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Lawrence Berkeley National Laboratory

Clean trucks standards consistent with carbon neutrality are economically and environmentally compelling

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In light of recent work suggesting rapidly declining electric truck costs, we conduct a high-level modeling effort to understand the cost and environmental impacts of the advanced clean trucks (ACT) standard currently proposed by CARB and to contrast it with alternative potential clean-trucks standards. In particular, we contrast the proposed standard with an alternative proposal (hypothesized for modeling purposes) that would be in line with Gov. Jerry Brown's 2045 carbon-neutrality goal for California established in Executive Order B-55-18 (herein referred to as the "climate-consistent" scenario). We find that the difference between the two proposals to be significant across various elements of analysis: while both proposals save money compared to business as usual, the climate-consistent ACT standard is found to cost $62 billion less than CARB's proposed standard by 2045. Our modeling also shows that, under the proposed CARB rule, 62-105% of the number of diesel-/gasoline-fueled trucks on the road today would still be there in 2045, and that carbon emissions from trucking would be 82% of what they are today; the climate-consistent scenario drives diesel-/gasoline-fueled trucks and carbon/air pollution from trucking to zero in 2045. We conclude that, given the substantially different impact of more and less stringent ACT standards, a more detailed study on the cost and environmental impacts of having a more stringent rule is merited.

Introduction

In the U.S., medium- and heavy-duty trucking accounts for 23% of direct greenhouse gas (GHG) emissions from transportation and will account for a third of NOx emissions from transportation by 2025[1,2]. Switching to zero-emission trucking is an indispensable step in managing air pollution and climate change. Technological constraints and economic conditions have generally suggested that electrifying this sector is challenging—however, the emerging reality is different. Given recent technological advances, as the California Air Resources Board contemplates new standards for zero-emission trucks, we have undertaken to compare their proposed advanced clean truck (ACT) standards with hypothesized alternative proposals to better understand the cost and pollution implications of adopting a particular ACT rule[3].

Two recent developments suggest that two widely understood barriers to electrification of long-distance trucking have diminished substantially. Battery costs have fallen drastically to levels unforeseen just a few years back. By 2019, lithium-ion battery costs had fallen more than 80%—to roughly $156/kWh—relative to their cost in 2010[4,5]. Battery prices are expected to continue decreasing due to intense competition, economies of scale, and improved processes to reduce production costs[6,7]. A cost of $100/kWh is expected by 2026 according to BloombergNEF[4], and by 2020 according to Tesla[8]. Second, the cost of electricity from clean renewables such as solar and wind has also fallen so steeply that it is cheaper than or in parity with the levelized cost of generation from new coal plants[9]. Perhaps recognizing that these trends will not go unnoticed by policy makers, several truck original equipment manufacturers (OEMs) are making substantial investments in electric trucks[10].

In light of these developments, we conducted two separate studies to reassess the techno-economic potential of electric trucking. Our work suggests that electrifying trucking can have substantial economic and environmental benefits over diesel trucking (see Figure 1), particularly when electricity tariffs are structured to facilitate off-peak charging[11,12]. Given these recent findings, and understanding California's policy target of achieving deep decarbonization, we conducted this preliminary analysis to investigate the impact of different ACT standards that could be adopted for the state of California.

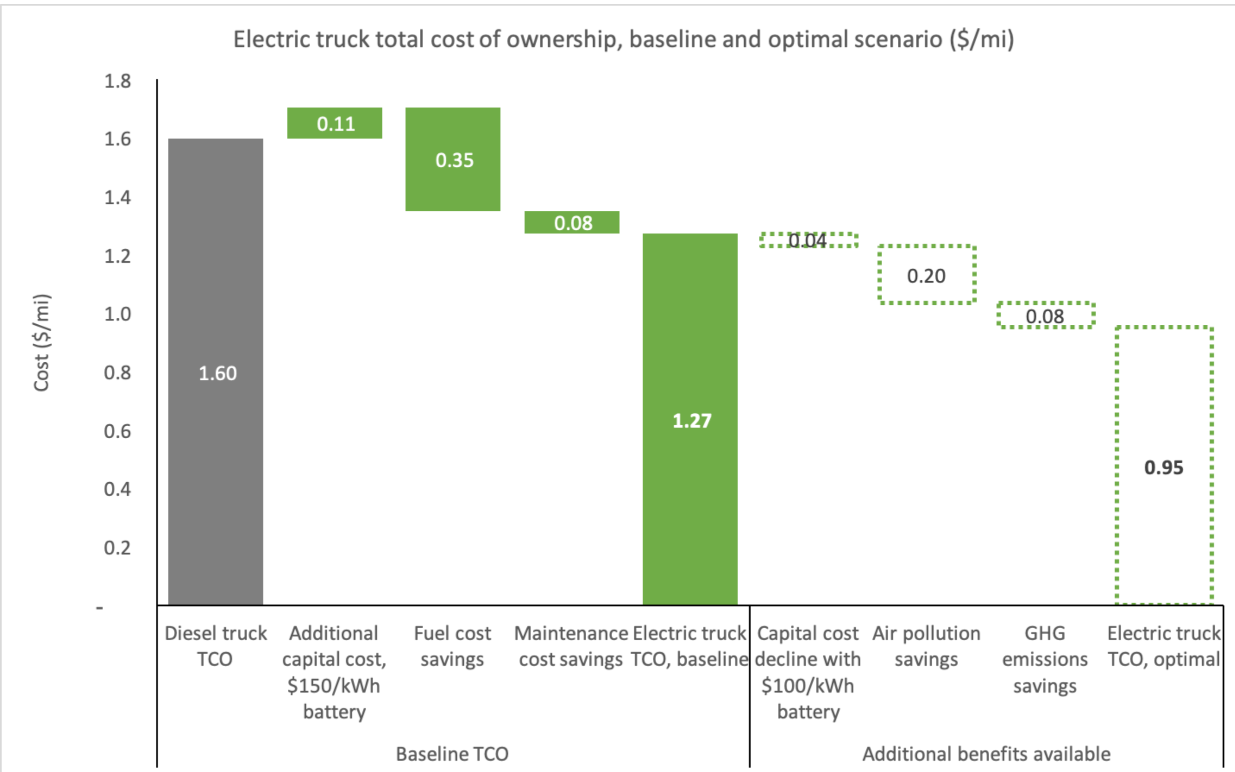

Figure 1. TCO per mile for diesel vs. electric truck with component-level breakdown of the cost differential. The baseline battery cost is $150/kWh. Additional benefits available represent further improvements in TCO if battery costs are $100/kWh and if air pollution/GHG emissions benefits can be monetized. These figures reflect trucks driving 400 miles/day, 260 days/year.[12]

In this work, we assess the cost and pollution impact of three different ACT standard scenarios: a business-as-usual scenario, which assumes no introduction of zero-emission trucks; the ACT standard currently proposed by the California Air Resources Board (CARB) as of August 2019; and an ACT standard (hereafter referred to as the "climate-consistent" proposal) that would be in line with California's 2045 carbon-neutrality goal, established by Gov. Jerry Brown's in Executive Order B-55-18.

Results

Our preliminary analysis suggest that the impact of different ACT standards could be substantial across each element analyzed and merits a more detailed assessment of the impact of more stringent clean trucks standards.

A: Cost

Cost: While both electrification scenarios save money compared to business-as-usual diesel scenarios, the net present cost of the proposed ACT standard is $62 billion more by 2045 than that of the climate-consistent proposal (see Figure 2). This figure includes carbon pollution costs reflecting the social cost of carbon as well as air pollution damages; however, even when omitting pollution costs, the proposed ACT standard still costs $25 billion more than the alternative. These figures assume a low-cost electricity scenario—however, even in the high-cost electricity scenario, the climate-consistent standard is still $51 billion cheaper than CARB's proposal when including pollution costs, and $14 billion cheaper when not doing so.

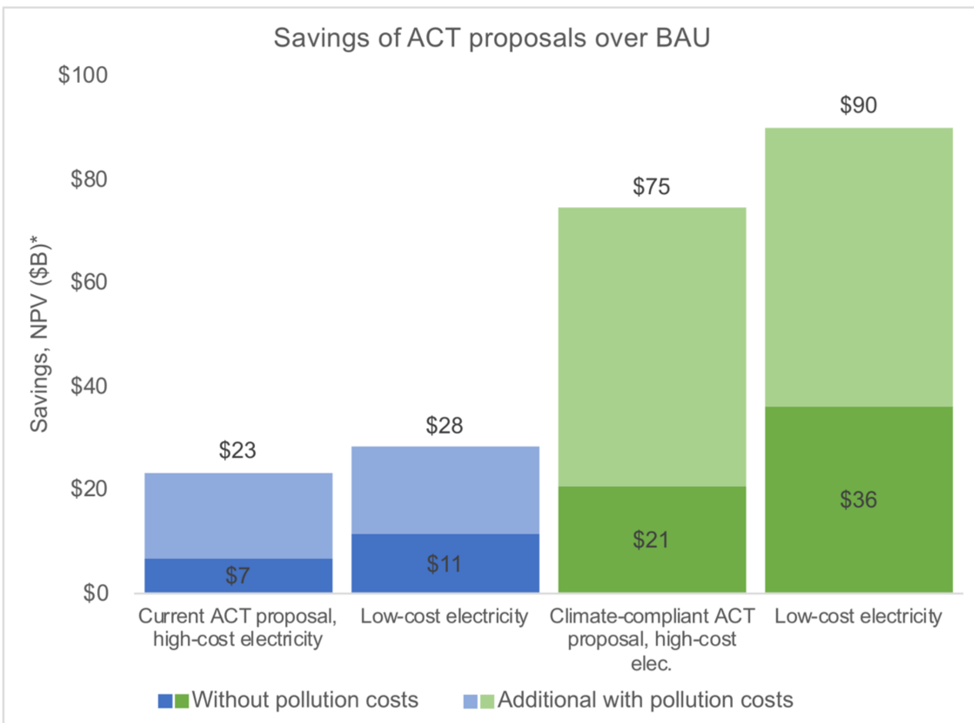

Figure 2. Savings of current and climate-compliant ACT proposals compared to BAU through 2045, under high- and low-cost electricity scenarios.

B: Trucks on the road

The proposed ACT standard will leave a significant portion of today's internal combustion engine (ICE; gas- and diesel-powered) trucks on the road through 2045. For class 4-8 (non-tractor) trucks, which face 50% ZEV sales by 2030, the number of ICE trucks on the road in 2045 is 62% of the number on the road today. For class 2B-3 and 7-8 tractor trucks, which face 15% ZEV sales by 2030, ICE trucks on the road in 2045 will number 105% of those on the road today—a net gain in the number of diesel- and gas-powered trucks given the proposed ACT standard and expected growth in vehicle population. In contrast, the climate-consistent proposal, which necessitates 100% ZEV sales by 2030 across all truck classes, leaves no ICE trucks on the road in 2045 as compared to today. (Because of the long lifetime of Class 8 trucks, to get all diesel trucks off the road by 2045 in our model, a 100% ACT standard is needed by 2030. Moving the 100% standard to 2035, however, only leaves 10% of the original Class 8 truck population number on the road in 2045.)

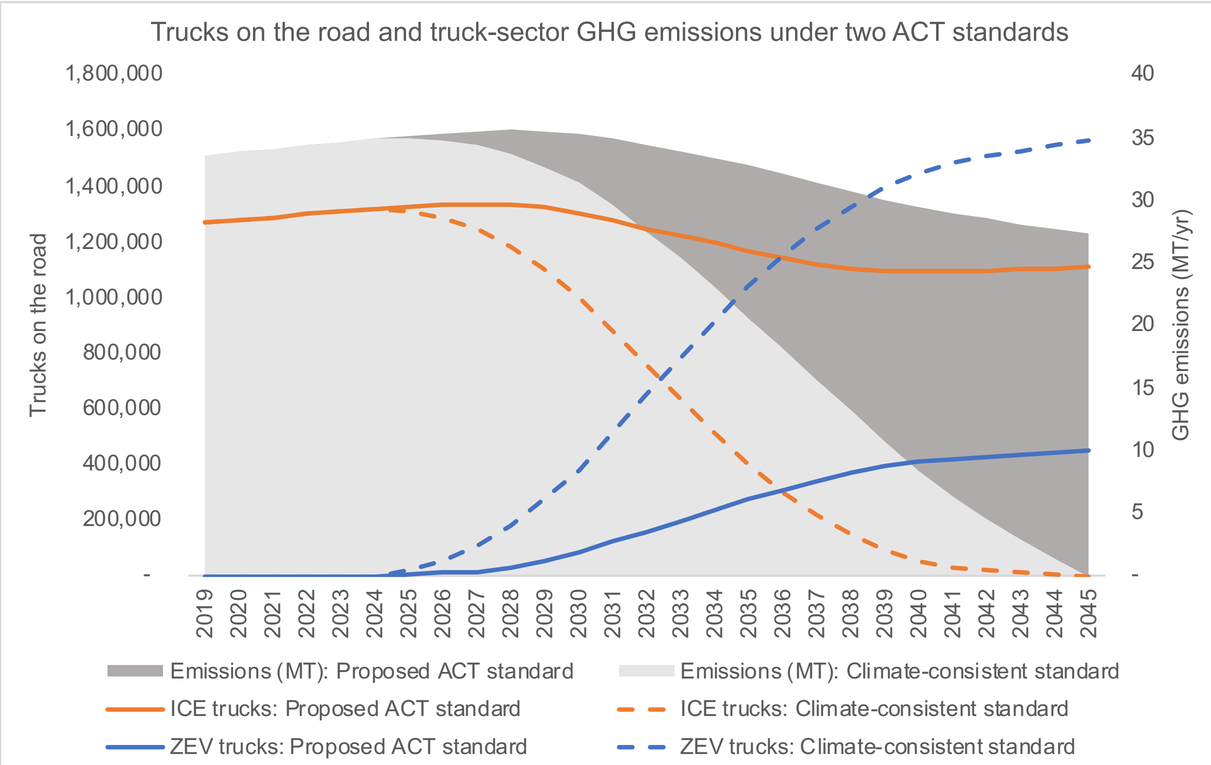

Figure 3. ICE and ZEV trucks on the road through 2045, and GHG emissions through 2045, under the proposed CARB ACT standard and the climate-consistent ACT standard.

C: Greenhouse gas emissions

The net present cost of carbon emissions in the climate-consistent proposal is $28 billion through 2045, 33% less than the cost of $41 billion under the current ACT proposal, and 42% less than the $48 billion carbon cost of business-as-usual. These figures assume a price on carbon consistent with the EPA's social cost of carbon. (The carbon cost of even the climate-consistent proposal is significant both because stock turnover from ICE vehicles to zero-emission vehicles takes time, and because future carbon savings are discounted.) Under the current ACT proposal, trucks would still be emitting 27 million tonnes per year of carbon in 2045, or about 82% of what our model shows they are producing today (see Figure 3).

D: Air pollution

Under the climate-consistent proposal, air pollution costs are $49 billion through 2045, 33% less than the cost of $72 billion under the current ACT proposal, and 41% less than the $83 billion cost of BAU. (The cost of air pollution from ICE trucks is higher than the modeled cost of their carbon emissions.) Trucks that have the lowest ACT targets under the current proposal—Class 2B-3 trucks and Class 8 tractors—are responsible for most air pollution costs today: Class 2B-3 trucks are estimated to contribute 24% of air pollution damages from trucks, and Class 8 trucks are estimated to contribute 55% (roughly half from tractors, half from non-tractors) (see Table 13).

Discussion

This model is intended to create a timely, first-order estimate of the high-level impacts of selecting a certain ACT standard. As such, there is room for a more detailed model that expands on this work. The principal simplifying assumptions we made in this model are as follows: first, we treat California as a closed system and assume that all trucks present in California are sold and driven in California. We do not attempt to analyze emissions from out-of-state ICE trucks being driven in California. We assume all classes of vehicles reach 100% ZEV sales in the same year, making no distinction between tractors and non-tractors or pickup trucks. We also rely heavily on data from 2002 in our modeling.

In terms of zero-emission technology, we only analyze battery electrification as a ZEV option, omitting other technologies, such as fuel cells. Our estimates of charging infrastructure needs are based on total energy required, rather than on a spatially oriented model such as a truck flow model. Finally, we hold diesel and electricity prices constant in real terms over the course of the analysis to reflect the uncertainty associated with projecting either into the future, given such trends as electrification and renewable buildout.

Each of the elements mentioned above could be modeled in more detail to better understand the impact of a certain standard. ACT standard. We have not considered here the practical aspects of implementing this proposal, although it is technically feasible. As such, we hope other efforts will expand on this work, given that the results presented here suggest that selecting a particular standard could have both cost and environmental impacts that vary on the scale of billions of dollars.

Methodology

To compare each scenario, we combined a stock model (see Section A) and a cost model (see Section B). We built each model around the specific vehicle classes included in the CARB proposal, using the gross vehicle weight rating (GVWR) boundaries we understood to apply to each class to translate data gathered from other sources into the relevant ARB classes.

ARB ZEV class[3]	Class 2B-3	Class 4-5	Class 6-7 (non-tractors)	Class 8 (non-tractors)	Class 7-8 tractors
GVWR (lbs)[13]	8,500-14,000	14,000-19,500	19,000-33,000	33,000+	26,000+

Table 1. Translating ARB ZEV classes into GVWR

We modeled three difference ZEV scenarios: a business-as-usual (BAU) scenario, assuming no transition to ZEV trucks; the current ACT proposal; and a proposal consistent with achieving 100% zero-emissions trucks on the road by 2045 (herein called the “climate-consistent” proposal for its alignment with Gov. Brown’s climate target). We model truck stocks and costs each year from 2019 to 2045.

The only zero-emission technology our modeling addresses is electrification—i.e., other clean trucking technologies, such as fuel-cell vehicles, are not addressed for simplicity.

A: Stock model

The stock model estimates the number of trucks on the road, both ICE and electric, in each vehicle class in each year from 2019 to 2045. To build this model, we estimated (1) the number of vehicles in each class on the road in 2019, (2) vehicle lifetime to understand turnover, and (3) how many electric trucks would come into the stock each year based on the proposed sales percentage schedule. We assumed a 0.8% annual growth rate for the truck population overall.

(1) Number of vehicles per class: To estimate the number of vehicles in each ZEV class on the road in 2019, we started with figures from the 2002 census of how many trucks were in each GVWR-based class nationally[13]. We then estimated 2019 numbers based on 2002 numbers, based on CAGRs calculated for single-unit and combination trucks registered from 2002-2015 (3.1% and 1.5%, respectively)[14]. Next, we estimated the percentage of the national truck fleet that could be attributed to California, based on the ratio of trucks registered in California to trucks registered nationwide in 2002 (11%) and truck-miles driven in California to truck-miles driven nationwide in 2010 (9%)[13,15]. Finally, we used 2002 census data to estimate the fraction of class 7-8 trucks that are tractors vs. non-tractors (46% and 54%, respectively)[13].

ZEV mandate class	Class 2B-3	Class 4-5	Class 6-7	Class 8
Number of trucks in class (thousands)[13]	3,933	772	1,347	2,154

Table 2. Vehicles by ZEV mandate class, national figures, 2002

ZEV mandate class	Class 2B-3	Class 4-5	Class 6-7	Class 8	Class 7-8 tractors
Number of trucks	649,709	127,537	222,545	144,772	123,735

Table 3. Estimated vehicles by ZEV mandate class, California, 2019

(2) Truck lifetime: To model how quickly trucks in each class would turn over, we estimated vehicle lifetime in each class. To do this, for each truck class we used the number of vehicles in 2002, the number of new vehicles sold each year, and the average annual increase in sales to estimate annual sales needed only to account for replacement (not growth). Based on the percent of the total truck population replaced each year, we estimated the lifetime of trucks in each class. The estimates for Classes 6 and 7 seemed unrealistic; without a better source of information, we designated their lifetime as 10 years (a rough average of the lifetime of other classes).

Truck class	2	3	4	5	6	7	8
Number of trucks, thousand (2002)[16]	28,041	691	291	166	1,710	180	2,154
New retail truck sales, thousand (2002)[16]	2,565	80	38	24	45	69	146
Avg. annual increase in sales, 1997-2007	4%	12%	1%	17%	12%	-5%	-2%
New retail truck sales for replacement of retiring fleet (thousand)	2,453	70	38	20	40	72	148
% of fleet replaced each year	9%	10%	13%	12%	2%	40%	7%
Lifetime, years	11.4	9.8	7.7	8.4	*10.0*	*10.0*	14.5

Table 4. Original data and calculations to produce lifetime estimates by truck class

ZEV mandate class	Class 2B-3	Class 4-5	Class 6-7	Class 8	Class 7-8 tractors
Lifetime (years)	11.0	8.0	10.0	15.0	15.0

Table 5. ZEV-class lifetime estimates

(3) Electric truck population: To analyze when electric trucks would come into the truck population under the proposed ACT rule, we used the sales percentages given by CARB, including exemptions for tractors and pickup trucks (see Table 6). For the BAU scenario, we assumed no ZEV trucks would be on the road by 2045. For the climate-consistent scenario, we assumed 100% ZEV truck sales by 2030.

Because pickups are exempt from the proposed rule until 2027, we had to estimate the fraction of class 2B-3 trucks comprised of pickups. To do so, we broke down our estimate by Class 2B and Class 3. We estimated fairly straightforwardly that 88% of Class 3 trucks are pickups (based on 2002 data)[13]. The fraction of Class 2B trucks that are pickups was harder to ascertain, as it involved segmenting Class 2 trucks into 2A and 2B, and Class 2B trucks into pickups and non-pickups[17–19]. As a consequence, our ultimate estimate was that 96% of Class 2B-3 trucks are pickups, which seems unusually high; however, it makes little difference to the results.

Model year	Class 2B-3 (excluding pickups until 2027)	Class 4-5	Class 6-7 (non-tractors)	Class 8 (non-tractors)	Class 7-8 tractors
2024	3%	7%	7%	7%	3%
2025	5%	9%	9%	9%	5%
2026	7%	11%	11%	11%	7%
2027	9%	13%	13%	13%	9%
2028	11%	24%	24%	24%	11%
2029	13%	37%	37%	37%	13%
2030 and beyond	15%	50%	50%	50%	15%

Table 6. Proposed ZEV sales percentage schedule by model year under current ACT proposal

B: Cost analysis model

The cost model took in the results of the stock model to assess annual system costs based on the number of electric and ICE trucks on the road in each year. The costs considered by the model are (1) charging infrastructure, (2) fuel, (3) greenhouse gas (GHG) emissions, (4) air pollution, and (5) the incremental cost of fleet electrification.

(1) Charging infrastructure: Charging infrastructure cost was modeled in two parts: the cost of charging stations and the cost of transmission buildout to support additional load. All charging stations are assumed to be connected at the transmission level; as such, distribution-level costs were not considered.

The assessment of how many charging stations were needed was made by calculating the total energy requirements that would need to be served and dividing over the energy provided by a single station operating at a given utilization factor. Further information on the methodology used to estimate the cost of these charging stations is available in the presentation "California semi truck electrification: Preliminary assessment of infrastructure needs and cost-benefit analysis."[20]

Charging station capacity[11]	18.75	MW
Average charging power[11]	80%	
Station utilization (% of time trucks are charging)[1]	20%	
Upfront cost of charging station[11]	$14.50	million/station
O&M cost of charging station[11]	$206,000	$/year
Discount rate[11]	5%	
Station lifetime[11]	20	years

Table 7. Inputs to charging station cost model

An estimate of transmission cost was made by drawing the median annualized cost of transmission from the CPUC Renewable Portfolio Standard calculator ($76/kW-year)[23]. It is assumed that the average load factor of transmission is somewhat higher compared to the utilization factor assumed for the station (30% versus 20%, respectively), and thus that less than 100% of the cost of the transmission build incurred will fall on the charging station owner.

(2) Fuel: Fuel cost—both electricity cost and diesel/gasoline cost—depends both on the cost of fuel and on vehicle efficiency. We used a high-cost and a low-cost scenario to model the price of electricity. The high-cost scenario draws on Southern California Edison's 2018 rate schedule for large customers—it assumes trucks charge at the lowest-cost times (averaging $38/MWh) and that delivery charges (levelized to $72/MWh) are paid[24]. Transmission cost is not considered separately in this scenario to avoid double-counting. The low-cost scenario considers a real-time pricing scenario that could be supported by future policy: costs considered are real-time wholesale electricity prices in CAISO (averaging $34/MWh) as well as transmission costs incurred[25]. Diesel and gasoline costs are assumed to be $3.16/gal and $2.73/gal, respectively—their 2018 prices[26]. Both electricity and diesel costs are held constant in real terms throughout the time period modeled.

ICE fuel economy is used as the baseline to calculate EV fuel economy. Fuel economy for each ZEV class was calculated from the 2002 census; improvements in Class 8 fuel economy were assumed to proportionally apply across all classes to update fuel economy to 2019 values. Finally, known values of Class 8 electric fuel economy were used to create estimates for other classes based on their ICE fuel economy[13,27]. Annual miles driven per truck were also collected for each class in order to calculate annual fuel use[16]. Finally, the percentage of each truck class using gasoline versus diesel was estimated by assuming that the 2018 diesel share of new sales for each class remained constant[16].

Class	**Class 2B-3**	**Class 4-5**	**Class 6-7**	**Class 8**
Fuel economy (mpg) (2002)[13]	13.8	8.3	6.9	5.7
Fuel economy (scaled to update to 2019)[27]	14.2	8.5	7.1	5.9
Fuel economy (mi/kWh)[27]	1.15	0.69	0.58	0.48

[1] Estimate based on current car DCFC utilization rate from Fitzgerald et al. (14%) and capacity factor assumed by Tong et al. under high alternative truck fueling penetrations (40%)[21,22]

Annual miles/truck[16]	12,869	14,060	14,387	45,739
% diesel by class[16]	0%	31%	83%	100%

Table 8. Inputs to fuel use model

(3) Greenhouse gas emissions: The cost of GHG emissions was estimated for both diesel and electricity use. Gasoline use emissions were assumed to approximate those from diesel use. The cost of emissions in this model is the social cost of carbon given by the EPA, using a 3% discount rate[28].

Year	2018$/tonne CO2
2015	$44
2020	$51
2025	$56
2030	$61
2035	$67
2040	$73
2045	$77

Table 9. Social cost of carbon

The per-gallon GHG emissions cost for diesel trucks was calculated by combining the emissions intensity and the energy density of diesel. The GHG emissions cost for electricity in California was calculated to be 0.24 tonnes/MWh in 2016 (based on reported emissions and electricity usage), is projected to be 0.17 tonnes/MWh in 2030, and will be 0.00 tonnes/MWh in 2045 if the SB 100 target of 100% carbon-free electricity is met by that year[29–31]. Straight-line averaging was used to estimate electricity emissions intensity between the given years.

Diesel energy density	137,381	Btu/gal diesel
Emissions intensity[32]	161	lbs CO2/million Btu
Conversion to metric tons	2,205	lbs/tonne

Table 10. Diesel GHG emissions intensity calculation

(4) Air pollution: Estimates of air pollution costs relied heavily on figures from Goodkind et al., who report nationwide damages by air pollutant, by vehicle weight and fuel (e.g., heavy duty diesel)[33,34]. We combined these figures with EPA reports of total tons of each pollutant, also reported by vehicle weight and fuel, to arrive at a calculation of damages per ton of pollutant.[35] We then combined these results with ARB reporting of tons/day of pollution by vehicle class and fuel to arrive at annual air pollution damages by class[36].

Air pollution damages from increased electricity production were calculated assuming that the marginal generator meeting load increases in 2019 was natural-gas-fired (a conservative estimate, given that our electricity cost calculations are meant to incorporate off-peak charging). It is assumed that these damages decline to zero by 2045 as the proportion of clean energy increases to 100%.

Pollutant	Tons of pollutant[35]	Damages ($B)[34]	Damages/ton ($/ton)

Nitrogen Oxides	2,561,463	$34.73	$13,559
Volatile Organic Compounds	213,454	$1.79	$8,386
PM2.5 Primary (Filt + Cond)	120,812	$20.94	$173,327
Ammonia	5,764	$0.57	$98,898
Sulfur Dioxide	3,189	$0.08	$25,084

Table 11. Damages from heavy-duty diesel vehicles in 2011, nationwide

Truck class	**ROG [VOC]** [36]	**NOX**[36]	**SOX**[36]	**PM2.5** [36]	**NH3**[36]	**GVWR ('000 lb)**[37]	**ZEV class**	**Daily cost ($2011M)**	**Annual cost ($2018 M)**
Light heavy duty gas trucks – 1	16.43	20.81	0.12	0.53	1.34	8.5-10	Class 2B-3	$0.67	**$274**
Light heavy duty gas trucks - 2	1.83	2.71	0.02	0.1	0.19	10-14	Class 2B-3	$0.09	**$38**
Medium heavy duty gas trucks	3.09	5.56	0.03	0.13	0.09	14-33	Class 4-5 & Class 6-7	$.13	**$55**
Heavy heavy duty gas trucks	0.55	1.43	0	0.01	0.01	>33	Class 8 tractors & non-tractors	$.03	**$11**
Light heavy duty diesel trucks – 1	2.58	64.49	0.07	0.98	0.04	8.5-10	Class 2B-3	$1.07	**$438**
Light heavy duty diesel trucks - 2	0.68	15.93	0.02	0.3	0.01	10-14	Class 2B-3	$0.28	**$112**
Medium heavy duty diesel trucks	4.69	80.75	0.16	3.31	0.39	14-33	Class 4-5 & Class 6-7	$1.75	**$716**
Heavy heavy duty diesel trucks	10.22	282.73	0.65	4.62	1.05	>33	Class 8 tractors & non-tractors	$4.84	**$1,979**

Table 12. Daily emissions in CA by truck weight and fuel, 2015 (tons/day); classification by ZEV class; calculation of total cost

Class	**Damages ($M/yr)**
Class 2B-3	$863
Class 4-5	$70
Class 6-7	$700
Class 8 non-tractor	$1,073
Class 8 tractor	$917

Table 13. Results: estimated air pollution damages by class

Marginal cost of increased electricity production from natural gas, NOx damages[34]	8.96	$thousands/ton
Marginal cost of increased electricity production from natural gas, SO2 damages[34]	19.11	$thousands/ton
CA emissions intensity, NOx[38]	0.7	lbs/MWh

CA emissions intensity, SO_2[38]	0.0	lbs/MWh

Table 14. Inputs to damage calculation from increased natural-gas-fired electricity production

(5) Fleet electrification: The incremental cost of fleet electrification was calculated assuming the major additional cost of an electric truck compared to an ICE truck is the cost of the battery. Some savings were also assumed based on the cost of the diesel drivetrain[12]. Battery cost projections were sourced from Bloomberg New Energy Finance[4]. Range and incremental cost differences were known for Class 8 trucks, and were roughly generalized to other truck classes based on Class 8 figures.

Incremental electrification cost was calculated as depreciation cost on a per-mile basis. Electric trucks introduced in a certain year were assumed to realize that per-mile cost of electrification and to recover the market-value cost of electrification in the year they were retired.

ZEV class	Diesel fuel economy (mpg)	Electric fuel economy (mi/kWh)	Diesel lifetime	Range (mi)	Other incremental differences
Class 2B-3	14.2	1.15	11.0	200	($5,000)
Class 4-5	8.5	0.69	8.0	200	($5,000)
Class 6-7	7.1	0.58	10.0	200	($10,000)
Class 8 (tractor or non-tractor)	5.9	0.48	15.0	500[39]	($22,000)[12]

Table 15. Inputs to incremental fleet electrification cost model

Year	Lithium-ion battery pack price (2018$/kWh)
2018	$176
2019	$162
2020	$149
2021	$135
2022	$121
2023	$108
2024	$94
2025	$89
2026	$83
2027	$78
2028	$73
2029	$67
2030	$62

Table 16. Battery capital cost predictions

Battery cycles[40]	2000	cycles/life
Depth of discharge[40]	0.75	% of total kWh available per cycle

Table 17. Additional inputs to per-mile depreciation cost calculation (in addition to inputs given in other tables—e.g., lifetime, annual mileage, fuel economy, discount rate)

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