Supply-side regulations to accelerate the market for zero-emission heavy vehicles: Best practices from major policies

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INTRODUCTION

As the technology to manufacture heavy-duty vehicles (HDVs) that produce zero tailpipe emissions grows increasingly mature, a path forward for addressing the climate and air quality impacts from these vehicles is emerging. Currently, HDVs are the second-largest source of greenhouse gas (GHG) emissions in the transport sector, after light-duty vehicles.[1] Often powered by diesel engines, the HDV segment is also the largest contributor to air pollutants such as particulate matter and nitrogen oxide. Exposure to these air pollutants leads to adverse health effects, particularly in communities with warehouses and other freight hubs that generate a high volume of truck activity.[2] Zero-emission HDVs powered by batteries or hydrogen fuel cells can eliminate air pollutants from tailpipes and significantly reduce life-cycle GHG emissions.[3]

1 Yihao Xie, Tim Dallmann, and Rachel Muncrief, *Heavy-Duty Zero-Emission Vehicles: Pace and Opportunities for a Rapid Global Transition* (ZEV Transition Council, 2022), https://theicct.org/publication/hdv-zevtc-global-may22/.

2 Gaige Hunter Kerr, Michelle Meyer, Daniel L. Goldberg, Joshua Miller, and Susan C. Anenberg, "Air Pollution Impacts from Warehousing in the United States Uncovered with Satellite Data," *Nature Communications* 15, 6006 (2024), https://doi.org/10.1038/s41467-024-50000-0.

3 Aviral Yadav, Adrian O'Connell, and Nikita Pavlenko, *A Comparison of the Life-Cycle Greenhouse Gas Emissions from Combustion and Electric Heavy-Duty Vehicles in India* (International Council on Clean Transportation, 2024), https://theicct.org/publication/life-cycle-ghg-combustion-and-electric-hdv-india-may24/; Adrian O'Connell, Nikita Pavlenko, Georg Bieker, and Stephanie Searle, *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels* (International Council on Clean Transportation, 2023), https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/; Ana Beatriz Rebouças and André Cieplinski, *Quantifying Avoided Greenhouse Gas Emissions by E-Buses in Latin America: A Simplified Life-Cycle Assessment Methodology* (International Council on Clean Transportation, 2024), https://theicct.org/publication/quantifying-avoided-ghg-emissions-by-e-buses-in-latin-america-a-simplified-life-cycle-assessment-methodology-aug24/.

Acknowledgments: This research was generously supported by ClimateWorks Foundation. We thank Anish Sinha, Dale Hall, Felipe Rodríguez, Pierre-Louis Ragon, and Ray Minjares of the ICCT; and Jennifer Helfrich Consulting and Sarah Sachs Consulting, in collaboration with the Drive Electric Campaign, for their helpful reviews, and also Lori Sharn and Jennifer Callahan for editing.

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Governments in some regions are using supply-side regulations (SSRs) to encourage or require greater uptake of zero-emission HDVs. Manufacturers risk penalties such as fines or losing the ability to sell new models of vehicles if they fail to comply with these rules. While most SSRs regulate vehicle original equipment manufacturers (OEMs), they can also apply to importers. Common forms of SSRs include vehicle fuel economy standards, vehicle and engine criteria air pollutant standards, vehicle and engine GHG emission standards, and zero-emission vehicle (ZEV) sales requirements.

Supply-side regulations have a strong track record of delivering cleaner and more efficient vehicles and can be grouped under two types.[4] One is a performance standard that sets a vehicle performance target, typically an emissions or energy consumption target that manufacturers or importers are required to meet through a demonstration of their products' performance. The other is a ZEV sales requirement, which directs manufacturers to sell a minimum share of vehicles that produce zero tailpipe emissions. Manufacturers must certify their vehicles as zero emission and report ZEV sales along with sales of all their other products.

There are three key advantages to using SSRs to promote ZEVs. First, SSRs provide assurance because they apply to all manufacturers. OEMs can be certain that competitors will also be selling more ZEVs and investing in both research and development and the components and infrastructure necessary to produce and support ZEVs. Second, the increased availability and diversity of zero-emission products from all manufacturers help boost demand from consumers while also decreasing prices through competition for these consumers. Third, as the number of OEMs is typically small, SSRs are easier to administer and enforce than programs aimed at consumers like purchase subsidies and tax credits.

When designed well, both sales requirements and vehicle performance standards have demonstrated effectiveness in increasing sales of ZEVs. Regulators can implement either or both types in their regions. This brief describes the design elements of the following three SSRs that encourage or require the adoption of zero-emission HDVs (other types of SSRs are not the focus):

- California's ACT regulation, which sets ZEV sales requirements
- The U.S. GHG emission standards for HDVs, which set emissions performance requirements
- The European Union's carbon dioxide (CO_2) standards for HDVs, which include both emissions performance and ZEV sales requirements

HISTORY OF THE THREE REGULATIONS

The three SSRs have evolved to reflect changing markets, technologies, and regulatory environments.

In 2011, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) adopted Phase 1 GHG emission standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles sold in model years (MYs) 2014 to 2017.[5] EPA introduced the Greenhouse Gas Emissions Model (GEM) as the compliance tool and established fleet-average standards and a credit

4 Sai Sudharshan Ravi, Sergey Osipov, and James W. G. Turner, "Impact of Modern Vehicular Technologies and Emission Regulations on Improving Global Air Quality," *Atmosphere* 14, no. 7 (July 2023): 1164, https://doi.org/10.3390/atmos14071164.

5 Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, 76 F.R. 179, (September 15, 2011), https://www.govinfo.gov/content/pkg/FR-2011-09-15/pdf/2011-20740.pdf.

banking and trading mechanism, among other features. Phase 2 standards, adopted in 2016, set more stringent limits on medium- and heavy-duty engine and vehicle GHG emissions and fuel efficiency for MYs 2021 to 2027.[6] The latest Phase 3 standards were finalized in April 2024 and will apply to MYs 2027 to 2032.[7] Unlike the earlier phases, Phase 3 targets full vehicles instead of engines only, does not update GHG emission limits other than CO_2, and is not accompanied by new fuel efficiency standards from NHTSA.

In the European Union, the Vehicle Energy Consumption calculation TOol (VECTO) was established as the simulation tool for certifying emissions under a regulation published in 2017.[8] In 2018, the European Union adopted a reporting and monitoring regulation for manufacturers and Member States to report certified CO_2 emission values and registrations of HDVs, among other data.[9] These set the stage for the CO_2 emission standards, which were first adopted in 2019 and required truck manufacturers to meet emission reduction targets for 2025 and 2030.[10] Subsequently, the European Union adopted the European Climate Law, which created a mandate and a legal basis for increasing ambition for decarbonization, and updated emission standards for HDVs were proposed in 2023 and then adopted in May 2024.[11] The revised regulation broadened the types of vehicles regulated, increased the stringency of targets, and introduced new targets for 2035 and 2040.

The California Air Resources Board (CARB) proposed the ACT regulation in October 2019, strengthened it in a revised proposal in April 2020, and then adopted the regulation in June 2020. The ACT requires the sale of increasing shares of zero-emission vehicles in OEMs' HDV sales starting in MY 2024.[12] Subsequently, 10 other U.S. states followed California's lead and adopted the ACT regulation.[13] In March 2023, EPA granted a waiver of preemption to CARB that allows California to adopt emission-related requirements different than the federal standards, and allows other states

6 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2, 81 F.R. 206, (October 25, 2016), https://www.govinfo.gov/content/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

7 "Final Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3," U.S. EPA, April 22, 2024, https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-standards-heavy-duty.

8 Regulation (EU) 2017/2400 of 12 December 2017 Implementing Regulation (EC) No 595/2009 of the European Parliament and of the Council as Regards the Determination of the CO_2 Emissions and Fuel Consumption of Heavy-Duty Vehicles and Amending Directive 2007/46/EC of the European Parliament and of the Council and Commission Regulation (EU) No 582/2011 (Text with EEA Relevance), (2017), https://eur-lex.europa.eu/eli/reg/2017/2400/oj.

9 Regulation (EU) 2018/956 of the European Parliament and of the Council of 28 June 2018 on the Monitoring and Reporting of CO_2 Emissions from and Fuel Consumption of New Heavy-Duty Vehicles (Text with EEA Relevance), (June 28, 2018), https://eur-lex.europa.eu/eli/reg/2018/956/oj.

10 Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 Setting CO_2 Emission Performance Standards for New Heavy-Duty Vehicles and Amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC (Text with EEA Relevance), (July 25, 2019), https://eur-lex.europa.eu/eli/reg/2019/1242/oj/eng; Felipe Rodríguez, *CO_2 Standards for Heavy-Duty Vehicles in the European Union* (International Council on Clean Transportation, 2019), https://theicct.org/publication/co2-standards-for-heavy-duty-vehicles-in-the-european-union/.

11 Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), (June 30, 2021), http://data.europa.eu/eli/reg/2021/1119/oj/eng; Regulation (EU) 2024/1610 of the European Parliament and of the Council of 14 May 2024 Amending Regulation (EU) 2019/1242 as Regards Strengthening the CO_2 Emission Performance Standards for New Heavy-Duty Vehicles and Integrating Reporting Obligations, Amending Regulation (EU) 2018/858 and Repealing Regulation (EU) 2018/956, (May 14, 2024), https://eur-lex.europa.eu/eli/reg/2024/1610/oj; Eamonn Mulholland, *The Revised CO_2 Standards for Heavy-Duty Vehicles in the European Union* (International Council on Clean Transportation, 2024), https://theicct.org/publication/revised-co2-standards-hdvs-eu-may24/.

12 "Advanced Clean Trucks Regulation," California Air Resources Board, accessed October 4, 2024, https://ww2.arb.ca.gov/rulemaking/2019/advancedcleantrucks.

13 The states include Massachusetts, New Jersey, New York, Oregon, and Washington (implementation beginning in MY 2025); Vermont (implementation beginning in MY 2026); and Colorado, Maryland, New Mexico, and Rhode Island (implementation beginning in MY 2027).

to adopt the ACT.[14] CARB went on to adopt the Advanced Clean Fleets regulation in April 2023. The regulation largely applies to the demand side, but includes a new requirement for manufacturers to end sales of HDVs with internal combustion engines (ICEs) by 2036.[15] In March 2024, CARB began an amendment of the ACT regulation to facilitate compliance in the wake of CARB's Clean Truck Partnership agreement with truck and engine manufacturers.[16] A staff proposal was approved by the CARB board in October 2024.[17]

KEY MECHANISMS

CO_2/GHG PERFORMANCE STANDARDS

Vehicle performance standards drive zero-emission HDV adoption by setting increasingly more stringent emission targets over time, measured in grams of CO_2 per unit of work, such as ton-miles or passenger-kilometers. In both the EU and U.S. regulations, the standards apply at a fleet-average level and not to individual vehicle models. In a fleet-average performance standard, vehicle manufacturers (or importers) have the flexibility to deploy different technologies and can lower their fleet-average emissions by offering battery electric and hydrogen fuel-cell electric models that produce no tailpipe emissions.

Both the EU and U.S. regulations are technology neutral, and ZEVs are just one of several strategies for lowering fleet-average emissions. In the EU CO_2 regulation, the exception is for urban buses which is a sales requirement instead of CO_2 reduction targets. However, manufacturers will have an incentive to shift to ZEVs if producing them is more profitable than improving ICE vehicles, especially as emission limits tighten over time.

Setting the baseline

Emission reduction targets are designed with a common baseline of current performance. In the United States, baseline emissions are absolute values measured in grams per ton-mile for regulated vehicle subgroups. The United States has records of CO_2 emissions for HDVs since MY 2014, when Phase 1 standards went into effect. The baseline for Phase 1 was determined through component testing and computer simulation modeling. The baseline for Phase 3 standards is the MY 2027 emission limits under the Phase 2 standards.

The European Union requires a percentage reduction in fleet-level CO_2 emissions from a baseline that was not determined when the regulation was finalized in 2019. To define the baseline, raw emissions data were collected from manufacturers, as required by the reporting and monitoring regulation adopted in 2018. Each vehicle segment has its own reference emission level, and that level is the industry-average emissions of all vehicles sold in the segment in the baseline year—2019, 2021, or 2025, depending on the vehicle

14 U.S. Environmental Protection Agency, "EPA Grants Waivers for California's On-Highway Heavy-Duty Vehicle and Engine Emission Standards," news release, March 31, 2023, https://www.epa.gov/newsreleases/epa-grants-waivers-californias-highway-heavy-duty-vehicle-and-engine-emission.

15 California Air Resources Board, "California Approves Groundbreaking Regulation That Accelerates the Deployment of Heavy-Duty ZEVs to Protect Public Health," news release no. 23-13, April 28, 2023, https://ww2.arb.ca.gov/news/california-approves-groundbreaking-regulation-accelerates-deployment-heavy-duty-zevs-protect.

16 California Air Resources Board, *Public Hearing to Consider Proposed Amendments to the Advanced Clean Trucks Regulation and the Zero-Emission Powertrain Certification Test Procedure Staff Report: Initial Statement of Reasons* (2024), https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2024/actzepcert/isor.pdf.

17 California Air Resources Board, *Amendments to the Advanced Clean Trucks Regulation and the Zero-Emission Powertrain Certification Test Procedure Resolution 24-5* (2024), https://ww2.arb.ca.gov/sites/default/files/barcu/board/books/2024/102424/prores24-5.pdf.

segment. The EU approach highlights one way to implement a forward-looking SSR without establishing a baseline in advance.

Setting the targets for emissions reduction

The effect of performance standards on the uptake of zero-emission HDVs depends heavily on how large of a reduction in emissions they require. The greater the emission reductions required, the more likely it is to lead to greater production and sale of ZEVs. The European Union's HDV regulation spells out increasingly stringent targets, especially in later years: a 65% reduction in emissions in 2035, relative to the baseline, followed by a 90% reduction in 2040. As conventional ICE HDVs will not be able to decarbonize to this extent, this ensures that ZEVs will play a dominant role in future production.[18]

The U.S. Phase 3 standards set grams per ton-mile targets that result in percentage reductions of 40% to 60% in MY 2032 compared with MY 2027; the largest percentage reduction is 60% for Class 2b–5 vocational trucks, which have a gross vehicle weight rating (GVWR) between 3,856 and 8,845 kg. It is expected that manufacturers will use a mix of more efficient ICE vehicles, hybrid vehicles, and ZEVs to achieve these targets.

Regulators typically weigh several factors when deciding on the emissions reduction target. In the U.S. Phase 3 rulemaking, EPA projected the technology feasibility and payback period of zero-emission HDV technologies for more than 100 types of HDVs in MYs 2027, 2030, and 2032. The agency then converted payback periods to ZEV adoption rates using a payback schedule.[19] HDV segments that have a shorter payback period are expected to transition to zero-emission technology faster, and these tend to be those with lighter GVWRs and shorter, closed-loop duty cycles. In the final rule, the percentage reduction in emissions for each HDV category matches the projected ZEV adoption rate for that category.

European regulators also considered the economic and technological feasibility of zero-emission technology in different HDV segments and set emission reduction targets that balanced feasibility with industry-wide CO_2 reduction ambitions. The European Climate Law requires the transport sector to cut CO_2 emissions by 90% by 2050 relative to 1990 levels.[20]

ZEV SALES REQUIREMENTS

Some SSRs require manufacturers to sell increasing percentages of ZEVs in their product lineup. These vehicles must use technologies such as battery electric and hydrogen fuel-cell electric; in some cases, certain plug-in hybrids called near-zero-emission vehicles or NZEVs are allowed in near-term targets. The sales requirements are independent of any performance standards for ICE vehicles and thus there are no baseline emissions to be established.

The most important metric in a ZEV sales requirement is the adoption rate. California's ACT regulation requires the sale of a certain percentage of zero-emission or near-zero-emission heavy-duty trucks from MY 2024 onward, defined in three vehicle groups and

18 Oscar Delgado and Felipe Rodríguez, *CO_2 Emissions and Fuel Consumption Standards for Heavy-Duty Vehicles in the European Union* (International Council on Clean Transportation, 2018), https://theicct.org/publication/co2-emissions-and-fuel-consumption-standards-for-heavy-duty-vehicles-in-the-european-union/.

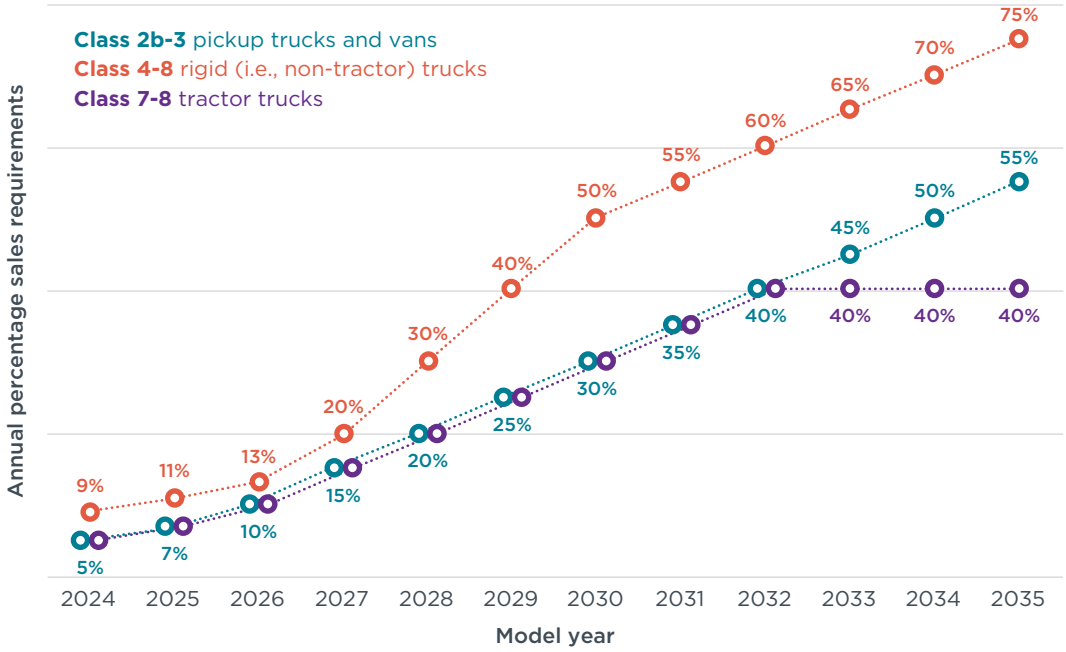
19 Eastern Research Group, *External Peer Review of Report: Heavy-Duty Technology Resource Use Case Scenario (HD TRUCS) Tool—Final Peer Review Summary Report* (U.S. Environmental Protection Agency, 2023), https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=548983&Lab=OTAQ; Matteo Muratori et al., "Exploring the Future Energy-Mobility Nexus: The Transportation Energy & Mobility Pathway Options (TEMPO) Model," *Transportation Research Part D: Transport and Environment* 98, (September 2021): 102967, https://doi.org/10.1016/j.trd.2021.102967.

20 Regulation (EU) 2021/1119 of the European Parliament and of the Council.

detailed in Figure 1: Class 2b–3 trucks and vans, GVWR of 3,856–6,350 kg; Class 4–8 rigid trucks, GVWR > 6,351 kg; and Class 7–8 tractor trucks, GVWR > 11,794 kg.[21]

Figure 1

Zero-emission sales required by vehicle group and model year in California's Advanced Clean Trucks regulation



Source: Buysse and Sharpe, *California's Advanced Clean Trucks Regulation*.

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The ZEV sales percentages in ACT are guided by goals legislated in the California Global Warming Solutions Act of 2006, which requires a 40% reduction in statewide GHG emissions from 1990 levels by 2030.[22] To determine the ZEV adoption rates in the three vehicle groups, CARB assessed the launch schedules and costs of zero-emission products. The higher sales percentage requirements for Class 4–8 rigid trucks reflect an expectation that vehicles in that category would be able to achieve the quickest cost and performance parity between zero-emission and ICE drivetrains.

Table 1 summarizes the three regulations and how they incorporate ZEVs.

21 Claire Buysse and Ben Sharpe, *California's Advanced Clean Trucks Regulation: Sales Requirements for Zero-Emission Heavy-Duty Trucks* (International Council on Clean Transportation, 2020), https://theicct.org/publication/californias-advanced-clean-trucks-regulation-sales-requirements-for-zero-emission-heavy-duty-trucks/.

22 California Global Warming Solutions Act of 2006: Emissions, 32 SB § 38566 (2016), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32.

Table 1

Key facts about three supply-side regulations for heavy-duty vehicles

Region	European Union	United States	California
Type	**Performance standard**	**Performance standard**	**ZEV sales requirement**
Regulated vehicles	Buses, trucks, and trailers	Class 2b–8 buses and trucks (only vocational vehicles of Class 2b–3)	Class 2b–8 trucks
Target years	2025, 2030, 2035, 2040 for originally regulated trucks; 2030, 2035 and 2040 for newly regulated trucks, coaches, and interurban buses; and 2030 and 2035 for newly regulated urban buses	MY 2027–MY 2032	MY 2024–MY 2035
Baseline	Industry average for 2019, 2021, and 2025 reporting periods	Phase 2 emission limits for MY 2027	No baseline
Stringency	Measured in reduction of tailpipe emissions relative to baseline for all but city buses[a] By 2040, 90% reduction for buses and trucks	Measured in reduction of tailpipe emissions relative to baseline 40%–60% reduction in MY 2032 compared with MY 2027, the largest for Class 2b–5 vocational trucks	Measured in ZEV sales 40%–75% ZEV share of sales, the largest for Class 4–8 rigid trucks
Metric	g CO_2/ton-km or g CO_2/passenger-km, specific to each manufacturer	g CO_2/ton-mile, fixed for all manufacturers	Annual ZEV sales percentage, fixed for all manufacturers
Role of ZEVs	One of many possible technologies allowed for compliance[a] Zero-emission is likely necessary to meet the increased stringency in later years	One of many possible technologies allowed for compliance	ZEVs and/or near-zero emission vehicles (these are plug-in hybrids that meet a minimum all-electric range) are required for compliance

[a] For city buses, the requirement is 90% zero-emission sales in 2030 and 100% zero-emission sales in 2040.

CREDIT SYSTEM AND COMPLIANCE

All three SSRs measure compliance with an accounting system for fleet-averaged credits and deficits.

DEFINITION OF CREDITS

In the federal CO_2 regulations for HDVs in the United States, manufacturers earn credits if their vehicle fleets have lower emissions relative to the grams per ton-mile emission limits for each vehicle subfamily and model year, and deficits if their vehicle fleets have emissions above the limits. The European Union, meanwhile, awards credits to manufacturers that lower their fleet-average specific emissions—defined as the sales-weighted average of the OEM's emissions in all segments—below a reduction trajectory line. This line represents a year-by-year linear reduction in emissions between target years; for example, the trajectory line will show the annual reductions needed to achieve a 43% total reduction in emissions in 2030 when starting at the 15% reduction target in 2025. Manufacturers acquire debts only in target years, if they do not achieve the required reductions, and the credits achieved in the intervening years can be used to offset these debts.[23]

In both the United States and European Union, the credit-deficit calculation works on an aggregated basis. This means that not every single vehicle sold by a manufacturer needs to meet the standards. They instead use fleet-averaged emissions; in the United States, the unit of compliance is the vehicle subfamily, and in the European Union, the units are freight vehicles (trucks and trailers) and passenger vehicles (buses).

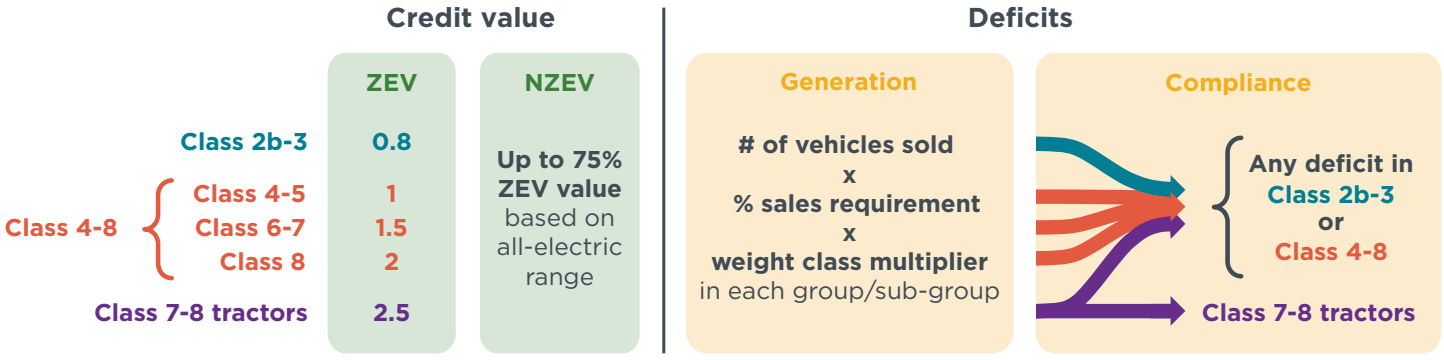
23 For a detailed explanation of the credit and debt system in the EU regulation, refer to Mulholland, *The Revised CO_2 Standards*.

Credits can be saved for future use, sometimes with an expiration date, and this practice is commonly referred to as "banking." In the United States, manufacturers can share excess credits within their subfamilies for HDV types, or they can trade or sell credits to other manufacturers that have a balance of deficits. New flexibilities in EU rules also allow some trading of vehicles within "economically connected" manufacturers to comply with targets, as well as trading of ZEVs among all manufacturers. This trading of emission credits and vehicles can be expected to incentivize industry-financed development of new, cleaner technologies.

In the EU and U.S. regulations, ZEVs lower the fleet-average emissions of vehicle manufacturers and help them earn credits. Regulators sometimes award extra credits to encourage research and development of ZEV technologies, especially in the early stages of a technology transition. In the U.S. Phase 2 standards for MYs 2018–2027, EPA awards advanced technology credit multipliers: credits generated by sales of plug-in hybrid vehicles are multiplied by 3.5, credits from the battery electric vehicle sales are multiplied by 4.5, and credits from sales of hydrogen fuel-cell electric vehicles are multiplied by 5.5. Under the Phase 3 regulation, ZEVs will no longer receive credit multipliers starting in MY 2028. The EU regulation also gave a multiplier of 2 to ZEVs between 2019 and 2024, which meant ZEVs were double counted in the manufacturer's average fleet-average emission calculations.[24]

The definition and accrual mechanism for credits and deficits are different in a ZEV sales requirement like ACT. These standards are independent of ICE vehicle performance, so manufacturers accumulate credits by selling ZEVs and NZEVs and deficits by selling ICE HDVs. Figure 2 illustrates the system. The value of ZEV and NZEV credits generated depends on the vehicle group and subgroup; credit values are equivalent to the respective weight class multiplier, which is proportional to the emissions footprint of the vehicle. Deficit calculations are also tied to the ZEV sales requirement and the weight class multiplier. Manufacturers need to generate enough credits to meet or exceed the number of deficits each year or else use banked credits from previous years. They are given 3 model years to make up any outstanding deficits, and these may only be satisfied with ZEV or NZEV credits. Deficits from Class 7–8 tractor trucks can only be offset with credits from that same vehicle group. Trading of surplus credits is allowed between manufacturers.

Figure 2
Credit values, deficit calculations, and regulatory compliance in Advanced Clean Trucks



Source: Buysse and Sharpe, *California's Advanced Clean Trucks Regulation*.

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24 Rodríguez, *CO_2 Standards for Heavy-Duty Vehicles*.

Additional credits were awarded for early compliance with the regulations. The U.S. EPA gave an early compliance credit value of 1.5 in the Phase 1 GHG standards for HDVs sold in MY 2013, 1 year before the Phase 1 standards came into effect.[25] In the European Union, manufacturers could accumulate early credits between 2019 and 2024, before the introduction of the first mandatory reduction target in 2025, and in California, manufacturers generated early credits by selling ZEVs and NZEVs from MY 2021 to MY 2023. Regulators put restrictions on these early credits. In the United States, the use of early compliance multiplier credits was restricted to within the same vehicle group during Phase 1 and phased out when Phase 2 standards came into effect. In the European Union, early credits accumulated between 2019 and 2024 can only be used for compliance in 2025 and are not valid thereafter. In California, early credits will expire after MY 2030, and surplus credits from can be banked for only 5 subsequent model years.

CREDIT AVERAGING, BANKING, AND TRADING

Both California's ACT and EPA's CO_2 emission standards allow credits to be pooled within a vehicle group for a single manufacturer (known as averaging), banked for future use when there is a surplus, and sold or traded with other manufacturers. Such programs have been a key flexibility provision in performance standards because they give manufacturers the freedom to choose compliance pathways that suit their strategies and strengths. Credits can also encourage manufacturers to over-comply because they can make money by selling excess credits. Regulators can limit credit transfers from vehicle categories where emission reduction technologies or ZEVs are easier to implement, such as lighter vehicles with less demanding duty cycles, to heavier vehicles. This ensures that manufacturers invest in technologies and products that deliver low- and zero-emission products across all weight classes and vehicle applications.

In California's ACT, deficits from Class 2b–3 and Class 4–8 vehicle groups can be met with credits from any vehicle group or subgroup, but deficits from Class 7–8 tractor trucks can only be offset with credits from the same vehicle group. This helps ensure that the most polluting Class 7–8 tractor trucks will also be electrified. In the U.S. federal standards, EPA allowed credit averaging and trading to occur only within averaging sets—subcategories based on vehicle weight class—during Phase 1 and Phase 2.[26] However, this restriction was removed in the Phase 3 standards. For MY 2027 to MY 2032 vehicles, emission credits can be averaged, traded, and banked across HDV averaging sets, with no limitations on the direction or volume of credits. Furthermore, EPA allows credit transfers from averaging sets of medium-duty vehicles certified to the light- and medium-duty vehicle standards to averaging sets of Class 2b–5 and Class 6–7 HDVs (i.e., light HDVs and medium HDVs). This flexibility could lead to an underinvestment and underproduction of low- and zero-emission HDVs in the larger weight classes, because manufacturers can produce lighter and smaller vehicles at a lower cost.

The EU regulation calculates fleet-average specific emissions by first adjusting the emissions for a vehicle segment by mileage and payload weighting factors and then weighting them by sales. HDV segments with greater payloads (measured in tons for freight vehicles, and number of passengers for passenger vehicles) and longer ranges count more toward a manufacturer's CO_2 emissions target. Given this, OEMs obtain greater CO_2 benefits from deploying ZEVs or fuel-saving technology in segments with a high mileage and payload weighting. This can encourage manufacturers to reduce emissions from the heaviest, most carbon-intensive segments. For credit and debt accounting, emissions from vehicle subgroups are aggregated into two averaging

25 Greenhouse Gas Emissions Standards and Fuel Efficiency Standards (2011).

26 The three averaging sets in EPA's GHG standards are light heavy-duty (Class 2b–5), medium heavy-duty (Class 6–7), and heavy heavy-duty (Class 8).

sets, one for freight vehicles (trucks and trailers) and one for passenger vehicles (buses and coaches). Credits and debts are not tradable between manufacturers; instead, manufacturers can trade vehicles from the 2025 reporting period onward. For conventional ICE vehicles, manufacturers from the same parent company can transfer an unlimited number of vehicles among themselves, but unrelated manufacturers cannot trade vehicles. For ZEVs, all OEMs have the flexibility to trade vehicles, limited to up to 5% of the receiver's sales volume in any given reporting period.

CREDIT MULTIPLIERS

Both the EU CO_2 and U.S. GHG emission standards have credit multipliers. As a ZEV sales requirement, ACT has no multipliers.

When the U.S. Phase 2 standards were finalized in 2016, virtually no zero-emission HDVs had been produced or sold. However, the market has changed pretty dramatically in the last 8 years: In 2023, 1,600 zero-emission Class 4–8 HDVs were registered in the United States.[27] Despite this growth, the multiplier credits—3.5 for plug-in hybrid electric, 4.5 for battery electric, and 5.5 for hydrogen fuel-cell electric vehicles—are allowed to continue in the Phase 3 standards through MY 2027 to further boost the market. Additionally, beginning in MY 2024, zero-emission HDVs sold in states that have adopted the ACT will also generate these advanced technology credits. This may create a large number of credits between MY 2024 and MY 2027, and these can be used up to MY 2030. To alleviate a potential excess of multiplier credits, EPA requires that base credits for coming in under emission targets be used first before manufacturers can apply multiplier credits.

The European Union has taken a more restrictive approach and provides fewer credits in a shorter window. Between 2019 and 2024, ZEVs have a super credit value of 2 and the super credits are allowed to reduce the average CO_2 emissions of a manufacturer by at most 3%. However, the EU regulation defines ZEVs as vehicles that emit less than 3 g CO_2/ton-km for trucks and 1 g CO_2/passenger-km for buses and coaches. This threshold means pure hydrogen and dual-fuel hydrogen combustion engines are classified as ZEVs. From 2025 onward, the super credit system no longer applies and is replaced by a benchmark system that applies after at least 2% of a manufacturer's sales are ZEVs or low-emission vehicles. The same emission reductions cap of 3% still applies, and the benchmark system will be phased out at the end of 2029.

TREATMENT OF PLUG-IN HYBRIDS AND OTHER ALTERNATIVE POWERTRAINS

The three regulations differ in their treatment of plug-in hybrids and hydrogen ICE vehicles, which produce some tailpipe emissions of CO_2. In the U.S. Phase 3 standards, plug-in hybrids must undergo testing to determine their GHG emissions; they are classified as an advanced technology and receive a credit multiplier of 3.5. Hydrogen ICE (H_2-ICE) is in the early development stage and there are currently no commercial applications; these vehicles can run on pure hydrogen or via dual-fuel, which uses diesel or natural gas in the combustion process. Though both types of H_2-ICE vehicles generate tailpipe emissions of air pollutants and GHGs, EPA deems H_2-ICE vehicles running on pure hydrogen to have zero tailpipe CO_2 emissions; there is, however, no advanced technology credit multiplier awarded to H_2-ICE vehicles.[28]

27 Yihao Xie, *Zero-Emission Bus and Truck Market in the United States: A 2022–2023 Update* (International Council on Clean Transportation, 2024), https://theicct.org/publication/zero-emission-bus-and-truck-market-in-the-us-2022-2023-update-june24/.

28 Zhun Hu and Ralph T. Yang, "Recent Progress and Future Challenges in Selective Catalytic Reduction of NO by H2 in the Presence of O2," *Industrial & Engineering Chemistry Research* 58, no. 24 (June 2019): 10140–53, https://doi.org/10.1021/acs.iecr.9b01843.

The ACT regulation refers to PHEVs as NZEVs.[29] While manufacturers can sell NZEVs to receive credits, they generate fewer credits than ZEVs and can only generate up to 75% of the ZEV credit value for each vehicle group or subgroup. NZEV credits also cannot be used to meet more than half of a manufacturer's annual deficits. The value of each NZEV credit is determined by multiplying the ZEV credit value by an NZEV factor value that is equal to the product of 0.01 and the vehicle's all-electric range, capped at 0.75. Beginning with MY 2030, NZEVs must have a minimum all-electric range of 75 miles to be eligible; this means the NZEV factor value will always equal 0.75.

The EU regulation follows a performance principle that rewards vehicles that emit less than half of the baseline CO_2 emissions for their vehicle subgroup, called low-emission vehicles (LEVs), through the zero- and low-emission vehicle (ZLEV) factor. In the super credit phase between 2019 and 2024, LEVs were counted as up to two vehicles in the averaging set depending on their emissions relative to the vehicle subgroup's baseline. In the benchmark phase from 2025 to 2030, each LEV is counted as between 0 and 1 vehicle. Trucks that emit less than 3 g CO_2/ton-km and buses and coaches that emit less than 1 g CO_2/passenger-km are defined as ZEVs in the EU regulation. The non-zero emissions threshold means pure hydrogen and dual-fuel hydrogen combustion engines are classified as zero-emission vehicles.

Finally, the U.S., EU, and California regulations do not consider ICE HDVs using electrofuels, or e-fuels for short, to have zero emissions. The European Commission has been directed to assess the role of a methodology for registering HDVs exclusively using CO_2-neutral fuels by 2025.[30]

MONITORING, REPORTING, AND NON-COMPLIANCE PENALTIES

Regular monitoring of compliance and public reports from regulators are important tools to assess the effectiveness of regulations and build manufacturer and consumer trust.

In California, CARB requires annual reporting from OEMs with yearly HDV production and sales exceeding 500 vehicles with a GVWR above 3,856 kg. These reports contain information about vehicle drivetrain, fuel type, classification, and model year of new HDVs sold.[31] From these reports, CARB publishes annual ACT credit summaries by model year, including vehicle sales and credits by manufacturer, total credits traded among manufacturers, and the total credit balance for all manufacturers.[32] In the original 2019 regulation, manufacturers were given one model year to make up any outstanding ACT deficits from the previous model year with ZEV credits. The 2024 amendments will lengthen the deficit makeup period to 3 model years. Failure to clear deficits results in a civil penalty of up to $37,500 per vehicle.[33] As of the end of MY 2023, all manufacturers in California have enough surplus credits to meet their estimated MY 2024 compliance obligations.

Compliance monitoring and reporting for the EU and U.S. emission standards are much more complex, as the regulated fleet includes ZEVs and ICE vehicles. To determine compliance, individual vehicle components must be tested in laboratory conditions and certified. Component data is then fed into physics-based computer models that

29 An NZEV is defined as "an on-road hybrid electric vehicle that utilizes an internal combustion or heat engine as well as an externally rechargeable energy storage system that affords the vehicle an all-electric range."

30 Regulation (EU) 2024/1610 of the European Parliament and of the Council.

31 California Air Resources Board, *Advanced Clean Trucks Reporting System (ACTRS) User Guide* (2023), https://ww2.arb.ca.gov/sites/default/files/2023-03/ACTRS-UserGuide.pdf.

32 California Air Resources Board, *Advanced Clean Trucks Credit Summary Through the 2023 Model Year* (2024), https://ww2.arb.ca.gov/resources/fact-sheets/ACT-Credits-Summary%202023.

33 Article 2 Manufacturers and Dealers, 43212 Health and Safety § (2018), https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=HSC&sectionNum=43212.

simulate the longitudinal dynamics of HDVs and calculate CO_2 emissions and fuel efficiency over standard duty cycles that simulate real-world driving conditions.

The European Environment Agency has published detailed official certification data of HDV performance and technology attributes starting from the 2019 reporting period, which spans July 2019 through June 2020. This data allows third parties—including industry analysts and public interest groups—to conduct in-depth studies of emissions performance and the adoption of technology.[34] The European Commission also publishes an annual "implementing decision" based on this monitoring and reporting data that shows official fleet-average specific CO_2 emissions, the CO_2 emissions reduction trajectory, and the number of emission credits per manufacturer for each reporting period.[35] The first implementing decision also included the reference or baseline emission levels by vehicle subgroup.[36]

Recall that the EU credit and debt system has two phases, one which ran from 2019 to 2024, and the second which will run from 2025 to 2029. Credits earned in the first phase can only be used to offset debts accrued in the 2025 reporting year. In the second phase, credits are valid for 7 years. Outstanding debts after all credits are used are known as excess emissions, and for these manufacturers must pay a penalty. After 2040, the credit and debt system will be phased out and noncompliance results in immediate penalties. Penalties for noncompliance are €4,250 per vehicle per g CO_2/ton-km exceeded.

The U.S. EPA does not publish the full certification data of all HDVs. Instead, it releases reports of credit balances by HDV subcategory for manufacturers that participate in its averaging, banking, and trading program.[37] As of October 2024, Phase 1 and Phase 2 compliance data was published for MY 2014–MY 2022.[38] Compared with what the European Environment Agency publishes, the data provided by EPA is at a much more aggregated level.

In the U.S. Phase 3 standards, deficits can be carried forward for a maximum of 3 model years. After 3 years, vehicles responsible for making CO_2 emissions exceed fleet-average limits will be deemed noncompliant. Manufacturers will be subject to civil penalties of up to $45,268 per noncompliant vehicle.[39]

34 Eamonn Mulholland, Pierre-Louis Ragon, and Felipe Rodríguez, *CO_2 Emissions from Trucks in the European Union: An Analysis of the 2020 Reporting Period* (International Council on Clean Transportation, 2023), https://theicct.org/publication/hdv-co2-emissions-eu-2020-reporting-jul23/; Pierre-Louis Ragon and Felipe Rodríguez, *CO_2 Emissions from Trucks in the EU: An Analysis of the Heavy-Duty CO_2 Standards Baseline Data* (International Council on Clean Transportation, 2021), https://theicct.org/publication/co2-emissions-from-trucks-in-the-eu-an-analysis-of-the-heavy-duty-co2-standards-baseline-data/.

35 Commission Implementing Decision (EU) 2024/2165 of 1 July 2024 on the Publication of a List Indicating Certain CO_2 Emissions Values per Manufacturer as Well as Average Specific CO_2 Emissions of All New Heavy-Duty Vehicles Registered in the Union Pursuant to Regulation (EU) 2019/1242 of the European Parliament and of the Council for the Reporting Period of the Year 2021 (Notified under Document C(2024) 4474)," (August 21, 2024), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202402165.

36 Ragon and Rodríguez, *CO_2 Emissions from Trucks in the EU*.

37 U.S. Environmental Protection Agency, *Final Phase 1 EPA Heavy-Duty Vehicle and Engine Greenhouse Gas Emissions Compliance Report (Model Years 2014-20)* (2022), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016IH4.pdf.

38 U.S. Environmental Protection Agency, *EPA Heavy-Duty Vehicle and Engine Greenhouse Gas Emissions Compliance Report* (2024), https://www.epa.gov/compliance-and-fuel-economy-data/epa-heavy-duty-vehicle-and-engine-greenhouse-gas-emissions.

39 US Environmental Protection Agency, *Clean Air Act Vehicle and Engine Enforcement Case Resolutions* (2024), https://www.epa.gov/enforcement/clean-air-act-vehicle-and-engine-enforcement-case-resolutions; How to comply with the fleet average CO_2 standards, 40 CFR 86.1865-12 Code of Federal Regulations § (2024), https://www.ecfr.gov/current/title-40/part-86/section-86.1865-12.

COMPARING THE SSRS

The two types of regulation are compared in Table 2. Ultimately, the choice between a performance standard and a ZEV sales requirement will be based on the market's political, legal, and regulatory structures and circumstances.

Table 2
Comparison of performance standards and ZEV sales requirements

	Performance standards	ZEV sales requirements
Metric	Multiple metrics: real-world application seen in CO_2 emission standards, and potential for both pollutant emission standards and fuel economy standards	One metric: ZEV sales as a percentage of total vehicle production/imports
Regulator resource needs	Require hardware for component testing and data collection, along with vehicle simulation software for both ZEVs and ICE vehicles; involves significant administrative and technical resources	Requires ZEV certification only, making administration less resource intensive
Certainty of ZEV deployment	ZEVs are usually not explicitly required; zero-emission products may or may not be necessary for compliance depending on stringency level	Zero-emission product production and sales guaranteed via ZEV adoption rate timeline
ICE vehicle efficiency improvements	Likely to be part of manufacturers' compliance strategy	Not part of compliance

There are ways to combine elements of a performance standard and a ZEV sales requirement into a single regulation. An earlier ICCT paper explored the idea of a "dual averaging sets" design.[40] Under this scheme, HDV production is split into two groups. Vehicle manufacturers would need to meet a ZEV sales requirement for the first group. Remaining vehicles not covered by the ZEV sales requirement would be in the second group and regulated by standards requiring reductions in the GHG emissions of ICE vehicles. The EU CO_2 emission standards are an example of this design as there is a ZEV sales requirement for city buses and emissions reduction goals for other types of buses, trucks, and trailers. This guarantees a certain level of ZEV uptake for some vehicle types while pushing down fleet-wide CO_2 and air pollutant emissions for ICE vehicles.

BEST PRACTICES

Drawing from these three real-world examples, here we explore some best practices for designing an SSR to promote the development of zero-emission HDVs. First, aligning SSRs with larger climate, clean air, or energy goals can give OEMs and other stakeholders confidence in the continuity of public policy. The EU CO_2 regulation and California's ACT are backed by laws mandating economy-wide, long-term emission reduction goals.

Interim targets that gradually progress from a baseline facilitate experience with new technologies and ramp up of economies of scale. This approach can help ensure that HDVs are on track to meet the longer-term standards. Annual targets in the United States and California allow for smoother tracking of emission reductions than 5-year increments such as in the European CO_2 regulation.

Regulators can adopt **targets for broad HDV segments** and do not need to spell out emission reduction or ZEV adoption targets for each type of HDV. This allows the

40 Ray Minjares and John Hannon, *Adapting U.S. Heavy-Duty Vehicle Emission Standards to Support a Zero-Emission Commercial Truck and Bus Fleet* (International Council on Clean Transportation, 2022), https://theicct.org/publication/us-hvs-standards-ze-fleet-feb22/.

market and manufacturers to decide how different vehicle segments can contribute to meeting the targets. While all three SSRs analyzed in this brief have differentiated targets depending on HDV segment, the European Union and California adopted targets for broader segments, unlike the U.S. EPA, which has the most granular subgroup targets.

For performance standards, **a common baseline representing available technologies need not be set *a priori***. Instead, regulators can finalize performance standards that require a relative emissions reduction and simultaneously collect emissions data to determine this baseline. The European Union collected data to create data-driven, reliable baselines after setting ambitious reduction targets for HDVs.

Compliance measured at an aggregated fleet level instead of individual vehicle level reduces the administrative burden on manufacturers and regulators. **Fleet-average metrics** also reduce the cost of compliance and incentivize industry innovation and investments in ZEVs. The performance standards in the United States and the European Union apply at the fleet level and make a credit-deficit system possible.

Allowing the **banking of credits** encourages manufacturers to achieve compliance ahead of the regulatory schedule, and **time limits on the use of banked credits** help ensure that manufacturers are motivated to constantly improve performance. All three regulations analyzed have time limits on banked credits. Both California and the European Union allow early credit generation, but these early credits are worth the same as regular credits and thus do not have an outsized impact on the size of the pool of credits available for OEMs to purchase.

The ability to **trade and transfer credits** can help achieve the overall objective of increased ZEV sales or emission reductions without directly dictating product lines, and **weighting factors** are used in all three SSRs to help ensure that smaller HDVs are not disproportionately used to generate credits. In the European Union, the mileage and payload weight factor means that some vehicle groups count more toward a manufacturer's CO_2 emissions target. A similar adjustment using payload and useful life, measured in miles, is part of how EPA calculates credits. In California, the weight class multiplier is proportional to the emission footprints of ICE vehicles. California keeps Class 7–8 tractors separate from the rest of the credit pool to encourage zero-emission products for that segment.

Credit multipliers can be an effective way to incentivize investments in early-stage technologies through performance standards, but many multipliers given over a prolonged time period can diminish the effectiveness of regulations. In the United States, EPA Phase 3 standards retain generous multiplier credits until 2027, 11 years after they were first introduced in Phase 2 standards. The European Union, meanwhile, will phase out super credits in 2025 and caps the contribution of super credits to 3% of a manufacturer's average emissions.

All three SSRs have enforcement measures built on the capacity of government agencies to collect data and monitor progress. Furthermore, **public disclosure of compliance data** helps build confidence and trust in regulations, especially during technology transitions. The European Union is a leader in this regard and publishes detailed vehicle certification data that enables independent verification of compliance. The summary reports published by EPA and CARB leave out technical details.

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