Clean Trucks Analysis

Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks

TECHNICAL REPORT — METHODOLOGIES & ASSUMPTIONS

June 2021

ERM

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Acknowledgments

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This technical report summarizes the methodology and data sources used to develop a state-based modeling framework intended to be used to estimate the costs, and the economic, public health, and climate benefits of state-level policy actions requiring manufacturers to increase the share of new medium- and heavy-duty vehicles that are no- and low-emissions. The modeling framework includes all on-road vehicles of more than 8,500 pounds gross vehicle weight, encompassing vehicle weight classes from Class 2b though Class 8 and covering a diverse set of mostly commercial vehicles including heavy-duty pickups and vans; school and transit buses; sanitation, construction, and other types of work trucks; and tractor-trailers that weigh more than 80,000 pounds when loaded.

Detailed results from using the framework to estimate net benefits of specific policy scenarios in various states will be published in separate reports.

This report was developed by ERM for the Natural Resources Defense Council and the Union of Concerned Scientists.

About ERM, formerly M.J. Bradley & Associates

M.J. Bradley & Associates (MJB&A) was acquired by ERM Group company in 2022. Continuing what MJB&A started, ERM provides strategic consulting services to address energy and environmental issues for the private, public, and nonprofit sectors. ERM creates value and addresses risks with a comprehensive approach to strategy and implementation, ensuring that clients have timely access to information and the tools to use it to their advantage. Our approach fuses private sector strategy with public policy in air quality, energy, climate change, environmental markets, energy efficiency, renewable energy, transportation, and advanced technologies. Our international client base includes electric and natural gas utilities, major transportation fleet operators, investors, clean technology firms, environmental groups, and government agencies. Our seasoned team brings a multi-sector perspective, informed expertise, and creative solutions to each client, capitalizing on extensive experience in energy markets, environmental policy, law, engineering, economics, and business. For more information we encourage you to visit our website, www.erm.com or www.sustainability.com.

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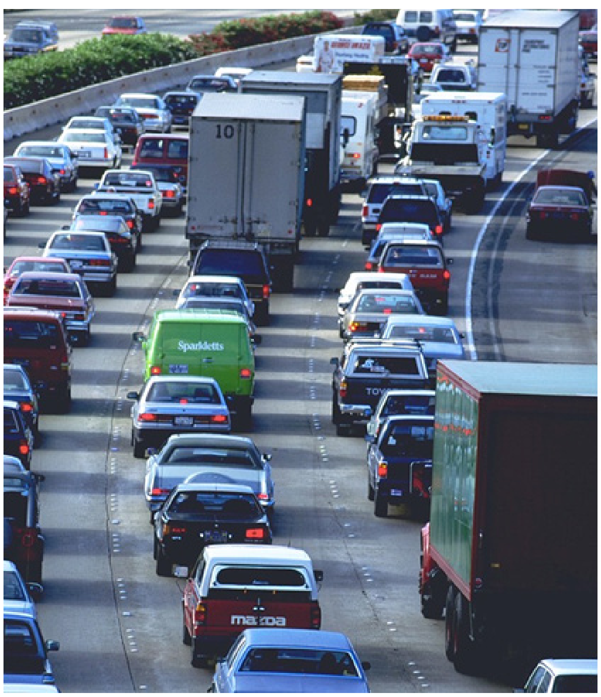
This report is available at www.ERM.com.

Introduction

ERM was commissioned by the Natural Resources Defense Council and the Union of Concerned Scientists to develop a state-based modeling framework that could be used to estimate the costs, benefits, and net societal benefits of state-level requirements for manufacturers to increase the share of new medium- and heavy-duty (M/HD) vehicles that are no- and low-emissions. The modeling framework includes all on-road vehicles of more than 8,500 pounds gross vehicle weight, encompassing vehicle weight classes from Class 2b though Class 8 and covering a diverse set of mostly commercial vehicles including heavy-duty pickups and vans; school and transit buses; sanitation, construction, and other types of work trucks; and tractor-trailers that weigh more than 80,000 pounds when loaded.

Collectively in the United States, the M/HD fleet includes more than 23 million vehicles that annually travel in excess of 423 billion miles and consume 54 billion gallons of petroleum fuels. These vehicles currently emit 574 million metric tons (MMT) of greenhouse gases (GHGs) annually, approximately 32 percent of all GHGs from the on-road vehicle fleet.[i] M/HD vehicles are also responsible for more than 60 percent of the nitrogen oxide (NOx) and particulate matter (PM) emitted by on-road vehicles. NOx and PM contribute to poor air quality and resulting negative health impacts in many urban areas, including low-income and disadvantaged communities that are often disproportionality impacted by emissions from freight movement due to their close proximity to transportation infrastructure.



This technical report summarizes the analytical methodologies and data sources used to develop and populate the modeling framework. Detailed results from using the framework to estimate net benefits of specific policy scenarios in various states will be published in separate reports.

This current work follows earlier work by MJB&A to evaluate community-scale emissions impacts from on-road and nonroad transportation sources, conducted in consultation with the New Jersey Environmental Justice Alliance, the Coalition for Healthy Ports, and NRDC. That work identified medium and heavy-duty truck traffic as a significant contributor to the overall emissions burden in the residential communities evaluated in the Newark, New Jersey, area. This project explores the specific benefits of state-level vehicle standards that could be implemented to address these air pollutants while also advancing state and national climate goals.

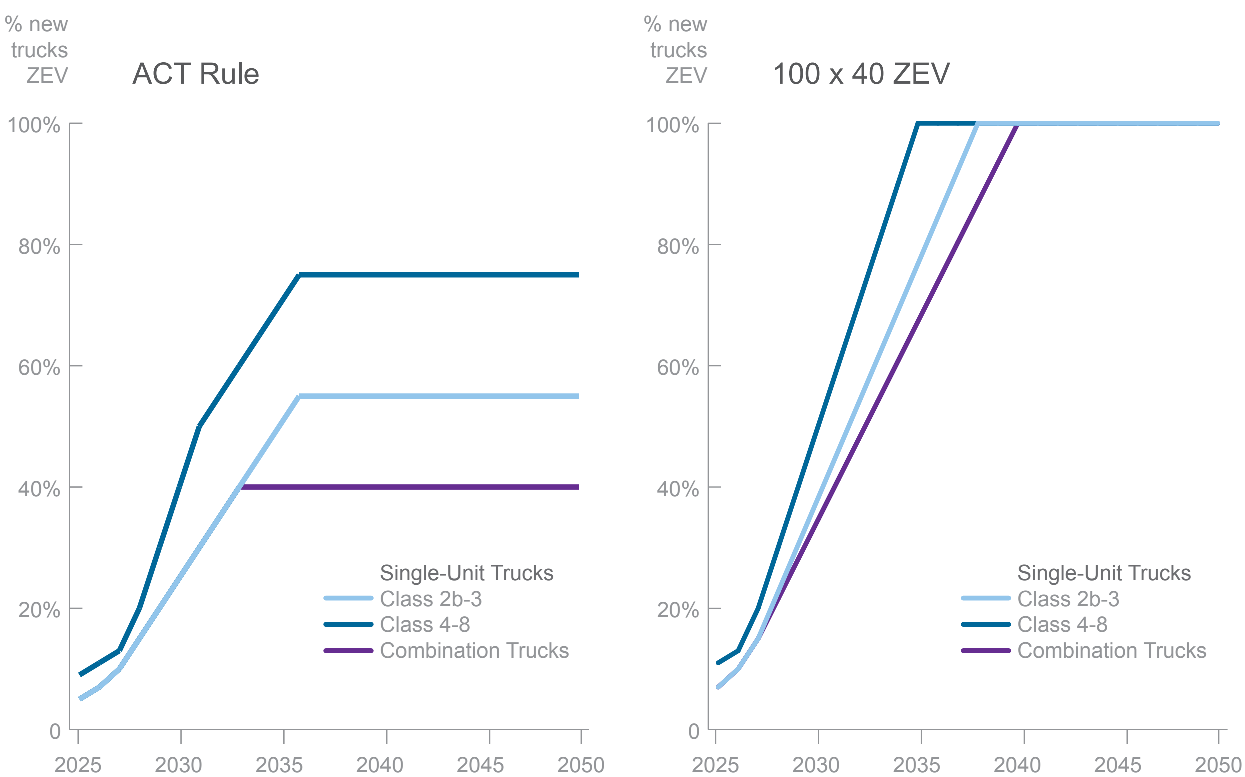
i The remainder of emissions are from passenger cars and light trucks.

Policy Scenarios

In state-level reports, ERM will use the modeling platform described here to model three specific policy scenarios:

- **ACT Rule:** The state adopts the requirements of the California Advanced Clean Truck (ACT) Rule, which mandates that an increasing percentage of new trucks purchased in the state be zero emission vehicles (ZEVs) beginning in the 2025 model year. The percentage of new vehicles that must be ZEVs varies by vehicle type, but for all types the required ZEV percentage increases in each model year between 2025 and 2037 (see Figure 1).
- **ACT Rule plus NOx Omnibus Rule:** In addition to adopting the ACT Rule, the state adopts California's NOx Omnibus Rule, which requires an additional 75 percent reduction in NOx emissions from the engines in new trucks sold in model years 2025 and 2026, and a 90 percent reduction for trucks sold beginning in the 2027 model year.[ii]
- **100 x 40 ZEV + Clean Grid:** In addition to adopting the ACT and NOx Omnibus Rules, the state takes additional actions to ensure continued increases in new ZEV sales, such that virtually all new trucks sold after 2040 will be ZEV (see Figure 1). In addition, the state enacts an aggressive Clean Energy Standard to ensure that electricity generation in the state will be virtually carbon free by 2050.

Figure 1 ZEV Sales in Clean Truck Policy Scenarios



ii Reductions are relative to current federal EPA new engine emission standards. This rule does not require additional PM reductions but includes anti-backsliding provisions to ensure that PM emissions do not increase relative to engines designed to meet current federal standards.

All three of these state policy scenarios will be compared with a baseline "business as usual" scenario in which all new trucks sold in the state continue to meet existing EPA NOx emission standards and ZEV sales increase only marginally, never reaching more than 1 percent of new truck and bus sales each year.[iii]

As described below, the modeling framework assumes that state M/HD annual vehicle miles traveled (VMT) will continue to grow through 2050 as projected by the Energy Information Administration, as the economy and population continue to grow.[iv] The modeled policy scenarios do not include freight system enhancements or mode shifting to slow the growth of, or reduce, M/HD truck miles.

Scope of the Modeling Framework

The modeling framework encompasses five interconnected analyses that together estimate the climate, air quality/health, and economic impacts of each policy scenario relative to the baseline scenario. These analyses are summarized in Figure 2. Climate and air quality impacts are estimated on the basis of changes in M/HD fleet fuel use and include both tailpipe emissions and "upstream" emissions from production of the transportation fuels used in each scenario. This includes the petroleum fuels (gasoline, diesel, and natural gas) used by conventional internal combustion engine (ICE) vehicles and the electricity and hydrogen used by ZEVs, which are assumed to include both battery electric (EV) and hydrogen fuel cell electric (FCV) vehicles.

Figure 2 Modeling Framework Scope

Fuel Use & Emissions Analysis	• Change in fuel use (diesel, gasoline, electricity, hydrogen) • Change in GHG emissions (CO_2, CH_4, N_2O) • Change in criteria pollutants (NOx, PM) • Includes tailpipe and upstream emissions. • Estimate monetized value of net emission reductions
Health Impacts Analysis	• Change in premature deaths, hospital visits, and restricted activity and lost workdays due to lower NOx and PM emissions • Estimate monetized value of net health benefits
Economic & Jobs Analysis	• Change in spending on vehicle purchase, fuel, and maintenance • Charging infrastructure investments • Change in net jobs, GDP, and wages across the economy
Utility Impact Analysis	• Change in electricity use and load • Utility net revenue • Impact on electricity rates
GAP Analysis	• Estimate state-level charging infrastructure needs. • Potential complementary incentive needs (state/federal)

iii The baseline ZEV sales assumptions are consistent with the Energy Information Administration's *Annual Energy Outlook 2021*.

iv Per the latest EIA projections, future M/HD VMT growth will vary by state and region depending on differences in population and economic growth.

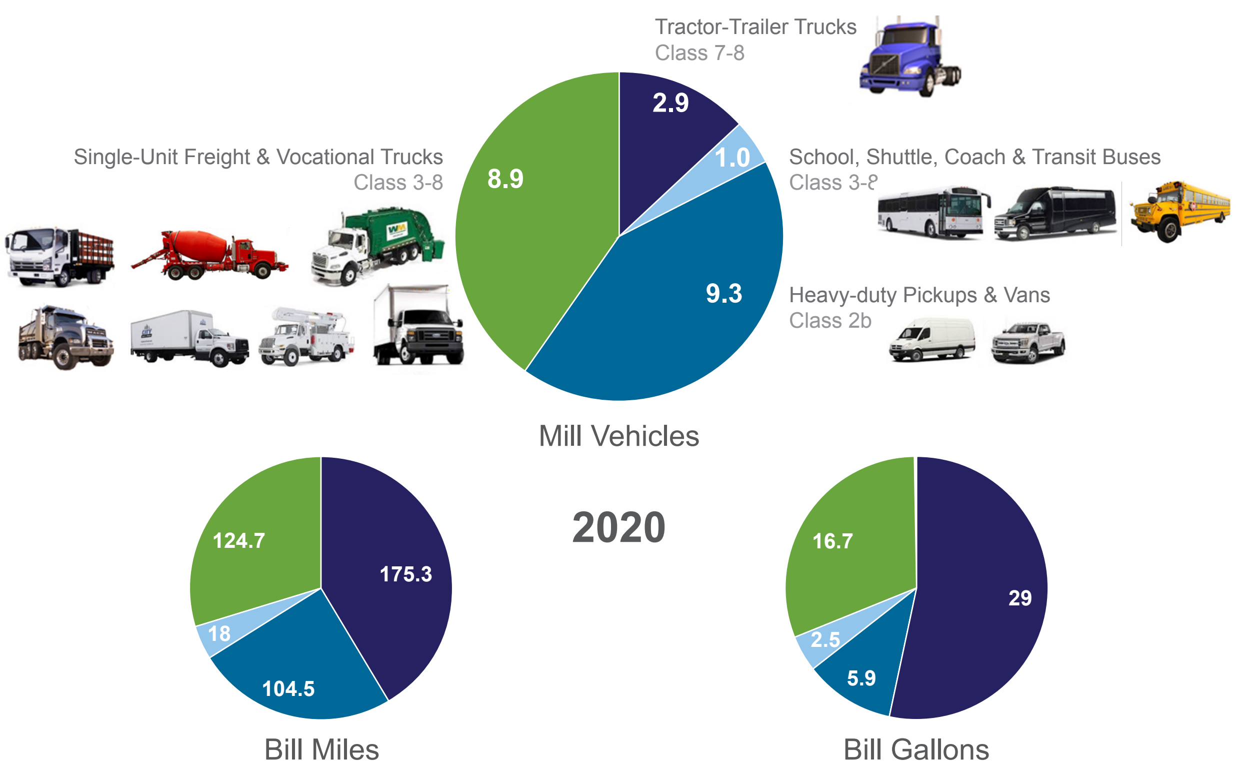
To evaluate climate impacts, the analysis estimates changes in all combustion-related GHGs, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). To evaluate air quality impacts, the analysis estimates changes in NOx and PM emissions and resulting changes in health metrics such as premature deaths, hospital visits, and lost work days.

The economic analysis estimates the change in annual M/HD fleetwide spending on vehicle purchase, charging/fueling infrastructure to support ZEVs, vehicle fuel, and vehicle and infrastructure maintenance. Currently ZEVs are more expensive to purchase than equivalent gasoline and diesel vehicles, but they have lower fuel and maintenance costs. Over time the incremental purchase cost of ZEVs is also projected to fall. On the basis of these changes in fleet costs, the analysis also estimates the macroeconomic effects on U.S. jobs, wages, and gross domestic product.

The utility impacts analysis assesses the total statewide change in electricity load (kW) and throughput (kWh) for M/HD EV charging, as well as the additional revenue and net revenue that would be received by the state's electric utilities for providing this power.[v] Based on projected utility net revenue, the analysis estimates the potential effect on state electricity rates for residential and commercial customers.

The infrastructure gap analysis estimates the total number of vehicle chargers—both depot-based chargers and shared "public" ones—that will be required to support the increase in M/HD EVs under each scenario compared with the existing charging network in the state.

Figure 3 U.S. Medium and Heavy-Duty Vehicles



v Utility net revenue is revenue minus the costs of procuring the necessary bulk electricity.

Methodologies and Assumptions

This section discusses the methodologies and major assumptions used in each section of the modeling framework. As noted, some assumptions will be common to all states, and some will vary by state. For those assumptions that vary by state one or more illustrative examples are provided here; more detail on the specific state-level assumptions used will be provided in the state reports.

All dollar values cited in this report are constant 2020$, unless otherwise noted.

Fuel Use and Emissions Analysis

The modeling framework uses MJB&A's STate Emission Pathways (STEP) Tool to generate, for each year through 2050, total fuel/energy use by the M/HD vehicle fleet at the state level under each modeled scenario [1]. Fuel use is disaggregated by major vehicle type (bus, single-unit truck, combination truck) and by fuel type (gasoline, diesel, natural gas, electricity, hydrogen) based on the modeled changes in fleet composition under each scenario. These annual projections are then used as inputs to the emissions analysis and the economic analysis.

The STEP Tool is a spreadsheet-based multi-sector model that allows users to analyze state and regional energy use and their CO_2 emission trajectories under a range of economy-wide policy scenarios. It lets users build detailed custom policy scenarios by selecting from various policy options in each sector of the economy—electric, transportation, residential, commercial, and industrial—while tracking in real time the associated overall electricity generation, portfolio mix, total energy use by fuel type, and vehicle miles traveled by type. The inclusion of multiple sectors of the economy allows users of the STEP Tool to examine certain energy-use interactions among the different sectors of the economy (e.g., the impact of electric vehicles on both the electric and transportation sectors).

To produce scenario projections quickly and efficiently, the STEP Tool uses a non-optimization approach to solve for and calculate future energy use and CO_2 emissions. It does not try to reach any equilibrium condition or optimize the system for any variables. Instead, it records each user selection to construct one or more policy scenarios and then calculates their impacts in terms of changes to existing patterns of energy use. It makes use of heuristics and simplifying assumptions to produce projections at an indicative level. STEP Tool outputs can be generated for the entire U.S. economy or for individual states or groups of states.

The STEP Tool relies, for the most part, on publicly available data sets from federal and state-level government agencies to build up detailed characterizations of historic energy use patterns for each sector of the economy. For example, for the transportation sector, the focus of this modeling framework, the STEP Tool uses the Federal Highway Administration's (FHA) "Highway Statistics" publication as the starting point for the development of state-by-state data on vehicle miles traveled, size of current vehicle stocks by vehicle type, and so on. Various sections of the EIA's Annual Energy Outlook and State Energy Data System data sets are used to add further detail to the final representation of the sectors in the STEP Tool and to provide a way to cross-check against a second calculation of overall energy use and associated emissions in the sector. For this modeling framework the STEP Tool was updated to the latest available data sets, including FHA 2019 fleet data [2], and EIA's Annual Energy Outlook 2021 [3].

The STEP Tool incorporates the state-to-state variability in M/HD vehicle stock and future VMT growth embedded in the FHA and EIA data sets, which will affect the outcomes of analyzed policy scenarios across different states. The STEP tool also incorporates assumed future improvements in fleet average vehicle fuel economy (MPG) as the fleet turns over to new conventional ICE vehicles compliant with current EPA new vehicle and engine fuel economy and GHG emission standards. These improvements are reflected in the baseline scenario and all analyzed policy scenarios.

For each policy scenario, annual net reductions in GHG emissions compared with the baseline are estimated on the basis of modeled changes in fuel use (gasoline, diesel, natural gas, electricity, and hydrogen). Calculated GHG emissions include CO_2, CH_4, and N_2O, with the latter two expressed in carbon dioxide–equivalent terms (CO_2-e) using their global warming potential over a 100-year period (GWP_{100} = 25 for CH_4 and 298 for N_2O), as estimated by the United Nations Intergovernmental Panel on Climate Change's *Fifth Assessment Report* [4].

Estimated GHG emissions include tailpipe emissions from gasoline and diesel vehicles[vi] and upstream emissions from production and delivery of the different fuels, including from generation of electricity to charge EVs and production of hydrogen to fuel FCVs.

Tailpipe emission factors for gasoline and diesel vehicles (g/gallon) were derived from the latest version of EPA's MOtor Vehicle Emission Simulator (MOVES3) model [5] by mapping STEP Tool vehicle types to vehicle types in MOVES.

Upstream emission factors (g/gallon for diesel and gasoline, g/kWh for electricity, g/kg for hydrogen) were developed using the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model developed by Argonne National Laboratory [6].

For electricity the framework uses weighted average GHG emission factors (g CO_2/kWh, g CH_4/kWh, g N_2O/kWh) that were developed using GREET emission factors for coal, natural gas combined cycle (NGCC), and zero-emitting electricity generation, and state-specific assumptions for the percentage of generation from each of these sources each year.

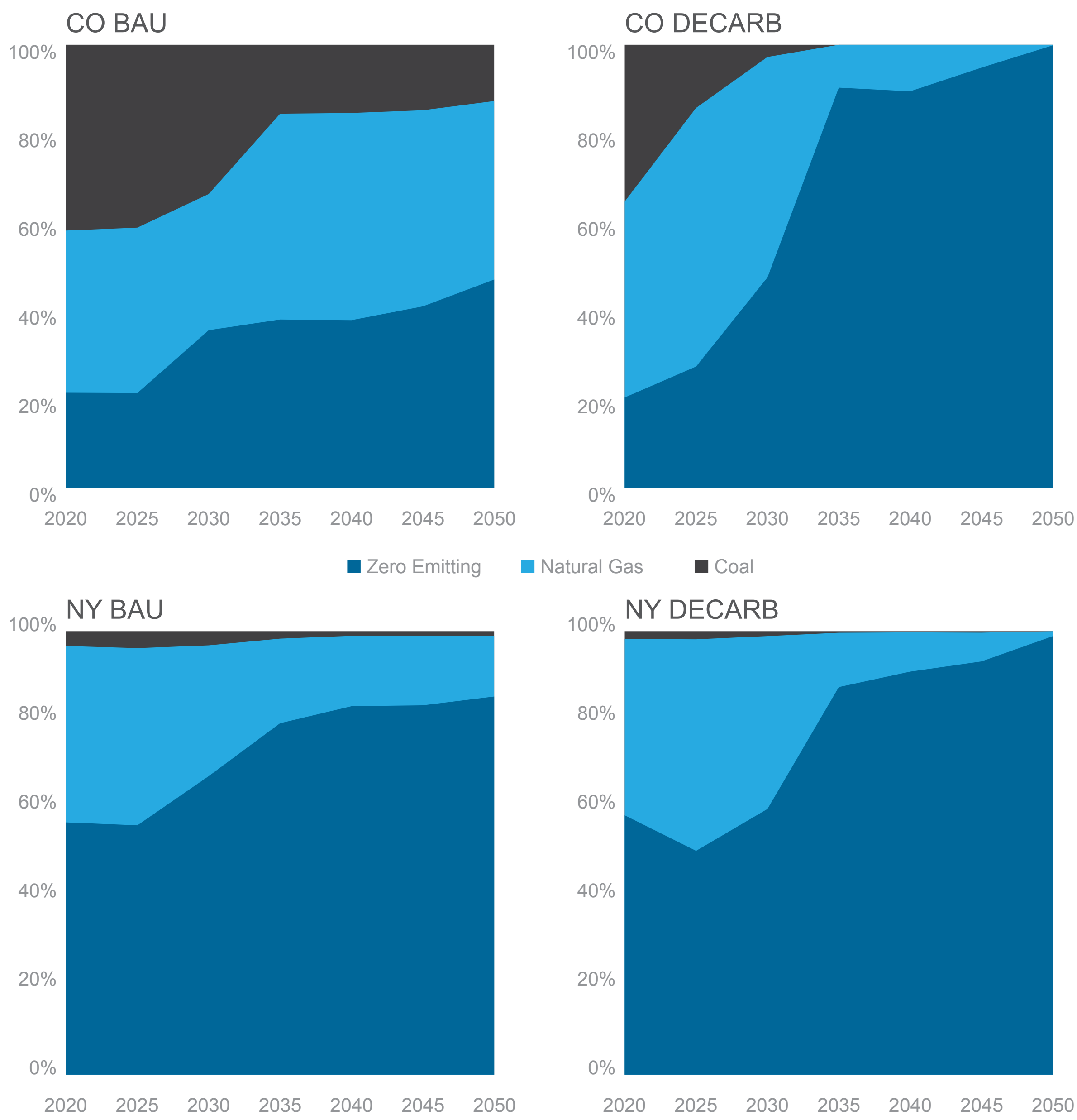
The state-specific grid mix assumptions were developed by the National Resources Defense Council using ICF International's Integrated Planning Model (IPM) [7]. For each state there are two scenarios: (1) a BAU grid mix representing current policy and (2) a decarbonized grid mix reflecting more aggressive federal energy policy. The BAU case was developed in the fall of 2020 and reflects state and federal policy as of July of that year, with assumptions around fuel costs, technology costs, and performance drawn from EIA's Annual Energy Outlook 2020 and NREL's Annual Technology Baseline 2020. Analysis of new, state-specific electricity policies, such as from more stringent Renewable Portfolio Standards, was beyond the scope of this study but would be expected to increase the usage of these renewable resources.

The decarbonized grid mix is an illustrative example of a national standard of 100 percent clean energy by 2035, with banking, applied to each state. The banking provisions result in a highly clean—but not 100 percent zero-emitting—grid by 2035; a 100 percent zero-emitting grid is reached in the later 2040s. In this modeling all zero-emitting resources are eligible, including nuclear and renewable resources such as wind, solar, and hydropower. The extent to which nuclear and hydro sources are included in the decarbonization scenario varies by state. The framework applies the BAU grid mix to the baseline, ACT, and ACT + NOx Omnibus policy scenarios. The decarbonized grid mix is applied to the more aggressive 100 x 40 ZEV + Clean Grid policy scenario, which represents state adoption of the ACT Rule plus additional actions to ensure that 100 percent of new M/HDVs are ZEV after 2040, in addition to enacting an aggressive Clean Energy Standard.

vi EVs and FCVs are assumed to have zero tailpipe GHG emissions.

Figure 4 shows the BAU and decarbonized grid mix assumptions for New York and Colorado, to illustrate the range of difference in assumed grid mixes across different states. Note that Colorado currently has a lot more coal generation and less zero-emitting generation than New York, and this is projected to continue under the BAU scenario through 2050.[vii] Under the decarbonized scenario, the two states are assumed to have a very similar grid mix after 2030 and to achieve virtually 100 percent zero-emitting generation by 2050, but New York's grid is "cleaner" in the near term (2020–2030).

Figure 4 Baseline and Decarbonized Grid Mix Assumptions, New York and Colorado



vii The NRDC IPM modeling results show a very small amount of biomass in the scenarios (less than 1%). For purposes of the ERM analysis, biomass electricity generation is not included in the "zero-emitting" category due to the NOx and PM emissions released. Because a small percentage of the grid mix is projected to be biomass and oil generation, for simplicity these sources were combined with coal and modeled as coal generation.

For production of hydrogen to fuel FCVs, the analysis assumes that in 2020, 90 percent was produced from natural gas using steam methane reforming (SMR), with the remainder produced from water using electrolysis and grid electricity. The percentage of hydrogen produced via SMR is assumed to fall each year, to 50 percent by 2028 and zero after 2032. To ensure that the modeled levels of "green" hydrogen are available, supportive local, state, and federal policies will be required; in the context of this report such polices could be included in aggressive and comprehensive state clean energy standards.

To calculate the monetized value of the net GHG reductions in each policy scenario (relative to the baseline scenario) the framework uses values for the Social Cost of Greenhouse Gases (CO_2, CH_4, and N_2O) that were developed by the U.S. government's Interagency Working Group [8]. The values used for CO_2 are $51 per metric ton (2020$) in 2020, rising to $85/MT in 2050; the values for CH_4 are $1,500/MT in 2020, rising to $3,100/MT in 2050; and the values for N_2O are $18,000/MT in 2020, rising to $33,000/MT in 2050.

The Interagency Working Group published social cost estimates based on average modeling results using 2.5 percent, 3 percent, and 5 percent discount rates, as well as 95th percentile results using a 3 percent discount rate. This framework uses the average values resulting from a 3 percent discount rate, which is in the middle of the range of estimated values. Total monetized GHG reduction benefits would be approximately 72 percent lower if using average values resulting from a 5 percent discount rate, 49 percent greater if using average values resulting from a 2.5 percent discount rate, and three times greater if using 95th percentile values resulting from a 3 percent discount rate.

The social value of GHG reductions represents potential societal cost savings from avoiding the negative effects of climate change, if GHG emissions are reduced enough to keep long-term warming below 2 degrees Celsius from preindustrial levels.

Annual net reductions in emissions of the criteria pollutants nitrogen oxide (NOx) and particulate matter (PM) relative to the baseline are estimated on the basis of modeled changes in fuel use (gasoline, diesel, natural gas, electricity, and hydrogen) for each policy scenario, as well as modeled uptake of "low NOx" engines that meet the requirements of the NOx Omnibus Rule, if applicable.

As with estimated GHG emissions, estimated NOx and PM emissions include tailpipe emissions from gasoline and diesel vehicles[viii] and upstream emissions from production and delivery of the different fuels, including from generation of electricity to charge EVs and production of hydrogen to fuel FCVs.

Tailpipe NOx and PM emission factors for gasoline and diesel vehicles in the fleet (g/gallon) were derived from EPA's MOVES3 model [5] by mapping STEP Tool vehicle types to vehicle types in MOVES.

Upstream NOx and PM emission factors (g/gallon for diesel and gasoline, g/kWh for electricity, g/kg for hydrogen) were developed using the GREET Model developed by Argonne National Laboratory [6].

In developing NOx and PM emission factors for electricity (EV charging) and hydrogen (FCV fueling), the same assumptions for incremental generating sources (electricity) and production methods (hydrogen) were applied as when developing GHG emission factors, as described above.

viii EVs and FCVs are assumed to have zero tailpipe GHG emissions.

Health Impacts Analysis

To estimate the monetized value of health benefits resulting from reduced NOx and PM emissions, ERM used EPA's CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool [9]. For a given change in annual PM and/or NOx emissions (MT) within a given geography, COBRA estimates the resulting change in ambient PM concentration and the resulting public health impacts. Estimated public health impacts include changes in premature mortality, hospital admissions and emergency room visits for asthma, reduced cases of acute bronchitis, exacerbated asthma and other respiratory symptoms, and reduced activity days and lost work days. COBRA also estimates the total monetized value of these health impacts ($/MT).

The COBRA health impact values for New York are shown in Table 1. For Highway Vehicles and for Fuel Combustion, Electric Utilities, these values represent impacts in New York from changes in emissions in New York. However, the values for Fuel Combustion, Petroleum Fuels Production represent impacts nationally from national changes in emissions. While the majority of modeled emission changes from vehicle use and electricity generation will be local to the state being modeled, the same is not true for upstream emissions from producing petroleum fuels. The majority of these emissions occur from production of crude oil and natural gas and from the refining of crude oil to gasoline and diesel fuel. These activities do not happen in every state; for example, New York has very little crude oil and gas production, and no major oil refineries. For gasoline and diesel fuel sold and used in New York, production and refining happen in other states. Most of the health benefits estimated by the framework will accrue to residents of the state being studied, but those associated with reduced petroleum fuel production will accrue to residents of other states. Moreover, there are additional health benefits (not captured by the modeling) that will accrue to residents of adjacent states from ZEV miles driven in these states.

As shown, health impacts per unit of emissions vary depending on the source, with the highest impacts from highway vehicles (tailpipe) and lower impacts from producing petroleum fuels (upstream refining) and from electricity production.[ix] As such, the framework calculates the health impacts of modeled emission changes from the three different sources separately and sums the results to estimate net effects (reduced tailpipe and upstream petroleum production emissions and increased emissions from electricity generation).

Also note that the magnitude of health effects (incidents/MT, $/MT) will vary by state, primarily according to relative population density; in more densely populated locations more people will be exposed to a given quantity of emissions, resulting in greater total health impacts. The framework uses COBRA health impact values specific to the state being modeled.

ix The higher impact from highway vehicles is due to greater population exposure because emissions are at ground level.

Table 1 Annual Health Impacts of NOx and PM Emmissions—New York

			NOx		PM	
			2020	2050	2020	2050
Highway Vehicles	Premature Deaths	Incidents/1,000 MT	1.4	1.4	58.5	57.0
	Hospital Admissions	Incidents/1,000 MT	0.9	0.9	40.1	39
	Emergency Room Visits	Incidents/1,000 MT	0.4	0.4	19.9	19.4
	Minor Cases	Incidents/1,000 MT	925	901	42,031	40,942
	Monetized Value	2020$/MT	$16,400	$15,975	$684,734	$666,984
Fuel Combustion, Electric Utilities	Premature Deaths	Incidents/1,000 MT	0.7	0.6	24.9	24.2
	Hospital Admissions	Incidents/1,000 MT	0.4	0.4	16.7	16.3
	Emergency Room Visits	Incidents/1,000 MT	0.2	0.2	7.6	7.4
	Minor Cases	Incidents/1,000 MT	388	378	16,896	16,458
	Monetized Value	2020$/MT	$7,707	$7,595	$291,216	$283,667
Fuel Combustion, Petroleum Fuels Production	Premature Deaths	Incidents/1,000 MT	1.2	1.4	20.3	23.8
	Hospital Admissions	Incidents/1,000 MT	0.7	0.9	12.1	14.2
	Emergency Room Visits	Incidents/1,000 MT	0.4	0.4	6.7	7.9
	Minor Cases	Incidents/1,000 MT	642	751	11,889	13,895
	Monetized Value	2020$/MT	$13,766	$16,089	$237,674	$277,777

COBRA only estimates health impacts from changes in ambient PM concentrations, due to PM emitted directly from combustion sources and "secondary" PM generated via chemical reactions in the atmosphere from combustion gases, including NOx. In many locations, changes in NOx emissions also affect the formation of ground-level ozone, particularly in the summer. Ground-level ozone also has negative effects on human health. The potential ozone-related health benefits from net reductions in NOx emissions under the modeled policy scenarios are not captured by the modeling framework; hence the estimated net health benefits of the modeled policy scenarios are a conservative estimate.

Economic & Jobs Analysis

Increased purchase of low-NOx and zero-emission vehicles under the modeled policy scenarios will have a significant impact on annual operating costs for vehicle owners. Both low-NOx and zero-emission vehicles are more expensive to purchase than "baseline" gasoline and diesel vehicles. ZEVs also require purchase and installation of electric vehicle charging and hydrogen fueling infrastructure; in addition to the up-front purchase cost, this infrastructure has ongoing annual maintenance costs.

On the other hand, electricity is less expensive than gasoline and diesel fuel, so ZEVs will have lower annual fuel costs than baseline ICE vehicles. ZEVs are also projected to have lower lifetime maintenance costs than the diesel and gasoline vehicles they replace.[x]

x For example, ZEVs do not require engine oil changes and will likely have less brake wear due to regenerative braking.

Fuel Costs

Net incremental fuel costs for each modeled policy scenario were calculated for each year using estimated changes in total motor gasoline, diesel fuel, electricity, and hydrogen calculated by the STEP tool, and projected annual energy prices. For diesel fuel and gasoline, regional average projected prices from the EIA's Annual Energy Outlook 2021 were used [3]. EIA projects that the average price of gasoline nationally will increase from $2.26/gallon in 2020 to $3.23/gallon in 2050, and that the average price of diesel fuel will increase from $2.52/gallon to $3.69/gallon (2020$). Projected regional prices vary slightly from the national average but have a similar trajectory over time.

This analysis framework assumes that all M/HD EVs will be charged at commercial facilities that pay commercial electric rates. For each state, an average 2019 rate for commercial customers ($/kWh) was calculated on the basis of total sales to (MWh) and total revenue from commercial customers reported to the EIA by utilities in the state [10]. For electricity costs in future years, the analysis assumes the same year-to-year percentage change as EIA's estimate of future average regional commercial electricity rates [11]. EIA estimates that, unlike diesel and gasoline, commercial electricity rates will fall over time in many regions (in 2020$), resulting in average costs in 2050 that are as much as 11 percent lower than in 2020. The analysis framework does not directly use EIA estimates for regional commercial electricity rates, because they mask potentially significant differences in rates for different states in the same region. For example, the average commercial rate in New York in 2019 was $0.158/kWh, while in New Jersey it was $0.127/kWh; these states are in the same EIA region.

Commercial customers typically pay both an energy charge ($/kWh) and a demand charge ($/kW-month). MJB&A's M/HDV charging analysis indicates that in locations with relatively high demand charges, some M/HD EV charging could incur average electricity costs ($/kWh) as much as 10 percent higher than average costs for a typical commercial customer, due to slightly higher monthly peak demand (kW) relative to monthly throughput (kWh). At the same time, the analysis indicates that the marginal cost for utilities to serve M/HD EV charging load will always be lower than the marginal revenue utilities receive. Given this, the framework implicitly assumes that over time, as charging demand increases, commercial rate structures will evolve to more equitably distribute actual demand costs, such that average electricity costs for EV charging will match average costs for other commercial uses.

For hydrogen costs the framework uses estimates from Bloomberg New Energy Finance [12], which are based on large-scale, centralized production using electrolysis, long-distance transmission by pipeline, and local delivery of hydrogen to vehicle fueling stations by truck as a compressed gas. The delivered cost of hydrogen is assumed to be $3.68/kg in 2020, falling to $1.52/kg in 2050 (2020$).

Vehicle Purchase and Maintenance Costs

Incremental purchase costs and incremental maintenance costs for M/HD EVs were estimated on the basis of an analysis by ICF International [13], conducted in the context of California Air Resources Board regulatory proceedings for the Advanced Clean Truck Rule adopted in 2020, adjusted as discussed below based on alternative assumptions for EV battery costs and recent pricing announced by Ford for the model year 2022 e-Transit commercial electric delivery van and F150 Lightning electric pickup.

The framework uses weighted averages of ICF estimated purchase costs for diesel and EV transit buses, school buses, Class 3 trucks, and Class 6 and Class 8 short-haul and long-haul trucks applied to the vehicle types used in the STEP Tool (Class 2b trucks, Class 3–8 buses, Class 3–8 single-unit trucks, and Class 8 combination trucks).

Estimated incremental EV purchase costs for Class 2b trucks are ICF's estimate for Class 3 trucks.[xi] Estimated incremental EV purchase costs for the STEP Tool bus category are a weighted average of ICF estimated incremental costs for transit bus (11 percent), school bus (49 percent), and Class 3 truck as a proxy for shuttle buses (40 percent). Estimated incremental EV purchase costs for the STEP Tool single-unit truck category are a weighted average of ICF estimated incremental costs for Class 3 truck (56 percent), Class 6 truck (24%) and Class 8 short-haul truck (20 percent). These vehicle category weightings are based on a national inventory of currently registered M/HD trucks [14]. Estimated incremental EV purchase costs for the STEP Tool combination truck category are ICF estimated incremental costs for Class 8 long-haul truck. For simplicity, this analysis assumes the same incremental cost for EVs and FCVs.

ICF provided estimated costs for model year 2020 and 2030 vehicles. Battery costs are a significant contributor to incremental EV costs; in their analysis, ICF assumed that in 2020 average battery costs were $375/kWh but that these costs would fall to $157/kWh in 2030. Recent data on actual battery costs for light-duty EVs indicate that ICF's assumption for future battery cost reductions was too conservative.

Figure 5 shows actual light-duty (LD) EV battery costs for 2015–2020, along with Bloomberg New Energy Finance (BNEF) estimated costs for 2020–2030 [15]. As shown, actual costs fell from $381/kWh in 2015 to $132/kWh in 2020. BNEF estimates that costs will continue to fall to $86/kWh in 2025 and $61/kWh in 2030. Based on ICF's battery cost estimate of $375/kWh in 2020, average costs for M/HD EV batteries currently lag LD EV battery costs by five years. Assuming this five-year lag continues as the M/HD EV market develops, Figure 5 also shows the estimated cost trajectory for M/HD EV batteries over the next 30 years. As shown, if current trends continue, M/HD EV battery costs should fall to $132/kWh in 2025, $86/kWh in 2030, and $61/kWh in 2035.

ERM used the M/HD EV battery cost trajectory shown in Figure 5 to adjust the ICF estimates of ZEV incremental cost for 2030 and to generate ZEV incremental cost estimates for 2040 and 2050. In addition, ERM adjusted ICF's estimated model year 2020 incremental costs for Class 2B and Class 3 trucks, based on recently announced pricing for the Ford e-Transit electric delivery van and Ford F150 Lightning electric pickup truck [16].

The resulting incremental ZEV costs used in the analysis framework are given in Table 2. As shown, by 2040 the purchase cost of ZEV Class 2B and combination trucks are estimated to be lower than the cost of equivalent ICE trucks, while other M/HD ZEV trucks are estimated to continue to carry a cost premium through 2050.

xi Class 2b (8,500–10,000 lb. gross vehicle weight rating [GVWR]) and Class 3 trucks (10,000–14,000 GVWR) are very similar. Many commercial truck models are available in multiple configurations that span Class 2b and Class 3.

Figure 5 Actual & Projected Battery Costs

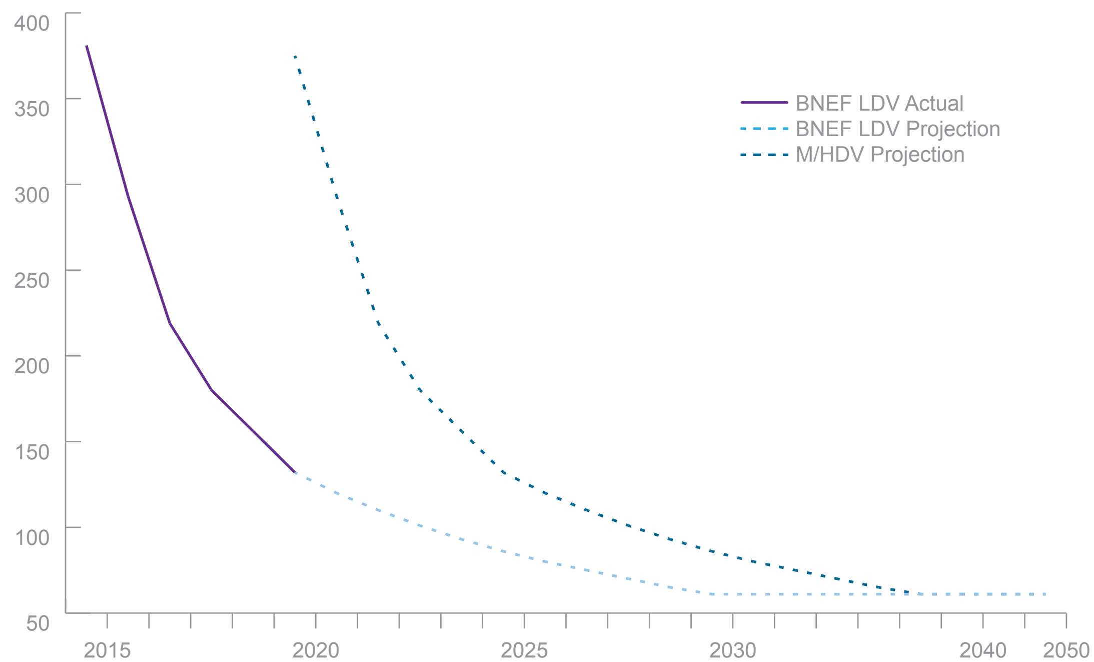


Table 2 Incremental ZEV Purchase Costs (2020$)

	2020	2030	2040	2050
Class 2b Truck	$17,000	$1,600	($800)	($1,500)
Bus	$126,000	$87,000	$79,800	$77,000
Single Unit Truck	$77,900	$10,700	$6,000	$4,800
Combination Truck	$217,000	$6,100	($9,600)	($12,900)

Incremental maintenance costs for ZEVs compared with baseline diesel and gasoline vehicles are also taken from the ICF report and are calculated for the STEP Tool vehicle categories using the same weighting factors as for vehicle purchase costs. Maintenance costs are assumed to be $0.10/mi. lower for ZEV Class 2 trucks, $0.094/mi. lower for ZEV buses, $0.056/mi. lower for ZEV single-unit trucks, and $0.021/mi. lower for ZEV combination trucks than for comparable diesel and gasoline trucks.

Incremental purchase costs for new vehicles with low-NOx engines, necessary to comply with the modeled NOx Omnibus Rule, were developed on the basis of cost estimates from the California Air Resources Board, developed in support of the Omnibus rulemaking [17]. These incremental costs are shown in Table 3. The values for Class 2b truck, school bus, and shuttle bus are a weighted average of estimated costs for 6/7-liter diesel and gasoline engines based on the proportion of total gasoline and diesel vehicles in the national fleet [14].

The values for single-unit truck are a weighted average of 6/7-liter diesel, 6/7-liter gasoline, and 12/13-liter diesel engines based on the proportion of total vehicles in the national fleet by fuel type and weight class. The values for transit bus and combination truck are estimated costs for 12/13-liter diesel engines.

Table 3 Incremental Vehicle Costs to Comply with NOx Omnibus Rule (202$/Vehicle)

Vehicle Type	2024	2027	2030	2040	2050
Class 2b Truck	$924	$1,662	$1,681	$1,672	$1,568
Transit Bus	$2,466	$5,173	$4,349	$4,742	$4,453
School Bus	$1,436	$2,914	$2,951	$2,933	$2,725
Shuttle Bus	$1,094	$2,080	$2,104	$2,092	$1,954
Single-Unit Truck	$1,803	$3,706	$3,397	$3,544	$3,313
Combination Truck	$2,466	$5,173	$4,349	$4,742	$4,453

Fueling Infrastructure Costs

To estimate charging infrastructure needs for M/HD EVs, the framework uses a charging scenario model that calculates, for different vehicle types, required charging capacity (kW/vehicle) and daily peak demand (kW/vehicle) based on typical daily energy use, available charging time, and charging location (depot-based or public). Eighty percent of buses, 90 percent of single-unit trucks, and 30 percent of combination trucks are assumed to use overnight depot-based charging, with 9–11 hours per day available for charging. Individual depot chargers will need to be capable of charging at 10 kW to 50kW for different vehicle types according to daily energy use and available charge time. The remainder of vehicles are assumed to be charged at higher-capacity (100–600 kW) shared public chargers, with only 2 hours/day/vehicle available for charging.

The resulting average required charger capacity and daily peak demand are shown in Table 4.

Table 4 Average M/HD EV Charging Infrastructure Requirements

	Average Charger Capacity (kW/vehicle)		Daily Peak Demand kW/vehicle
	Depot	Public	
Class 2b Truck	3.7	1.1	3.8
Transit Bus	30.2	8.0	21.1
School Bus	8.7	0	2.9
Shuttle Bus	8.7	2.4	7.4
WTD AVG Bus	11.0	1.8	6.7
Single Unit Truck	7.3	2.1	7.6
Combination Truck	13.6	44.4	7.6

Charging infrastructure costs ($/kW) were estimated using data developed by the International Council on Clean Transportation [18]. ICCT estimates that in 2020 the purchase cost of chargers averaged $450–$500/kW depending on size, with larger (public) chargers at the lower end and smaller (depot) chargers at the higher end. These costs are projected to fall by 18–25% through 2040 (2020$) as the market matures and sales increase. ICCT also estimates that installation costs are about $500/kW for installation of only a small number of chargers per location (small fleet) but are as low as $100/kW for larger installations (large fleet). Installation costs are not projected to fall over time (in constant dollars)

Using these values, and assuming 75 percent of installations will be by large fleets, the framework assumes that purchase and installation of depot-based chargers will cost $700/kW in 2020, falling to $610/kW in 2050, and that purchase and installation of shared public chargers will cost $650/kW in 2020, falling to $533/kW in 2050 (2020$).

To estimate total infrastructure costs each year, the number of new ZEVs purchased in that year is multiplied by the average required charging capacity of depot and public chargers (kW/vehicle) and the average charger cost ($/kW). There is relatively little information available on the cost of hydrogen fuel stations to support FCVs; this analysis therefore assumes that FCVs will have the same infrastructure costs ($/vehicle) as EVs.

On the basis of ERM project experience in evaluating charging implementation for electric buses, the framework assumes that EV chargers will require 12 hours/year of preventive maintenance activities for every 50 kW of capacity. Assuming a labor rate of $78/hour [19] and average annual charger utilization (MWh per kW capacity) from the charging scenario model, this equates to $8.65/MWh maintenance costs for combination truck charging, $8.57/MWh for single-unit truck charging, $15.00/MWh for bus charging, and $15.25/MWh for Class 2b truck charging. Maintenance costs vary by vehicle type due to differences in average annual utilization (kWh per kW capacity). To calculate total annual infrastructure maintenance costs, these values were multiplied by total annual charging energy for each vehicle type (MWh).

Jobs Analysis

This analysis framework uses IMPLAN software to estimate net macroeconomic effects on jobs, wages, and gross domestic product (GDP) of the modeled policy scenarios relative to the baseline. IMPLAN is a proprietary input–output modeling system that uses data from the U.S. Bureau of Economic Analysis, Bureau of Labor Statistics, U.S. Census Bureau, and other sources [20]. Private companies, governmental agencies, and academic institutions regularly use IMPLAN to evaluate the macroeconomic effects of policies, programs, and specific infrastructure investments.

Within an economy, IMPLAN depicts interindustry relationships, such as how output from one sector becomes input in another sector. It uses multipliers to assess the interindustry effects. The estimation of multipliers relies on input–output models and a technique for quantifying interactions among firms, industries, and social institutions within a local, regional, or national economy.

IMPLAN assigns each industrial or service activity (e.g., agriculture, mining, manufacturing, trade, services) to an economic sector. The number of sectors is determined by the desired level of detail.

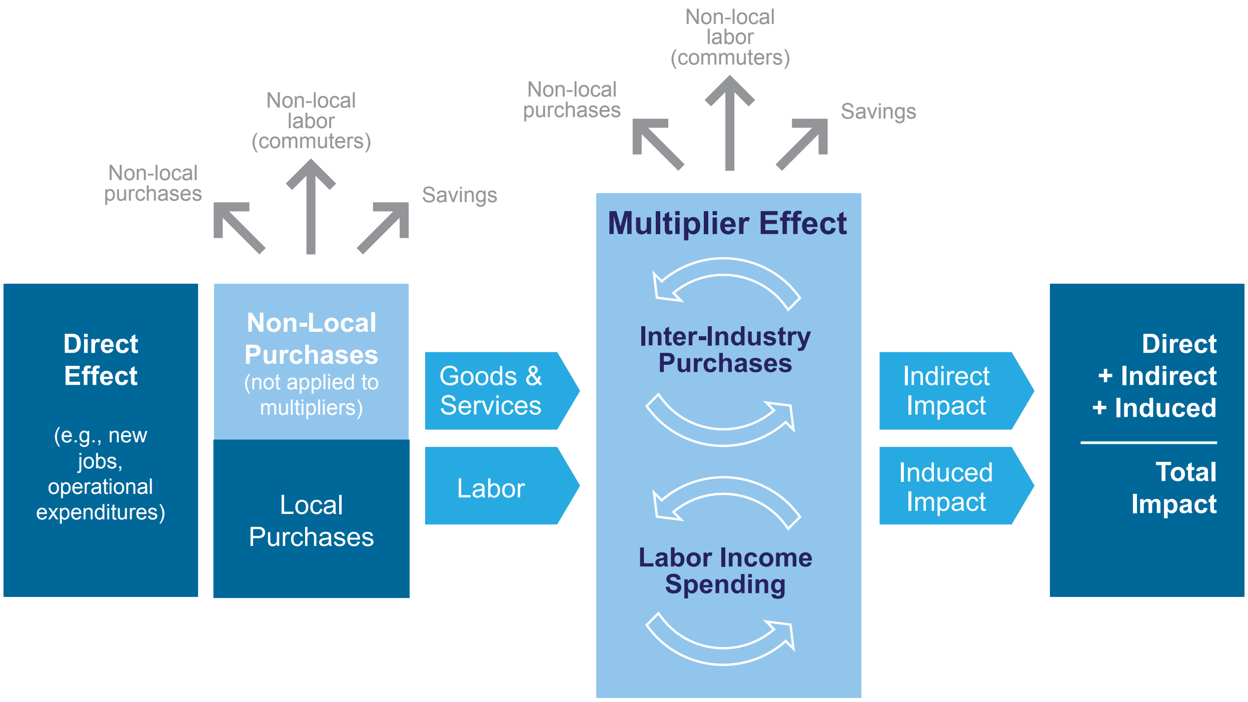
Using detailed U.S. Department of Commerce information, IMPLAN relates the purchases of goods and services each industry makes from other industries to the value of output in each industry. In so doing, IMPLAN describes the supply chain of each industry in terms of output, value added, labor income, employment levels, and state and local tax revenue.

For example, when a firm starts a major capital expenditure project, it purchases construction materials, hires local labor and contractors, leases equipment, and uses other in-state and out-of-state suppliers. Those suppliers then have their own associated expenses and wages that spread the money throughout the economy. IMPLAN models these transactions throughout the economy to calculate the total economic impact of the investment.

As depicted in Figure 6, IMPLAN estimates three types of impacts, which are combined to estimate the total impact of each modeled policy scenario:

1. *Direct impact*—the initial change in the value of the output, employment, and labor earnings from the activity or project;
2. *Indirect impact*—the resulting increase in the output, employment, and labor earnings in the industries supporting the activity or project; and
3. *Induced impact (household spending)*—the resulting increase in spending by workers in the analyzed industry and the supplying industries whose earnings are affected by the increase in output from the various industries.

Figure 6 Input-Output Conceptual Model



Source: AKRF "IMPLAN, RIMS-II, and REMI Economic Impact Models," *May 2013*, https://www.ilw.com/seminars/JohnNeillCitation.pdf.

For this analysis, net changes to three national-level macroeconomic metrics from increased ZEV and low-NOx engines uptake were estimated:

- *Employment*—A job in IMPLAN is equal to the annual average of monthly jobs in an industry. One job lasting 12 months equals two jobs lasting 6 months or three jobs lasting 4 months. A job can be either full time or part time.
- *Labor income*—This comprises all forms of employment income, including employee compensation (wages and benefits) and proprietor income.

- *Gross domestic product (GDP)*—Also known as value added, this result captures the compensation of employees, proprietor income, taxes on production and imports less subsidies (previously indirect business taxes and non-tax payments), and gross operating surplus. Value added is the value of output less the value of intermediate consumption; it is a measure of the contribution to GDP made by an individual producer, industry, or sector.

To calculate these effects, outputs from the cost analysis were summarized to calculate the net annual change in spending within relevant "industries" for input to IMPLAN, as summarized in Table 5.

Incremental spending on fueling infrastructure was disaggregated to spending for equipment purchase and for installation (construction), as these components of total cost affect significantly different industries. Similarly, net incremental ZEV purchase cost was separated into *reductions* in spending on conventional drivetrains (ICE engine and transmission) and increased spending on electric drivetrains and storage batteries. Net incremental costs for purchase of low-NOx engines were separated into increased spending on engines and on after-treatment systems, as both engine changes and additional/improved after-treatment are projected to be needed to meet the requirements of the modeled NOx Omnibus Rules [21].

Table 5 IMPLAN Inputs

Cost Element		Incremental Spending	IMPLAN Industry/Commodity
Energy	Gasoline, diesel	Decrease	3154 – Refined petroleum products
	Electricity	Increase	3039 – Electricity
	Hydrogen	Increase	3039 – Electricity
Maintenance	Vehicle maintenance	Decrease	512 – Automotive repair and maintenance
	Charger maintenance	Increase	60 – Maintenance and repair construction of nonresidential structures
Fueling Infrastructure	Purchase	Increase	329 – Power, distribution, and specialty transformer manufacturing (60%) 339 – All other misc. electrical equipment (40%)
	Installation	Increase	55 – Construction of new commercial structures
Vehicle Manufacturing	Engine and transmission	Decrease	284 – Other engine equipment; includes diesel engines (66%) 349 – Motor vehicle transmission and power train parts (30%) 347 – Motor vehicle gasoline engines (3%)
	ZEV batteries	Increase	333 – Storage batteries
	ZEV electric drivetrain	Increase	330 – Motor and generator manufacturing (50%) 329 – Power, distribution, and specialty transformer manufacturing (50%)
	Low-NOx engines	Increase	284 – Other engine equipment; includes diesel engines (24%) 347 – Motor vehicle gasoline engines (1%) 336 – Other motor vehicle parts manufacturing; includes automotive catalysts and exhaust system parts (75%)

IMPLAN does not include an industry for hydrogen production. In this analysis incremental spending on hydrogen fuel was allocated to the electricity generation industry in IMPLAN because, as discussed above, over the full time frame of this analysis it is assumed that most hydrogen will be produced from water using electrolysis.

Note that for this modeling framework IMPLAN will be run at the national level to calculate net economic changes to the U.S. economy from implementation of each modeled policy scenario in each state. When spending within an industry changes, there is some "leakage" due to imports of equipment and supplies from other countries; that is, some of the increased spending results in job, wage, and GDP changes in these exporting economies and is not included in IMPLAN results for the U.S. economy. The amount of leakage depends on the industry; for example, on the basis of current industry structure, IMPLAN assumes that 80 percent of economic activity in industry 329 (power, distribution, and specialty transformer manufacturing) is in the United States, but only 50 percent of economic activity in industries 333 and 330 (storage batteries and motor and generator manufacturing, respectively) are in the United States.

Given that the M/HD ZEV industry is in the early stages of development, it is not clear how jobs will be distributed geographically as the industry grows. Industry development could also be significantly affected by federal, state, and local government policies. For the state-level analyses, IMPLAN will be run assuming that 100 percent of incremental economic activity related to ZEV production will be U.S. based, to estimate the maximum possible job impacts as the industry grows and develops.

Note that IMPLAN estimates only those changes in economic activity that flow directly from changes in spending within the affected industries; it does not assess potential secondary effects from major structural changes in the economy. For example, IMPLAN does not estimate how significant changes in demand for a commodity (e.g., fuel) will affect the market price of that commodity, or how market price changes will affect economic activity in the sectors of the economy that are not being directly modeled. IMPLAN also does not assess how fleet operators would spend, invest, or distribute net annual operating cost savings (from vehicle purchase, fuel, and maintenance) that could result from greater ZEV penetration in later years of the analysis, or the resulting indirect and induced effects from distribution of these savings.

To address this latter issue of future net fleet operating cost savings, and utility net revenue from M/HD EV charging (see Utility Impact Analysis, below), this analysis models what would happen if a portion of the fleet savings (or losses) and utility net revenue were passed on to consumers in the form of lower prices. In the case of fleet savings, it is assumed that a portion of these savings are passed on to fleet customers as lower transportation rates, which are then passed on to consumers via lower prices for shipped goods. In the case of utility net revenue, it is assumed that a portion of this net revenue would be returned to residential and commercial customers via future electricity rate reductions, in accordance with normal rate-setting procedures of public utility commissions.

IMPLAN cannot reflect price changes. Therefore, these net fleet savings and utility net revenue are treated as an increase in income for consumers since their current income will now be able to purchase more goods. For conservatism, the model allocates 60 percent of annual net fleet savings and 80 percent of utility net revenue to increased consumer income. This increased consumer income is allocated in IMPLAN among nine income levels according to percent of total economy-wide demand attributable to each income level. The net fleet savings are allocated using general consumer demand for all commodities, and utility net revenue is allocated using demand for electricity. For example, the income range from $50,000 to $70,000 has 12 percent of demand for all commodities, and 14 percent of electricity demand. Note that the income increase being passed on to consumers is based on net savings, considering both the higher and the lower costs. For some states in the early years of the analysis period (prior to approximately 2035), annual net fleet savings are negative (a net cost) and the allocated change in consumer income is also negative (lower, not higher, income).

Utility Impact Analysis

On the basis of the results of the fuel and emissions and cost analyses discussed above, the framework estimates annual incremental electric load (MW), throughput (MWh), and utility revenue (2020$ millions) from M/HD EV charging under each modeled policy scenario. The framework then uses EIA estimates for average regional transmission and generation costs [22] and state-specific estimates of incremental peak capacity costs ($/MW-year)[xii] to estimate the utilities' cost of providing this energy. By subtracting this cost from incremental revenue, the framework estimates the annual net revenue (revenue minus costs) that utilities will realize due to the incremental EVs in each scenario, compared with the baseline.

In general, a utility's costs to maintain its distribution infrastructure increases each year with inflation, and these costs are passed on to utility customers in accordance with rules established by the state public utilities commission via periodic increases in residential and commercial electric rates. The net revenue resulting from increased EV charging can be used to support system operations, in effect putting downward pressure on future rate increases for all utility customers, whether they are EV owners or not. Based on estimated net revenue and estimated total system throughput, the framework estimates the potential reductions in future rates for commercial and residential customers from increased EV penetration in each policy scenario.

Infrastructure Gap Analysis

To estimate charging infrastructure needs for M/HD EVs, the framework uses a charging scenario model that calculates, for different vehicle types, the required number of chargers and charger capacity (kW/vehicle) based on typical daily energy use, available charging time, and charging location (depot based or public). Table 6 summarizes assumed charging locations and resulting estimates of charging needs (ports per 1,000 ZEVs).

Table 6 Charging Infrastructure Needs (Port per 1,000 ZEVs)

Metric			Class 2b Truck	Shuttle Bus	School Bus	Transit Bus	Single-Unit Truck	Combination Truck
Charging Location	Depot		90%	90%	100%	80%	90%	30%
	Public		10%	10%	0%	20%	10%	70%
Depot Chargers	Avg. kW/port		10	20	10	50	10	50
	Ports/1,000 ZEVs		855	810	850	680	855	285
Public Chargers	Ports/1,000 ZEVs	150 kW	7.4	22.2	0	0	14.8	0
		500 kW	0	0	0	20	0	84.8

As shown in Table 6, most M/HD vehicles are assumed to charge overnight at their depot, since they are typically used for local or regional operations in which they begin and end the day at the same location and generally travel less than 100 miles per day. This results in the need for a relatively large number of depot charge ports (almost one per vehicle), but the required capacity per port is low (average <20 kW/port).

xii These estimates are generated from a range of sources, depending on the state, including capacity market prices, utility integrated resource plans, and estimates from the regional transmission operator.

The exception is combination trucks. While approximately 30 percent of these vehicles are used for local/regional hauling and can use overnight depot charging, the remainder are used primarily for long-haul freight operations. Long haul trucks do not return to the same location every night and can travel 500 miles or more per day. As such, these vehicles will need to use a shared, public network of higher-power chargers (500+ kW/port), with one port for approximately every 12 EVs.[xiii]

The analysis framework estimates the number of new charge ports of each type that must be installed each year under each policy scenario, based on the number of new ZEVs purchased each year and the values in Table 6.

xiii The “public” chargers shown for transit buses are in-route chargers shared by multiple buses on a given route throughout the day; they are not open to other vehicle types. This charging scenario may be required in some cities where bus route speeds result in high daily mileage per bus.

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