BRIEFING

APRIL 2022

Benefits of the 2020 Multi-State Medium- and Heavy-Duty Zero-Emission Vehicle Memorandum of Understanding

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A diverse coaltion of seventeen states and the District of Columbia have signed a Memorandum of Understanding (MOU), committing themselves "to work together to foster a self-sustaining market for zero-emission medium- and heavy-duty vehicles."[1] The signatories of this Multi-State MOU share a goal of at least 30% medium- and heavy-duty (M/HD) zero-emission vehicle sales by 2030 and 100% sales no later than 2050. The MOU further recognizes the importance of "low-NO_x heavy-duty trucks to reduce harmful emissions of NO_x, particulate matter, and toxic air contaminants that adversely impact public health." Taken together, the combined actions of these signatories have the potential to accelerate the national transition toward a fleet of low-NO_x and increasingly zero-emission M/HD vehicles.

Altogether, the signatories account for 35% of national M/HD vehicle stock.[2] Among the signatories, California is home to the largest share of the national fleet—around 10%—and has adopted the most far-reaching regulatory framework in pursuit of low-NO_x and zero-emission vehicles. The state has implemented the 2018 Innovative Clean Transit (ICT) rule requiring 100% zero-emission transit bus purchases by 2029, the 2020 Advanced Clean Trucks (ACT) rule requiring at least 30% zero-emission truck sales by 2030, and the 2020 Heavy-Duty Omnibus rule requiring a 90% reduction in NO_x emissions below existing federal tailpipe emission standards.

1 The current signatories are California, Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, Nevada, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Washington, and the District of Columbia, "Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding," (July 14, 2020), https://www.nescaum.org/documents/mhdv-zev-mou-20220329.pdf/. The Canadian province of Quebec also participates in the initiative.

2 US Department of Transportation, "State Motor Vehicle Registrations – 2019," (2020), https://www.fhwa.dot.gov/policyinformation/statistics/2019/mv1.cfm.

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The California rulemakings will generate large reductions in air pollutant and greenhouse gas emissions. From 2020 to 2040, the California Air Resources Board (CARB) estimates the ACT rule alone will cumulatively reduce 17.3 million metric tons of carbon dioxide-equivalent emissions (CO_2e),[3] avoiding between 398 million and 1.7 billion dollars in climate-related damages.[4] By 2040, the rule will reduce nitrogen oxide (NO_x) emissions by 27.9 tons per day and particulate matter ($PM_{2.5}$) emissions by 0.85 tons per day. This decline in outdoor air pollution exposure will avoid an estimated 943 premature deaths and $8.9 billion in health damages through 2040. In addition, CARB estimates the separate HDV Omnibus rule will reduce NO_x emissions by an additional 24 tons per day in 2031 and avoid 3,900 premature deaths cumulatively through 2050.[5]

Signatories of the MOU intend to lead the transformation of the medium- and heavy-duty fleet towards zero-emission engines. As the first to act, California benefits from its unique authority to set new motor vehicle standards that are "at least as protective of public health and welfare as federal standards."[6] Section 177 of the Clean Air Act provides MOU signatory states the authority to adopt standards identical to California's with a lead time of two model years.[7] Adoption of the Heavy-Duty Omnibus Rule, the Advanced Clean Transit Rule, and other California regulations may be necessary for states to fulfill their shared ambitions.

The primary aim of this paper is to estimate the shared climate and air quality benefits that MOU signatories could realize if, by following the precedents set by California, they achieve their stated aim to see 30% zero-emission truck sales in 2030 and 100% by 2050.

METHODS

We model annual fleet-wide emissions of NO_x, PM, and well-to-wheel (WTW) CO_2 emissions in 14 states and the District of Columbia, including Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington. We exclude California from our modelling, since the California Air Resources Board has published the benefits of its zero-emission HDV and low-NO_x policies.[8] Nevada, Virginia, and Quebec joined the MOU more recently and are not included. For the group of states we evaluate, we assume their share of the U.S. M/HD vehicle stock remains at 25% through 2050.

3 In this paper, CO_2 is given in units of metric tons and criteria pollutants are given in units of short tons.

4 California Air Resources Board "Attachment C: Updated Costs and Benefits Analysis for the Proposed Advanced Clean Trucks Regulation, Proposed Amendments to the Advanced Clean Trucks Regulation," (2020), https://ww3.arb.ca.gov/regact/2019/act2019/30dayattc.pdf.

5 California Air Resources Board, "Facts about the Low NO_x Heavy-Duty Omnibus Regulation," (2020), https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/hd-low-nox-omnibus-regulation-fact-sheet.

6 Clean Air Act. 1990. Title 42 Section 7543. State Standards. Accessed August 2, 2021. https://www.law.cornell.edu/uscode/text/42/7543#a.

7 Clean Air Act. 1990. Title 42 Section 7507. Accessed August 2, 2021. https://www.law.cornell.edu/uscode/text/42/7507.

8 The 2020 Mobile Source Strategy presented to the California Air Resources Board on 28 October 2021 estimates the combined benefits of 100% sales of zero-emission medium- and heavy-duty vehicles in 2035 would result in statewide WTW GHG emissions in 2050 that are 71 percent below the 2020 baseline. For further information see California Air Resources Board, "2020 Mobile Source Strategy," (2021), https://ww2.arb.ca.gov/sites/default/files/2021-04/Revised_Draft_2020_Mobile_Source_Strategy.pdf.

Our analysis evaluates the following three primary scenarios:

Reference scenario: Assumes no increase in zero-emission sales shares through 2050, no further improvements in new ICE vehicle energy efficiency after 2027, EIA reference grid carbon intensity, and no change to federal U.S. Environmental Protection Agency (EPA) 2010 emissions standards or additional state low-NO_x standards.

Zero emission (ZEV) 2050 scenario: Assumes at least 30% zero-emission M/HD sales in 2030 and 100% in 2050, no backsliding on ICE energy efficiency after 2027, and grid carbon intensity reflecting the EIA reference grid and a net zero carbon grid by 2050.

Zero emission (ZEV) 2040 scenario: Assumes 100% zero-emission M/HD sales in 2040, no backsliding on new ICE vehicle energy efficiency, and grid carbon intensity again reflecting the EIA reference grid and a net zero carbon grid by 2050.

For each primary scenario, we considered the benefits of additional NO_x emission controls through the adoption of the California HDV Omnibus standards. A set of secondary scenarios assume the states evaluated adopt California HDV Omnibus standards beginning in 2025, labeled 'low NO_x' in this study.

Each of these scenarios contain more specific assumptions. For example, each scenario contains specific zero-emission sales targets and internal combustion engine (ICE) efficiency improvements by vehicle market segment. These are described in more detail below.

We used ICCT's Roadmap Emissions Model to evaluate emissions changes under each scenario.[9] Data on current and projected nationwide M/HD vehicle stock, sales, and vehicle activity in the United States were obtained from EPA's Motor Vehicle Emission Simulator (MOVES), version 3.[10] We extracted detailed MOVES outputs by source type, fuel, and model year for the years 2000, 2010, 2015, 2030, and 2050, then separately estimated stock, sales, and activity values for each intermediate year. We then linearly interpolated these data for every year from 2000 to 2050. Using sales estimates and reported vehicle stock by model year, we then calculated annual survival rates, such that the number of vehicles sold in intermediate years aligned with the number of vehicles of that model year given by MOVES in later years. We calculated vehicle activity based on vehicle stock and total miles traveled for each vehicle from ages 0 to 30. Per-vehicle activity was linearly interpolated by vehicle age for each intermediate year. We assume that vehicles within each segment have the same per-vehicle activity rates regardless of fuel, so we applied stock-weighted average activity across all powertrain types. The resulting database provides current and projected vehicle stock, sales, and activity by source type, fuel type, and model year in each calendar year from 2000 to 2050.

We then incorporated into this database assumptions of zero-emission M/HD vehicle sales shares represented by each emissions scenario in each market segment (see Figure 1). We assume that changes in M/HD vehicle sales by powertrain type do not affect the total level of vehicle activity, i.e., that annual activity per vehicle is the same

9 Miller, Joshua, and Lingzhi Jin, "Global Progress toward Soot-Free Diesel Vehicles in 2018," (Washington, D.C.: ICCT, 2018), https://theicct.org/publications/global-progress-toward-soot-free-diesel-vehicles-2018.

10 US Environmental Protection Agency,"Latest version of Motor Vehicle Emissions Simulator (MOVES)," (2021),https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

across fuel types within each segment. We also account for the benefits of all M/HD ZEVs sold in compliance with sales targets, regardless of where vehicles operate. We input these sales shares and activity data into version v1.6 of the ICCT Roadmap model, aggregating the ten MOVES source types into four Roadmap M/HD vehicle categories: light commercial trucks, rigid trucks, tractor-trailers, and buses (See Table A11).

ZERO-EMISSION SALES SHARES

Based on 2020 sales data for the U.S. market, zero-emission vehicles accounted for less than 1% of all M/HD vehicle sales, with the exception of transit buses, which had a zero-emission sales share of approximately 4%. These zero-emission sales shares are the starting point in this study across the group of states evaluated in this analysis. Figure 1 shows the projected annual change in the share of zero emission vehicles sold in key segments of the M/HD vehicle market. (See Table A4 for more detailed sales share assumptions.)

The first scenario, the Reference scenario, assumes no increase in zero-emission M/HD vehicle sales shares among the MOU signatories, not including California, from 2020 to 2050.

The second scenario, ZEV 2050, assumes the states evaluated adopt the same sales requirements contained in California's ACT rule through 2035, then steadily increase their zero-emission M/HD vehicle sales shares to 100% by 2050. For transit buses, the scenario assumes that the states do not adopt the zero emission bus purchase requirements in California's ICT rule but instead adopt requirements similar to the ACT pathway for rigid trucks from 2024 to 2035.[11] Transit buses, refuse trucks, and school buses are then assumed to reach 100% zero-emission sales shares by 2040, short-haul tractor-trailers and trucks by 2045, and all other M/HD vehicles including Class 2b/3 light commercial vehicles and long-haul tractor-trailers by 2050.

The third scenario, ZEV 2040, assumes a 100% zero-emission M/HD vehicle sales share in 2040—ten years faster than the stated goal of the MOU. For transit buses, the scenario assumes the states evaluated harmonize with California's ICT rule, reaching 100% zero-emission transit bus sales by 2029. Refuse trucks and school buses are assumed to follow the ACT pathway for rigid trucks until 2029, and then reach 100% zero-emission sales shares by 2030. Such a jump in sales share from 2029 to 2030 would likely require a large-scale procurement effort with enough lead time for manufacturers to ramp up production. Short-haul tractor-trailers and trucks are assumed to follow the ACT pathway to 2030 then ramp up assuming a constant annual growth rate, to 100% zero-emission sales by 2035. Long-haul tractor-trailers and trucks are assumed to follow the ACT pathway to 2032, increase their zero-emission share by 5 percentage points per year to 2035, then ramp up, assuming a constant annual growth rate, to 100% zero-emission sales by 2040. All other M/HD vehicle types are assumed to align with ACT to 2035 then ramp up, assuming a constant annual growth rate, to 100% zero-emission sales by 2040.

11 The California Advanced Clean Trucks rule requires sales of zero-emission rigid trucks in the Class 4-8 weight class to represent, on average, at least 11 percent of all truck sales in this category in 2025, 50 percent in 2030, and 75 percent in 2035. For more details of ACT requirements, see Claire Buysse and Ben Sharpe, "California's Advanced Clean Trucks Regulation: Sales requirements for zero-emission heavy-duty trucks," (Washington, DC: ICCT, 2020), https://theicct.org/publication/californias-advanced-clean-trucks-regulation-sales-requirements-for-zero-emission-heavy-duty-trucks/.

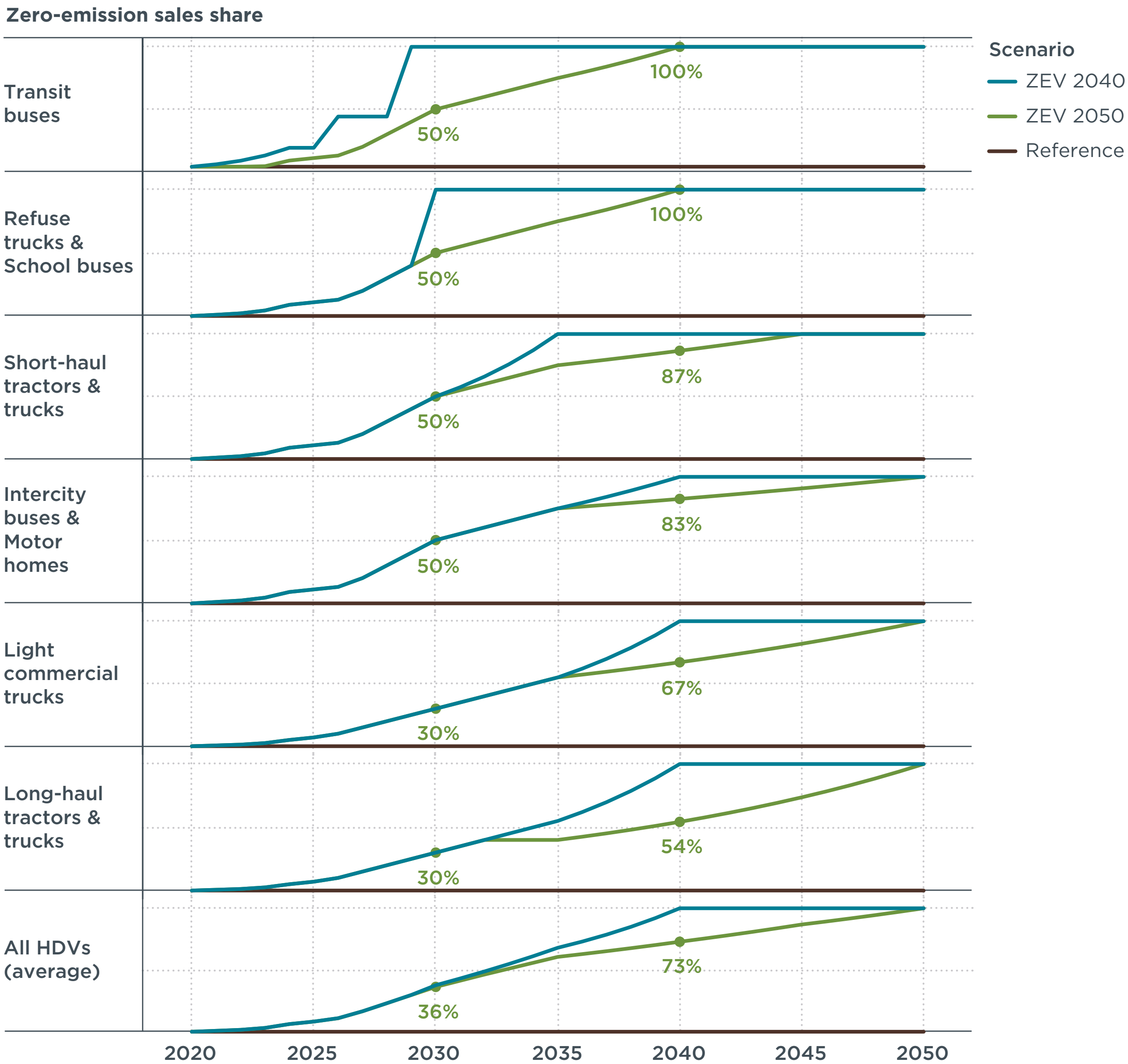

Figure 1. Assumed sales shares by market segment of new zero-emission medium- and heavy-duty vehicles vehicles in MOU signatories, not including California, from 2020–2050.

INTERNAL COMBUSTION ENGINE VEHICLE EFFICIENCY IMPROVEMENTS

All scenarios consider the improvements in ICE vehicle efficiency needed to meet the U.S. HDV GHG Phase II standards.[12] Figure 2 shows the projected improvements in ICE efficiency required to meet these standards across key vehicle market segments, including changes to these requirements as zero-emission vehicle sales grow. Higher volumes of zero-emission sales will count toward manufacturer compliance with existing GHG standards, lowering the ICE efficiency improvements needed for compliance. This effect is magnified by Advanced Technology Credits, which further reduce the ICE compliance burden by multiplying the actual GHG reductions of each

12 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2. CFR. Vol. 40. https://www.govinfo.gov/content/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

electric vehicle sold. We factor in these effects when determining the ICE efficiency improvements needed to comply with the Phase II standards.

In the Reference scenario, we calculate ICE efficiency improvements to 2027, assuming zero-emission sales shares in California increase in line with ACT and ICT requirements. This scenario assumes a continuation of 2020 zero-emission sales share growth in the rest of the country. Depending on the vehicle type, this translates to a reduction in fuel consumption (e.g., gallons per mile) of 11%–25% for new diesel vehicles and 4%–6% for new gasoline vehicles sold in 2027 compared to 2017. The scenario assumes no further improvements in new ICE vehicle efficiency after 2027.

For the ZEV 2050 and ZEV 2040 scenarios, we calculate ICE efficiency improvements to 2027 based on the following assumptions: zero-emission sales shares in California increase in line with the ACT and ICT requirements; zero-emission sales shares among the other states evaluated follow the scenario assumptions shown in Figure 2; and continuation of 2020 zero-emission sales shares in the rest of the country. The required ICE efficiency improvements under these scenarios are smaller than they are in the Reference scenario: approximately 7%–18% for new diesel vehicles and 3%–4% for new gasoline vehicles sold in 2027, relative to 2017. These scenarios assume no backsliding in new ICE vehicle efficiency after 2027, i.e. the average fuel consumption of new ICE vehicles does not increase from one year to the next. Backsliding is a possible result if existing policies were extended beyond 2027.

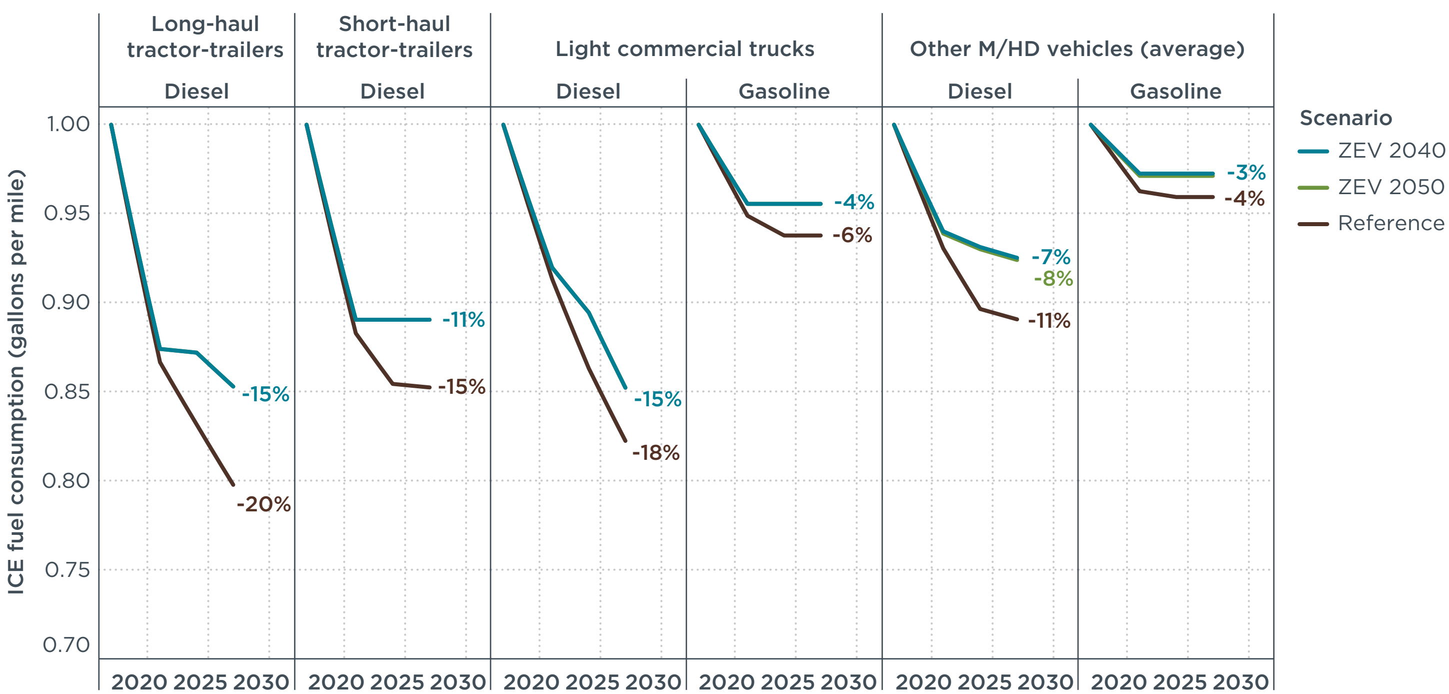

Figure 2. Internal combustion engine vehicle fuel consumption normalized to model year 2017. Data labels show the percent change from 2017 to 2027.

WELL-TO-WHEEL EMISSIONS

The well-to-wheel (WTW) CO_2 benefits of zero-emission vehicles are shaped by the current and future carbon intensity of the power grid. This study incorporates well-to-wheel CO_2 emissions using two sets of electricity grid carbon intensity assumptions. The first, EIA reference, conservatively assumes that the carbon intensity of the electricity grid follows the same pathway as the U.S. Energy Information Administration (EIA) 2020 Annual Energy Outlook (AEO) Reference scenario.[13] This EIA reference scenario corresponds to a 24% reduction in average grid carbon intensity between 2020 and 2050 (see Figure 3). The second assumes the states evaluated, not including California, reach net zero grid carbon intensity by 2050 (Net zero). The basis for this pathway to net zero is New York state's grid carbon intensity projections used in combination with Princeton University's Net-Zero America study projections for the other states evaluated, not including California.[14]

In this study, the Reference scenario reflects EIA reference grid assumptions only. Results for the ZEV 2040 and ZEV 2050 scenarios include EIA reference and Net zero grid carbon intensity. Scenarios applying the EIA reference grid carbon intensity are labeled ZEV 2040 - EIA reference and ZEV 2050 - EIA reference. Scenarios applying the Net zero trajectory are labeled ZEV 2040 -Net zero and ZEV 2050 - Net zero.

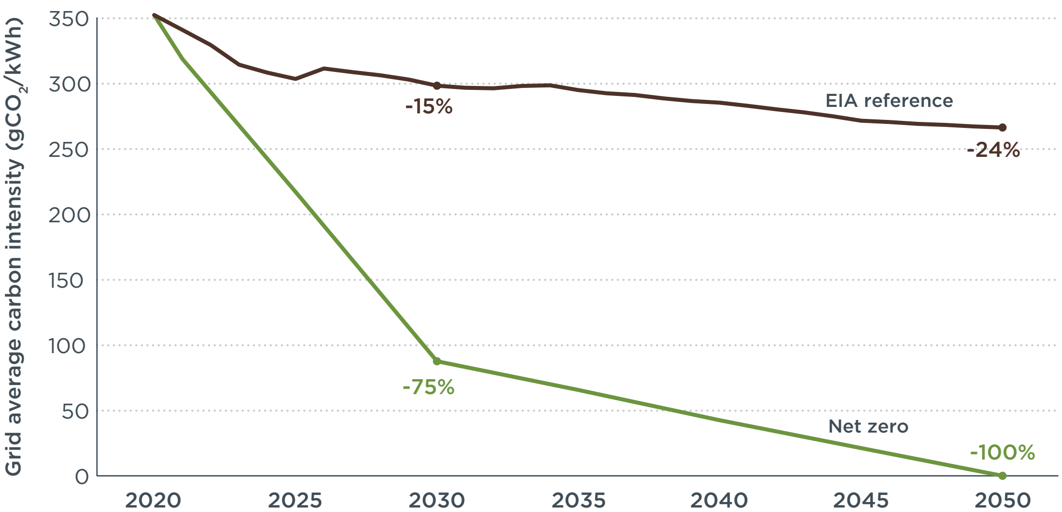

Figure 3. Grid carbon intensity pathways. Data labels show the percent change compared to 2020.

13 U.S. Energy Information Administration, "Table 8: Electricity Supply, Disposition, Prices and Emissions, Annual Energy Outlook 2021," (2020). https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2021&cases=ref2021&sourcekey=0.

14 Minjares, Ray, and Jeff Houk, "Benefits of Adopting California Medium- and Heavy-Duty Vehicle Regulations in New York State." (Washington, DC.: ICCT, 2021), https://theicct.org/publications/nys-hdv-regulation-benefits-may2021 and Larson, Eric, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, Robert Williams, Steve Pacala, and Robert Socolow. 2020. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Interim Report." (Princeton, NJ: Princeton University, 2020), https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.

RESULTS

VEHICLE STOCK BY FUEL TYPE

Figure 4 shows the projected change in the number of M/HD vehicles in the transportation fleet, including the change over time in the fuels the fleet uses. Under the Reference scenario, the stock of ZEV M/HD vehicles remains primarily diesel- or gasoline-powered, with the latter comprised of mostly light commercial trucks and medium-duty vehicles. Under the ZEV 2050 and ZEV 2040 scenarios, zero-emission M/HD vehicles comprise 9% of stock in 2030. After 2030, these two scenarios diverge where zero-emission M/HD vehicle stock reaches between 74% and 82% by 2050.

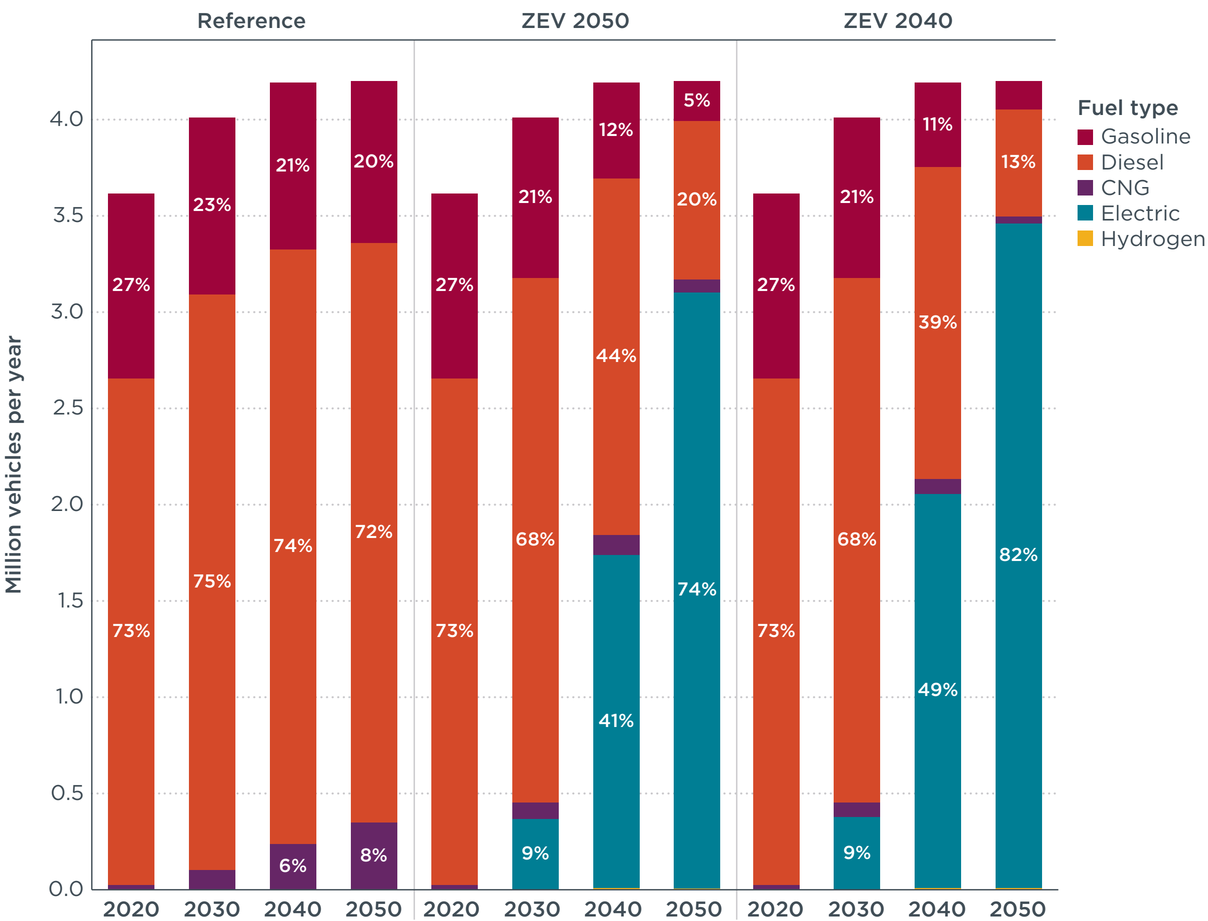

Figure 4. Comparison of M/HD vehicle stock by fuel type across scenarios. Data labels show the share of stock by fuel type. Data does not include California.

VEHICLE ACTIVITY BY FUEL TYPE

Figure 5 shows the change in vehicle activity of the M/HD fleet over time, including the change in fuels used across the fleet. Vehicle-miles traveled (VMT) of zero-emission M/HD vehicles is unchanged in the Reference scenario. The higher proportion of diesel activity compared to gasoline is due to the dominance of diesel engines in long-haul applications. In the ZEV 2050 and ZEV 2040 scenarios, zero-emission M/HD vehicles comprise 9% of VMT in 2030. After 2030, these two scenarios diverge, where ZEV M/HD vehicles reach 72%–82% of VMT by 2050. The zero-emission share of VMT is slightly larger than its share of the total vehicle population because newer vehicles tend to generate more activity than older vehicles.

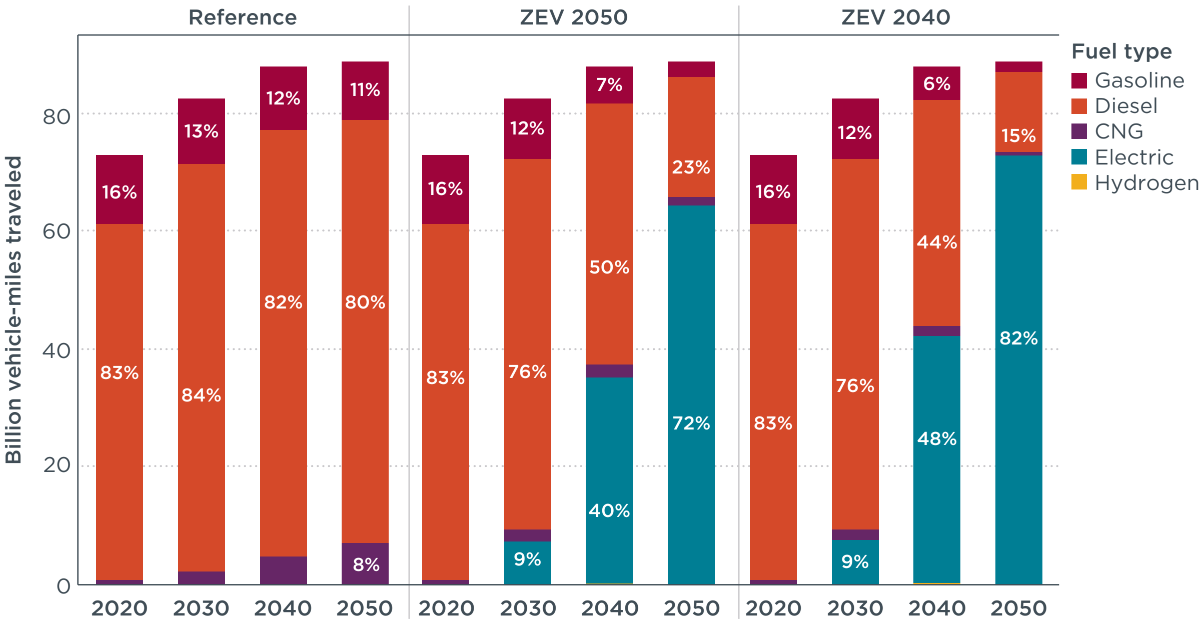

Figure 5. Comparison of medium- and heavy-duty vehicle activity by fuel type across scenarios. Data labels show the share of activity by fuel type. Data does not include California.

WELL-TO-WHEEL CO_2 EMISSIONS

Achieving the goals in the MOU in the states evaluated will generate significant reductions in WTW CO_2 emissions. Figure 6 shows projected WTW CO_2 emissions for five scenarios: the Reference scenario and each of the zero-emission scenarios (ZEV 2040 and ZEV 2050) under two grid carbon intensity pathways. In the Reference scenario, implementation of U.S. HDV Phase II GHG standards leads to CO_2 reductions of 23% from 2030 to 2050.

Prior to 2027, the CO_2 emission differences among scenarios are relatively small. In the short term, some of the benefits of zero-emission M/HD vehicles are expected to be offset by smaller than expected improvements in ICE efficiency compared to what would otherwise be necessary to comply with U.S. HDV Phase II GHG standards. The regulatory design of Phase II GHG standards, particularly the availability of Advanced Technology Credits, are what generate lower than expected ICE efficiency improvements, and not the availability or cost-effectiveness of ICE efficiency technology. Future regulations, such as a Phase III GHG standard, may provide a mechanism to recover some of this unrealized ICE efficiency potential.

The remaining four WTW CO_2 scenarios show consistently decreasing emissions from 2027 to 2050. The least ambitious of these is the ZEV 2050—EIA reference scenario, which achieves a 38% reduction in CO_2 emissions by 2040 and a 66% reduction by 2050 compared to 2020 levels. The grid decarbonization version of this scenario, ZEV 2050—Net Zero, would produce substantially greater CO_2 benefits: a 44% reduction in 2040 and a 77% reduction in 2050 compared to 2020 levels.

A faster transition to zero-emission M/HD vehicles would produce greater CO_2 benefits in the 2040 timeframe, 43%–50% below 2020 levels, depending on grid assumptions. The most ambitious scenario, ZEV 2040—Net zero, produces the greatest WTW CO_2 reductions by a considerable margin. In 2040, its CO_2 emissions are more than 50% below 2020 levels; and in 2050, its CO_2 emissions are 85% below 2020 levels, despite increased M/HD vehicle activity. These findings underscore the importance of treating vehicles and fuels as a single system, pursuing policies to transition M/HD vehicles to zero-emission powertrains in parallel with policies to fully decarbonize the power grid.

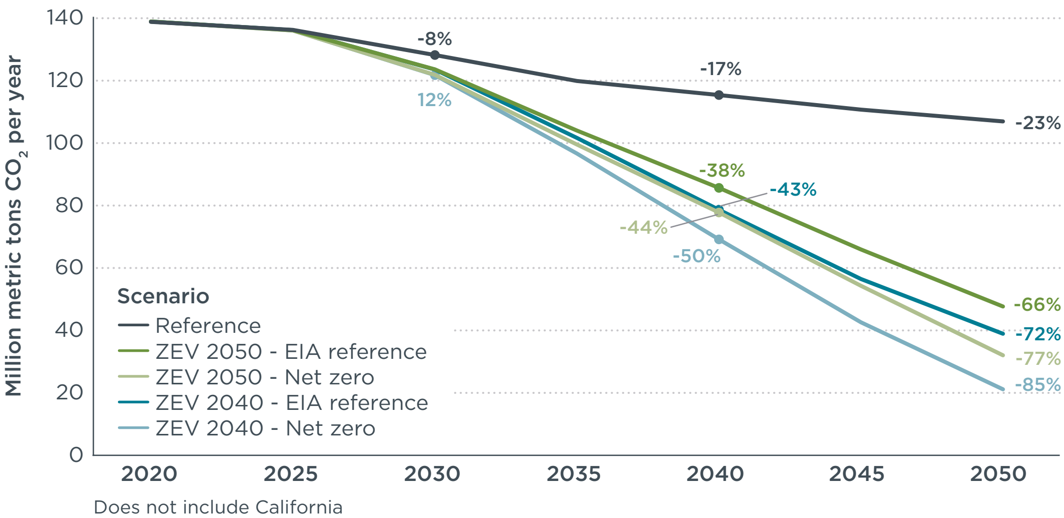

Figure 6. Comparison of medium- and heavy-duty vehicle fuel lifecycle CO_2 emissions across scenarios. Data labels show the percent change compared to 2020.

TAILPIPE NO_x EMISSIONS

Additional actions beyond fleet electrification can accelerate the reduction in tailpipe NO_x emissions. Figure 7 illustrates the tailpipe NO_x emissions across the scenarios. The Reference scenario, which does not assume adoption of HDV Omnibus standards, projects tailpipe NO_x emissions will decline until the late 2030s as pre-U.S. 2010 HDVs and pre-Tier 3 medium-duty vehicles retire from the fleet. However, without further policies, fleet wide NO_x emissions increase after 2040.

Adoption of the HDV Omnibus standards would deliver significant additional NO_x emissions reductions through 2040, after which zero-emission vehicles are needed to provide further NO_x reductions. Without low-NO_x standards, increased zero-emission M/HD uptake could reduce tailpipe NO_x emissions by about 14%–16% in 2035, compared to adopted policies. The introduction of HDV Omnibus standards would approximately double these NO_x emission benefits to 26%–31% in 2035. Compared to the Reference scenario, the most ambitious scenario, ZEV 2040—low NO_x, would reduce NO_x emissions by 89% in 2050 and avoid 896,000 tons cumulatively from 2025–2050. (See Table A9 for detailed NO_x emissions estimates.)

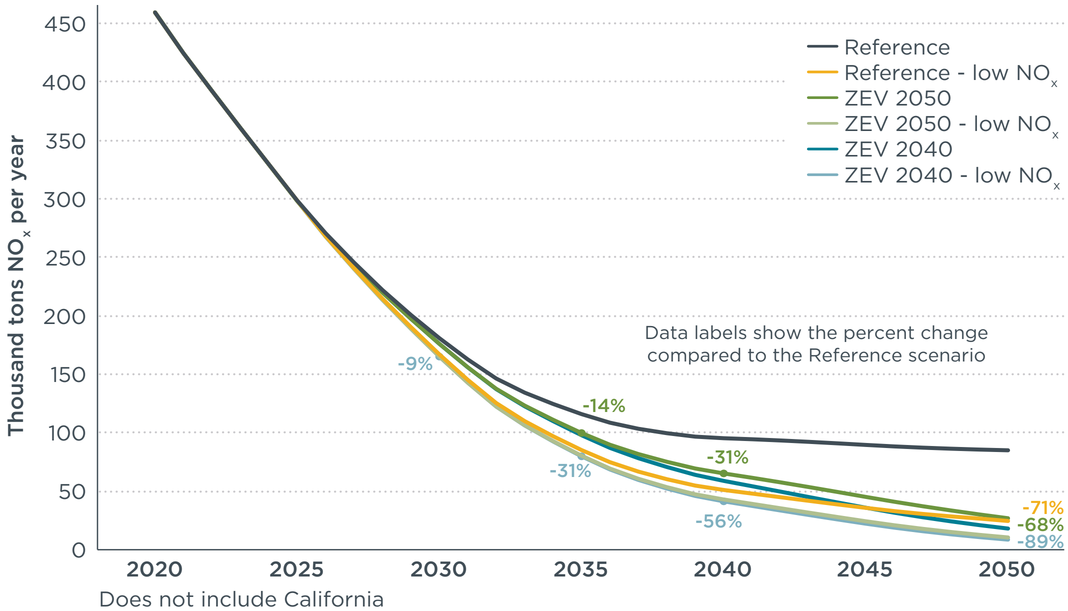

Figure 7. Comparison of medium- and heavy-duty vehicle tailpipe NO_x emissions across scenarios. Data labels show the percent change compared to the Reference scenario.

TAILPIPE $PM_{2.5}$ EMISSIONS

Figure 8 shows the projected change in $PM_{2.5}$ emissions over time across the M/HD fleet. Fleet electrification plays a key role in reducing tailpipe $PM_{2.5}$ emissions after 2030. Without new policies, tailpipe $PM_{2.5}$ emissions are projected to decrease until around 2037 as pre-U.S. 2010 heavy-duty and pre-Tier 3 medium-duty vehicles are removed from the fleet. From 2038, tailpipe $PM_{2.5}$ emissions remain stable. In contrast, the ZEV 2050 and ZEV 2040 scenarios would reduce tailpipe $PM_{2.5}$ emissions by another 15%–17% in 2035 and by 64%–76% in 2050, compared to adopted policies. Compared to the Reference scenario, the most ambitious scenario, ZEV 2040, could avoid 17 thousand tons of tailpipe $PM_{2.5}$ cumulatively to 2050 (See Table A10 for more detailed PM emissions estimates.)

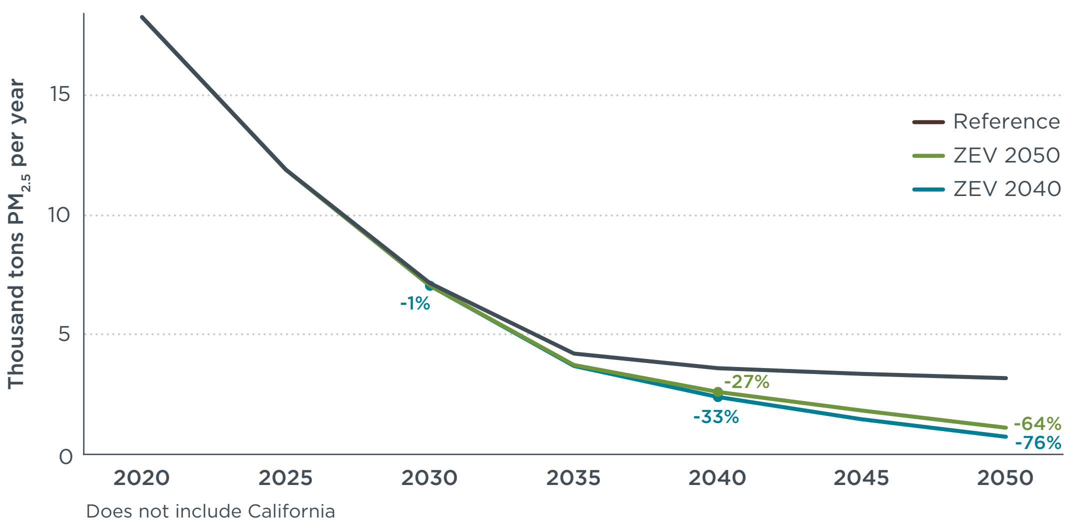

Figure 8. Comparison of medium- and heavy-duty vehicle tailpipe $PM_{2.5}$ emissions across scenarios. Data labels show the percent change compared to the Reference scenario.

CONCLUSION

In the absence of new federal policy, seventeen states and the District of Columbia have joined together under the Multi-state MOU to accelerate the transition to a zero-emission medium- and heavy-duty vehicle fleet. Their ambition is to achieve a zero-emission sales share of 30% in 2030 and 100% in 2050. California, the signatory with the largest share of the national M/HD market, has adopted a series of policies towards this end.

This paper estimates the multiple benefits of achieving the zero-emission targets of the MOU in Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Washington, and the District of Columbia. The study evaluates multiple scenarios, including no change in policy from 2020, a pathway to 100% zero-emission M/HD sales in 2050, and an accelerated pathway to 100% zero-emission M/HD sales in 2040. Each of these scenarios capture the upstream CO_2 emissions induced by demand for electricity from a growing electric fleet. This study goes one step further to estimate the additional benefits of powering this fleet with net zero carbon electricity by 2050. Finally, the study evaluates the additional benefits of implementing the HDV Omnibus rule, which would require 90% lower NO_x emissions from new internal combustion engines that will continued to be sold even under the most aggressive electrification scenarios.

Without new policies, this study finds that baseline reduction in well-to-wheel CO_2 emissions of the M/HD fleet across 14 states and the District of Columbia are on a path to reduce 8% below 2020 levels by 2030 and 23% below 2020 levels by 2050. NO_x emissions are projected to decline through the late 2030s as the oldest generation of ICE vehicles are replaced with newer vehicles manufactured to comply with U.S. 2010 and Tier 3 emission standards. These vehicles carry the latest generation of emissions control technology currently required by U.S. EPA.

The MOU endorses the goal of 30% M/HD zero-emission sales by 2030. Adoption of the California Advanced Clean Trucks rule in the states evaluated, which reflects this as a minimum target across all weight categories, would lead to 36% of all new M/HD vehicles powered by zero-emission engines in 2030. In that year, 12% of vehicle miles traveled would be zero-emission, and well-to-wheel CO_2 emissions would decline to 4% below 2020 levels.

The MOU also endorses the goal of 100 percent zero-emission M/HD sales by 2050. Achieving such a target would deliver well-to-wheel CO_2 emissions that are 38% below 2020 levels by 2040. Emissions would further decline to levels 66% below 2020 levels by 2050 and avoiding a cumulative 646 million metric tons of CO_2 emissions from 2020-2050. Table 1 summarizes the key findings of this paper with respect to emission reductions expected across the states evaluated.

Although not endorsed by the MOU, this study evaluated a faster pace of electrification of 100% zero-emission medium- and heavy-duty sales by 2040. Achieving such a goal in the states evaluated would reduce well-to-wheel CO_2 emissions to levels 43% below 2020 levels in 2040 and 72% in 2050, cumulatively avoiding more than 120 million metric tons of additional CO_2 from 2020 to 2050.

The carbon intensity of the electric grid shapes the magnitude of climate benefits expected from fleet electrification. Full decarbonization of the electric grid to net zero CO_2 emissions in 2050 would increase the benefits of the MOU 2050 target in the states evaluated by 174 million metric tons of avoided CO_2, while coupling grid decarbonization to a faster 2040 100% ZEV sales target would deliver even larger benefits of 324 million tons of avoided CO_2. By 2050, both sales target scenarios in combination with a net zero grid would bring fleet-wide CO_2 emissions to 72% and 85% below 2020 levels, respectively.

The MOU will reduce other pollutants in the states evaluated as well. The 2050 target would cumulatively avoid 15 thousand tons of tailpipe $PM_{2.5}$ through 2050, while faster uptake of 100% ZEV sales by 2040 would deliver 17 thousand avoided tons.

Finally, the states studied can expect their M/HD ZEV goals to reduce fleet-wide NO_x emissions 14%–16% in 2035, compared to no new action. The adoption of the Heavy-Duty Omnibus rule in combination with these policies would result in 25%–31% lower emissions by 2035, approximately doubling the benefits of fleet electrification. The most ambitious scenario for NO_x control would be 100% M/HD ZEV sales in 2040 combined with the Heavy-Duty Omnibus rule, cumulatively avoiding 896,000 tons of NO_x emissions from 2020 to 2050.

States working to fulfill the stated ambition of the multi-state MOU can take immediate regulatory action by adopting California's ACT and HDV Omnibus regulations. In addition, states can introduce a range of market enabling measures, such as electricity rate reform and vehicle and infrastructure incentives to mobilize investment in the power grid that will be necessary to support the growing electric fleet. Finally, states can increase the climate benefits of these measures by ensuring the power grid is net zero carbon no later than 2050.

Table 1. Cumulative emissions reductions in MOU jurisdictions, not including California, compared to the Reference scenario, 2020–2050.

		WTW CO_2 (million metric tons)	Tailpipe NO_x (thousand tons)		Tailpipe $PM_{2.5}$ (thousand tons)
Vehicle scenario	**Grid scenario**			HDV Omnibus scenario	
Reference		-	-	896	-
ZEV 2050	**EIA reference**	646	648	1,071	15
	Net zero	820	-	-	-
ZEV 2040	**EIA reference**	767	762	1,097	17
	Net zero	969	-	-	-

APPENDIX

This appendix includes data for projected sales, stock, and activity of total M/HD vehicles and zero-emission M/HD vehicles among the MOU signatories evaluated, excluding California. It also includes data for the estimated WTW CO_2, tailpipe NO_x, and tailpipe $PM_{2.5}$ reductions of each new policy scenario compared to the reference scenario.

Table A1. Projected M/HD vehicle sales in thousands among MOU signatories, not including California or post-2020 signatories.

Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Tractor-trailers	113	113	114	116	115	115	114
Rigid trucks	171	186	200	211	222	233	244
Buses	26	25	25	24	24	23	23
Light commercial trucks	25	23	20	17	16	14	13
Total M/HD vehicles	**335**	**347**	**359**	**368**	**377**	**385**	**394**

Table A2. Projected M/HD vehicle stock in millions among MOU signatories, not including California or post-2020 signatories.

Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Tractor-trailers	1	1	1.1	1.2	1.2	1.2	1.2
Rigid trucks	1.7	1.9	2.1	2.1	2.2	2.2	2.2
Buses	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Light commercial trucks	0.6	0.5	0.5	0.4	0.3	0.3	0.3
Total M/HD vehicle stock	**3.7**	**3.8**	**4.1**	**4.1**	**4.2**	**4.2**	**4.2**

Table A3. Projected M/HD vehicle activity in billion vehicle-miles traveled among MOU signatories, not including California or post-2020 signatories.

Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Tractor-trailers	42	46	49	51	54	55	55
Rigid trucks	20	23	24	25	26	26	26
Buses	4	4	5	5	5	5	5
Light commercial trucks	6	5	4	4	3	3	3
Total M/HD vehicle activity	**72**	**78**	**82**	**85**	**88**	**89**	**89**

Table A4. ZEV sales as a percent of M/HD sales among MOU signatories, not including California or post-2020 signatories, by scenario.

Scenario	Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Reference	Tractor-trailers	0%	0%	0%	0%	0%	0%	0%
	Rigid trucks	0%	0%	0%	0%	0%	0%	0%
	Buses	1%	1%	1%	1%	1%	1%	1%
	Light commercial trucks	0%	0%	0%	0%	0%	0%	0%
ZEV 2050	Tractor-trailers	0%	9%	38%	55%	68%	85%	100%
	Rigid trucks	0%	11%	49%	74%	85%	97%	100%
	Buses	1%	11%	50%	75%	100%	100%	100%
	Light commercial trucks	0%	7%	30%	55%	67%	82%	100%
ZEV 2040	Tractor-trailers	0%	9%	38%	74%	100%	100%	100%
	Rigid trucks	0%	11%	51%	94%	100%	100%	100%
	Buses	1%	12%	99%	99%	100%	100%	100%
	Light commercial trucks	0%	7%	30%	55%	100%	100%	100%

Table A5. Zero-emission M/HD sales among MOU signatories, not including California or post-2020 signatories, by scenario.

Scenario	Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Reference	Tractor-trailers	-	-	-	-	-	-	-
	Rigid trucks	-	-	-	-	-	-	-
	Buses	260	250	250	240	240	230	230
	Light commercial trucks	-	-	-	-	-	-	-
ZEV 2050	Tractor-trailers	-	10,170	43,320	63,800	78,200	97,750	114,000
	Rigid trucks	-	20,460	98,000	156,140	188,700	226,010	244,000
	Buses	260	2,750	12,500	18,000	24,000	23,000	23,000
	Light commercial trucks	-	1,610	6,000	9,350	10,720	11,480	13,000
ZEV 2040	Tractor-trailers	-	10,170	43,320	85,840	115,000	115,000	114,000
	Rigid trucks	-	20,460	102,000	198,340	222,000	233,000	244,000
	Buses	260	3,000	24,750	23,760	24,000	23,000	23,000
	Light commercial trucks	-	1,610	6,000	9,350	16,000	14,000	13,000

Table A6. ZEV stock as a percent of M/HD stock among MOU signatories, not including California or post-2020 signatories, by scenario.

Scenario	Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Reference	Tractor-trailers	0%	0%	0%	0%	0%	0%	0%
	Rigid trucks	0%	0%	0%	0%	0%	0%	0%
	Buses	0%	0%	0%	1%	1%	1%	1%
	Light commercial trucks	0%	0%	0%	0%	0%	0%	0%
ZEV 2050	Tractor-trailers	0%	1%	8%	20%	34%	50%	68%
	Rigid trucks	0%	1%	9%	25%	42%	59%	75%
	Buses	0%	2%	11%	27%	45%	61%	76%
	Light commercial trucks	0%	1%	8%	21%	35%	52%	72%
ZEV 2040	Tractor-trailers	0%	2%	9%	26%	47%	66%	81%
	Rigid trucks	0%	1%	9%	28%	50%	68%	83%
	Buses	0%	2%	12%	31%	51%	69%	83%
	Light commercial trucks	0%	1%	8%	21%	41%	64%	85%

Table A7. Zero-emission M/HD vehicle stock among MOU signatories, not including California or post-2020 signatories, by scenario.

Scenario	Roadmap M/HD vehicle category	2020	2025	2030	2035	2040	2045	2050
Reference	Tractor-trailers	-	-	-	-	-	-	-
	Rigid trucks	-	-	-	-	-	-	-
	Buses	-	-	-	4,000	5,000	5,000	5,000
	Light commercial trucks	-	-	-	-	-	-	-
ZEV 2050	Tractor-trailers	-	10,000	88,000	240,000	408,000	600,000	816,000
	Rigid trucks	-	19,000	189,000	525,000	924,000	1,298,000	1,650,000
	Buses	-	8,000	44,000	108,000	225,000	305,000	380,000
	Light commercial trucks	-	5,000	40,000	84,000	105,000	156,000	216,000
ZEV 2040	Tractor-trailers	-	20,000	99,000	312,000	564,000	792,000	972,000
	Rigid trucks	-	19,000	189,000	588,000	1,100,000	1,496,000	1,826,000
	Buses	-	8,000	48,000	124,000	255,000	345,000	415,000
	Light commercial trucks	-	5,000	40,000	84,000	123,000	192,000	255,000

Table A8. WTW CO_2 emissions reductions in million metric tons compared to the Reference scenario, not including California or post-2020 signatories.

Scenario	2030	2035	2040	2045	2050	Cumulative to 2050
ZEV 2050 - EIA reference	5	16	30	45	59	646
ZEV 2050 - Net Zero	6	20	38	57	75	820
ZEV 2040 - EIA reference	5	17	37	54	68	767
ZEV 2040 - Net zero	7	23	46	68	86	969

Table A9. Tailpipe NO_x emissions reductions in thousand tons compared to a Reference scenario without low-NO_x standards, not including California or post-2020 signatories.

Scenario	2025	2030	2035	2040	2045	2050	Cumulative to 2050
Reference - low NO_x	2	14	31	44	54	60	896
ZEV 2050	0	5	16	30	44	58	648
ZEV 2050 – low NO_x	3	15	35	54	65	75	1,071
ZEV 2040	0	5	18	36	54	67	762
ZEV 2040 - low-NO_x	3	16	36	55	67	76	1,097

Table A10. Tailpipe $PM_{2.5}$ emissions reductions in thousand tons compared to the Reference scenario, not including California or post-2020 signatories.

Scenario	2030	2035	2040	2045	2050	Cumulative to 2050
ZEV 2050	0.1	0.3	0.7	1.0	1.4	15
ZEV 2040	0.1	0.4	0.8	1.3	1.6	17

Table A11. Mapping of MOVES source types to Roadmap M/HD vehicle categories.

MOVES source type	Roadmap M/HD vehicle category
Long-haul tractor-trailers	Tractor-trailers
Short-haul tractor-trailers	Tractor-trailers
Motor homes	Rigid trucks
Single-unit long-haul trucks	Rigid trucks
Single-unit short-haul trucks	Rigid trucks
Refuse trucks	Rigid trucks
School buses	Buses
Transit buses	Buses
Intercity buses	Buses
Light commercial trucks (Class 2b-3)	Light commercial trucks