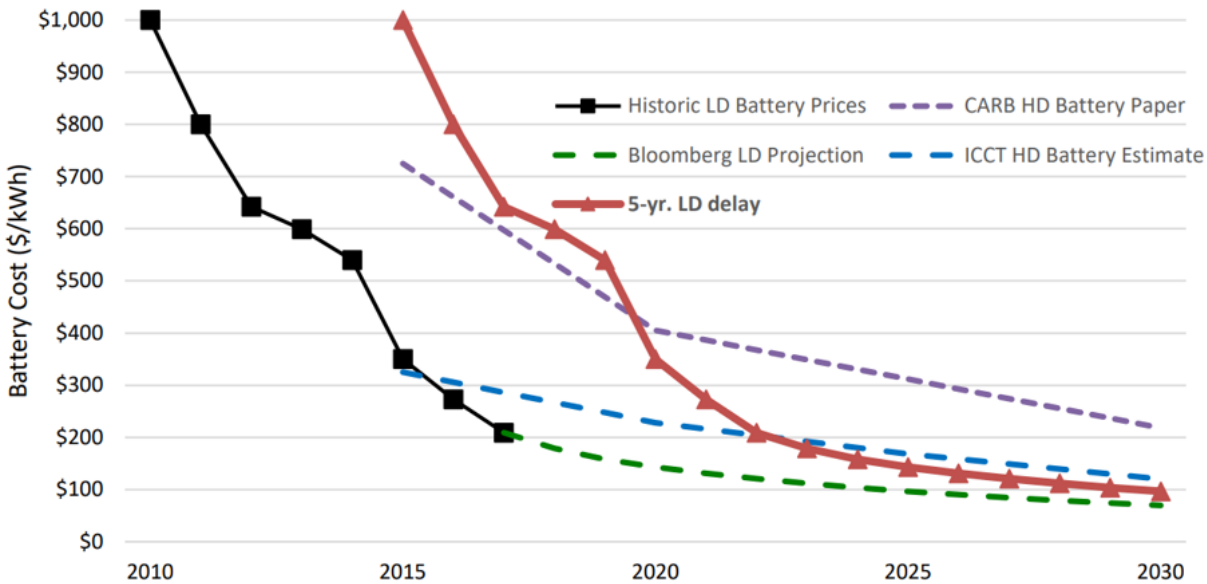
[9] See Lutsey (2019), Figure 4.

[10] For example, at the average price for regular unleaded gas in California in 2019 ($3.60 per gallon according to the US Energy Information Administration), and otherwise using the default assumptions in Pacific Gas & Electric's EV calculator, five-year savings amount to $692 for a GM Bolt over a Honda Insight Touring; the Kia Soul electric saves $5,296 over the Kia Soul gasoline-fueled model; and the Hyundai Ioniq electric saves $7,809 over the Hyundai Ioniq gasoline-fueled model. These comparisons include consumer incentives of $2,800 for the Bolt and $10,300 for the Soul and Ioniq model. Also see Wappelhorst et al. (2020).

[11] Regulatory documentation states: "At the December 4th, 2018 [ACT] workgroup meeting, a number of manufacturers suggested we use light-duty battery prices with a five-year delay to reflect battery-price projections that are applicable to heavy-duty vehicles," (CARB 2019a), page IX 9-10.

In Figure 2 below[12], the curve labeled "5-yr LD delay" shows the future cost scenario for truck batteries used in CARB's evaluation of the proposed rule. The curve representing trends in battery costs for light-duty vehicles is labeled "Historic LD Battery Prices."

Figure 2. Battery cost expectations in CARB's regulatory analysis[12]



Source: CARB (2019a)

We note the existence of an engineering reason to expect that truck batteries will be less expensive on an energy-equivalent basis than batteries for electric cars. An ICCT report explains: "A decreasing pack-to-cell ratio with increasing pack capacity is assumed, meaning larger battery packs (e.g., for 250-mile range SUV) have lower per-kilowatt-hour pack costs."[13] Such engineering-based economies of scale are why the ICCT report forecasts that SUV batteries will cost about 10 percent less than compact car batteries by 2030.[14]

The same dynamics leading ICCT to expect that larger battery packs within the light duty market will cost less should also factor into battery pack pricing for medium- and heavy-duty trucks. The average medium- or heavy-duty truck battery will be larger capacity than the average light duty vehicle. We also note that the battery cells at the heart of battery-electric storage are not use-specific. On the other hand, with respect to the size of battery market in terms of number of units, light duty will always dwarf the medium- and heavy-duty scale of the light duty market, which is a factor putting upward pressure on cost from the perspective of production economies of scale.

[12] This figure is "Figure IX-3: Battery Price History and Projections," on page IX-10 in CARB (2019a).

[13] See Lutsey (2019) page 5. For more information, see footnote 6 on the same page, which cites Safoutin et al. (2018).

[14] See Lutsey (2019), Table 2, which shows the cost of SUV batteries dropping faster than compact car batteries over the 2018-2030 period. SUV batteries fall from 175 to 165 $/kWh and compact car batteries fall from 177 to 173 $/kWh.

On balance, we consider it likely battery costs for medium- and heavy-duty electric trucks more closely track the light duty market. As detailed further below, we also estimate results for the lower battery costs that were obtained on a two-year lag instead of the five-year delay in CARB's evaluation.

METHODS

The California EPS is a quantitative tool for evaluating the economic, environmental, and health impacts of energy policies. For this research, we developed a customized version of the California EPS by reprogramming dozens of key transportation-related variables in the model to align with evidence developed in the regulatory record.

We devoted particular attention to properly calibrating the model to capture the effect of the policy on new truck sales in California. Emissions effects in this report are calculated for the Assembly Bill 32 (2006) "boundary," i.e., reflecting emissions covered in the state's annual emission inventory. To correctly capture these effects, the model tracks overall truck miles driven by a broader set of vehicles, including trucks purchased out of state and later registered in California.

The research developed separate medium- and heavy-duty vehicle models to analyze the impacts of the proposed rule. Running these two customized models allows for more precise calibration of input variables for key variable differences between medium- and heavy-duty trucks, such as battery size.

For example, analyzing the effect of the proposed rule on heavy-duty trucks is a simple matter of setting the strength of the policy to reach 55 percent in 2035 as well as aligning the EPS policy schedule to match the year-over-year changes. Calibrating the policy for heavy-duty trucks is the most straightforward calculation because it corresponds to a single category in CARB's analysis, class 7-8 tractors. The medium-duty category requires blending truck classes kept separate in CARB's analysis. Input variables are found as the weighted average of California new truck sales in different classes. The input data files and program code to run the model are open-source resources, available here.

THE CALIFORNIA EPS

The EPS is a systems dynamics model combining elements of economic models, namely price responsiveness and other incentive effects, with engineering models and offering detailed technology specifications. The California EPS is an open-source model, accessible either through a web interface or the Vensim code, with freely downloadable input data.[15] Appendix B provides more details about input variable modifications and methodology used for this study.

[15] Web application address: https://california.energypolicy.solutions/. Download the Vensim model and input data at this address: https://california.energypolicy.solutions/docs/. Additional documentation found in Busch and Orvis (2020).

The California EPS accounts for “stock” and “flow” dynamics needed to track the evolution of California’s truck fleet over time. “Stocks” are variables whose values are carried forward from one time-step to the next. “Flows” are variables that increase or decrease stock levels. For this report, the number of trucks carried forward into the next year are the stock variables of interest and the purchase of new trucks or the retirement of trucks are flows of interest. The California EPS’s capital stock and flow modeling capabilities allows for year-by-year resolution on variables such as the number of vehicles, the fuels that power them, their fuel efficiency, for the stock of trucks as well as for new sales and retirements.

DEFINING THE BASELINE AND PROPOSED RULE SCENARIOS

Policy evaluation is carried out with the California EPS by comparing two policy scenarios.[16] Scenarios, driven by user-defined policy settings, are used to produce economy-wide representations of technology use, energy use, and travel demand. These and other outputs offer a complete picture of energy, emissions, and energy-related spending (covering private spending on capital, fuel, other operational and maintenance expenses, and impacts on government budgets through new spending or revenue). Together, the outputs of each EPS scenario provide a comprehensive, economy-wide accounting of direct expenditure effects, tracking cost categories quite similar to those considered in CARB’s analysis.

The ACT impact evaluation results below are calculated by comparing energy use, emissions, and a range of costs in the form of a Proposed Rule Scenario and a Baseline Scenario, in which assumptions are fully aligned with CARB’s. These scenarios compare energy use, emissions, and costs under two different possible futures.

The first research question is informed by comparing emissions with and without the proposed rule, comparing emissions in the Proposed Rule Scenario with those in the Baseline Scenario. The second research question—considering the effect of a two-year lag—is informed by comparing the Lower Battery Cost Scenario with the Baseline Scenario. Key details of each scenario follow.

Baseline Scenario

As in CARB’s analysis, the Baseline Scenario supposes no ACT rule is implemented. Under these circumstances, the Baseline Scenario includes the effects of the existing Low Carbon Fuel Standard as well as existing tailpipe pollutant standards that apply to trucks through 2027. Trends in sales of new medium- and heavy-duty trucks in California are based on data from the state’s EMFAC model, including a small number of electric medium-duty trucks. [17] There is no uptake of electric heavy-duty trucks in the Baseline Scenario. The carbon intensity of electricity is lowered over time in accordance with the Senate Bill 100 requirement for 60 percent renewable energy by 2030 and 100 percent carbon-free electricity by 2045.

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[16] Section 3.2 of the model documentation offers further discussion of how impact evaluation works in the California EPS: https://energyinnovation.org/wp-content/uploads/2020/05/Insights-from-the-California-Energy-Policy-Simulator_5.6.20.pdf

[17] The name “EMFAC” is derived from the term “EMission FACtor.” The EMFAC model web address is https://arb.ca.gov/emfac/emissions-inventory.

Proposed Rule Scenario

The Proposed Rule Scenario reflects the compliance requirements and schedule shown in Table 1 above. Having calibrated the model to California truck sales, it is straightforward to represent the proposed policy in the California EPS using the model's minimum EV sales policy lever. The policy works in the model just as it is formulated in the proposed rule, through the ramping up of future shares of new electric truck sales. CARB's analysis assumes that the value of LCFS credits created through truck electrification accrues to owners and is based on an assumed LCFS credit price of $125 per metric ton. LCFS prices have been above $150 per ton since June 2018.[18] This assumption likely undervalues this future stream of revenue, but may be appropriate given the lack of a minimum price for LCFS credits.

Based at least in part on an industry recommendation, CARB's evaluation assumes that the cost of truck batteries will lag five years behind batteries for the light-duty market.[19] This scenario maintains that assumption.

Lower Battery Cost Scenario

This scenario's reasoning is discussed in the section above titled "Battery Cost Expectations." Specifically, the Lower Battery Cost Scenario tests the implications of the cost of medium- and heavy-duty truck batteries lagging light-duty vehicle batteries by two years instead of by five years, as CARB's evaluation assumes. In this scenario, the trend of falling costs observed empirically to date in light-duty vehicles translates less sluggishly into price reductions in batteries for electric trucks.

DIFFERENCES WITH CARB'S MODELING

This discussion of differences between the California EPS methodology and CARB's methodology begins with some macro observations before moving on to explain specific differences relevant to results.

At a high level, the main difference between CARB's analysis of the proposed rule and the California EPS modeling pertains to scope. The California EPS is a single, economy-wide model. CARB's modeling includes specialized, transportation-specific models that are combined, also known as an integrated assessment approach.

CARB's transportation sector models better capture the full range of complexity across many different types of trucks. The EPS is much simpler because it allows for just two types of freight trucks, medium- and heavy-duty. More specialized models at the sector level will always have the capacity to capture more detail within their respective domains than is possible in a multi-sector, economy-wide context.

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[18] Based on CARB's LCFS dashboard data, table entitled "Monthly LCFS Credit Price and Transaction Volume," accessed June 2, 2020, from the web address: http://ww3.arb.ca.gov/fuels/lcfs/dashboard/creditpriceserieswithoutargusopis.xlsx

[19] "At the December 4th, 2018 [ACT] IX-10 workgroup meeting, a number of manufacturers suggested we use light-duty battery prices with a five-year delay to reflect battery-price projections that are applicable to heavy-duty vehicles," (CARB 2019a), page IX 9-10.

From these high-level structural contrasts, we pivot to discuss specific modeling differences driving differences in results. The time and resources available to complete this study in a timeframe relevant to the policy process precluded precisely matching every aspect of CARB's modeling.

Manufacturing cost refers to changes in vehicle cost. CARB selected this nomenclature to be transparent about the simplifying choice made to ignore the issue of profit margins, which can vary significantly across vehicle classes. Manufacturing costs for the proposed rule are greater in CARB's results, driven by two factors, financing costs and whether or not innovation in batteries continues past 2030.

On the first factor, the California EPS includes no financing costs, instead representing vehicle costs as lump sum purchases in the year in which they take place. CARB's analysis adds financing charges assuming a five-year loan for vehicle purchasers.

On the second factor, in CARB's analysis, technological innovation freezes in 2030. This means that in CARB's analysis battery costs stop falling in cost after 2030 and, by extension, electric truck costs remain constant in 2031 and later years.[20] In the California EPS, innovation and falling battery costs are expected to continue in 2031 and beyond, albeit at an exponentially slower rate as the technology matures.

Technology innovation in the California EPS is modeled using empirically derived learning curves. In fact, to project future battery prices, the California EPS uses the same method as BNEF. Future cost reductions are based on the historical learning rate, derived as the mathematical relationship between reductions in cost and the growth in installed capacity of a new technology. In the case of batteries, each doubling of globally installed capacity reduces costs by 18 percent (BNEF 2017). Innovation-related declines in battery costs continue during the 2030s in California EPS modeling, though at a slower pace as the technology matures. Appendix B includes a graphic illustrating the battery cost pathways underlying in results obtained by CARB in comparison to those in California EPS results.

RESULTS OF CALIFORNIA EPS EVALUATION OF THE PROPOSED RULE

Pollution reduction and economic impact results are similar to those found in the regulatory analysis under modeling with the California EPS using CARB's future battery cost estimates. Therefore, on the first research question, this work corroborates that inputs embedded in the regulatory record lead to the conclusions vis-à-vis environmental and economic benefits portrayed in CARB's analysis.

[20] This is not stated explicitly in the analysis. We understand this to be the case because of the nomenclature in Table IX-7: ZEV Price Forecast. The right-most column of that table is labeled "2030+ MY [model year]," implying prices remain constant in later years.

EMISSIONS BENEFITS

Clean air and public health benefits are the rule's primary goal. The California EPS finds the rule would reduce emissions of smog-causing NOx by almost 60,000 tons by 2040. This finding is similar to CARB's estimate that the rule would avoid more than 58,000 tons of NOx emissions. CARB estimates air quality improvements from the proposed rule will deliver $8.9 billion in public health benefits, including 943 premature deaths avoided.[21]

The truck rule is also an important step in the evolution of California's climate strategy. Innovation in EVs coupled with the state's commitment to carbon neutrality make transportation an important target for building out the policy apparatus necessary to fulfill the state's visionary commitments. The California EPS estimates that the proposed rule would reduce climate pollution by 17.6 MMT of CO_2e, compared to reductions of 17.3 MMT of CO_2e in CARB's assessment.

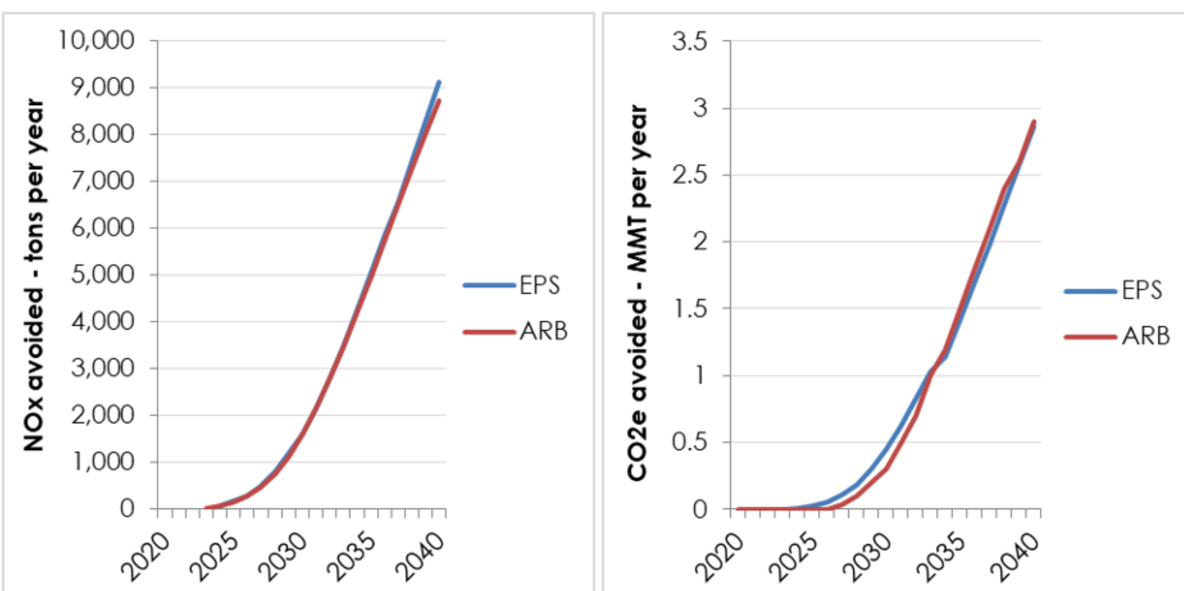
Table 3 presents results, from both CARB's analysis and this study, for emissions reductions through 2040 for NOx and CO_2e. Figure 3 graphs the same results on an annual basis.

Table 3. Air quality and climate benefits from the proposed ACT rule

	CARB's assessment	EPS result
NOx (oxides of nitrogen) emission reductions through 2040	58,000 tons	60,000 tons
CO_2e (carbon dioxide equivalent) emission reductions through 2040	17.3 MMT of CO_2e	17.6 MMT of CO_2e

Source: California EPS and CARB (2020B)

Figure 3. Avoided emissions of NOx and CO_2e



[21] See Table II-2 in Appendix C (CARB 2020c).

Source: California EPS and CARB (2020b).

ECONOMIC OPPORTUNITY

Cutting-edge research has demonstrated that electric trucks' fuel economy advantage is even greater in city driving—about five to seven times more efficient than diesel trucks—than was previously understood (CARB 2018). CARB is cautious in translating these findings to average energy efficiency advantage for electric trucks. The regulatory analysis sets the estimated energy efficiency advantage, technically the energy efficiency ratio, at 3.4 – 3.8 for battery electric trucks compared to diesel trucks, up from the value of 2.7 that had been estimated using much more limited data in 2007. Given recent findings, future work may well show the fuel efficiency advantage of electric trucks to be still greater.

While in the past the energy efficiency advantages of EVs were overshadowed by vehicle cost differences, rapid technological progress and economies of scale in batteries mean a new era has dawned. Transportation electrification now presents an economic opportunity, as evidenced by the results of this study.

Evaluation using the California EPS finds total savings of over $7 billion when using CARB's battery cost forecast for medium- and heavy-duty trucks.[22] This estimate is comparable to CARB's estimate of approximately $6 billion in savings.[23] When the California EPS is re-programmed for the Lower Battery Cost Scenario, total savings increase by about $5 billion, growing to more than $12 billion in total through 2040.

Table 4. Comparison of total savings to CARB's results

	CARB's assessment	EPS results	EPS results (lower battery costs)
Total savings* (2018 $s)	$5.9 billion	$7.3 billion	$12 billion

Source: California EPS and CARB (2020c)

* Total savings are defined as the sum of undiscounted, direct effects on spending due to the proposed regulation. In the documentary evidence developed to support rule development, these are called "Total Economic Costs and Savings."

Next we define several terms used in the detailed, annual results on added costs and savings that follow in Figures 4 and 5. Some of the terminology used is explained by their labels themselves—such as "Fuel Cost" and "Maintenance"—while others merit definition.[24] "Manufacturer cost" refers to changes in vehicle cost. This term is used because CARB's analysis looks at changes in the cost to produce a vehicle but does not attempt to define manufacturer and dealer profit margins.

[22] Total savings are defined as the sum of direct economic effects, positive and negative, referred to as "Total Economic Costs and Savings" in CARB's regulatory analysis. These are undiscounted results. All monetary results in this report are given in undiscounted 2018 dollars.

[23] See Table IV-8 in Appendix C (CARB 2020c).

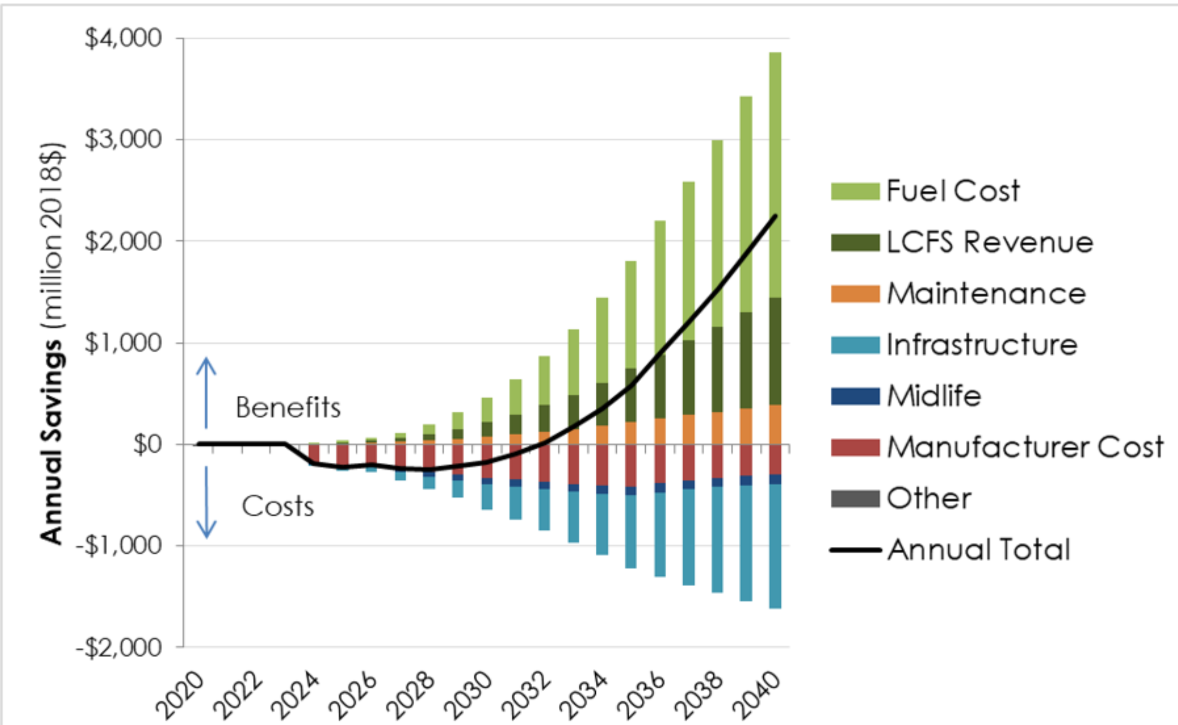
[24] CARB's discussion of the aforementioned Figure IV-4 (CARB 2020c) may also prove useful in clarifying terms.

"LCFS (low carbon fuel standard) revenue" refers to a stream of revenue expected for ZEV truck owners. We follow CARB's convention in tracking LCFS revenue as an economic benefit. From another perspective, LCFS revenue might be considered a transfer from one party to another.

The "Infrastructure" category refers to the cost of installing charging infrastructure and related electrical system upgrades. The "Midlife" category includes added costs of battery replacements for some trucks and accounts for expected resale differences. The "Other" category includes changes to government fees, covering registration, sales, and excise taxes.

Figures 4 and 5 show the annual flow of costs (below the $0 line) and benefits (above $0 line) over time. These figures use the same labeling as in CARB's presentation of results.[25]

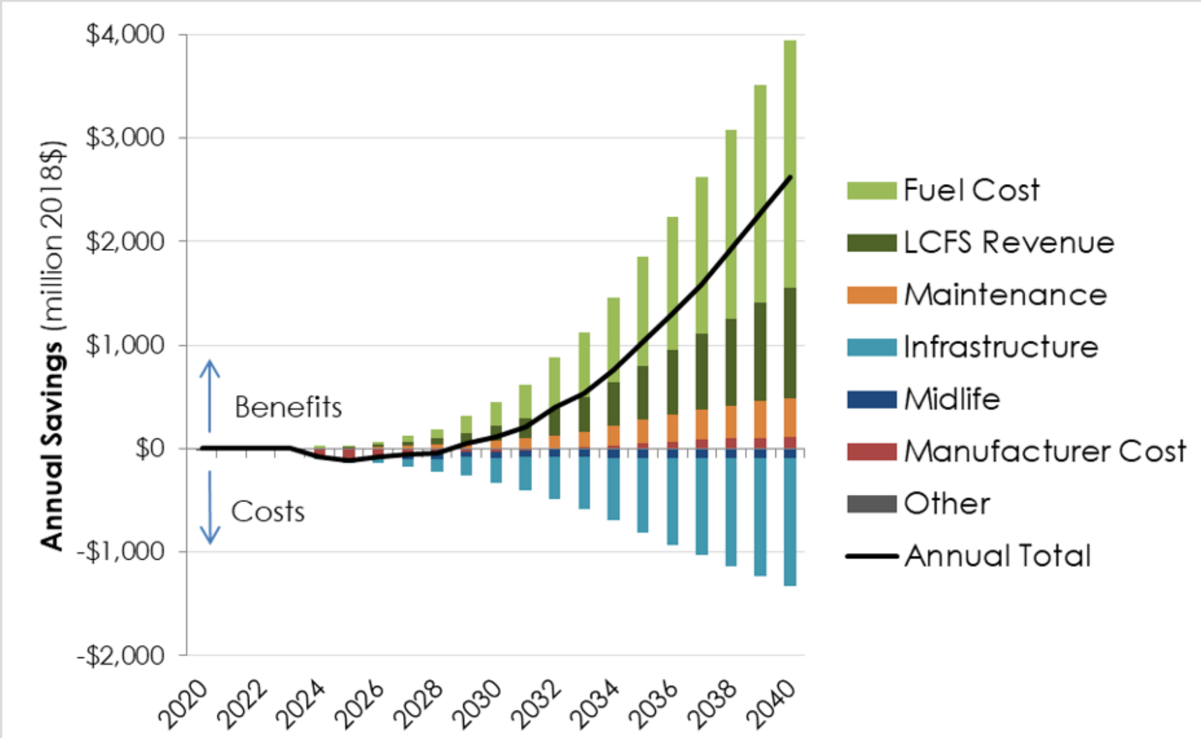
Figure 4. Total savings (CARB battery costs)



Source: California EPS

[25] See "Figure IV-4: Total Estimated Direct Costs of Proposed Updates Relative to the BAU Baseline" in Appendix C (CARB 2020c).

Figure 5. Total savings (lower battery costs)



Source: California EPS

A comparison of Figure 4 above and the analogous figure from CARB's analysis shows that after 2030, CARB's results show a higher EV premium, labeled "manufacturer costs."[26] In California EPS results, the impact in the manufacturer cost category reaches a maximum of $410 million in 2035. In CARB's results, as Table IX-8 shows, manufacturer costs increase each year, reaching a maximum of $836 million in the last year modeled, 2040.[27] The subsection above entitled "Differences with CARB's Modeling" explains two key factors driving this difference, namely:

1. CARB's analysis adds financing costs associated with purchases, and
2. CARB's analysis truncates innovation in 2030 whereas innovation continues at a slower rate in California EPS modeling.

Results have so far been given in undiscounted terms, following the approach used in CARB's analysis. We also provide results in terms of net present value, using the 5 percent rate that CARB employs in evaluating effects on a total cost of ownership basis.[28] CARB intends this method of valuation to be representative of the method a fleet owner would use in comparing different technology options.

[26] See Figure IV-4: Total Estimated Direct Costs of Proposed Updates Relative to the BAU Baseline in (CARB 2020c).

[27] See Table IV-8: Total Estimated Direct Incremental Costs of Proposed Updates Relative to the BAU Baseline in (CARB 2020c).

[28] The total cost of ownership analysis is found in Appendix H (CARB 2019b).

Table 5 presents average cost per avoided ton of CO_2e, calculated as total savings divided by cumulative emission reductions expected from the proposed rule. The results are calculated through 2040 for both the numerator and denominator of this metric. In addition, Table 5 presents average savings per ton, as well as the undiscounted and total savings estimates in present value terms, calculated with a 5 percent discount rate.

Table 5. Total savings and average savings, with and without discounting (2018 $s)

	EPS results with CARB battery costs		EPS results with lower battery costs	
	Total savings	Average savings per avoided ton of CO_2e*	Total savings	Average savings per avoided ton of CO_2e*
Undiscounted	$7.3 billion	$414 per metric ton	$12.4 billion	$708 per metric ton
Discounted (5%)	$6.3 billion	$358 per metric ton	$10.7 billion	$612 per metric ton

Source: California EPS and CARB (2020c)

* Average cost is calculated as total savings divided by the sum of emissions reductions through 2040.

DISCUSSION

MYRIAD MARKET FAILURES NECESSITATE ADOPTION OF THE PROPOSED RULE

Clear indications of greater battery innovation in the pipeline signal that electric cars and SUVs will cost less to produce than petroleum-fueled competitors in the coming years.[29] In light of the increasingly compelling economics, some readers of this study may wonder why government action is necessary. Some might imagine that the "invisible hand" of the market will deliver electric trucks. What would be missing from such an analysis is the oil industry's lock on California's transportation fueling system.

Despite the increasingly clear economic potential, existing policy and market momentum are likely insufficient on their own to deliver optimal change. Even in normal times, myriad market failures create a type of inertia strongly favoring the current dominant fuel source, petroleum.[30]

The uncertainty created by the current economic crisis creates a new drag on investment, and the amount of capital required to fund the transition is immense. A 2019 survey found automakers were planning over $400 billion in investments over five years to develop electric cars equipped with technology that automates much of the task of driving (Ewing 2019). In addition to technology development, costs include retooling factories and retraining workers.

[29] See Lutsey (2019), Figure 4.

[30] Per the Institute of Transportation Studies at the University of California, Davis: "There are many market failures and market conditions that riddle the energy system, many of them unique to transportation, that result in consumer and business decisions not in the best interest of society. These market conditions include network effects of additional coordination among fuel producers, vehicle manufacturers, and fuel distributors energy security externalities related to petroleum imports; long time horizons needed for investments in fuel infrastructure; the lack of fuel-on-fuel competition; the diffuse nature of biofuel industries; and the market power of oil companies and OPEC countries. Energy markets are particularly inefficient and ineffective at addressing end use technology efficiency and demand reduction," (Yeh and Sperling 2013, page 1).

Absent government action, investment is almost guaranteed to be sub-optimally slow. Public policies, such as the proposed rule and complementary policies described next, are needed to condition the market and send the right signals that the requisite investments will pay off. Such policies are necessary to overcome uncertainties and other hurdles, in order to unlock investment at the required pace. The proposed rule and complementary policies will provide greater certainty vis-à-vis market demand, accelerating the requisite investments and pace of the transition to zero-emission trucks.

ADDITIONAL SUPPORTIVE POLICIES NEEDED

Turning from the market failures and conditions that necessitate the proposed rule, several other important actions are needed in addition to the proposed rule itself. Some of these supportive measures are already ongoing. For example, CARB is developing purchase requirement for fleets, a potentially important complementary policy associated with the proposed rule's requirements for manufacturers.

Policies are needed to counterbalance transition costs, including charging infrastructure, as well as manufacturer cost. While electric trucks will probably become less expensive to purchase than their conventional counterparts, electric truck purchasers may face additional upfront purchase costs in the earlier years of the proposed rule's implementation, starting in 2024. While these costs will be more than offset by the operating cost savings that electric trucks provide, policymakers should employ several measures to smooth the transition and mitigate potential distributive impacts. Such measures could include incentives and financing support as well as continued development of the measures and market mechanisms to make the most of the ability to shift charging or use vehicles as local sources of power. Workforce development programs and economic strategy to grow good jobs through expanding local supply chains are also important considerations for policymakers. We recognize, however, that the current economic and state budget crisis constrains the near-term funding outlook.

A rapid transition will introduce new coordination challenges, too, including complicated interactions with the electricity system. It will demand creative problem solving and investment in governance to make the transition a success. Having identified the payoff, we acknowledge that a transition to zero-emission trucks will not be effortless or even easy.

BLIND SPOTS ON EQUITY

We must acknowledge some limitations of this study. Equity has been an important pillar of California's environmental policy for decades. For example, California's Senate Bill 535 (2012) requires that disadvantaged communities receive at least 25 percent of funds earned at auctions of carbon cap-and-trade permits.

The California EPS is a state-level model that does not currently estimate community-level impacts. Public health impacts of local air pollutants are tightly linked to local concentrations. The results presented here do not shed light on matters of environmental justice, except to the extent that intergenerational equity issues are embedded in climate policy. Further, while the

EPS is able to differentiate impacts for consumers, industry, and government, results do not offer visibility into effects on people in different income groups. The findings in this report add little in the way of insights on how income inequality or other aspects of economic fairness would be affected.

Since disadvantaged communities suffer disproportionately large harms from air pollution, we suspect that the proposed ACT rule will provide the greatest health benefits in disadvantaged communities. This hypothesis and other urgent equity concerns deserve rapid evaluation, to allow for policy design adjustments before program requirements begin in earnest in 2024.

CONCLUSION

This report explains the results of customizing the California EPS for evaluation of the proposed ACT rule. Results obtained using the California EPS and documented in this report independently corroborate CARB's regulatory analysis of the proposed ACT rule.

The proposal would bring relief to millions of Californians suffering from some of the nation's worst air quality. While better local air quality air is the primary motivation, the proposed rule would be a significant step in the direction of carbon neutrality in the transportation sector.

The economic benefits anticipated from the proposed rule were estimated to be significant in both CARB's regulatory analysis and California EPS modeling. We find total savings of more than $7 billion using CARB's battery cost assumptions or $6.3 billion with a 5 percent discount rate. Undiscounted savings increase by about $5 billion to $12 billion when the analysis is run with lower future battery costs.

The proposed ACT rule is a significant step toward a healthier, more sustainable, lower-cost, clean energy future. While the potential is clear and the vision compelling, the transition to advanced transportation technologies is far from guaranteed. The successful transformation envisioned will require supportive complementary policies, and more research is needed to understand equity impacts outside the scope of the California EPS. Creating change is always harder than giving into inertia, and the road ahead will certainly serve up speed bumps. But it is also clear that technology innovation is opening up an opportunity to build a lower-cost, healthier transportation system, served by zero-emission medium- and heavy-duty trucks.

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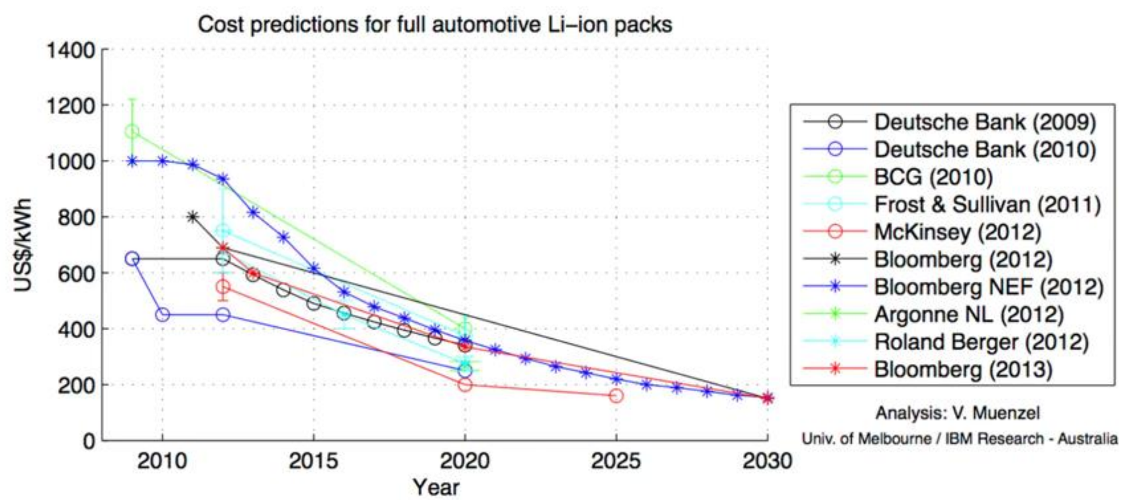
APPENDIX A. COMPARISON OF FORECAST VS. ACTUAL BATTERY COSTS

The body of this paper documents historical changes in the cost of battery storage. This appendix shows how battery cost predictions have underestimated the pace at which battery cost falls.

BNEF has been at the leading edge of anticipating rapid technological progress in battery storage technologies. Figure A-1 shows that even BNEF's battery cost forecasts have consistently underestimated future reductions. Figure A-1 presents a collection of battery cost forecasts assembled in 2014, including a 2012 forecast from BNEF, which projected a 2018 price for battery packs of over $400 per kWh. The actual price of battery packs in 2018, however, was $154 per kWh (Henze 2019).

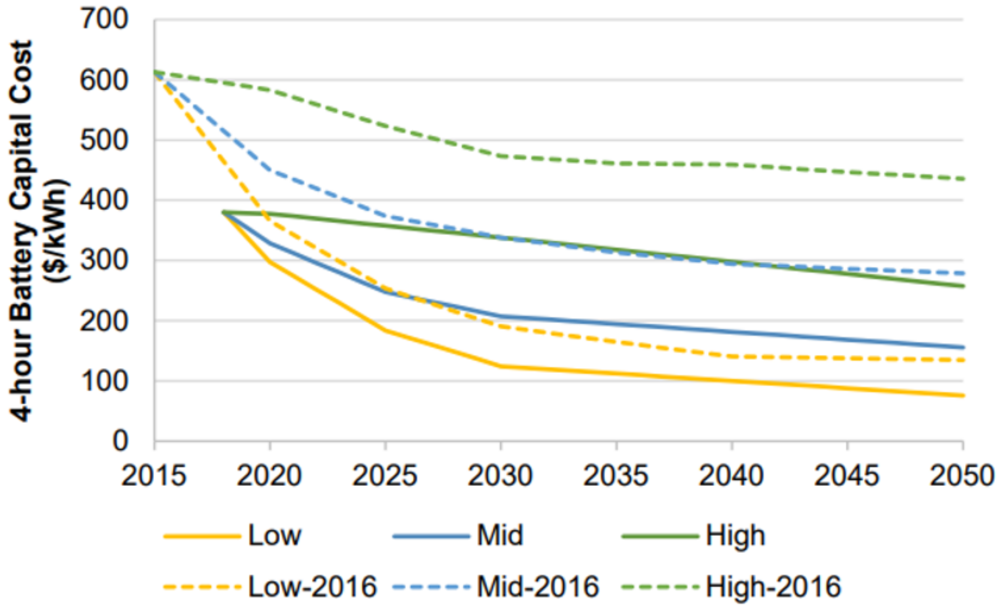
Figure A-1. Future battery cost expectations viewed from a 2014 perspective



Source: *Vishwanath and Kalyanaraman (2014)*

Research from the National Renewable Energy Laboratory offers further evidence that real-world declines in the cost of battery storage have outpaced expectations. Figure A-2 shows the expected cost trend in 2016 and 2019.

Figure A-2. National Renewable Energy Laboratory battery costs forecasts in 2016 (dashed lines) and 2019 (solid lines)



Source: Cole and Frazier (2019)

Figure A-2 shows how 2019 expectations (solid lines) compare to 2016 expectations (dashed lines). The distinct reduction in future prices in the 2019 projection indicates that previous work underestimated the technological progress and cost improvements that occurred since 2016. Though Figure A-2 refers to utility-scale battery storage, the insights more broadly represent how analysts have consistently been too conservative in their projections. Time and again, battery cost outlooks have underestimated rapid declines in the cost of battery storage.

APPENDIX B. ADDITIONAL INFORMATION ON METHODS

Appendix B offers further description of our modeling approach using the California EPS (v1.4.3.2). We developed separate models for medium- and heavy-duty trucks to allow for more precise tailoring of input data. The model allows for specifying different electricity prices for each economic sector, but that means is applied to all transportation demand. The two-model approach allowed us to evaluate the impacts of the proposed rule using different electricity prices expected for medium- and heavy-duty trucks.

The standard version of the California EPS extends through the year 2030, but data inputs extend to 2050. Therefore, it was relatively straightforward to extend the model run to 2040 by changing the variable "Final Time." The input data themselves—showing detailed source data and underlying calculations—are made available here as part of the open-source research. Note that the model download includes an "Input data.xls" file, which defines and helps new users locate variables.

Updates to the model input assumptions draw largely upon the *Initial Statement of Reasons* (CARB 2019a), *Appendix C: Updated Cost Benefit-Analysis* (2020c), *Appendix D: Emissions Inventory Methods and Results* (CARB 2020b), and *Appendix H: Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document* (CARB 2019b).

MEDIUM-DUTY TRUCK INPUTS CALCULATED AS NEW-SALES WEIGHTED AVERAGE

For medium-duty vehicles, the analysis involved finding weighted average values as a function of new vehicle sales grouped by class. Calculation of battery size for medium-duty vehicles is presented as an example. The first step involves calculating sales for each class, drawing on data from Table IX-2: Estimated Number of Annual Sales per Vehicle Group (CARB 2019a). We arrive at proportions shown in Table B1.

Table B1. Shares of new sales by class of medium-duty truck

Vehicle class	Proportion of new sales
2b-3	79%
4-5	10%
6-7	11%

Source: (CARB 2019a)[31]

[31] CARB's Table IX-2 provides these data for the 2024-2030 period. California EPS inputs are estimated assuming these shares are maintained over the remainder of the time series for this analysis, from 2031 to 2040. The analysis excludes the small number of class 8 vocational type trucks, as distinguished from class 8 tractors, because class 8 vocation vehicles are not covered in Appendix H (CARB 2019b), which provides inputs on several variables not otherwise represented in the California EPS structure, involving expenditure categories such as midlife and registration cost.

BATTERY SIZE REQUIREMENTS

The calculation of the new-sales-share weighted average for medium-duty trucks illustrates how values for different truck classes are synthesized. Table B2 lists the battery size requirements for electric trucks in CARB's analysis.

The trend in battery size over time in CARB's analysis is explained in the right-most column of Table B2. Battery sizes are time invariant in the California EPS. To align the inputs as much as possible, we develop a "Time-weighted average," which collapses the information on battery size anticipated for that year (as annotated in the "Trend over time column") according to the new-sales-share of EVs in each year. Combining these data with the class sales shares estimates in Table B1 yields an overall weighted average for the medium-duty category of 96 kWh.

Table B2. Battery size requirements for truck classes in EPS medium-duty category

Category	Long	Normal	Time-weighted average	Trend over time
Classes 2b-3	55 kWh	80 kWh	67 kWh	> 70% of sales to fleets-50% long range after 2030 > 30% of sales to individuals - all long range
Classes 4-5	135 kWh	200 kWh	161 kWh	100% normal range until 2030 50% long range after 2030
Classes 6-7	200 kWh	300 kWh	241 kWh	100% normal range until 2030 50% long range after 2030
Medium-duty overall			96 kWh	

Source: (CARB 2019a; 2020c)

The heavy-duty value can be directly drawn from the regulatory record because it was designed to correspond to CARB's Class 7-8 Tractor group. Therefore, the California EPS's heavy-duty truck battery size is estimated to be 400 kWh. The EPS values for medium- and heavy-duty truck battery sizes are shown in Table B3.

Table B3. Battery size by EPS truck category

Category	Battery size
Heavy-duty	400 kWh
Medium-duty	96 kWh

Source: (CARB 2019a; 2020c)

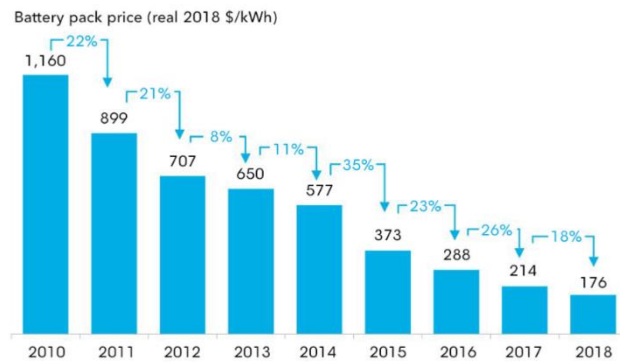
DETAILS OF FUTURE BATTERY COST SCENARIOS

The California EPS includes mechanics to represent innovation for four emerging technologies—solar power generation, wind power generation, battery-electric storage, and carbon capture and sequestration. The basis for battery cost reductions in the California EPS relies on the concept of learning curves, which also lie at the heart of BNEF's forecasts shown in Figure B1.

Learning curves refer to the cost reductions typically observed over time for new technologies, which occur due to the learning that comes with experience and the economies of scale that are achieved as production scales up.

The EPS's endogenous innovation module represents the effect of innovation by delivering lower cost for equal performance. The research here uses the 18 percent learning rate BNEF has cited. Operationally, this learning rate is a reduction in cost applied with each doubling of global installed capacity, reflecting historical patterns. The rate of innovation over time is modeled as a function of business-as-usual deployment (i.e., BAU growth in installed capacity) as well as additional capacity installed due to model policy additions.

Figure B1. Historical battery pack prices[1]



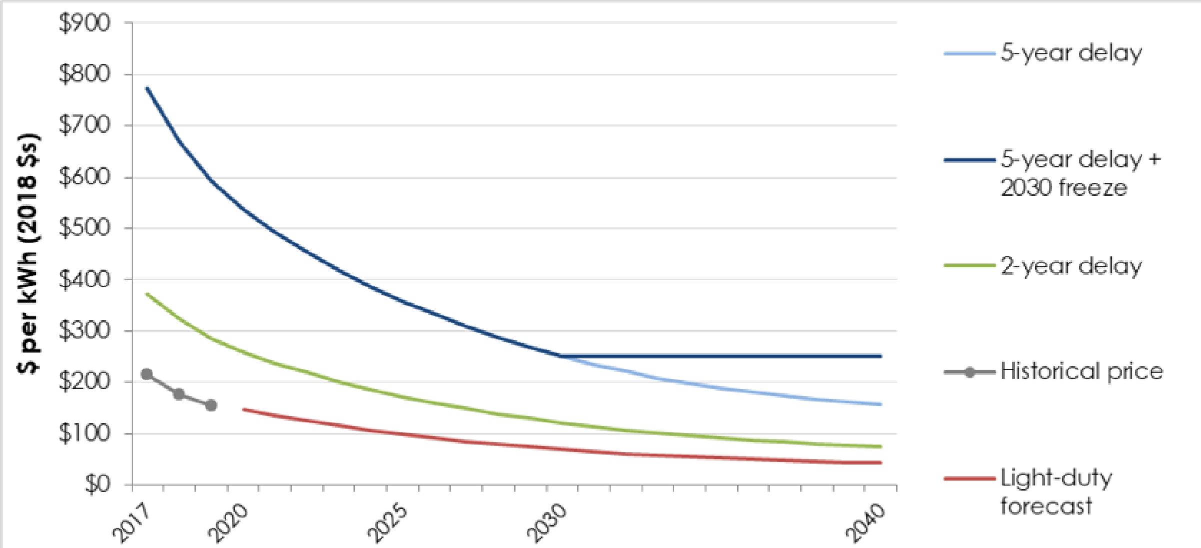
Source: Bloomberg New Energy Finance (Goldie-Scot 2019)

The only specific information given about the particular BNEF forecast used, other than the graphic from CARB's analysis reproduced as Figure 2 in the body of this report, is a rather generic two-term description: Bloomberg 2018. We were unable to find more specific information about the origin or date of the Bloomberg data on trends. We approximate this input variable using information in the public domain, shown in Figure B1.

Using the annual values in Figure B1, it is straightforward to count backwards in time to the appropriate number of years—two to five years depending on the scenario—to identify the appropriate value for the start year. The California EPS requires only this initial value, because the value in future years is a function of the start year value and innovation effects due to learning calculated by the model. The model's start year is 2017, which aligns with the most recent statewide inventory data available at the time of publication. In the five-year delay scenario, the 2017 start year uses the 2012 value, $707 per kWh. In the two-year delay scenario, the 2017 start year is based on the 2015 value of $373 per kWh. BNEF estimated the actual volume-weighted average price for battery packs to be $214 per kWh in 2017.

The battery cost scenarios used in California EPS analysis are shown in Figure B2 using light blue and green curves, respectively. In CARB's modeling, there are no cost improvements associated with innovation after 2030. With innovation frozen, truck battery prices in CARB's analysis hold constant in 2031 and later years. Figure B2 also graphs three historical values from the light-duty battery forecast.

Figure B2. Battery costs under different scenarios



Source: California EPS, CARB (2019a), BNEF (Goldie-Scot 2019)

NEW VEHICLE SALES IN CALIFORNIA

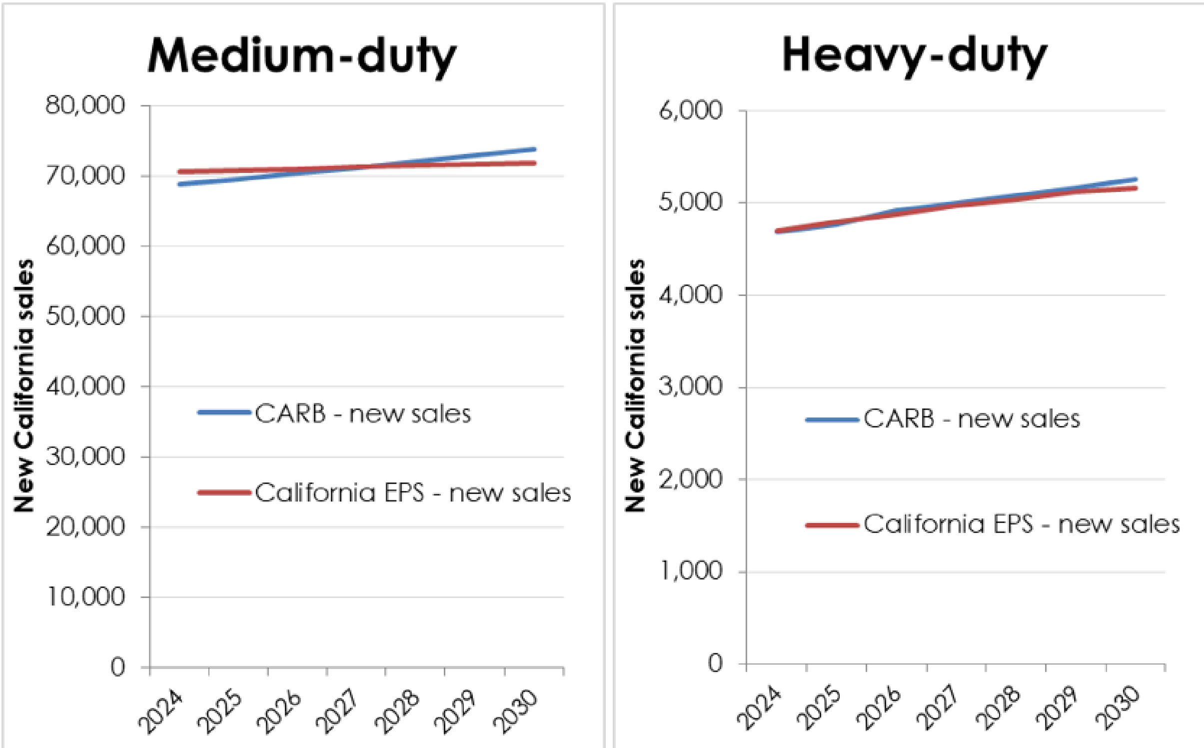
The proposed rule can only apply within state borders to new California sales. The model is not structured in anticipation of a significant inflow of motor vehicles from outside the model boundary. New vehicle sales is a critical driver of policy impacts because it sets off a cascade of fuel, emissions, and cost effects. CARB has invested significant effort to capture these dynamics. We handle this challenge by directly calibrating new vehicle sales in the EPS with California new sales in CARB's analysis. The Initial Statement of Reasons (CARB 2019a) included year-by-year figures for new sales by class in California for the 2024-2030 period. Figure B3 graphs those data against annual sales in California EPS results obtained for this study, whereas Table B3 shows total sales in comparison.

New vehicle sales data is not an input variable that can be directly specified or manipulated in the EPS. Instead, it is an example of one of several optimization modules within the model. The model determines both the level of new vehicle demand (a function of capital-stock-and-flow dynamics) and the shares of vehicle by fuel type, diesel, gasoline, electricity, and natural gas.

To align with the regulatory analysis we constrain electric trucks in the baseline scenario to be only a small fraction of medium-duty new truck sales and zero for heavy-duty trucks. Specifically, this is accomplished using the "Max Percent Growth by Technology" variable, which inputs a schedule of the maximum annual growth in the Baseline Scenario. In modeling implementation of the proposed rule, we simulate the effect of deploying advanced vehicles at a pace specified in the proposed rule. The EPS "Electric Vehicle Sales Mandate" policy lever overcomes the growth constraint to approximate the levels implied by the proposed rule.

Because the level of new vehicle sales is not an input variable, there is still some variation between the EPS and CARB analysis, as illustrated in Figure B3 and Table B4.

Figure B3. New truck sales in California EPS and CARB analyses



Source: California EPS and CARB (2019a)

Table B4. New truck sales in California 2024-2040

	Medium-duty	Heavy-duty	Total
California EPS	1,214,024	92,871	1,306,895
CARB's analysis	1,214,066	93,103	1,307,169

Source: California EPS and CARB (2020b)

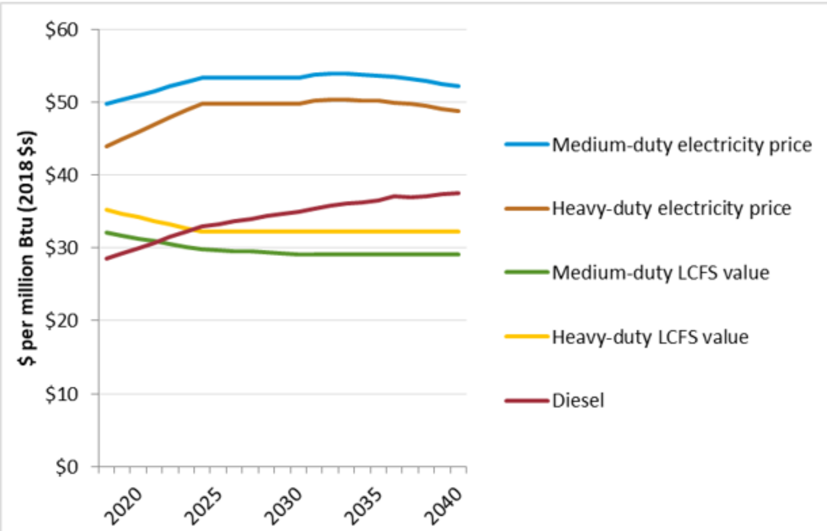
Turning to California vehicle miles traveled, we observe that this figure includes a broader set of vehicles than just new sales in California. The EPS does not separately track the stock of in-state and out-of-state vehicles, but it does have a separate input variable to reflect business-as-usual annual change in travel demand compared to the start year. It can be delinked from the stock of vehicles to permit separate and consistent accounting of California travel demand value including out-of-state inflows.

CARB's regulatory analysis held truck distance traveled constant in its modeling, in both the baseline and proposed rule scenarios. We disabled the travel demand price effect otherwise included in the standard model. Doing so better enables this research to provide an independent check on the regulatory analysis conducted in the ACT proceeding.

FUEL PRICE

Fuel prices are a crucial variable for cost effectiveness. Diesel and electricity prices were adjusted to align with the regulatory analysis. For diesel fuel, prices are $3.60 per gallon in 2017 and grow to $4.60 per gallon in 2040. As mentioned, the analysis involves separate modeling of medium- and heavy-duty types of trucks to allow for distinct electricity price forecasts for medium- and heavy-duty trucks.[32] For heavy-duty trucks, the price of electricity starts at $0.15 per kWh in 2017 and increases to $0.17 per kWh in 2040. For medium-duty trucks, the electricity price starts at $0.17 per kWh in 2017 and increases to $18 per kWh in 2040. Figure B4 converts both energy units for prices to a common unit, British thermal units (Btus), allowing for easier comparison.

Figure B4. Fuel price expectations in California EPS and CARB analyses



Source: CARB (2019a, 2019b, 2020c).

INFRASTRUCTURE AND OTHER COSTS

Several variables important for this analysis are not directly represented in the structure of the EPS. Where the EPS structure excluded variables from CARB's regulatory analysis, our analysis included these variables through parallel calculations of their effect, which were then added in post-processing of model results. Generally, the approach was to find incremental differences between electric and diesel trucks, based on CARB's Appendix H (2019b), and to add these differences in post-processing of model results.

CARB's charging infrastructure costs are attributed in this way, on an annual basis, mirroring the 20-year, 5 percent financing assumption in the regulatory analysis (2019c). Infrastructure costs are constant over time in the analysis.

The EPS tracks maintenance costs for the electricity sector but not for vehicles, and so this was also calculated in parallel on a per mile basis and added to model results.

[32] The regulatory documentation released April 28, 2020, included updated electricity prices for Class 2b-3 passenger vans, the most numerous type of truck, lowering them by about 10 percent. That update is reflected in EPS input values. As stated in the ACT proceeding, "The electricity cost for Class 2b-3 vehicles using these assumptions was $0.189/kWh, roughly $0.02/kWh lower than the previous assumptions for Class 2b-3 ZEVs," (CARB 2020c).

CARB's investigation of total cost of ownership expresses the value of LCFS credits by vehicle type in dollar per kilowatt-hour ($/kWh) units, making it straightforward to directly incorporate this value in ex-post processing of results as a function of electricity used by medium- and heavy-duty trucks. LCFS values are also shown in Figure B4. The LCFS revenue stream was calculated annually based on additional electricity use in trucks spurred by the rule.

The category "midlife costs," includes battery replacements for heavy-duty trucks as well as differences caused by changes in "residual value." Lastly, the category, "other costs" covers effects on registration fees and government taxes. The difference between electric and diesel trucks are calculated for midlife costs and other costs and then applied on a per vehicle basis at the time of sale.