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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	**R.2024-017**
PROPOSED CLEAN CAR AND	)	
TRUCK STANDARDS	)	**(Rulemaking – Air)**

COMMENTS AND QUESTIONS OF THE TRUCK AND ENGINE MANUFACTURERS ASSOCIATION REGARDING RULE PROPONENTS' PRE-FILED TESTIMONY

October 24, 2024

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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	**R.2024-017**
PROPOSED CLEAN CAR AND	)	
TRUCK STANDARDS	)	**(Rulemaking – Air)**

Introduction

The Truck and Engine Manufacturers Association (EMA) hereby submits its comments and questions regarding the pre-filed testimony that the rule proponents (hereinafter, Petitioners) submitted on September 16, 2024, in support of their request that the Illinois Pollution Control Board (IPCB) adopt California's most recent regulations limiting the emissions from medium-duty and heavy-duty (MHD) trucks. The specific California regulations at issue include the "Omnibus Low-NO_x" (Omnibus) rule, and the Advanced Clean Trucks (ACT) rule.[1]

EMA is the not-for-profit trade association that represents the interests of the world's leading manufacturers of MHD vehicles, the types of vehicles regulated under California's Omnibus and ACT regulations. EMA was actively engaged in the rulemaking procedures and hearings before the California Air Resources Board (CARB) that led to the adoption of the Omnibus and ACT rules. Accordingly, EMA has a direct and significant interest in this matter.

In July of 2023, EMA and its MHD OEM members entered into the Clean Trucks Partnership agreement with CARB to collaborate more fully toward cleaner air and the increasing transition of the transportation sector, including MHD trucks, to zero-emission vehicles (ZEVs). As it relates to this matter, EMA and its members have agreed (in Appendix D to the Agreement) not to oppose states' adoption of the Omnibus regulations for implementation in the 2027 model year and later, and have similarly agreed to be neutral with respect to any state's proposals to adopt CARB's ACT regulations, "provided, however, EMA and the OEMs may provide written and verbal comments expressing concerns or issues of implementation, including infrastructure concerns and lack of complimentary policies." EMA and CARB have also agreed "to work together to resolve any issues that may warrant regulatory amendments to either the Omnibus or ACT regulations, and to actively promote further needed infrastructure development." EMA is submitting these comments consistent with the relevant terms of the Clean Trucks Partnership agreement.

As discussed in more detail below, EMA has a number of concerns related to the proposed adoption of the Omnibus and ACT rules in Illinois. EMA's main concerns are as follows:

[1] Petitioners have also requested that the IPCB adopt California's Advanced Clean Cars II (ACC II) rule, a rule setting increasing zero-emission sales mandates for passenger cars. Since EMA represents the interests of the MHD vehicle industry, EMA is not commenting on the merits of that request.

i. Pursuant to the Clean Trucks Partnership Agreement noted above (copy attached), CARB's Omnibus Low-NO_x emission standards for MHD trucks will become fully aligned with EPA's low-NO_x standards for MHD trucks (which will be implemented under EPA's recently adopted Clean Trucks Program, see 88 Fed. Reg. 4296 (Jan. 24, 2023) starting in the 2027 model year. That alignment will take place two years in advance of the assumed effective date of Petitioners' proposed opt-in to the Omnibus rule. The IPCB should consider the efficacy of the proposed Omnibus opt-in in light of that timing issue.

ii. EPA also has recently adopted "Phase 3" regulations to further limit the greenhouse gas (GHG) emissions from MHD trucks. (See 89 Fed. Reg. 29440, April 22, 2024.) Those Phase 3 regulations establish implied mandates that will require MHD vehicle manufacturers to sell increasing percentages of MHD ZEVs starting in model year 2027, again, two years before the proposed implementation in Illinois of CARB's ACT ZEV-sales requirements. The IPCB should take that into account in evaluating the feasibility and cost-effectiveness of the proposed adoption of the ACT program in Illinois, especially since separate state opt-ins will require separate tracking of ACT credits and deficits, which in turn will increase the complexities and costs of meeting the mandated ZEV-truck deployment targets.

iii. CARB is currently in the process of amending both the Omnibus and ACT rules, in part because those rules have led to unintended shortages of new MHD trucks for sale in California. The IPCB will need to conform its opt-in regulations with those amendments, which may require additional opt-in rulemakings in the future. The IPCB should consider deferring any opt-ins until CARB completes all of its revisions and amendments to the underlying Omnibus and ACT regulations.

iv. To assist the IPCB in considering this matter, the Petitioners should quantify the *relative incremental* emissions-reduction and public health benefits that the proposed adoption of the ACT and Omnibus rules (starting in 2029) will have when compared against the implementation of EPA's low-NO_x and Phase 3 rules in Illinois (starting two years earlier in 2027).

v. The Petitioners also should quantify the extent and cost of the ZEV-truck recharging and hydrogen-refueling infrastructures that will need to be developed and installed in Illinois to support any implementation of the ACT regulations. In that regard, it should be noted that that the pending amendments to the ACT regulations will require that all MHD trucks sales –100% of sales – must be ZEVs starting in 2036. (See CARB Public Hearing Notice for October 24, 2024; Proposed Cal. Regulatory section 1936.6.) Similarly, Petitioners should quantify the financial incentives that Illinois will need to provide to new truck buyers to spur the purchase of MHD ZEVs in the state to the extent required under the ACT regulations. In that regard, the potential $40,000 tax credit that is available to ZEV-truck buyers under the federal Inflation Reduction Act (IRA) is not sufficient on its own to cover the difference in price between a ZEV-truck and a conventionally-fueled truck. Indeed, the 15% Federal Excise Tax (FET) on the purchase of new trucks, including more costly ZEV trucks, by itself will more than offset the IRA tax credit.

vi. The IPCB will need to assess whether the adoption of CARB's Omnibus and ACT programs could lead to shortages in the availability of new MHD trucks for sale in Illinois. Such shortages are occurring in California as an unintended consequence of the ACT and Omnibus rules, and are starting to have similar impacts in the other states (including Oregon and Massachusetts) that have opted-in to CARB's rules. CARB is pursuing regulatory amendments and issuing "enforcement discretion" notices to try to mitigate those product shortages, but it is uncertain whether the current market disruptions will be fully remedied.

Set forth below is additional detail (and supporting exhibits) regarding each of the foregoing concerns. Again, while EMA is neutral regarding the outcome of the Petitioners' rulemaking requests, the IPCB should address all of the highlighted concerns in making its informed decision.

Multiple Issues Need to be Addressed in Acting on the Petitioners' Request for the Adoption of California's Regulations

1. The Omnibus Regulations Will Soon Become Aligned With EPA's Low-NO_x Regulations in 2027

As described above, in July of 2023, EMA and its MHD manufacturer members entered into the Clean Trucks Partnership Agreement (copy attached) with CARB to establish a more collaborative strategy toward cleaner air and an increasing conversion of the trucking industry to ZEV trucks. One of the core elements of that collaboration is that CARB has agreed "to amend the Omnibus Regulation's 2027 and later model year requirements to align with the United States Environmental Protection Agency's (EPA) Clean Trucks Plan (CTP) Oxides of Nitrogen (NO_x) Final Rule," which became final on January 24, 2023. (See 88 Fed. Reg. 4296.) CARB has announced its intent to adopt those agreed-upon aligning amendments no later than the third quarter of 2025. Thus, it is now clear that the Omnibus low-NO_x standards will be the same as EPA's nationwide low-NO_x standards, including in Illinois, starting in 2027. The net result is that EPA's nationwide regulations, with which CARB will be aligning, will take effect in Illinois two years before the proposed implementation of the Omnibus regulations.

Under section 177 of the federal Clean Air Act, a state must provide two full model years of lead-time between the date of the state's adoption of a California mobile source regulation and the date of any attempted enforcement of that regulation. (See 42 U.S.C. §7507.) The Petitioners have recognized the practical impact of that two year lead-time requirement, and have noted in their filing that the timeline of these rulemaking proceedings, which likely will extend into 2025, "may result in the Proposed Rules taking effect in model year (MY) 2029, rather than MY 2028." That timing stems in part from the fact that mobile source model years can begin as early as January 2nd of the preceding year, which means that if the pending rulemaking extends beyond January 2, 2025, the rulemaking could be deemed to have extended into the 2026 model-year. Adding the two-year lead-time requirement to the 2026 model year Omnibus-adoption date will result in a 2029 model year Omnibus-effective date in Illinois. Consequently, the IPCB would be adopting a California rule that will be identical to a federal rule that will already have been in effect in Illinois for two full model years. The IPCB should carefully assess the relative efficacy of such a rulemaking.

2. EPA's Phase 3 GHG Regulations Will Take Effect in Illinois Two Years Before the ACT Regulations Would Take Effect

A similar situation applies to the proposed adoption of CARB's ACT regulations. For the same reasons noted above, the ACT regulations would not take effect in Illinois until the 2029 model year. That will be two full model years after EPA's nationwide Phase 3 GHG regulations take effect in Illinois. The stringent MHD GHG standards established under the Phase 3 regulations amount to the establishment of implied mandates for OEMs to sell increasing percentages of ZEV trucks nationwide, including in Illinois. (See 89 Fed. Reg. at 29452, 29567, Tables ES-3 and II-29, April 22, 2024.) Once again, therefore, the IPCB would be adopting California ZEV-truck regulations that would not take effect until two full years after the implementation of federal regulations similarly aimed at increasing the sales of ZEV trucks, which raises similar efficacy issues as those pertaining to the implementation of the Omnibus regulations in Illinois.

3. CARB's Regulations Are Still Subject to Significant Amendment

CARB's Omnibus and ACT regulations have proved to be difficult to implement and have caused unintended disruptions to the new MHD truck market in California. As a result, CARB has taken and continues to take multiple steps to try to remedy the unintended market impacts and new truck shortages that have arisen in California. More specifically, CARB has taken or will be taking the following measures: (i) CARB previously amended the Omnibus regulations to allow for the sale of increased percentages (45% to 60%) of "legacy" engines certified to 2023 MY emission standards, provided that OEMs offset with ZEV credits the "excess" NO_x emissions from those legacy engines; (ii) CARB has issued Manufacturer Advisory Correspondence (MACs) and "enforcement discretion" letters to shield MHD truck manufacturers, dealers and fleet operators from potential liability to the extent that new MHD vehicles, including vehicles with legacy engines, originally intended for sale and use outside of California nonetheless end up in the state; (iii) because the California market continues to experience product shortages, CARB is amending the ACT regulations to align the accounting benchmarks for purchases and sales of new trucks, and to extend the makeup period for the allowed 30% carryover of ZEV-truck deficits from one year to three; and (iv) at the same time, CARB is proposing to amend the ACT regulations to require that starting in 2036, 100% of new truck sales must be ZEVs. (See Proposed ACT Section 1936.6.) In addition, as discussed above, CARB will be amending the Omnibus regulations next year so that they align with EPA's CTP regulations starting in 2027.

As the foregoing makes clear, the Omnibus and ACT regulations remain in flux as CARB works to address the concerns related to the MHD truck market in California. That is significant because, under section 177 of the CAA, any state that opts-in to the Omnibus and ACT regulations must ensure that the regulations they adopt remain "identical" to CARB's regulations and corollary enforcement policies – which will now include the 100% ZEV-truck sales mandate as of 2026. As a result, Illinois would have to take additional rulemaking steps in the near future to ensure that the proposed opt-ins conform in full to any regulatory amendments and corollary enforcement policies that CARB has adopted and may yet adopt in order to maintain the requisite identicality under CAA section 177.

Given the in-flux nature of CARB's Omnibus and ACT regulations, the IPCB should consider the proper timing of any potential adoption of those regulations, especially when corollary federal low-NO_x and ZEV-truck programs will be implemented in Illinois two years before any amended CARB regulations could take effect in the state. In that regard, it may make more sense to defer any opt-ins until CARB has completed all of the necessary amendments to the Omnibus and ACT regulations, especially since it is only CARB, not the IPCB, that is in a position to make those necessary amendments. Thus, it may be more prudent for Illinois to wait to assess what the fully amended CARB programs will be and how they will compare to the corollary federal programs before taking any final action with respect to this matter.

4. The Petitioners Should Quantify the Incremental Emission and Public Health Benefits from the Proposed Opt-Ins

The original petition and pre-filed testimony contain a number of statements about the emissions reductions and public health benefits that could result from the implementation of the Omnibus and ACT regulations in Illinois. However, those statements, and the underlying analysis, do not take into account the fact that federal EPA low-NO_x and ZEV-truck regulations will take effect in Illinois in 2027, resulting in the accrual of emissions reductions and public health benefits in Illinois two years before the proposed opt-ins would take effect. Thus, the Petitioners have not yet quantified the **marginal incremental** benefits that could result from implementing CARB's regulations two years *after* the corollary federal nationwide regulations take effect, especially when the Omnibus regulations will be identical to EPA's CTP low-NO_x regulations starting in 2027. The IPCB should ensure that the Petitioners provide that relevant information.

5. The Petitioners Should Quantify the ZEV Infrastructure Needs and Related Costs Under the Proposed Opt-Ins

The proposed opt-in to CARB's ZEV-truck sales mandates will create a need for the development in Illinois of an extensive infrastructure for the recharging of the mandated numbers of battery-electric ZEV-trucks and the refueling of the envisioned number of hydrogen fuel-cell ZEV trucks. The Petitioners should help the IPCB to quantify the magnitude of that challenge.

Recently, independent experts at Ricardo prepared an analysis of what will be required to implement the final federal Phase 3 mandates across the country and in Illinois. That analysis (a copy of which is attached) is instructive, particularly since the ZEV-infrastructure needs and costs associated with CARB's ACT regulations will be greater than under the Phase 3 program.

Ricardo's report includes a number of key findings directly applicable to Illinois. More specifically, Ricardo's analysis shows that Illinois will need to install 4% of the nation's MHD ZEV-truck chargers by 2032, including: 2,073 350 kW DC fast-chargers (DCFCs); 612 150 kW DCFCs; 5,291 50 kW DCFCs; and 46,341 Level-2 chargers. The cost of that requisite truck-recharging infrastructure will exceed $1 billion (not including the very significant utility interconnection costs). Illinois also will need to construct and make operational 45 MHD hydrogen-refueling stations at an additional cost of $270 million. The year-over-year ZEV-truck infrastructure requirements in Illinois from 2025 through 2032 are detailed in Tables 31 and 37 of the Ricardo report. (See Ricardo Report, pp. 26, 29, 47, 53, 76 and 85.) By comparison, under the National Electric Vehicle Infrastructure (NEVI) program, Illinois has announced funding grants totaling $25.3 million to build 182 new charging port over the next several years, primarily for light-duty passenger cars. (See Illinois Department of Transportation, Drive Electric Illinois, https://idot.illinois.gov/transportation-system/environment/drive-electric.)

Importantly, Ricardo's analysis relates to the infrastructure requirements under the nationwide Phase 3 GHG program, not under CARB's more aggressive ACT targets for ZEV-trucks. More specifically, the federal Phase 3 targets for ZEV-trucks in 2029 range from 10% to 19% (with some temporarily exempt categories), and increase to ZEV-truck targets ranging from 16% to 60% in 2032. (See Phase 3 Final Rule, 89 Fed. Reg. at 29567 (Table II-29).) By comparison, under CARB's ACT program, the ZEV-truck targets in 2029 range from 25% to 40%, and increase to 100% in 2036. Thus, the infrastructure needs and costs in Illinois under the ACT program could be nearly double the requirements under EPA's Phase 3 program. It is vitally important for the IPCB to develop an accurate assessment of the relevant infrastructure costs before acting on the Petitioners' rulemaking requests.

Similarly, the Petitioners should address the types of incentive programs that will be necessary to allow for the mandated deployment of ZEV-trucks and the corollary deployment of the ZEV-truck infrastructure under the ACT regulations. As it stands, Illinois' anticipated implementation of the NEVI program (discussed above), along with the availability under the federal Inflation Reduction Act of a $40,000 tax credit for the purchase of ZEV-trucks, constitute the mainstays of the ZEV incentive programs currently available in Illinois. That will not be sufficient to offset the increased initial purchase costs of ZEV trucks, which currently cost at least two-times more than conventionally-fueled trucks, or to cover the more than $1.2 billion that will be needed to build-out the requisite ZEV-truck recharging and hydrogen-refueling infrastructures.

The Petitioners' pre-filed testimony provides (in footnote 11) a listing of potentially available incentive funds, including the funds available under the NEVI program, for ZEV infrastructure in Illinois. However, the majority of those potential funds likely will be directed toward the light-duty passenger car sector. Moreover, the proposed testimony also notes that "Illinois has announced the opening of the first four EV charging sites" under the "Driving a Cleaner Illinois" program, and that a portion of approximately $115 million in additional federal funding could go to "address heavy-duty charging infrastructure." (Proposed Urbaszewski Testimony, pp. 6-7.) The IPCB will need to consider whether that level of infrastructure build-out and funding is sufficient or whether additional funds (and in what amount) will be necessary to support the adoption of the ZEV-truck mandates under California's ACT regulations.

On this point, it is instructive to note the multiple types of ZEV-truck incentive programs being offered in California. In that state, tens of billions of incentive dollars are being allocated to spur the deployment of ZEV trucks and to build-out the necessary recharging and hydrogen-refueling infrastructures. For example, California's Business and Development Office has created a website dedicated to highlighting the available ZEV funding resources available in the state. (See https://business.ca.gov/industries/zero-emissins-vehicles/zev-funding-resources.) Similarly, CALSTART, an association of businesses and agencies focused on the clean-transportation industry, has developed a web-based "MHD ZEV Toolbox" that details all of the multiple incentive programs in California for the purchase and deployment of MHD ZEV trucks, including through a comprehensive "Funding Finder" program. (See https://zevtoolbox.org.) In addition, Southern California Edison has developed its own "EV Funding Tool" that combines all of the available funding programs for ZEV-truck purchases and infrastructure developers. (See https://evfundingtool.sce.com). Illinois is likely not in a position to match the myriad incentive programs available in California.

6. Petitioners Should Evaluate the Potential Market Impacts From the Proposed Adoption of the Omnibus and ACT Rules

CARB's Omnibus and ACT rules have led to unintended disruptions in the MHD truck markets in California and in the early opt-in states. There are several reasons for this. MHD truck OEMs have only been able to certify a limited number of engine families to the current Omnibus low-NO_x standards and requirements. It is for that reason, among others, that CARB has agreed to align its Omnibus program with EPA's CTP low-NO_x regulations starting in the 2027 model year.

Moreover, since the ACT regulations currently require OEMs to ensure that 7% to 11% of their truck sales are ZEVs, OEMs may need to reduce their sales of conventionally-fueled trucks to make the ZEV-truck sales mandates more achievable. That is still difficult given the current state of the infrastructure for MHD ZEVs and given the higher purchase price for ZEV trucks. Faced with those realities, some OEMs are requiring that their new truck dealers agree to take specified numbers of ZEV trucks into their inventories in order to receive an allotment of conventionally-fueled trucks. That too is putting constraints on the distribution and sale of new trucks in California and the early opt-in states, specifically Oregon and Massachusetts.

These concerns are not just anecdotal. For example, new truck registration data that Polk and S&P Global Mobility have tracked in California show that new truck registrations are down by approximately 50% for the period from January 2024 through June 2024 compared to the prior year period. In addition, ZEV-truck sales are down by approximately 12% as well.

Petitioners should assess the potential future market impacts of the proposed opt-ins in their presentations to the IPCB.

<u>Specific Questions Related to Petitioners' Pre-Filed Testimony</u>

The IPCB's Notice of Hearing, issued on August 21, 2024, established an October 28th deadline for the pre-filing of questions based on the Petitioners' pre-filed testimony. Consistent with the issues and concerns discussed above, EMA recommends that the IPCB seek answers to the following questions, among others, related to the Petitioners' testimony and arguments regarding the proposed adoption of CARB's Omnibus and ACT regulations in Illinois:

1. Since CARB has committed under the Clean Trucks Partnership agreement to align its Omnibus low-NO_x standards with EPA's low-NO_x standards starting in the 2027 model year, what quantifiable incremental emissions and public health benefits will accrue in Illinois from implementing the identical Omnibus standards two years later in 2029?

2. Similar to Question #1, what is the quantifiable amount of marginal incremental emission reductions and health benefits that will accrue in Illinois if the ACT regulations are implemented in 2029, two years after the implementation of EPA's Phase 3 program in Illinois?

3. What will be the total costs in Illinois for the ZEV-truck recharging and hydrogen-refueling infrastructure required to implement the ACT regulations in Illinois? How do those total ZEV-truck infrastructure costs compare to the anticipated required infrastructure costs under EPA's Phase 3 regulations as implemented in Illinois?

4. What is the timeline and pace of deployment for installing the ZEV-truck infrastructure in Illinois that would be required to implement the ACT regulations? How does that compare with the current pace of deployment of a MHD ZEV infrastructure in Illinois?

5. What incentive funds are currently earmarked in Illinois for the purchase of MHD ZEV-trucks, and the development of the necessary ZEV-truck infrastructure, as would be necessitated under the ACT regulations? How does the total of the available incentive funding compare to the total anticipated costs of the ACT program?

6. How do the purchase costs of MHD ZEV-trucks compare to the purchase costs of their conventionally-fueled counterparts, and how will those price differentials impact sales? What impacts will the FET have on the sales of higher-priced ZEV-truck products?

7. How many MHD ZEV-trucks have been sold and registered in Illinois to date? How many MHD ZEV-truck recharging stations and ports are installed and operational in Illinois? How many ZEV-truck hydrogen-refueling stations are installed and operational in Illinois?

8. What impacts have the Omnibus and ACT regulations had on the MHD ZEV-truck markets, including with respect to the sales of new MHD ZEV-trucks, in California and the early opt-in states, which include Oregon and Massachusetts?

9. What studies have been completed and published that detail how the implementation of the ACT regulations in Illinois – including the 100% ZEV-truck sales mandate as of 2036 – will work?

10. Is the adoption of California's ACT mandates for the increasing sales of ZEV trucks – mandates that will reach 100% by 2036 – the type of "major question" that should be specifically addressed by the Illinois Legislature as opposed to the IPCB in response to a petition for rulemaking?

Conclusion

EMA appreciates the opportunity to submit these comments, and we look forward to participating at the initial hearing on this matter on December 2-3, 2024. As noted at the outset, EMA is neutral with respect to the disposition of the proposed rulemakings, and is submitting these comments solely for background and information consistent with the Clean Trucks Partnership agreement.

Respectfully submitted,

TRUCK & ENGINE
MANUFACTURERS ASSOCIATION

Agreement

The California Air Resources Board ("CARB"), the Truck and Engine Manufacturers Association ("EMA"), and the undersigned heavy-duty on-highway (HDOH) manufacturer members of EMA (the "OEMs") (collectively, the "Parties") recognizing the importance of: (i) preserving and protecting the environment; (ii) ensuring current and future CARB regulations affecting new HDOH vehicles and engines will achieve significant reductions of air pollutants from such vehicles and engines; (iii) promoting the transition of the HDOH commercial vehicle industry to zero -emissions; (iv) maintaining a strong and viable industry; and (v) providing certainty and stability for the HDOH industry and its customers, do hereby agree as follows:

1. CARB staff commits to initiate the actions set forth in Appendices A, B, and C and, where required for implementation, will recommend such actions to the CARB Board for its approval. The intent of the actions set forth in Appendix A is to revise the existing compliance flexibility provisions of CARB's Omnibus Regulation[1] by raising the existing caps on legacy engines and streamlining certain other provisions without increasing emissions compared to the preexisting Omnibus Regulation. The intent of the actions set forth in Appendix B is (i) to clarify which authorities and regulations remain status quo in California, (ii) to specify which regulations are covered by the OEMs' commitment in point 2 below, and (iii) to amend the Omnibus Regulation's 2027 and later model year requirements to align with the United States Environmental Protection Agency's (U.S. EPA) Clean Trucks Plan (CTP) Oxides of Nitrogen (NOx) Final Rule,[2] except for certain specified exceptions, subject to separate CARB provisions and control. Appendix C also describes actions related to CARB's Emission Warranty and Information Reporting (EWIR) program, CARB's Advanced Clean Trucks (ACT) regulation,[3] and certain other matters. In addition, Appendix C contains CARB's commitment on implementation flexibility for automatic recalls during the 2024 to 2034 model year timeframe for the EWIR and In Use Compliance Regulations, as well as ongoing efforts on ACT and Advanced Clean Fleet (ACF) Regulations.

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[1] The Omnibus regulation is comprised of new California Code of Regulations (Cal. Code Regs.), title 13, sections 2139.5, and 2169.1 through 2169.8; amendments to, Cal. Code Regs., title 13, sections 1900, 1956.8, 1961.2, 1965, 1968.2, 1971.1, 1971.5, 2035, 2036, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2121, 2123, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2133, 2137, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2166, 2166.1, 2167, 2168, 2169, 2170, 2423, and 2485; and amendments to Cal. Code Regs., title 17, sections 95662 and 95663.

[2] U.S. EPA. Final Rule. Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards. Federal Register, Vol. 88, No. 15, January 24, 2023

[3] The ACT regulation is set forth in Cal. Code Regs., title 13, sections 1963, and 1963.1 through 1963.5. The ACT regulation also includes a one-time fleet reporting requirement for owners and brokers of vehicles exceeding 8500 lbs GVWR in Cal. Code Regs., title 13, sections 2012, 2012.1, and 2012.2.

2. The OEMs commit to meet, in California, the relevant provisions of the CARB regulations set forth in Appendices A and B, and any agreed upon modifications to such regulations as set forth in this Agreement, irrespective of the outcome of any litigation challenging the waivers or authorizations for those regulations or of CARB's overall authority to implement those regulations.

3. The Parties acknowledge and recognize that some states have adopted certain of the CARB regulations set forth in Appendix B pursuant to Section 177 of the federal Clean Air Act ("177 States") and that those or other states may act to adopt other CARB regulations set forth in Appendices A and B. The Parties have agreed as set forth in Appendix D to certain actions they mutually or separately will take with respect to current or future 177 States. The intent of the provisions set forth in Appendix D is that the Parties will work together cooperatively to resolve issues that may warrant regulatory amendments to CARB's regulations, and that they will actively promote the infrastructure development needed to support the successful implementation of CARB's ACT regulation. The principles set forth in Appendix D are further intended to memorialize the positions that EMA and the OEMs commit to take with respect to their advocacy in current or future 177 States.

4. EMA and the OEMs will not (i) challenge CARB's issuance of the regulations set forth in Appendix B; (ii) file a Petition for Review or otherwise challenge any U.S. EPA waiver or authorization granted for such regulations; (iii) file amicus briefs supporting challenges to such waivers or authorizations, or such regulations; or (iv) support stay motions or similar motions practice challenging such waiver or authorization decisions, or such regulations.

5. In recognition of the OEMs desire for regulatory leadtime and stability, CARB's Executive Officer will direct the CARB staff to propose, and recommend that the CARB Board adopt, minimum four (4) year leadtime and three (3) year stability periods for future criteria emissions regulations affecting new HDOH engines and vehicles. The Executive Officer's direction above also will apply to CARB's planned ACT 2 rulemaking. However, that direction will not apply to the implementation of the regulatory changes included in Appendices A and B.

6. The Parties acknowledge that it is important to implement the actions contemplated by this Agreement as soon as reasonably possible. CARB's Executive Officer will release a Notice of Public Comment Period to Consider Proposed Amendments to the Heavy-Duty Engine and Vehicle Omnibus Regulation to amend the existing compliance flexibility provisions of the Omnibus regulation to raise legacy caps and streamline other provisions in Omnibus as described in Appendix A as soon as possible and no later than August 29, 2023. In addition, no later than sixty (60) days after signing this Agreement, CARB's Executive Officer will advise the CARB Board of his direction to the staff regarding leadtime and stability as set forth in Section 5 above and, no later than ninety (90) days after signing this Agreement, will inform the CARB Board of the balance of the provisions set forth in this Agreement. The Parties acknowledge that all applicable provisions of California's Administrative Procedures Act must be followed in implementing the terms of this Agreement. CARB staff will use its best efforts to commence the contemplated 2027 and later model year amendments to CARB's Omnibus regulations, as described in Section

1(iii) above, as soon as possible, with a workshop to be held no later than the first quarter of 2024 and a formal rulemaking notice released no later than the third quarter of 2025.

7. CARB will send a follow-up letter to the Petition for Reconsideration it filed with U.S. EPA regarding U.S. EPA's 2027 Low NOx rule informing U.S. EPA that CARB plans to harmonize with the U.S. EPA 2027 CTP NOx rule with the exceptions noted in Appendix B. CARB will not seek additional changes to U.S. EPA's 2027 Low NOx rule, provided the U.S. EPA does not make changes to its rule inconsistent with this Agreement.

8. The Parties acknowledge the efforts that have resulted in this Agreement and their respective commitments to follow through in implementing the Agreement.

Signature pages to follow

California Air Resources Board

By: Steven S. Cliff, Ph.D.

Title: Executive Officer

Date: July 5, 2023

Signature: ______________________

Truck and Engine Manufacturers Association

By: Jed R. Mandel

Title: President

Date: June 28, 2023

Signature: Jed R. Mandel

Cummins Inc.

By: Shelley Knust

Title: Vice President Product Compliance and Regulatory Affairs

Date: June 28, 2023

Signature: ______________________

Daimler Truck North America By:

Sean Waters

Title: Vice President Product Compliance

Date: June 28, 2023

Signature: Sean Waters

General Motors Company

By: Hon. David Strickland

Title: Vice President Global Regulatory Affairs

Date: June 28, 2023

Signature:

Hino Motors Limited, Inc.

By: Takashi Katou

Title: North American Manager - Regulation and Certification Div.

Date: 6/29, 2023

Signature: Takashi Katou

Isuzu Technical Center of America, Inc.

By: Jeffery A. Marsee

Title: Exec. Dir, Vehicle Compliance

Date: 6/30/2023

Signature:

Navistar, Inc.

By: Michael Noonan

Title: Director - Certification and Compliance

Date: 06/28/23

Signature: Michael Noonan

PACCAR Inc

By: John Rich

Title: CTO

Date: 28 June 2023

Signature:

Stellantis N.V.

By: Thomas McCarthy

Title: SVP, Technical Safety & Regulatory Compliance

Date: June 29, 2023

Signature:

Volvo Group North America

By: Dawn D Fenton

Title: Vice President, Government Relations & Public Affairs

Date: June 28, 2023

Signature: Dawn D Fenton

California Air Resources Board

By: Steven S. Cliff, Ph.D

Title: Executive Officer

Date: July 5, 2023

Signature: ____________________

Ford Motor Company

By: Cynthia Williams

Title: Global Director, Sustainability, Homologation & Compliance

Date: July 5, 2023

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Appendix A – Amendments to Omnibus Legacy Provisions in Title 13 California Code of Regulations (CCR) 1956.8 to Ease Transition

Each manufacturer must pick one option and cannot switch between options for the 2024-2026 model year (MY) period. The denominator for all percentages shown below includes total medium-duty diesel (MDD), light heavy-duty diesel (LHDD), medium heavy-duty diesel (MHDD), and heavy heavy-duty diesel (HHDD) California distribution of engine certified products. The denominator excludes chassis certified products.

Option 1

Applicable to all OEMs. The following caps would apply:
45 percent[1] legacy cap in 2024, 25 percent[1] legacy cap in 2025, 10 percent[1] legacy cap in 2026

Option 2

Only applicable to OEMs that make MHDD engines and heavy-duty diesel engines in another primary intended service class
MHDD – 60 percent[2] legacy cap in 2024, 60 percent[2] legacy cap in 2025, 0 percent legacy cap in 2026
Other service class (Total MD + LHDD + HHDD) – 15 percent[1] legacy cap in 2024, 8 percent[1] legacy cap in 2025, 0 percent legacy cap in 2026

To give certainty regarding what happens if legacy thresholds are exceeded, CARB has clarified the consequence if the legacy caps are exceeded, as detailed in footnotes 1 and 2.

[1] For the legacy percentage caps shown, the first number (e.g., 45 percent for Option 1 for 2024 MY) is a threshold. Deficits for legacy engine sales between 0 and the threshold of total heavy-duty diesel production volume would need to be offset at the nominal rate (i.e., 1 Mg NOx credits per 1 Mg excess NOx from a legacy engine). All deficits from sales between the threshold and 1 percent more than the threshold (e.g., between 45 and 46 percent for Option 1 for 2024 MY) would have to be offset at four times the nominal rate (i.e., 4 Mg NOx credits per 1 Mg excess NOx from a legacy engine). All sales volume above 1 percent more than the threshold (e.g., above 46 percent for Option 1 for 2024 MY) would be considered as non-compliant sales.

[2] For MHDD engine sales under option 2, the first number (e.g., 60 percent for 2024 MY) is a threshold. Deficits for legacy engine sales between 0 and the threshold of total heavy-duty diesel production volume would need to be offset at the nominal rate (i.e., 1 Mg NOx credits per 1 Mg excess NOx from a legacy engine). All deficits from sales between the threshold and 5 percent more than the threshold (e.g., between 60 and 65 percent for 2024 MY) would have to be offset at four times the nominal rate (i.e., 4 Mg [NOx credits per 1 Mg excess NOx from a legacy engine). All sales volume above 5 percent more than the threshold (e.g., above 65 percent for 2024 MY) would be considered as non-compliant sales. For example, a manufacturer uses option 2 and sells 100 total heavy-duty engines in 2024 MY. At the end of 2024 MY, the manufacturer determines that it has sold 70 legacy medium heavy-duty engines. The manufacturer must offset the emissions from 60 medium heavy-duty engines at the nominal rate. The manufacturer must offset the emissions for 5 medium heavy-duty engines (65-60=5) at four times the nominal rate. Finally, the manufacturer must also recall 5 medium heavy-duty engines (70-65=5).

Additional changes:

CARB commits that it will initiate rulemaking actions and present the following provisions through the public review process:

1. To extend the legacy engine provisions flexibility through 2026 MY (under option 1 only) to allow manufacturers to certify engines to the exhaust emissions standards for NOx and particulate matter (PM) specified in title 13, California Code of Regulations, section 1956.8(a)(2)(C)3, provided the manufacturers offset any NOx or PM deficits generated from this option.

2. To allow engine manufacturers in MY 2024 to certify legacy engines prior to certification of Omnibus-compliant engine families.

3. To allow manufacturers to offset any increases in NOx or PM emissions by undertaking projects targeted at California disadvantaged communities in the same model year that they utilize the proposed legacy engine provisions.

4. Manufacturers can carry over deficits from 2024 to 2025 MY and offset with HD-ZEP credits without any applicable multipliers.

CARB staff also commits to prepare the following Manufacturers Advisory Correspondence (MAC) documents in consultation with EMA and all member HDOH OEMs:

1. A MAC prescribing how to demonstrate legacy engine cap compliance (for example, via labeling data). CARB staff’s intent is to be flexible regarding de minimus accidental leakage of non-legacy engines to California.

2. A MAC with further guidance on how to pursue projects targeted at California disadvantaged communities. Such projects may include infrastructure projects aimed at facilitating use of HD ZEVs.

Appendix B – CARB Truck Regulations Compliance and U.S. EPA Clean Trucks Plan Harmonization

CARB Carries Out Its Authority Per the Following:

1. California will maintain its certification program. That is, manufacturers will still be required to submit applications for certification including test data, certification documents, etc. to demonstrate compliance with applicable California requirements. CARB will independently evaluate whether to issue Executive Orders.

2. CARB is not committing to issue "deemed to comply certifications" based on U.S. EPA certifications.

3. CARB will maintain its On-Board Diagnostic (OBD) program, and manufacturers will need to meet CARB OBD requirements in order to be certified in California.

4. CARB will maintain its EWIR program but will implement the clarifications outlined in Appendix C of this agreement.

5. CARB will maintain its heavy-duty in-use compliance program for both diesel and Otto-cycle engines, including in-use testing conducted by manufacturers and in-use testing conducted by CARB. CARB will maintain its authority for all the elements pertaining to heavy-duty in-use requirements as described in the Omnibus regulation; however, CARB proposes to adopt the 2-Bin Moving Average Window (2B-MAW) Methodology, and the off-cycle standards and in-use duty cycle standards as shown below. In addition, as mentioned in Appendix C, CARB will use its discretion to not do automatic recalls at the required trigger points for the 2024--2034 model year engines but will take into consideration the newness of the technology and information submitted by manufacturers before making recall decisions, as well as U.S. EPA's recall decisions. CARB will also evaluate during the alignment rulemaking if it is warranted to align certain aspects, or holistically, to the U.S. EPA's In Use Compliance program.
6. CARB will maintain its mandatory Clean Idle Label requirement for California-certified engines but will propose to align with U.S. EPA's 10 grams per hour standard level.

The OEMs Commit to Meet CARB Truck Regulations

The OEMs commit to meet, in California, the requirements of the relevant regulations as specified below and any agreed upon modifications per this Agreement, regardless of the outcome of any litigation challenging the waivers/authorizations for those regulations, or CARB's overall authority to implement those regulations.

1. The Omnibus regulation,[1] as it existed on December 22, 2021, and the Standards and Test

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[1] The Omnibus regulation is comprised of new title 13, California Code of Regulations (Cal. Code Regs.) sections 2139.5, and 2169.1 through 2169.8; amendments to title 13, Cal. Code Regs., sections 1900, 1956.8, 1961.2, 1965, 1968.2, 1971.1, 1971.5, 2035, 2036, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2121, 2123, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2133, 2137, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2166, 2166.1, 2167, 2168, 2169, 2170, 2423, and 2485; and amendments to title 17 Cal. Code Regs. sections 95662 and

procedures incorporated in the Omnibus regulation, as they existed on December 22, 2021. As specified above, CARB commits to initiate actions resulting in future amendments to the Omnibus regulation. Assuming those amendments are finalized, the OEMs agree to fully comply in California with the requirements of the Omnibus regulation and any standards and test procedures incorporated in the Omnibus regulation, as affected by such amendments.

2. The ACT regulation,[2] as it existed on March 15, 2021, and the 100 percent ZEV sales requirement set forth in Cal. Code Regs title 13, section 2016, as it existed on April 28, 2023. As specified above, CARB commits to initiate actions resulting in future amendments to the ACT regulation. Once those amendments are finalized, the OEMs agree to fully comply in California with the requirements of the ACT regulation and any standards and test procedures incorporated in the ACT regulation, as affected by such amendments.

3. The Zero Emission Airport Shuttle regulation,[3] as it existed on January 30, 2020.

4. The Zero Emission Powertrain Certification Procedure,[4] as it existed on January 21, 2020, and the Standards and Test procedures incorporated in the Zero Emission Powertrain Certification Procedure, as they existed on January 21, 2020, and

5. The 2018 HD Warranty Amendments,[5] as they existed on June 12, 2019, and the Standards and Test Procedures for 2004 and subsequent model year Heavy-Duty Diesel Engines and Vehicles, as amended April 18, 2019.

CARB Omnibus/U.S. EPA Clean Trucks Alignment and Exceptions

1. Revisions to the Temperature Adjustment & Compliance Allowance

As described in further detail below, CARB proposes to incorporate a modified version of the temperature adjustment function and the interim compliance allowance for a limited period of time.

95663.

[2] The ACT regulation is set forth in title 13, California Code of Regulations (Cal. Code Regs.), sections 1963, and 1963.1 through 1963.5. The ACT regulation also includes a one time fleet reporting requirement for owners and brokers of vehicles exceeding 8500 lbs GVWR in title 13, Cal. Code Regs., sections 2012, 2012.1, and 2012.2.

[3] The Zero Emission Airport Shuttle regulation is comprised of new sections 95690.1, 95690.2, 95690.3, 95690.4, 95690.5, 95690.6, 95690.7, and 95690.8, title 17, Cal. Code Regs.

[4] The Zero Emission Powertrain Certification Procedure is comprised of amendments to title 13, Cal. Code Regs., section 1956.8 and title 17, Cal. Code Regs., section 95663.

[5] The 2018 HD Warranty Amendments are comprised of amendments to title 13, California Code of Regulations (Cal. Code Regs.) sections 1956.8, 2035, 2036, and 2040.

A. Interim Compliance Allowance

CARB will propose to amend the Omnibus Regulation to include the following interim compliance allowance schedule:

- 15 mg/hp-hr applicable to MHDD and HHDD for MYs 2027-2034
- No interim compliance allowance for 2035 and subsequent MYs

The proposed interim compliance allowance would apply to both in-use duty cycle NOx emissions standards (FTP/RMC/LLC) as well as off-cycle NOx emissions standards.

B. Temperature Adjustment

For MYs 2027 to 2030, the in-use off-cycle standards for bins 1 and 2 would remain constant at temperatures above 20 ºC. The proposed temperature adjustment would apply to temperatures between 5 to 20 ºC.

For 2031 and subsequent MYs, the proposed temperature adjustment would only apply to the 0-5 ºC range.

2. Summary of Proposed CARB Emissions Standards for NOx

The CARB proposed FTP, RMC, LLC and idle NOx emissions standards are shown in Table 1 for **MHDD and HHDD** engines. As indicated earlier, the proposed interim compliance allowance would only apply to the 2027-2034 MY period.

LHDD engines - There is no applicable compliance allowance for 2027 and subsequent MYs, and CARB will propose to harmonize with the U.S. EPA duty cycle standards for the FTP/RMC (35 mg/hp-hr) and LLC (50 mg/hp-hr) NOx emissions standards.

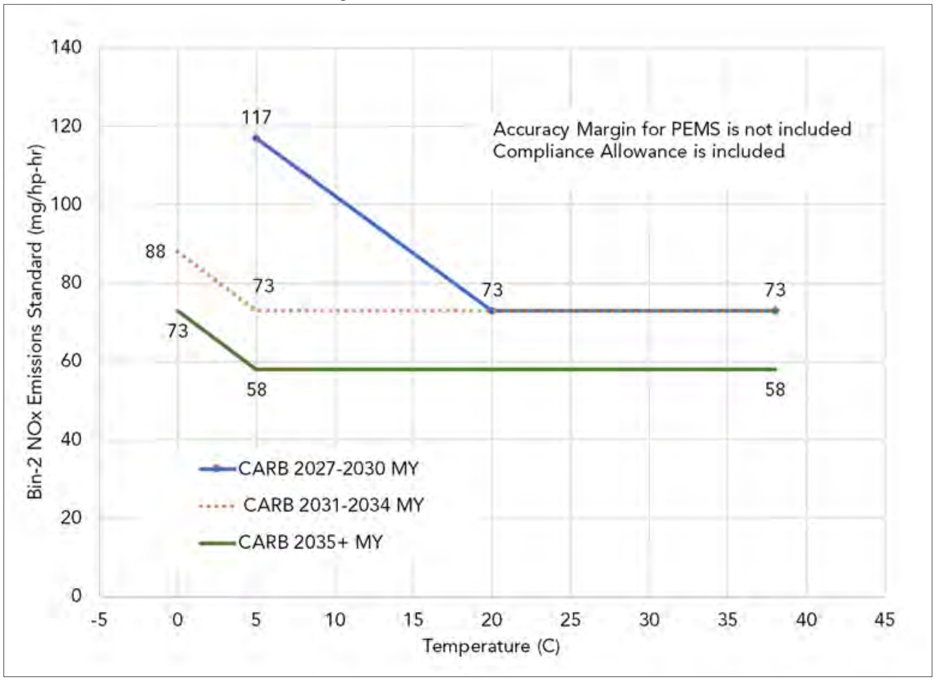
Table 1. CARB Proposed In-Use Duty Cycle NOx Emissions Standards[1] For MHDD and HHDD Engines

MY	FTP/RMC (mg/hp-hr) *	LLC (mg/hp-hr) *	Idle (g/hr)
2027-2034 and 2024-2026 complying early with 2027	50	65	10
2035 & Subsequent	35	50	10

[1]Corresponding NOx family emission limits are calculated according to §1036.104(c)(3)
***** Compliance allowance is included in the proposed NOx emissions standards

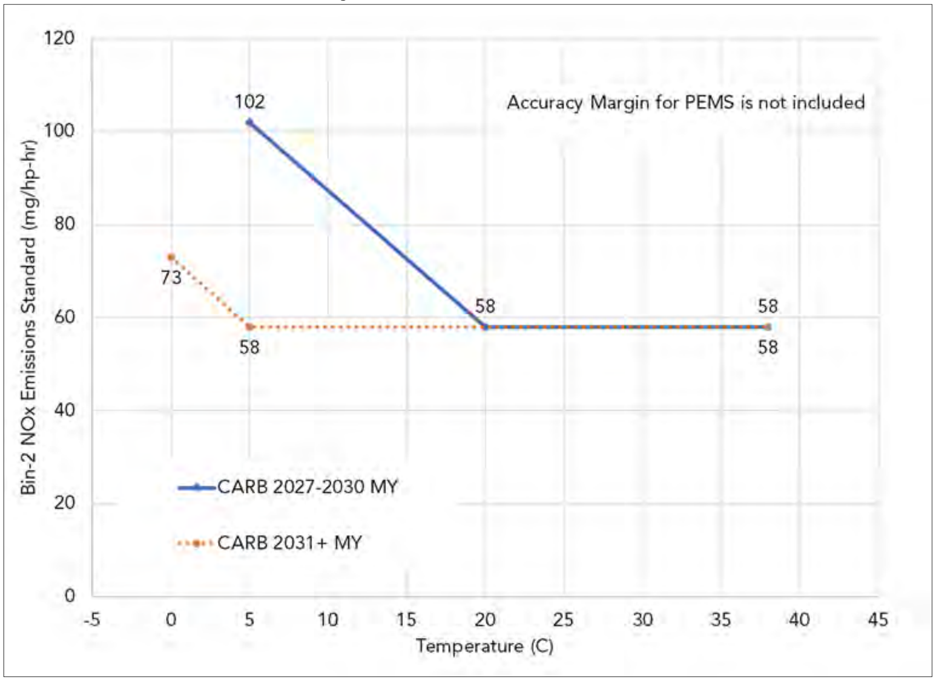
The proposed bins 1 and 2 off-cycle NOx emissions standards are shown in Figures 1 to 3 below. These figures include the impacts of both the temperature adjustment and the interim compliance allowance for various MYs.

Fig. 1 – CARB Proposal for MHDD & HHDD[1]
Bin-2 Off-Cycle NOx Emissions Standards



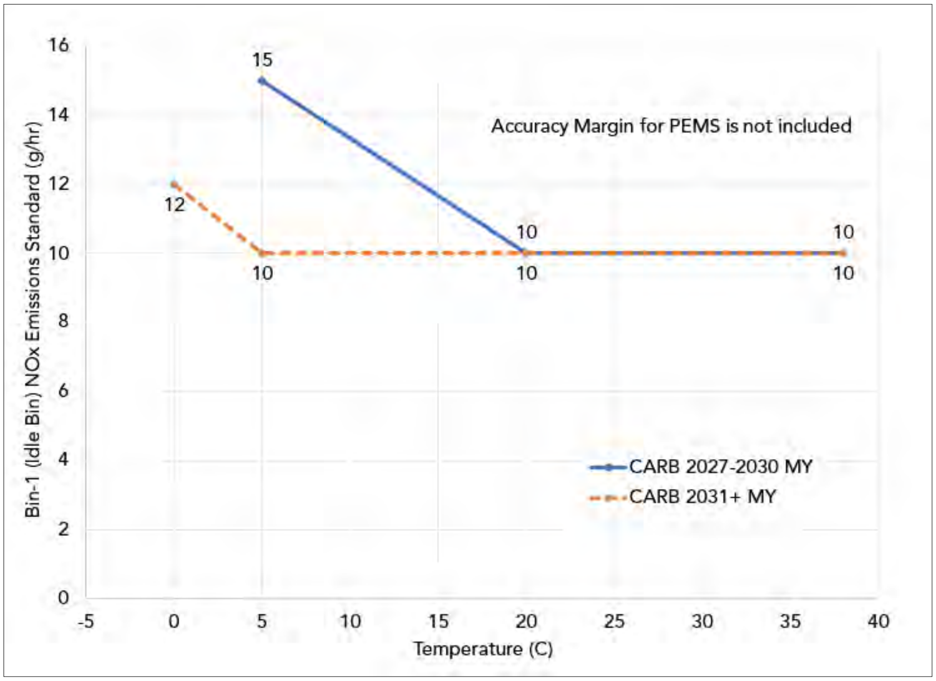
[1]Corresponding NOx family emission limits are calculated according to §1036.104(c)(3)

Fig. 2 – CARB Proposal for LHDD[1]
Bin-2 Off-Cycle NOx Emissions Standards



[1]Corresponding NOx family emission limits are calculated according to §1036.104(c)(3)

Fig. 3 – CARB Proposal for Bin-1 (Idle Bin) Off-Cycle NOx[1] Emissions Standards. Applicable to LHDD, MHDD, HHDD Engines



[1]Corresponding NOx family emission limits are calculated according to §1036.104(c)(3)

3. Confirmation of NOx Credits

CARB confirms that NOx credits generated under U.S. EPA CTP interim provisions, defined in §1036.150 and calculated according to §1036.705, may be used for 50-state engine certification for MY 2027 and later. CARB will propose and recommend that the Board adopt, starting in MY 2027, a single national ABT program for NOx standards for medium- and all classes of heavy-duty engines and vehicles, administered by U.S. EPA and CARB.

Appendix C – Emission Warranty Information Reporting, In Use Compliance, Advanced Clean Trucks and Advanced Clean Fleet Regulatory Implementation Efforts

A. Interpretation of 13 California Code of Regulations (CCR) 2143 for MYs 2024 to 2034 to Ease Transition

California Code of Regulations, Title 13, Section 2143 provides that CARB's Executive Officer is authorized to consider specified information in determining whether a recall of a vehicle or engine family is required:

"§ 2143. Failure Levels Triggering Recall and Corrective Action.

An engine family, test group, a vehicle family, a trailer family or a subgroup shall be subject to a recall when the number of failures of a specific emission-related component exceeds the failure level set forth below, unless the Executive Officer determines from the emission information report that a recall is unnecessary pursuant to the criteria set forth in Section 2148(a) and (b). … In the case of 2024-2026 MY California-certified heavy-duty diesel and Otto cycle engines, and heavy-duty vehicles, vehicles or engines in an engine family or test group shall be recalled or subject to other corrective action at the following failure levels: 4 percent or 25 (whichever is greater). In the case of 2027-2030 MY California certified heavy-duty diesel and Otto-cycle engines, and heavy-duty vehicles, vehicles or engines in an engine family or test group shall be recalled or subject to other corrective action at the following failure levels: 4 percent or 25 (whichever is greater) for the first five years of the warranty period, and 5 percent or 35 (whichever is greater) for years 6 through 7 of the warranty period and 7 percent or 50 for years 8 through 10 of the warranty period."

Recognizing the challenges associated with making engines and aftertreatment systems to a much stricter emissions standard, for MYs 2024 through 2034, CARB's Executive Officer confirms that he will objectively evaluate all information submitted by a manufacturer pursuant to 13 CCR sections 2146 and 2148 in assessing whether a recall is required if a vehicle or engine family triggers the recall criteria in 13 CCR sections 2143, 2167, 2168; under the manufacturer-run in-use testing provisions in 86.1915.B of the Diesel Test Procedures; or pursuant to in-use testing run by CARB in 13 CCR sections 2139.5 and 2140. CARB will also consider USEPA's recall decisions.

B. Advanced Clean Trucks/Advanced Clean Fleets

In a show of good faith, in calendar year 2023, CARB issued guidance on ACT credit reporting, clarifying that compliance determination and sales reporting requirements are both defined when vehicles are produced and delivered for sale in California. CARB staff will also propose to initiate a rulemaking action to that effect in calendar year 2024. Staff also will propose to modify section 1963.3(b) to lengthen the number of years a manufacturer has to make up a deficit from one year to three years.

- OEMs have requested a credit pooling concept for credits and deficits generated in states that have adopted the ACT regulation under section 177 of the federal Clean Air Act. In calendar year 2023, CARB will introduce the concept of pooling across states via a public workshop. CARB staff will work with OEMs and section 177 states in an effort to develop and implement a pooling structure for states that have adopted the ACT regulation to provide OEMs flexibility. To the degree new California rules are required, CARB staff will propose the pooling concept to the Board as early as possible.

- In calendar year 2023, CARB will hold a public workshop to discuss the appropriate role of hydrogen-fueled internal combustion engines towards meeting the requirements of the ACT and ACF regulations.

Appendix D – Support for CARB's Regulations and for States that have Adopted CARB Regulations per S177 CAA

EMA and the OEMs have agreed to limit their advocacy, as set forth below, in states that either already have elected to adopt through Section 177 CARB's Omnibus or ACT rules, or that may choose to do so in the future.

A. In all such cases, EMA and the OEMs will not legally challenge or support others' legal challenges to any state's adoption of the regulations set forth in Appendices A and B.

B. The OEMs commit to comply with the 2027 and later model year provisions of the Omnibus regulations, as may be amended by Appendices A and B, adopted in any Section 177 state irrespective of the outcome of any litigation that has been filed or may be filed challenging the waivers or authorizations for those regulations or CARB's or any state's overall authority to implement those regulations.

C. EMA and the OEMs will support or not oppose the adoption of CARB's Omnibus regulations in any prospective Section 177 states provided the adoption is for 2027 and later model years.

D. EMA and the OEMs agree to be neutral (using the three-tier support, neutral, oppose system) in response to any prospective Section 177 states' proposals to consider adopting the Omnibus, as may be amended by Appendices A and B, regulation for 2024 through 2026 model years; provided, however, that EMA and the OEMs can provide written and verbal comments expressing concerns or issues of implementation, including engine availability for their fleet customers, and can provide other legal requirements of disclosure on business impacts.

E. EMA and the OEMs agree to be neutral (using the three-tier support, neutral, oppose system) in response to any prospective Section 177 States' proposals to consider adopting CARB's ACT regulations; provided, however, EMA and the OEMS can provide written and verbal comments expressing concerns or issues of implementation including infrastructure concerns and lack of complimentary policies.

F. The OEMs commit to put forth their best efforts to sell as many zero emission trucks as reasonably possible in every state that has or will adopt CARB's ACT regulations, even potentially exceeding any future U.S. EPA Phase 3 Greenhouse Gas requirements, irrespective of the outcome of any litigation that has been filed or may be filed challenging the waivers or authorizations for those regulations or CARB's or any state's overall authority to implement those regulations.

G. CARB, EMA and the OEMs mutually agree to work together to resolve any issues that may warrant regulatory amendments to either the Omnibus or ACT regulations and to actively promote further needed infrastructure development.

Feasibility Study of EPA FRM Phase 3 GHG Standards for Medium Heavy-Duty Vehicles

September 25, 2024

Version: Final

Prepared For:

Truck and Engine Manufacturers Association

Project Team:

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Executive Summary

The Environmental Protection Agency (EPA) published the final rule for “Phase 3” greenhouse gas (GHG) standards in March 2024. The final Phase 3 rule will require the increasing deployment of zero-emission (ZE) trucks starting in 2027. The readiness of the charging/hydrogen refueling infrastructure for ZE trucks and the related cost impacts warrant a deeper analysis. Ricardo investigated the two core infrastructure readiness issues below to provide an assessment of the magnitude of the challenge of transitioning to ZE trucks as contemplated under the Phase 3 rule:

Magnitude of MHD ZEV adoption

To fully implement the Phase 3 standards, medium- and heavy-duty (MHD) zero-emission vehicle (ZEV) sales through 2032 are expected to reach nearly 1.5 million battery-electric vehicles (BEVs) along with 111,000 fuel-cell electric vehicles (FCEVs) and hydrogen internal combustion engine (H2-ICE) vehicles. California is expected to continue to lead in the rates of overall ZE-truck adoption, while Texas is estimated to be the highest adopter of FCEV and H2-ICE vehicles. Medium-duty (MD) (Class 2b-5) short-haul single-unit trucks (no trailers) are expected to represent over 80% of BEVs by 2032. Roughly 60% of FCEV and H2-ICE are expected to be used for the multi-purpose long haul (200 miles daily mileage) and regional haul (420 miles daily mileage) applications.

Charging infrastructure readiness assessment to support the BEV adoption

Under our assessment, which in part utilizes EPA’s “HD TRUCS” model, more than 92% of the BEV trucks on the road will be using depot-based Level 2 (L2) or direct-current fast-charging (DCFC) 50 to 350 kW overnight charging. Those types of chargers have been commercialized and available for use by light-duty vehicles (LDVs) for over 10 years.

Unlike LDVs, however, there are no national EV charging standards for MD/HD trucks. To date, the Federal Highway Administration (FHWA) has not provided any guidance for MHD BEV charging. With EPA’s proposed Phase 3 ZE-truck adoption rates ramping up beginning in 2027, it is important to develop a comprehensive strategy for the deployment of a sufficient BEV-truck infrastructure to ensure that the targeted BEV adoption rates can be met year-over-year.

The results of this study have led to several conclusions and recommendations, which are intended to inform and support policymakers, utilities, and site operators in planning for the deployment of the necessary BEV-truck charging infrastructure, and in assessing progress toward that goal.

Conclusions:

1. With a low population of approximately 3,300 of MHD ZEVs currently on the road, the existing charging infrastructure at fleet depots is mostly limited to meeting ongoing pilot programs

2. Current BEV adoption rates among national truck fleets are low, at just 2% of the total 2023 fleet size
3. The envisioned ZEV truck adoption rates anticipated under EPA's Phase 3 GHG standards will accelerate MHD BEV adoption exponentially, resulting in nearly 1.5 million BEV MHDVs on the road by 2032
   a. Under EPA's HD TRUCS model, 92% of on-road MHD BEVs in 2032 will utilize and require depot-based charging
   b. 82% (~1.2 million) of the chargers required are assumed to be Level 2 type chargers
   c. Charger deployment rates will need to increase nearly 30-fold from 40 chargers/day in 2024 to 947 chargers /day in 2032 to allow for the required deployment of MHD BEVs
4. Unlike the national electric vehicle infrastructure program (NEVI) that focuses on light-duty (LD) BEVs, there are limited State and Federal funding programs specifically dedicated to accelerating the charging infrastructure for MHD BEVs
5. Using conservative assumptions, an estimated additional investment of $27 billion is required through 2032 to develop a charging infrastructure that can support the projected on-road MDH BEV population
   a. The $27 billion estimate is based on the assumptions that EPA utilized in its HD TRUCS model for the charger types used for each truck class and use-type
   b. It must be emphasized that the estimated investment is sensitive to the charger types used for MHD BEV charging; if more DCFCs are required, costs will increase substantially
6. In addition to the scope of the necessary infrastructure investments, the timely deployment of chargers is critical to successful MHD BEV adoption. The pace of charger deployments under the NEVI program is a real-world example of the likelihood and importance of deployment timelines and the adverse impacts of delays

Recommendations:

Policy makers should take steps to ensure the availability of:

1. Dedicated federal funding for a comprehensive MHD BEV charging infrastructure
   a. Similar to the NEVI program, the federal government should set up funding to develop a dedicated MHD BEV charging infrastructure at public and private depots nationwide
2. FHWA guidance and standards for the development of MHD BEV charging stations
   a. To ensure a steady adoption of MHD BEV stations to meet EPAs Phase 3 GHG emission targets, the FHWA should use a two-phased approach to develop MHD BEV charging standards: Phase 1 should cover depot-based charging standards; and Phase 2 should cover highway-based charging standards
3. Charging site design recommendations
   a. FHWA should establish MHD BEV charging site designs requirements as part of developing the MHD charging standards
   b. Government agencies need to take the necessary steps to ensure collaboration among utilities and fleet operators
   c. Although the aggregate impact of electrical demand from charging MHD BEVs is not overly significant, it will be important for utilities to work closely with fleet operators to leverage smart charging to manage electrical load and ultimately reduce TCO for fleet operators

Hydrogen supply infrastructure readiness and cost impact analysis to support

forecasted FCEV+H2 ICE adoption

We also compared the anticipated hydrogen demand from the targeted adoption rates for FCEVs and H2-ICEs with the current and planned capacity of the HD hydrogen refueling infrastructure. To meet the 2032 hydrogen availability target, an estimated investment of nearly $7.2 billion (for approximately 1192 stations) will be required for HD refueling stations. With estimated available incentive funding of $0.5 billion, an additional investment of $6.7 billion from various sources will need to be allocated evenly over the next 8 years for the required hydrogen refueling stations. Although FCEV and H2-ICEs are in the early pre-commercial stage, it is critical to build out the requisite hydrogen refueling infrastructure well ahead of the ramp-up of FCEV and H2-ICE sales to facilitate adoption.

Conclusions:

1. The aggregate hydrogen demand is expected to be 0.9M tons/year by 2032
2. Regional-haul applications will comprise over 60% of total hydrogen demand by 2032
3. California and Texas are the dominant States that will drive hydrogen demand
4. 1192 HD hydrogen refueling stations need to be developed by 2032 to meet the 2032 FCEV and H2-ICE targets. 380 stations are expected to be deployed in Texas and California by 2032
5. The estimated capital cost in 2030 is approximately $7.1 million for each hydrogen refueling station with a dispensed capacity of 4000kg/day
6. With a total estimated available funding of ~$0.5 billion, the required additional investment in the hydrogen infrastructure beyond current commitments is $6.7 billion.

Recommendations:

1. As over 50% of FCEVs and H2-ICEs are expected to be deployed for longer mileage (>200 daily miles) applications, many hydrogen-fueled applications may not return to base daily. Thus, it is important to accelerate the deployment of hydrogen refueling corridors and hydrogen public refueling stations in truck hubs, such as ports, airports, railroads, warehouses, and freight centers
2. Increased dedicated incentive funding for HD hydrogen refueling stations will be necessary. Insufficient incentives or funding programs currently exist for the hydrogen refueling infrastructure
3. There is a critical need for increased incentives for HD refueling stations. As the capital cost of a HD hydrogen refueling station is much higher than that of charging station or LD refueling station, the incentives should be designed to reflect the increased financial investment
4. HD FCEV and H2-ICE demonstration and pilot projects in California and Texas are important test cases for broader national deployment. It is beneficial for refueling infrastructure providers to deploy their products in fleet applications to monitor performance, concerns, and successes. These pilot and demonstration projects can lead to an improved generation of FCEV, H2-ICE, and hydrogen refueling stations for HD fleets

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1 Introduction

With the final "Phase 3" GHG standards, EPA has put regulations in place that will indirectly mandate the large-scale sale and deployment of medium-duty and heavy-duty (MHD) zero-emission vehicles (ZEV) (electric, hydrogen ICE, and FCEVs) across all segments of transport. (See Table 1, below.)

As MHD ZEV sales rise, the corresponding challenges associated with widespread ZEV adoption may not be fully appreciated, and the magnitude of the necessary MHD ZEV charging/refueling infrastructure and the corollary cost impacts warrant a deeper analysis and understanding.

Table 1: EPA final rule ZEV Adoption Rates for MY 2027 -2032 Technology Packages[1]

Regulatory subcategory	MY 2027 (%)	MY 2028 (%)	MY 2029 (%)	MY 2030 (%)	MY 2031 (%)	MY 2032 (%)
LHD Vocational	17	22	27	32	46	60
MHD Vocational	13	16	19	22	31	40
HHD Vocational	0	0	13	15	23	30
MHD All Cab and HHD Day Cab Tractors	0	8	12	16	28	40
Sleeper Cab Tractors	0	0	0	6	12	25
Heavy Haul Tractors	0	0	1	1	3	5
Optional Custom Chassis: School Bus	13	16	19	22	31	40
Optional Custom Chassis: Other Bus	0	0	13	15	23	30
Optional Custom Chassis: Coach Bus	0	0	0	0	0	0
Optional Custom Chassis: Refuse Hauler	0	5	10	15	16	16
Optional Custom Chassis: Concrete Mixer	0	0	0	0	0	0
Optional Custom Chassis: Emergency Vehicles	0	0	0	0	0	0
Optional Custom Chassis: Recreational Vehicles	0	0	0	0	0	0
Optional Custom Chassis: Mixed Use	0	0	0	0	0	0

[1] Final Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles - Phase 3 (published April 22, 2024)

2 Background

In this study, Ricardo investigated the challenges involved in meeting the MHD ZEV adoption rates anticipated under EPA’s Final Phase 3 GHG emission standards, and developed a detailed analysis of the following key issues:

1. Scale of forecasted adoption of battery-electric vehicles (BEVs) and hydrogen-fueled heavy-duty trucks under EPA’s Final Phase 3 GHG emission standards
2. Readiness of the charging and electrical supply infrastructure to support the forecasted BEV truck adoption rates, and the associated costs
3. Readiness of the hydrogen supply infrastructure to support the forecasted HCFC and H2-ICE truck adoption rates, and the associated costs

The results of the study will be used to provide input for the periodic “progress reviews” that are called for under the Final Phase 3 rulemaking, with specific focus on infrastructure readiness to support the implementation of the regulations.

3 ZEV Sales Forecast

EPA has provided projected MHD ZEV sales for calendar years 2027 through 2032. To evaluate the gaps between the current capacity and future demand of the MHD ZEV charging and hydrogen refueling infrastructure on a nationwide and state level, Ricardo has analyzed the following factors:

1. MHD ZEV national sales between calendar years 2024 to 2026
2. Anticipated adoption rates and MHD ZEV sales by state from calendar years 2024 to 2032
3. Hydrogen ICE (H2-ICE) sales forecasts

MHD ZEV sales forecasted as of 2032 have been segmented according to vehicle class (regulatory classes) and vocation (source use types). This section explains the approach that Ricardo used to estimate MHD ZEV sales (2027-2032) and adoption rates by state, and presents the results across MHD ZEV technology packages and vehicle segments. The forecast covers BEVs, FCEVs, and H2-ICE vehicles.

3.1 Methodology

3.1.1 2024 – 2026 Sales Forecast

To estimate the interim growth of MHD ZEV sales between 2024 and 2026, Ricardo calculated the average annual growth rate to bridge the gap between MHD ZEV sales as of 2023 and the projected MHD ZEV sales assumed by EPA to ramp-up under the Phase 3 standards starting in 2027. The sales forecast approach is presented in Figure 1.

The MHD ZEV adoption rate as of 2023 is estimated based on the number and mix of actual MHD ZEVs sales.[2] The annual growth rate is assumed to remain the same from 2024 to 2026.

[2] CALSTART (2024), Zeroing in on Zero-Emission Trucks, https://calstart.org/wp-content/uploads/2024/05/ZIO-ZET-May-2024-Market-Update_Final.pdf

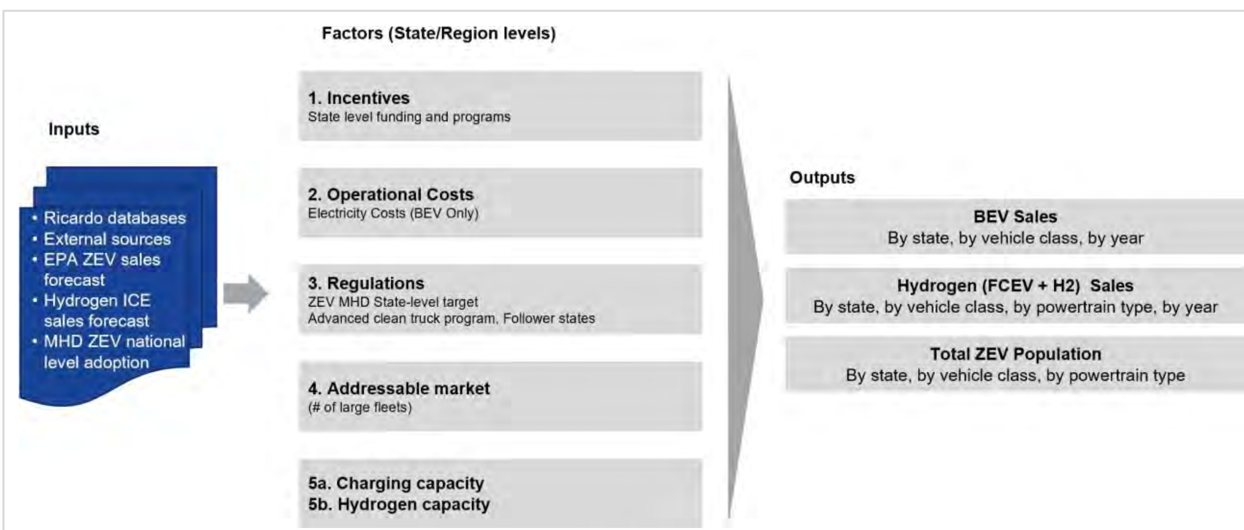
Figure 1: 2024-2026 Sales Forecast Approach

3.1.2 MHD ZEV Sales by State

As this study aims to assess the regional readiness of the ZE-truck charging and hydrogen-refueling infrastructure, Ricardo estimated the MHD ZEV sales and adoption rate by state.

Technology costs, regulations, and charging infrastructure are the key factors limiting MHD ZEV adoption rates. Thus, the projections modeled in this study are estimated based on national MHD ZEV data and five quantitative and qualitative parameters at the state level (Figure 2). Firstly, Ricardo estimated the state adoption rate compared to the national level based on the assessment of the five parameters shown below. Then, the ZE-truck sales by state were calculated from the currently available vehicle registration data and the state-calculated adoption rate.

Figure 2: Methodology of State Adoption Rate Estimation



Technology Costs

Capital costs and operational costs are additional critical factors impacting ZE-truck adoption rates. In that regard, available incentives and electricity costs play key roles.

1. **Incentives**
   The impact of state incentive programs is a key driver of MHD ZEV adoption rates, especially in the nearer-term. Incentives for upfront vehicle and infrastructure costs, and for charging or refueling costs can enable ZEVs to approach cost-parity with conventional vehicles more quickly, and thereby encourage ZEV adoption.
2. **Electricity Costs**
   Electricity costs and hydrogen refueling costs are the major adoption-enabling factors affecting operational costs. Due to the limited availability of hydrogen refueling stations across the states, the costs of hydrogen refueling are not considered as significant as the costs of the necessary refueling infrastructure when considering key adoption enabling factors.

Regulation

The ZEV-sales regulations, applicable purchase requirements, GHG and criteria emissions targets all create a regulatory framework for accelerating the growth of ZE-truck adoption rates.

Addressable Market

The size of the MHD vehicle market is a significant factor in the sale of MHD ZEVs at the state level.

Charging Infrastructure and Hydrogen Refueling Stations

MHD ZEV adoption rates, on the one hand, and the readiness of the requisite ZEV charging and refueling infrastructure, on the other, amount to a chicken-and-egg problem. Seen in that light, the available MHD charging capacity and hydrogen refueling capacity could be either the accelerator or barrier to increasing ZE-truck adoption rates.

To assess the scope of the potential problem, we developed estimates of the sales of new MHD ZEVs by state. As noted above, we assessed the states based on five key quantitative and qualitative parameters (Table 2) to determine their relative adoption rates compared to national adoption rates.

Table 2: State Adoption Parameters

Parameter	Description
Incentives	MHD ZEV incentives for vehicle and infrastructure deployment (capital costs, installation costs), weight exemption and utility incentives, and programs on BEV charging costs (Time-of-Use, demand charge)
Electricity Price	Average state-level electricity price[3]
Regulations	ZEV mandates, GHG regulations, ZEV targets
Addressable Market	Number of top 500 fleets in the state[4]
Charging Infrastructure or hydrogen capacity	BEV: current number of charging stations in each state, including both private and public charging stations[5] Hydrogen FCEV/ H2-ICE: current and potential hydrogen production capacity, current number of hydrogen refueling stations, hydrogen transportation infrastructure (pipelines)

Ricardo designed a scorecard (separate scorecards for BEV and hydrogen FCEV/ H2-ICE) to reflect different adoption rates by state. An example of this assessment is shown in Figure 3.

Figure 3: Example of BEV Scorecard

	California	Texas	Washington
Incentives	1	2	2
	• Adopted the Advanced Clean Trucks Rule • Highest number of MHD ZEV incentives/tax credits/grants	MHD ZEV incentives/tax credits/grants	Adopted ACT
Regulations	1	4	2
	Emission Target: 100% carbon-free by 2045	No Target	100% carbon-free electricity by 2045
Electricity Price	3	2	2
	Electricity price higher than average	Lower than average	Lower than average
# of top 500 fleets	1	1	3
	Rank #5	Rank #1	Rank #24
Charging Infra	1	2	2
	>30% of national capacity	> 5% of national capacity	>3% of national capacity
Overall	1	2	2

[3] EIA, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_5_06_a
[4] FleetOwner, 2023, https://cdn.baseplatform.io/files/base/ebm/fleetowner/document/2023/01/FO_500_EQ_FEAT_FINAL_2023.63d945d138b05.pdf
[5] DOE, https://afdc.energy.gov/fuels/electricity_locations.html#/find/nearest?fuel=ELEC

3.2 Sales Forecast Results

This section details the results of the MHD ZEV sales forecast through 2032 by state, regulatory class, and use types.

3.2.1 MHD ZEV Sales by State

MHD ZEV sales through 2032 are expected to reach nearly 1.5 million BEVs and 111,000 FCEVs and H2-ICE vehicles.

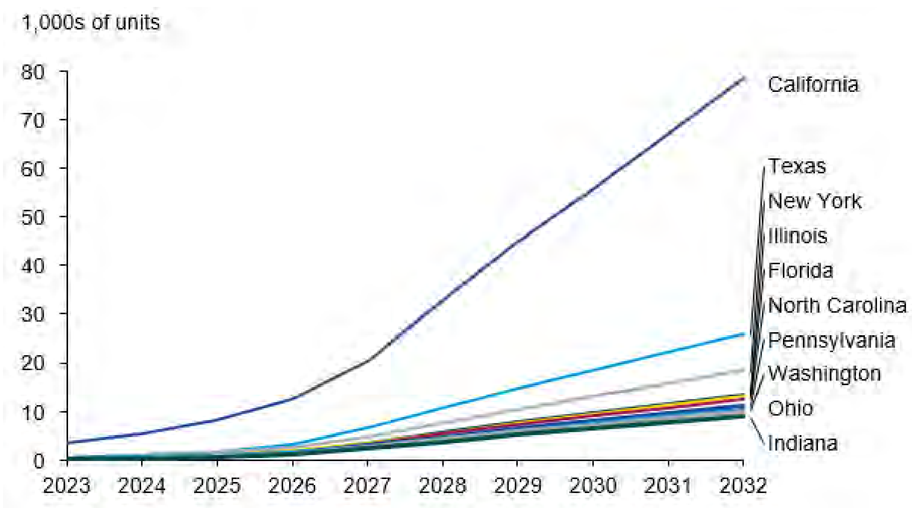
California is expected to continue to lead the pace of ZE-truck adoption (see Figure 4 and Figure 5). California has established a wider portfolio of regulations, legislation, incentives, and processes to support the transition to MHD ZEVs. The key mandates and incentives that accelerate the deployment of MHD ZEVs are highlighted below:

1. Mandates: Advanced Clean Trucks (ACT) Regulation, Innovative Clean Transit (ICT) regulation, Advanced Clean Fleet (ACF) Regulation
2. Incentives: Hybrid and Zero Emission Truck and Bus Voucher Incentive (HVIP), Low Carbon Fuel Standard (LCFS), California Electric Vehicle Infrastructure Project (CALeVIP), The Clean Off-Road Equipment Voucher Incentive Project (CORE), Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE)

In addition to the regulatory and incentive program support, California also is leading the deployment of MHD charging infrastructure and hydrogen refueling stations. More than 27% of the nation’s Level 2 chargers and DC fast chargers (DCFC) are currently located in California. HD hydrogen refueling stations in the U.S. are primarily in California.

MHD ZEV sales between 2022-2026 make up significantly less than 10% of total nationwide MHD ZEV sales projected by 2032. Beyond 2026, the anticipated ZEV adoption ramp-up curve calls for exponential growth, driven by the Final Phase 3 GHG standards and other regulatory mandates and incentives. The resultant projected MHD ZEV sales by state are shown in Figure 4.

Figure 4: BEV Sales by State



Texas is expected to be the highest adopter of FCEV and Hydrogen ICE vehicles. Texas has significant advantages in hydrogen technology adoption, especially in production, storage, and transportation. Texas has ready access to renewables and natural gas, along with extensive oil and gas facilities. The state also has hydrogen storage, salt caverns, and a developed port infrastructure. Texas also owns approximately 1,000 miles of hydrogen pipelines, representing 64% of the total mileage in the U.S. Projected FCEV and H2-ICE sales by state are shown in Figure 5. National ZEV sales are shown in Figure 6.

Figure 5: FCEV and H2-ICE Vehicles Sales by State

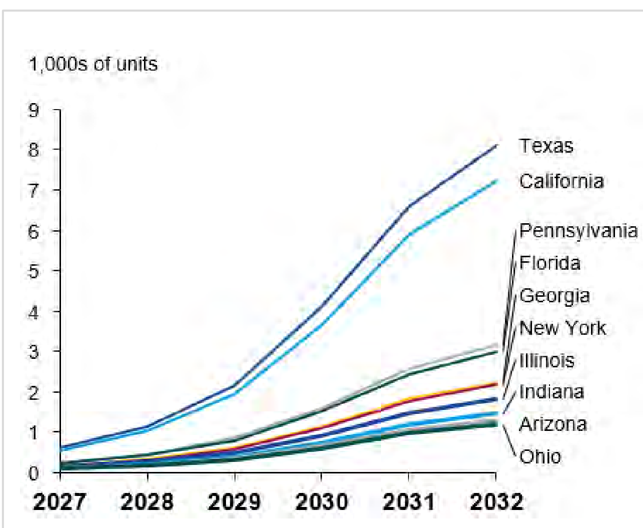
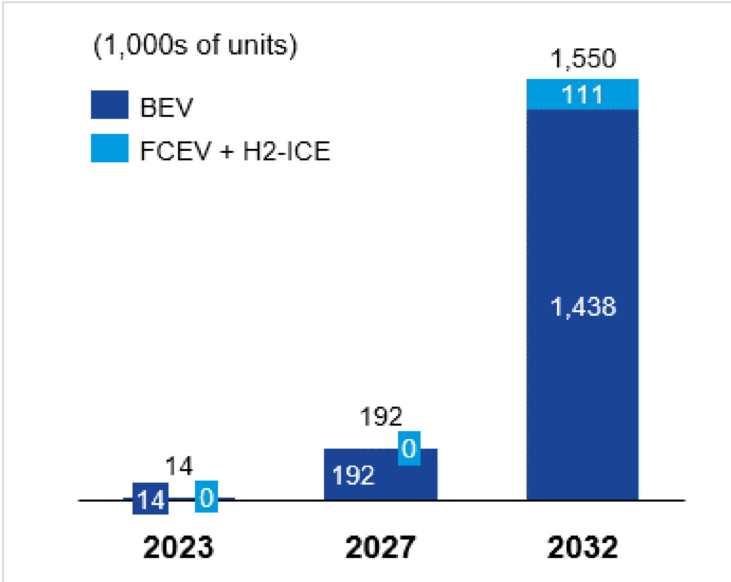


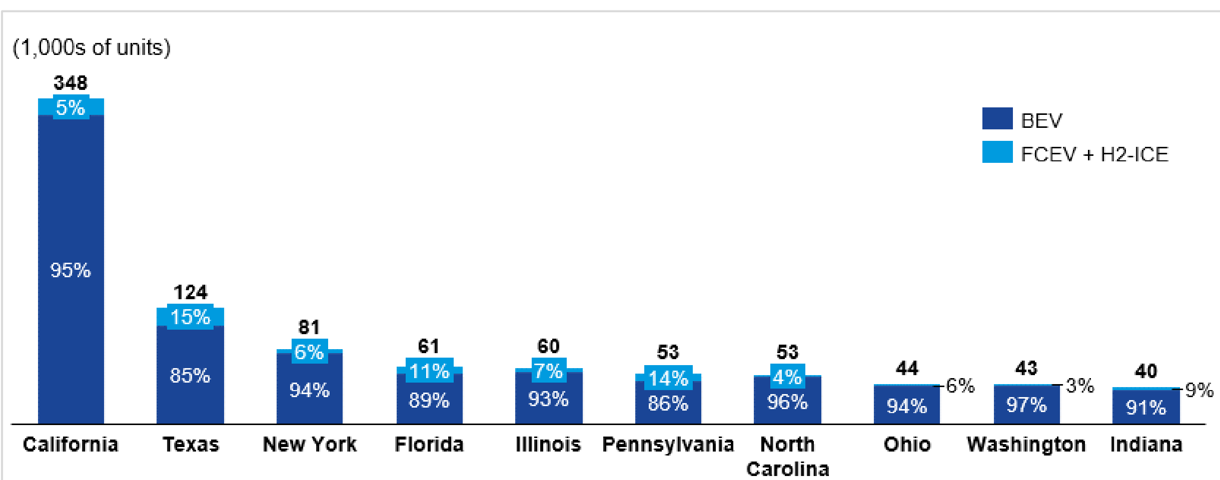
Figure 6: National Total ZEVs On the Road by 2032



As shown in Figure 7 below, the top 10 states for MHD ZEV sales represent ~60% of total projected nationwide MHD ZEV sales, led by California, which accounts for nearly 23% of total sales followed by Texas, New York, Florida, and Illinois, which individually account for over 3.5% of total ZEV sales.

EPA has not provided any sales forecasts for H2-ICE vehicles. Thus, Ricardo estimated those sales based on the IHS forecast and Ricardo's own analysis. Because of the advantages in performance and range, major applications for hydrogen ICE vehicles are heavy-duty and long-haul. As a transition technology, hydrogen ICEs are estimated to be adopted at 20% of FCEV in 2030, and are assumed to grow in sales by 30% year-over-year from 2030 to 2032.

Figure 7: Top 10 States of ZEV on road by 2032



3.2.2 MHD ZEV Sales by Class and Use Types

This section discusses the projected MHD ZEV sales by class and use types, as utilized by EPA in the "HD TRUCS" model. See Figure 8.[6]

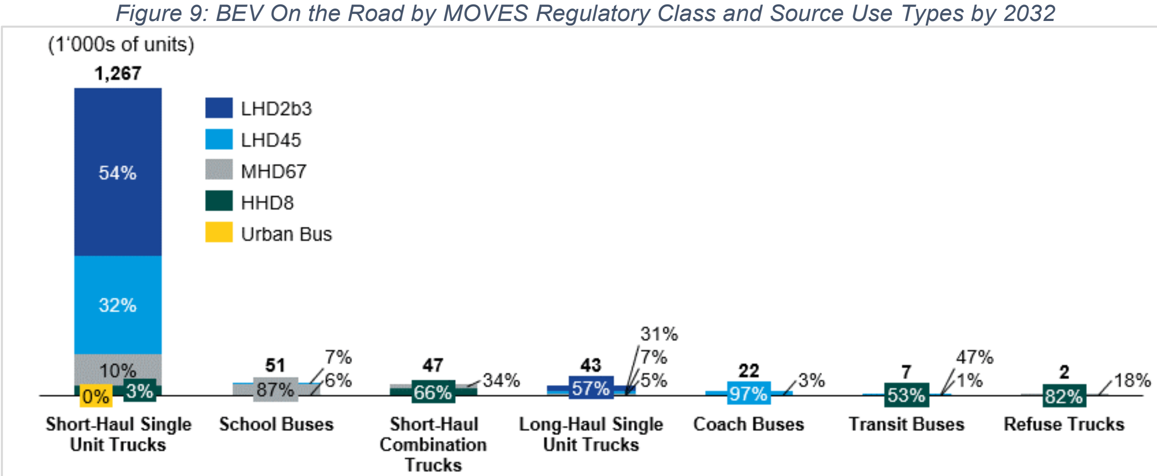
Figure 8: Matrix of Source Type – Regulatory Class Combinations in MOVES3

		Source Use Types												
		Motorcycles	Passenger Cars	Passenger Trucks	Light Commercial Trucks	Other Buses	Transit Buses	School Buses	Refuse Trucks	Short-Haul Single Unit Trucks	Long-Haul Single Unit Trucks	Motor Homes	Short-Haul Combination Trucks	Long-Haul Combination Trucks
Regulatory Classes		11	21	31	32	41	42	43	51	52	53	54	61	62
MC	10	X												
LDV	20		X											
LDT	30			X	X									
LHD2b3	41			X	X			X	X	X	X	X		
LHD45	42					X	X	X	X	X	X	X		
MHD67	46					X	X	X	X	X	X	X	X	X
HHD8	47					X	X	X	X	X	X	X	X	X
Urban Bus	48						X							
Gliders	49													X

The sales summarized in Figure 9 below reflect the forecast accumulated MHD BEV sales through 2032.

Over 80% of MHD BEVs are projected to be short-haul single-unit trucks (no trailer). Within short-haul applications, approximately 85% will be medium-duty (MD) vehicles (class 2b-5). Based on the Daily Operational VMT assumed in the HD TRUCS Model, the average daily range of MD short-hauls is below 80 miles. The MD short-hauls are primarily used for freight deliveries (return-to-base) and delivery of various local services, including utility companies. Thus, based on the duty cycle (return-to-base and less than 80 miles daily mileage), the MD short-hauls are expected to dominate the BEV-truck applications.

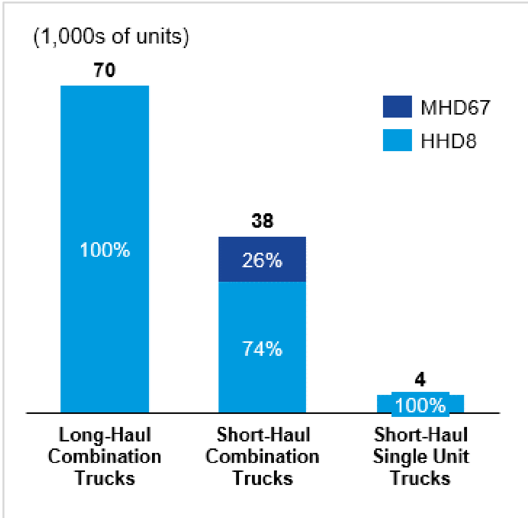
Figure 9: BEV On the Road by MOVES Regulatory Class and Source Use Types by 2032



[6] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

Currently, over 90% of the Class 7 and Class 8 trucks have diesel engines (IHS).[7] Since FCEVs and Hydrogen ICEs are still in the early demonstration stage, their adoption rate is not expected to ramp up until 2030. Due to the constraints in hydrogen capacity (production, transportation) and the relatively high fuel cost ($/kg), FCEV and hydrogen ICE vehicles are estimated to be only approximately 7% of the total MHD ZEV sales by 2032 and will be limited to long-haul applications.

Figure 10: FCEV + H2 ICE On the Road by 2032 by Regulatory Classes and Use Types



3.3 Summary of Key Insights

MHD ZEV sales through 2032 are expected to reach nearly 1.5 million BEVs and 111,000 FCEV and H2-ICE vehicles.

California is expected to continue to lead the pace of MHD ZEV adoption. Second to California, Texas is expected to be the highest in FCEV and H2-ICE vehicle adoption.

Based on EPA's modeling, over 80% of MHD BEVs by 2032 are expected to be short-haul single-unit trucks (no trailer). Within short-haul applications, approximately 85% will be medium-duty (MD) vehicles (Class 2b-5).

Over 60% of FCEVs and H2-ICE vehicles are expected to be used for the multi-purpose long haul (200 miles daily mileage) and regional haul (420 miles daily mileage).

[7] IHS Insight, 2024

4 Charging Infrastructure Demand Analysis

4.1 Methodology

To assess the charger demand from medium- and heavy-duty vehicle (MHDV) BEVs, we used the forecasted numbers of on-road MHDVs in 2032 along with specific charger size, type, and charging characteristic assumptions derived through EPA's HD TRUCS model.

4.1.1 Charging Characteristics

Charging behaviors were modeled to represent the average U.S. fleet for each MHDV segment. Refer to Table 33 in the Appendix, which lists charger location and charging characteristic assumptions for each MOVES vehicle class and source use type. Except for 4 HHD Class 8 use types, and based on EPA's HD TRUCS assessment, we assumed all fleets would use depot-based overnight charging to minimize the cost of charging.[8] The 4 HHD Class 8 use-types will rely on highway-based opportunity charging.

We assume stationary wired charging only to reflect the industry as it is developing in the United States. As noted, the charger size and type used for charging are based on input from EPA's HD TRUCS model. Table 3 below lists the characteristic charging inputs based on charger location.

Table 3: Charging Characteristic Inputs Based on Charger Location

Charger location	Charging type	Charger size and type	Total charging duration	Charger per vehicle	Charging sessions per day	Charging rate
Depot	Overnight	Based on input from the HD TRUCS model[9] 1. L2 19.2 kW 2. DCFC 50 kW 3. DCFC 150 kW 4. DCFC 350 kW	8 hrs.	1	1	Nominal power distributed over 8 hrs.
Highway	Opportunity		4 hrs.	0.16	6	Peak charger capability

[8] PG&E Business EV rate plans, https://www.pge.com/pge_global/common/pdfs/solar-and-vehicles/ev-charge-network/BusinessEVrate-fs.pdf
[9] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

4.2 Results

4.2.1 Charging Infrastructure Needs

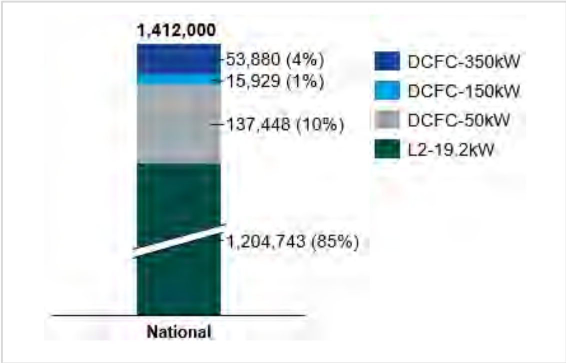
With the three inputs below, we determined national and state-level requirements for chargers in 2032.

1. 2032 national and state level MHDV ZEVs on road
2. Charging characteristics
   a. Charger location
   b. Charger size and type
   c. Charger per vehicle

4.2.2 National Level Charging Infrastructure Needs in 2032

Figure 11 below shows the national-level charger needs by each of the four charger types defined as per HD TRUCS[10] tool

Figure 11: National-level charger needs by charger size and type in 2032



[10] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

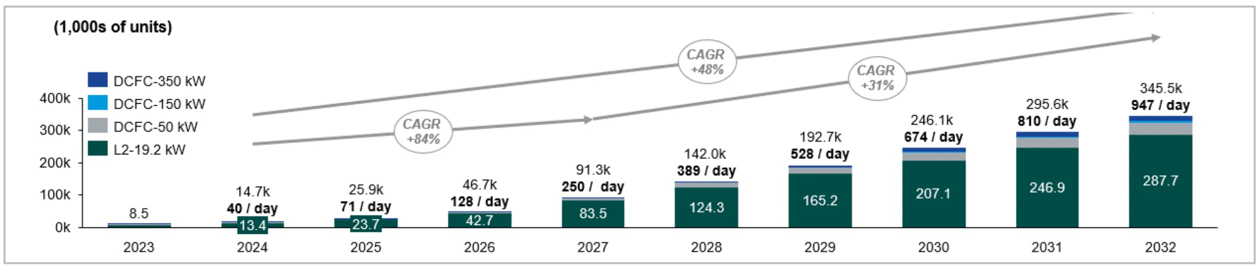
Based on forecasted BEV MHDV adoption rates and charging characteristics, we project a need for approximately 1.4 million electric chargers to support on-road MHD BEVs in 2032. Approximately 1.2 million (85%) of the chargers required are assumed to be L2 19.2 kW depot-based chargers, along with approximately 140,000 (10%) 50 kW DCFC fast chargers. With over 96% of the total MHDV population expected to charge at depot-based chargers, only 0.5% of total charger installations are assumed to be located on or adjacent to highways.

Table 4: Charger needs 2032 by location and charger size and type

Charger location	L2-19.2 kW	DCFC-50 kW	DCFC-150 kW	DCFC-350 kW	Total
Depot	1,204,743	137,448	15,929	44,262	1,402,399
Highway				9,601	9,601

When evaluating the requirement to have approximately 1.4 million MHD electric chargers installed by 2032 on an annualized deployment basis, the annual charger port deployment numbers start from a low of 40 charger ports/day in 2024 and climb to 947 charger ports / day in 2032, a roughly 24-fold increase. This amounts to an annualized growth rate of 48% from 2024 to 2032. Figure 12 below shows the annualized charger deployment rates from 2024 to 2032 along with expected annualized growth in charger deployment rates.

Figure 12: National charger deployment rates to reach ~1.4 million chargers by 2032



4.2.3 State-Level Charging Needs in 2032

Figure 13 below shows the total charger needs for the top 10 states in the U.S. California and Texas will need the largest numbers of chargers by 2032.

Figure 13: State-level charger needs by charger size and type in 2032

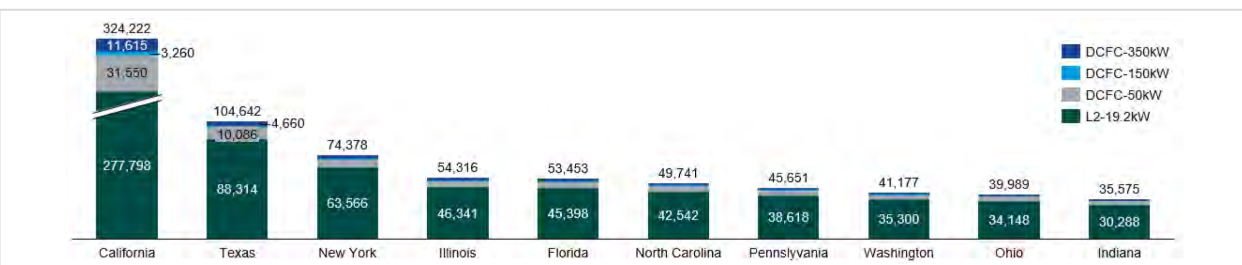


Table 5: List of national and state-level charger needs in 2032

State	DCFC-350kW	DCFC-150kW	DCFC-50kW	L2-19.2kW	% Of national charger needs
National	**53,880**	**15,929**	**137,448**	**1,204,743**	**100%**
California	11,615	3,260	31,550	277,798	23%
Texas	4,660	1,583	10,086	88,314	7%
New York	2,769	802	7,241	63,566	5%
Illinois	2,073	612	5,291	46,341	4%
Florida	2,186	700	5,169	45,398	4%
North Carolina	1,821	507	4,870	42,542	4%
Pennsylvania	1,971	655	4,406	38,618	3%
Washington	1,454	393	4,030	35,300	3%
Ohio	1,505	438	3,899	34,148	3%
New Jersey	1,401	425	3,461	30,288	3%

The top 10 states account for roughly 60% of the nation's charging needs. California accounts for the largest percentage share at 23%, 3-times more than the next state Texas, which will need approximately 105,000 total chargers. Table 31 in the appendix shows the year-over-year charging needs in the top 10 states.

4.3 Summary of Key Insights

The charging characteristics of MHD BEV trucks will vary by class and use type. Based on HD TRUCS, approximately 96% of the MHD BEVs are assumed to use depot-based overnight charging, requiring a nominal power demand through the assumed 8-hour charging session using either a L2-19.2 kW, DCFC 50,150-, or 350-kW charger.

With every MHD BEV expected to have a dedicated charger connector at the depot, this translates to a need for approximately 1.4 million depot-based chargers and 9,600 highway-based chargers.

In terms of annualized deployment rates, the annual charger port deployment numbers start from a low of 40 charger ports/day in 2024 and climb rapidly to 947 charger ports/day in 2032 to meet the target of approximately 1.4 million chargers.

It should be noted that the very high estimated number of L2 chargers is based on EPA's assumptions regarding the prevalence of depot-based charging, and the universal availability of overnight charging. If those assumptions are changed, the mix of chargers changes as well.

5 Charging Infrastructure Readiness

This section discusses the current MD/HD charging infrastructure and the gaps between the current charging infrastructure and the infrastructure required to meet the expected deployment of MHD ZEVs by 2032. In addition, Ricardo has provided recommendations to help achieve the necessary charging infrastructure development to meet EPA's ZE-truck adoption targets.

5.1 Current Charging Infrastructure

5.1.1 LDV vs. MHDV

As compared to LDVs, MHD ZEVs require larger battery packs to support the applications' more demanding range and service requirements. That, in turn, results in increased charging time and/or charger capacity requirements for charging MHD BEVs. Table 33 in the Appendix lists the assumed average battery size for MHD BEVs by sales class and use type.

LDV charging sites are not designed to accommodate the pull-through spaces, turning radii, or ingress/egress requirements for MHD BEVs, so LDV sites will provide little benefit for the majority of MHD BEVs.

The difference in battery pack size, charger requirements, and charging site infrastructure between LDVs and MHD BEVs will result in very limited interoperability between LDV and MHD BEV charging infrastructures, which necessitates the design and construction of dedicated MHD charging infrastructure solutions.

5.1.2 Current MHD Installations

The current charging infrastructure in the United States is primarily focused on LDV charging with approximately 205,000 charger ports nationwide.[14] Out of those total LDV charger ports, roughly 159,000 (~78%) ports are L2-kW charging ports, with the remaining 46,000 (~22%) being DC fast chargers. By contrast, there are currently only approximately 3,000 MHD BEV charging ports nationwide, with many of those being limited primarily to private depot-based installations.

[14] https://afdc.energy.gov/stations/#/analyze
[15] Figure 6: National Total ZEVs On the Road by 2032

5.2 Charging Infrastructure Investment Requirements by 2032

Using the forecasted number of chargers required to support the forecasted MHD BEV population on the road in 2032, we estimated the total capital investment needed to develop the charging infrastructure using a unit cost metric, "project cost per connector." The costs are estimated from NREL, NEVI, and ICCT- published data sources from prior installations and industry research. The project cost per connector is inclusive of the following costs:

1. Labor
2. Materials (charger port, electrical equipment for grid connection, etc.)
3. Permits
4. Taxes

Table 9 below shows the estimated cost for each charger type along with forecasted cost reductions (based on ICCT data)[19] primarily due to the economics of scale advantage from higher future EV adoption rates across all vehicle segments.

Table 6: EV Charger Installation Project Cost per Connector

Charger type	Project cost per connector 2022	% Forecasted cost reduction	Project cost per connector 2032
L2 19.2 kW	$ 8,000	25 %	$ 6,000
DCFC 50 kW	$ 79,500	35 %	$ 51,675
DCFC 150 kW	$ 171,000	25 %	$ 128,250
DCFC 350 kW	$232,500	35 %	$ 151,125

[19] https://theicct.org/wp-content/uploads/2021/06/ICCT_EV_Charging_Cost_20190813.pdf

5.2.1 Results

Table 10 below shows the total capital investment required to develop the charging infrastructure to support the forecasted numbers of MHD BEVs on the road in 2032, both on a nationwide basis and in the top ten states.

Figure 14: Investment Required to Develop Charging Infrastructure to Support Forecasted MHDV Vehicles on road in 2032

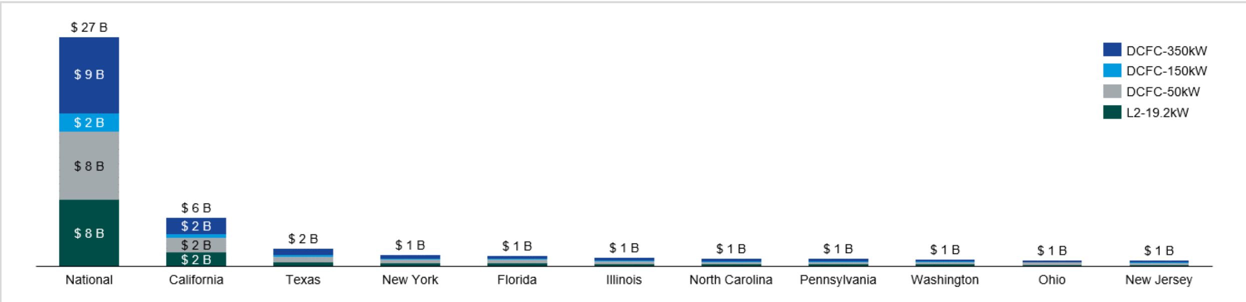


Table 7: Investment Required to Develop Charging Infrastructure to Support Forecasted MHDV Vehicles on road in 2032

State	DCFC-350kW	DCFC-150kW	DCFC-50kW	L2-19.2kW	The total investment needed ($ Billion)	% National Investment	No. of charge connectors
National	8.99	2.23	8.06	7.88	27.2	100%	1412000
California	1.91	0.45	1.74	1.69	5.79	21%	324222
Texas	0.79	0.22	0.57	0.56	2.14	8%	104642
New York	0.46	0.11	0.41	0.40	1.39	5%	74378
Florida	0.37	0.10	0.40	0.41	1.28	5%	54316
Illinois	0.35	0.09	0.30	0.29	1.03	4%	53453
North Carolina	0.32	0.08	0.27	0.26	0.93	3%	49741
Pennsylvania	0.33	0.09	0.25	0.25	0.92	3%	45651
Washington	0.25	0.06	0.26	0.26	0.83	3%	41177
Ohio	0.25	0.06	0.23	0.23	0.77	3%	39989
New Jersey	0.22	0.05	0.22	0.21	0.71	3%	35575

The estimated nationwide investment required to develop the necessary charging infrastructure to support the forecasted numbers of MHD BEVs on the road in 2032 is approximately $27.2 billion. That investment would support the installation of approximately 1.4 million MHD charger ports nationwide.

It is important to understand that the foregoing estimated investment is conservative, since it is premised on EPA's assumptions regarding the prevalence of depot-based charging and the universal availability of overnight charging. If those assumptions are changed, the need for higher-power DC fast chargers increases, which would increase the estimated capital investment substantially.

5.3 Charging Infrastructure Investment Required Scenario Analysis

As noted in the results above for the base case, we used EPA's HD TRUCS model to assess the charger types required for each type of MHD BEV. However, based on ongoing pilot programs and interviews of fleet operators, the more likely real-world scenario will require fleet operators to install higher-power 50 kW DC fast chargers to support fleet charging at depots. This would significantly increase the investment needed to develop the necessary charging infrastructure.

To determine the potential variation in investment required, we compared two additional scenarios to the base case forecasted capital investment of $27.2 billion.

Table 8: Charger type required scenarios

Scenario	Description
Base	Relies on EPA's HD TRUCS model to determine charger type by vehicle class and source-use type
A	Assumes that **DCFC-50 kW** chargers will be required for all vehicles using L2-19.2 kW chargers in the Base scenario
B	Assumes that **DCFC-150 kW** chargers will be required for all vehicles using L2-19.2 and DCFC 50kW chargers in the Base scenario

Figure 15: Total no. of charging stations in 2032 by charger type for each scenario

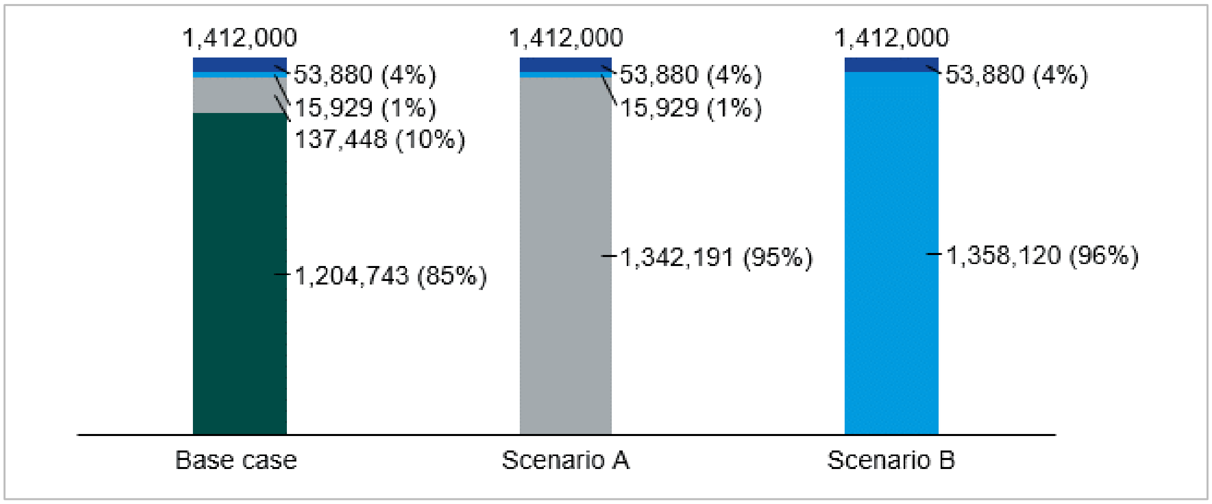
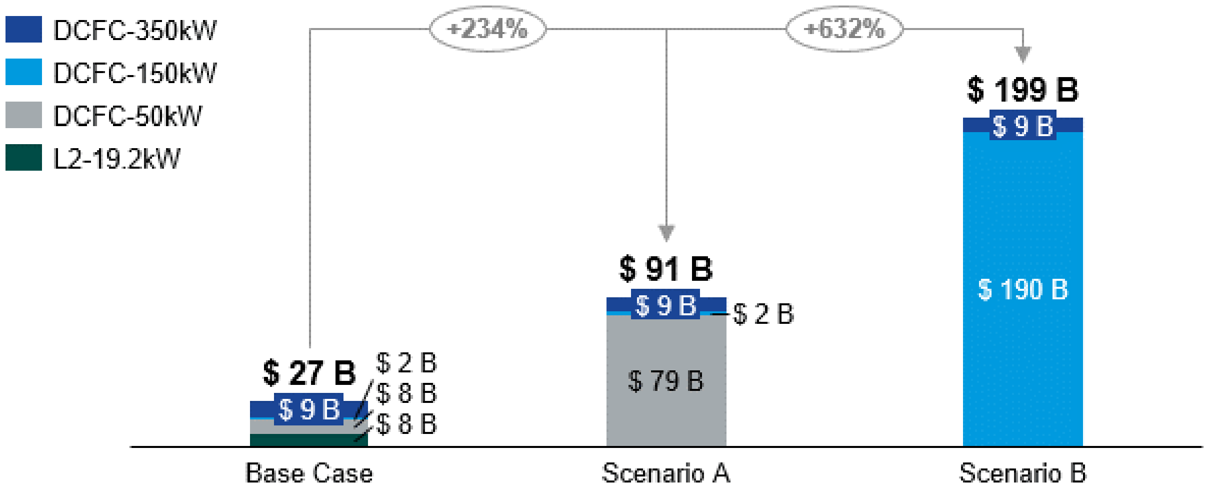


Figure 16: Investment required to support forecasted MHDV charging infrastructure in 2032



5. **Results for Scenario A:** With an increase in the number of required DCFC-50 kW chargers, the total required investment is approximately $91 billion, which is $64 billion (234%) higher than the Base case scenario
6. **Results for Scenario B:** Assuming DCFC-150 kW chargers as a standard charger type significantly increases the required investment to a total of approximately $199 billion, which is $172 billion (632%) over the Base case scenario
    a. The increased cost is primarily driven by the much higher cost for DCFC 150 kW chargers vs. L2 chargers ($128,250 vs. $6,000), using 2032 estimates.

5.4 State and Federal Charging Infrastructure Incentives and Funding

Table 12 below shows a summary of available state and federal charging infrastructure incentives and funding programs.

Table 9: Summary of State and Federal Incentives and Funding Eligible for MHDV Charging Infrastructure

Program	Public MHDV charging infra.	Private MHDV was charging infra.	Public vehicles	Private fleet vehicles	Eligibility Restrictions	Cumulative funding and duration
Grants for buses and bus facilities program[20]	X		X		None	**$2 billion** (5 yrs.)
Clean heavy-duty truck program[21]	X	X	X	X	None	**$1 billion** (10 yrs.)
Expansion of EV charging in underserved communities[22]	X				Justice40 underserved areas	NA
Alternative fuel infra. tax credit[23]	X	X			Low-income and non-urban communities with at least 20% poverty	NA (10 yrs.) 30% of equipment cost to the max of $100,000
CUPC – California public utilities[24]	X	X	X	X	70% percent toward MHDV charging	**$1 billion** (5 yrs.)

Federally funded programs like the grants for buses and bus facilities program, expansion of EV charging in underserved communities, and alternative infrastructure credit have restrictions that only support a specific vehicle class and/or limit nationwide eligibility.

[20] https://www.transit.dot.gov/bus-program
[21] https://www.epa.gov/inflation-reduction-act/clean-heavy-duty-vehicle-program
[22] https://www.energy.gov/articles/biden-harris-administration-announces-funding-zero-emission-medium-and-heavy-duty-vehicle
[23] https://afdc.energy.gov/laws/10513
[24] https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-adopts-transportation-electrification-program-to-help-accelerate-electric-vehicle-adoption

Our assessment is that these incentive programs will have minimal impact on supporting the development of the required MHD BEV charging infrastructure installations at private depots across the country.

Clean heavy-duty truck and CUPC programs are the only programs with funding eligible for private fleet vehicles to install charging infrastructure at private depots, with a total of $2 billion dollars of cumulative program value.

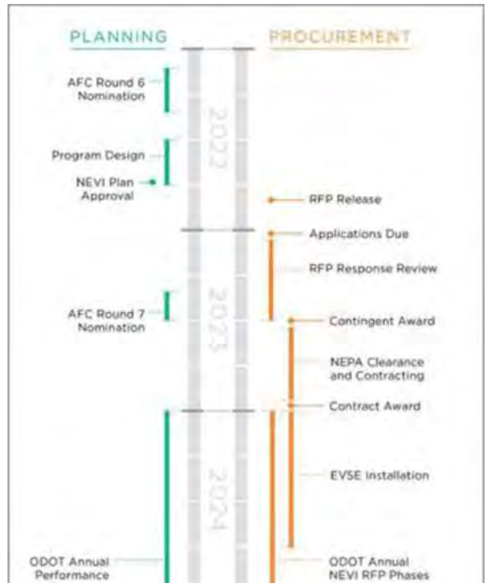
As allocated under the CUPC program, we have assumed that 70% ($1.4 billion) of the total available amount of $2.0 billion would be available for the development of MHD BEV charging infrastructure over the next 5 years.

5.4.1 Case study: NEVI LDV charging infrastructure deployment

As part of the 2021 Federal Bipartisan Infrastructure Law (BIL), the National Electric Vehicle Infrastructure (NEVI) Formula Program was established to provide funding to states to deploy EV charging infrastructure. The NEVI program required states to develop infrastructure deployment plans by June 2022 with a requirement for plans to be updated annually. $5 billion in NEVI funding is directed to build out a national network for recharging electric vehicles along designated Alternative Fuel Corridors, particularly along the interstate highway system. In September of 2022, the NEVI program approved state plans for charger deployments starting in 2023.

The Joint Office of Energy and Transportation released the Q3 2024 NEVI Quarterly Update on August 30th, 2024. There are now 69 NEVI-funded public charging ports in operation across 17 stations in 8 states. This is more than twice the number of NEVI ports as were operational in the previous quarter. Forty states have released their first round of solicitations, with 29 having issued conditional awards or having put agreements in place. Still, all in, those agreements cover the development of only approximately 2,800 fast charging ports at approximately 700 charging stations.

Figure 17: Ohio NEVI Implementation Timeline



Example: Ohio NEVI implementation[25]

1. First state in the nation to release RFP within a month after NEVI funding approval, running through January 2023 when the RFP closed
2. Received over 300 applications and provided contingent award to 30 sites – which equated to 120 charge ports
3. The first round of awards was announced in July 2023
4. Construction for Round 1 locations began in October 2023
5. Ohio Department of Transportation released the RFP for Round 2 in November of 2023, with Round 2 selections made in May of 2024
6. As of September 2024, the status of the Round 1 locations is as follows (by number of charging stations):
    - Operational: 6
    - Under construction: 12
    - Planning phase: 5

[25] https://drive.ohio.gov/programs/electric/infrastructure/nevi/nevi

Table 10: NEVI Round 1 Details for Several Leading States

State	Round 1 Awards Announced	Round 1 Construction Start	Total Round 1 Station Locations	Operational Station Locations
California[26]	Oct. 2023	NA	26	0
Michigan[27]	Jun. 2024	NA	39	0
New York[28]	NA	NA	23	3
Ohio	Jul. 2023	Oct. 2023	23	6
Pennsylvania[29]	Jun. 2023	Feb. 2024	52	2
Rhode Island[30]	Dec. 2023	Feb. 2024	4	4

[26] Cal GOV
[27] MDOT NEVI
[28] NY State NEVI Formula Program Plan Update July 2023
[29] PennDOT NEVI
[30] State of Rhode Island Office of Energy Resources

As seen in the Ohio NEVI implementation example and in the timeline in Figure 20, the first rounds of charger deployments from the NEVI program are expected to take longer than 2 years. As of September 2024, it has been 2 years since the Round 1 RFP opened in Ohio and only 6 of 23 charging station locations are operational. Furthermore, several states have highlighted the following barriers for NEVI-planned charging infrastructure deployment:

1. CA: New service utility interconnectors averaged 9 months, which delayed projects for 6 to 12 months
2. CA: PG&E estimates current proposed interconnection time will range from 3 to 5 months
3. NY: Transformer lead times will be in excess of one year
4. IL: “Buy America” supply chain readiness will constraint eligibility for federal funding

Once established installation processes are in place, charger deployment times are expected to shorten and will primarily depend on 2 key factors:

1. State resources for an effective and timely application review and approval process
2. Supply chain readiness of:
    a. Charger hardware providers
    b. Utilities (Transformers and Interconnections)

As states complete the first round of NEVI charger installations, stakeholders should continue to track the progress of the NEVI program through 2024 and into 2025 to assess lessons learned, to implement measures to reduce the charger-deployment timelines, and to develop enhanced programs for the required MHD BEV charging infrastructure.

5.5 Summary of Key Insights

The necessary MHD BEV vehicle charging infrastructure has limited interoperability with the LDV charging infrastructure primarily due to the following:

1. Larger battery size in MHD BEVs
2. Charging site requirements
    a. Drive-thru
    b. Turning radius
    c. Ingress/Egress

The primary differences between LDV and MHD BEV charging infrastructure requirements warrant a separate dedicated MHD charging infrastructure to support the forecasted population of MHD BEVs by 2032.

Current nationwide charging installations are designed to support LDV charging, with most of them located for public access. Charger installations at MHD fleet depots are currently limited to supporting ongoing BEV pilot programs.

The conservatively estimated investment required to develop the charging infrastructure necessary to support the forecasted numbers of MHD BEVs on the road by 2032 is approximately $27.2 billion. That investment would support the nationwide installation of approximately 1.4 million charger ports through 2032, with 85% of the ports being Level 2 chargers.

State and federal incentives and funding programs are constrained to supporting specific vehicle classes and regions. The CUPC program in California and the Clean Heavy-duty Truck Program from the Inflation Reduction Act of 2022 are the only programs that directly support MHD charging infrastructure development, with approximately $1.4 billion in eligible funding.

At a minimum, an additional investment of $ 26 billion in private and public funds will be required to address the shortfall and develop a sufficient charging infrastructure dedicated to MHD BEV charging at depots and near highways.

It must be emphasized that the estimated investment is highly sensitive to the types of chargers assumed to be necessary for efficient MHD BEV charging. If more DCFCs are required, costs will increase substantially, potentially by up to approximately $200 billion.

Apart from the size of the investments required, another critical factor to successful BEV-truck adoption is the “on-time” deployment of the necessary charging infrastructure. The pace of NEVI deployment is a real-world example for policy makers emphasizing the importance of EV charging infrastructure deployment times, and the inherent risks of delays.

6 BEV Charging Infrastructure Deployment Recommendations

Dedicated federal funding for MHD BEV charging infrastructure

The upfront costs of MHD BEV charging stations are significant, especially when considering the large installations required by MHD fleet operators. However, fewer incentives and funding programs are currently available for the MHD charging infrastructure due to the earlier stage of adoption of MHD BEVs compared to LD BEVs. As reflected in Table 12, there are only two ZEV incentive or funding programs eligible for MHD BEV charging infrastructure development. Similar to the NEVI,[31] which has allocated $7.5 billion to develop a nationwide network of 500,000 chargers to accelerate LD BEV adoption, a dedicated MHD BEV charging infrastructure program would facilitate the deployment of the necessary MHD charging infrastructure, which in turn would facilitate meeting EPA's Phase 3 GHG emission targets and ZE-truck adoption rates.

In setting up a dedicated federal funding program for MHD BEVs, it is imperative to consider the lessons learned from the deployment of the NEVI program and to compare the assumed vs. real-world charger deployment rates.

1. The pace of NEVI charger deployment is a real-world example of the delays that can frustrate both the deployment of the necessary EV charging infrastructure and the increased adoption rate of BEVs.
2. As states complete the first round of NEVI charger installations, stakeholders should track the NEVI program through 2024 and 2025 to gain insights for how to avoid delays and for developing enhanced programs for the MHD charging infrastructure.

FHWA guidance on MHDV charging standard

Based on EPA's Phase 3 GHG emission standards, the adoption of MHD BEVs is expected to grow to 11% of new vehicle sales by 2027, and the number will increase even further, up to 41% of new vehicle sales by 2032. To support such a steadily increasing adoption rate over the next five years, the Federal Highway Administration (FHWA) should work with truck OEMs, fleet operators, charging service providers, utilities, and other stakeholders to develop guidance for MHD ZE-truck charging standards. This will help provide stakeholders an opportunity to address specific needs as well as share their experience to develop a standardized MHD charging standard.

Ongoing technological innovation for MHD BEV charging is anticipated, including megawatt charging which is likely to be used for charging Class 8 BEV trucks at highway-based charger installations. However, based on the adoption rate targets set in the EPA Phase 3 GHG emission standards, short-haul single-unit trucks are forecasted to have the highest BEV adoption rates. Those are vehicles that will primarily return to their depots for overnight charging.

[31] https://www.fhwa.dot.gov/environment/nevi/

We recommend that FHWA consider a two-phased approach for issuing guidance and standards: first, for depot- based charging installations to support vehicle applications that return to the home base every day; and second, for highway-based charging installations.

Charging site design recommendations

Larger sizes of MHD BEVs present accessibility constraints. Listed below are a few factors which need to be considered when designing an MHD BEV charging site:

1. Drive-thru accessibility
2. Turning radius
3. Ingress/egress
4. Longer dwell times

We recommend FHWA include charging site design considerations as part of the development of MHD BEV charging standards.

The government needs to take the necessary steps to drive collaboration among utilities and fleet operators

To manage the forecasted increase in electrical demand from the required MHD BEV charging infrastructure, utilities need to develop programs to leverage the existing smart charging and fleet management software, based on unique fleet use cases and sizes. That will help utilities:

1. Plan their load profiles and develop custom service contracts with individual customers
2. Manage a more certain load forecast, eventually benefitting fleet customers' TCO
3. Utilize efficient workforce planning and training

While also helping fleet operators to:

1. Understand any potential supply chain issues that will impact the fleet electrification road map
2. Plan investments for fleet electrification and associated infrastructure costs

As part of the development of MHD BEV charging standards and grant program, we recommend that the federal government take the necessary steps to ensure that utilities and fleet operators collaborate to plan and develop efficient charging infrastructure solutions leveraging smart-charging technology.

7 Hydrogen Demand Analysis

MHD BEVs are being developed for a range of applications. However, electrification has been considered a challenge for higher-mileage and heavier-load vehicle applications. FCEVs and H2-ICEs are expected to be used for a significant share of HD regional and long-haul applications. As FCEVs and H2-ICEs are at a pre-commercial stage, EPA projected the FCEVs ramp-up to begin in 2030.

This section discusses the hydrogen demand to meet the projected FCEV and H2-ICE sales from 2030 to 2032.

7.1 Methodology

Ricardo calculated the hydrogen demand for both FCEVs and H2-ICEs based on EPA's projections (national FCEV sales) and Ricardo's forecasts (state FCEV sales, national and state H2-ICEs sales) and the relevant duty-cycle parameters. Ricardo multiplied the total volume of FCEVs and H2-ICEs between 2030 and 2032 by the daily mileage, fuel efficiency, and annual working days to calculate the aggregate hydrogen demand.

An example of the calculation procedures for determining the national hydrogen demand for multi-purpose long-haul and regional haul trucks is shown in Table 11.

Table 11: Example of Hydrogen Demand Estimation

Parameters	MOVES Source TypeID	Long-Haul Combination Trucks	Long-Haul Combination Trucks
	MOVES RegClassID	HHD8	HHD8
	Vehicle ID	78Tractor_SC_Cl8_MP	79Tractor_SC_Cl8_R
Daily Operational VMT (miles per day)		200	420
Fuel Efficiency(kWh/mile)		3.57	3.56
FCEV Fuel Efficiency (H2 kg/mile)		0.104	0.104
Annual Average Working Days (number of days)		260	260
Annual Hydrogen Demand per FCEV (H2 kg)		**5,408**	**11,357**
National FCEV Sales by 2032		16,729	43,016
Total FCEV Hydrogen Demand (H2 kg)		**90,470,432**	**488,524,108**

The values of daily mileage and fuel efficiency (kWh/mile) were obtained from the EPA's HD TRUCS Model. The values used for estimating hydrogen demand are shown in Table 12 by source type, regulatory class, and vehicle ID.

Table 12: Values from HD TRUCS Model

MOVES Source TypeID	MOVES RegClassID	Vehicle ID	Daily Operational VMT (miles per day)	Fuel Efficiency (kWh/mile)
41 Other Buses - Coach Bus	47 HHD8	17B_Coach_Cl8_R	158	3.13
41 Other Buses - Coach Bus	47 HHD8	18B_Coach_Cl8_MP	158	3.13
62 Long-Haul Combination Trucks	47 HHD8	78Tractor_SC_Cl8_MP	200	3.57
62 Long-Haul Combination Trucks	47 HHD8	79Tractor_SC_Cl8_R	420	3.56
52 Short-Haul Single Unit Trucks	47 HHD8	80Tractor_DC_Cl8_HH	106	5.17
61 Short-Haul Combination Trucks	46 MHD67	81Tractor_DC_Cl7_R	120	2.88
61 Short-Haul Combination Trucks	47 HHD8	82Tractor_DC_Cl8_R	216	3.51
61 Short-Haul Combination Trucks	47 HHD8	84Tractor_DC_Cl8_U	216	3.51

Ricardo converted the fuel efficiency from kWh/mile to kg/mile according to DOE's conversion factors.[32]

1. GGE = Electricity kWh x 0.031
2. GGE = H2 kg x 1.019

The fuel efficiency of H2-ICE is estimated to be approximately 19% worse than FCEV between 2030 and 2032 [33].

7.2 Results

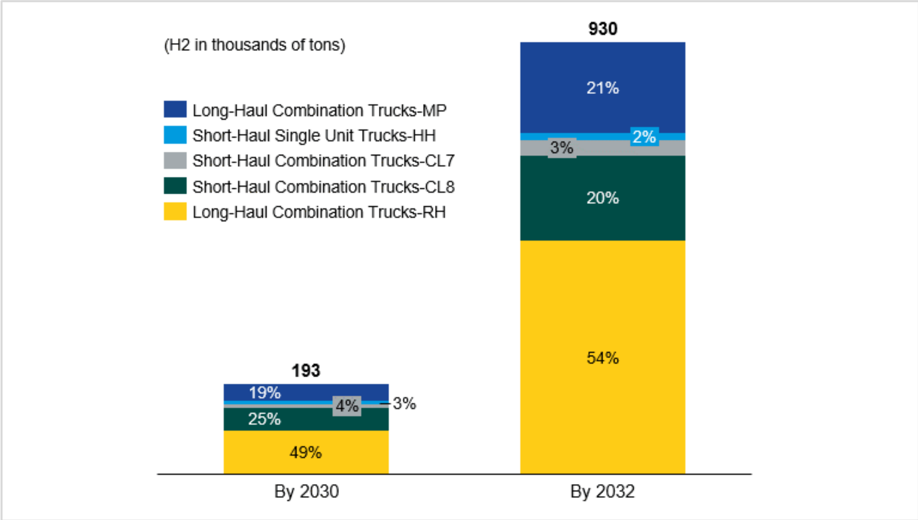
To achieve the targeted adoption rates of FCEVs and H2-ICEs (see Figure 6), the estimated hydrogen demand is 190 thousand tons/year by 2030 and 930 thousand tons/year by 2032 (Figure 18). Regional-haul applications comprise over 50% of total hydrogen demand, followed by Class 8 short-haul combination (with trailer) applications, which make up approximately 15% of the total share.

The daily range of both regional-haul and Class 8 short-haul combinations exceed 200 miles. As discussed previously, FCEVs and H2-ICEs are expected to take a significant share of higher-mileage and heavier-load applications.

The hydrogen demand analysis results by each state, source type, and class are shown in Figure 19.

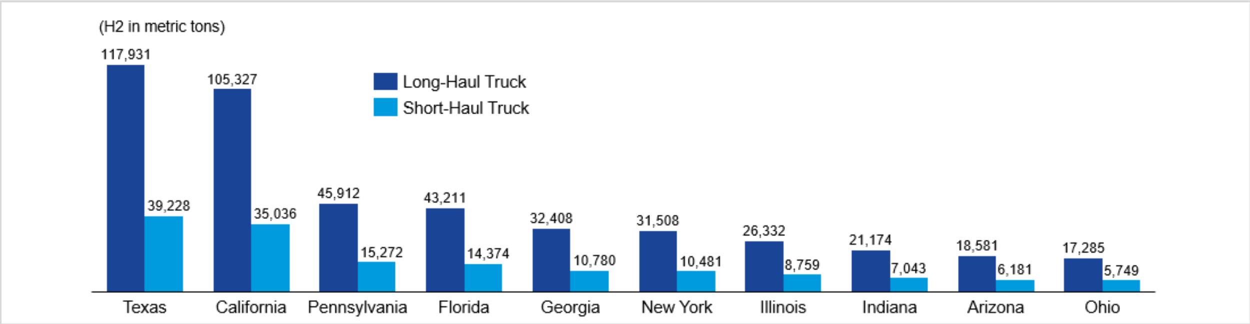
[32] DOE, https://epact.energy.gov/fuel-conversion-factors
[33] 43rd International Vienna Motor Symposium, 2022, https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Figure 18: Annual Hydrogen Demand



Texas and California will lead the hydrogen demand. California is pushing the decarbonization of HD vehicles, while Texas has a large HD truck market and significant advantages in hydrogen resources to promote hydrogen adoption.

Figure 19: Top 10 States of Annual Hydrogen Demand by 2032



7.3 Summary of Key Insights

The nation's hydrogen demand is expected to be 0.93 M tons/year by 2032. Regional-haul applications will comprise over 50% of total hydrogen demand. California and Texas are projected to be the dominant players in driving hydrogen demand.

8 Hydrogen Infrastructure Readiness

This section discusses the hydrogen infrastructure capacity and the gap between the current hydrogen infrastructure capacity and the hydrogen demand projected by 2032. In addition, Ricardo has provided recommendations to help accelerate the adoption rate for the hydrogen market.

8.1 Hydrogen Infrastructure Capacity

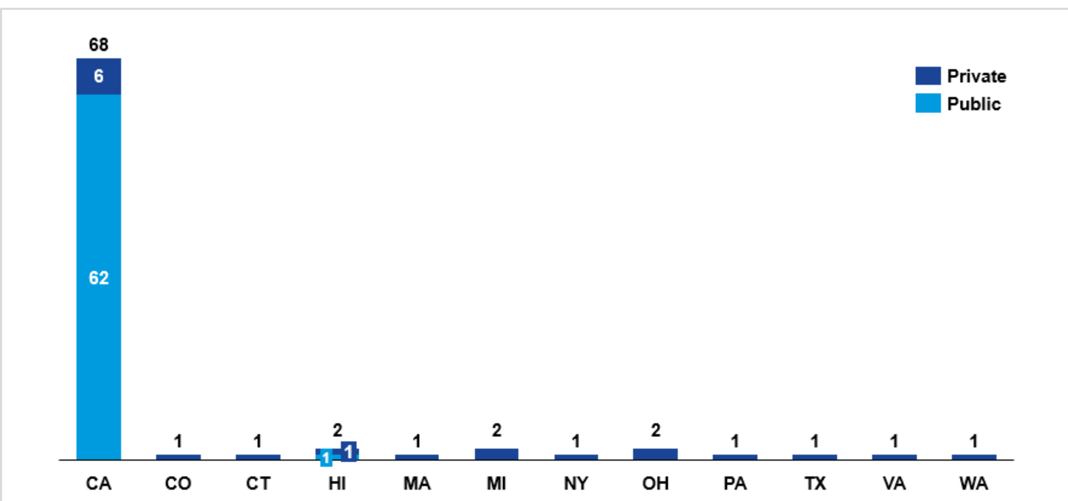
8.1.1 Current LDV Hydrogen Infrastructure Capacity

A robust hydrogen infrastructure is a critical element of MHD FCEV and H2-ICE adoption. Although LD FCEVs are commercialized, only 82 refueling stations are open nationally as of August 2024.[34] More than 80% of those LDV refueling stations are located in California.

LDV hydrogen refueling stations are typically sited at gas stations (~56% of LDV hydrogen stations are in gas stations). Other key facility types are shown below:

1. Public: Convenience store, college campus, dealer, office building
2. Private: Fleet garage

Figure 20: Hydrogen Refueling Station - LDV



8.1.2 HDV Infrastructure Requirements Compared to LDV

Due to constraints in storage capacity and fueling rate, a LD hydrogen refueling station is not expected to dispense at the volume or rate that an HD FCEV or H2-ICE will require.

[34] DOE, August 2024, https://afdc.energy.gov/stations#/

Thus, the capacity of LD hydrogen refueling stations is not factored into this assessment. The two main constraints of LD refueling stations are noted below:

Storage Capacity

Current LDV stations do not have enough storage capacity to fuel MHDVs at scale. A high-volume refueling operation may cause the LDV station to terminate fueling, as the system may consider that higher volume to be a leak in the tank or some other fault. Standards for LDV fueling are generally not compatible with HDVs. SAE J2601 (for LDVs) only allows fueling for tanks that have a maximum storage capacity of 10 kg, but HD trucks are expected to have a much larger tank system (40–100 kg).

Fueling rate

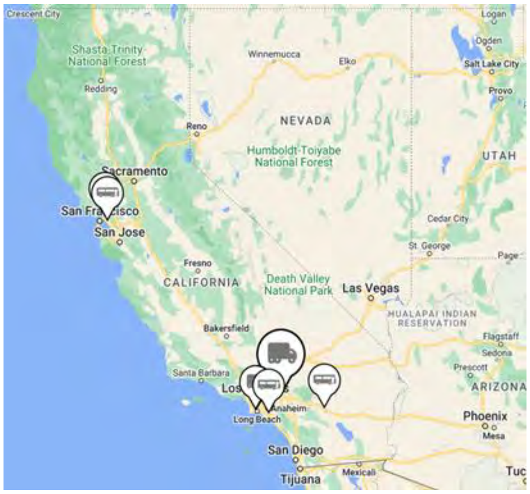
SAE J2601 (LDVs) only allows for fueling at a maximum rate of ~3.6 kg per minute. HD FCEVs require an average rate of ~8-10 kg per minute, which is the diesel-equivalent fueling rate for a Class 8 truck using DOE's interim target for 2030 of 8 kg per minute.

8.1.3 HDV Infrastructure Capacity

As HD FCEVs and H2-ICEs are in earlier stages of development than LDVs, very few HD hydrogen refueling stations have been deployed. Seven HD refueling stations are deployed in California through the Hydrogen Fuel Cell Partnership (Figure 21).[35] Four of them were deployed for HD fuel cell electric buses (FCEB), and the other three are at Shell stations designed for HD trucks.

Other than the seven deployed HD hydrogen refueling stations, another 12 stations (45 dispensers) have been funded by California Energy Commission (CEC) as of August 2024 and are to be deployed in California in the future (deployment dates unknown). The capacity of the funded stations range from 2000 kg to 6000 kg.

Figure 21: HD Hydrogen Refueling Stations in California



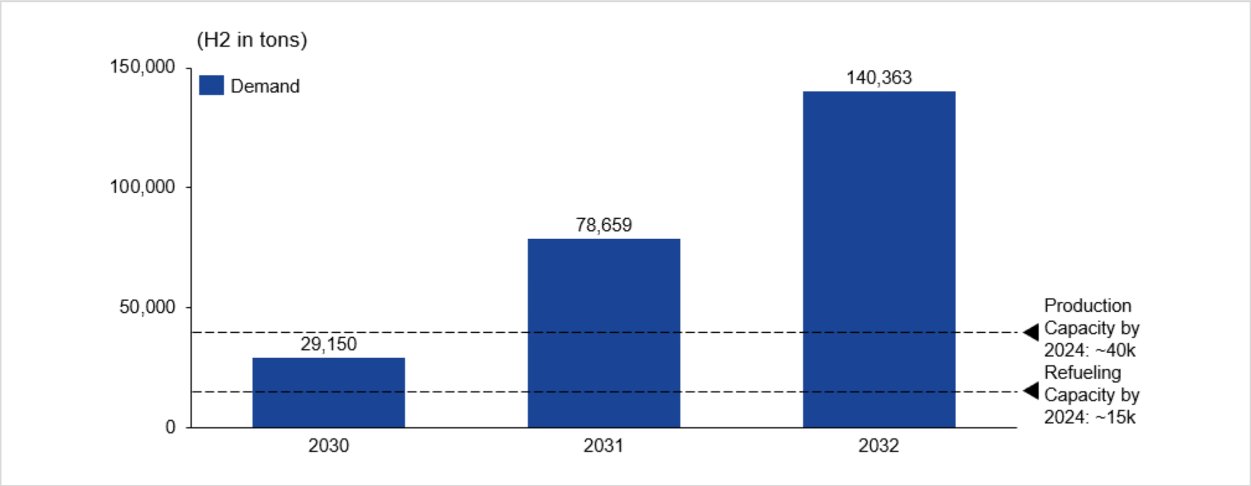
[35] Hydrogen Fuel Cell, https://h2fcp.org/stationmap

Although more than 300 fuel cell electric buses (FCEB) have been deployed,[36] most of the FCEB fleets have less than five hydrogen buses and use hydrogen refueling stations with coordinated on-site production.[37] The hydrogen refueling stations with on-site production are for private purposes and with lower capacity compared to HD refueling stations. Thus, the capacity of small FCEBs fleets (less than 5 FCEBs) with on-site production is not factored into the capacity estimation.

Based on a CALSTART California hydrogen market assessment report,[38] the hydrogen refueling capacity in California's truck clusters is estimated to be approximately 15 thousand tons/year. That refueling capacity is projected to be half of the required annual demand by 2030. Accordingly, a hydrogen gap of over 125 thousand tons/year will need to be filled in California by 2032.

[36] CALSTART, Feb 2024, Zeroing on ZEBs, https://calstart.org/wp-content/uploads/2024/02/Zeroing-in-on-ZEBs-2024_Final-022324a.pdf
[37] NREL, https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html
[38] CALSTART, Mar 2023, Roadmap to Fuel Cell Electric Truck Commercialization

Figure 22: Hydrogen Refueling and Production Capacity by Funded Projects



Ricardo conducted public domain research on the planned and funded hydrogen refueling stations from various sources (e.g., industry and state governmental agencies). However, only a few states have developed roadmaps for hydrogen infrastructure. It is unclear what total refueling capacity is included in funded projects. Thus, Ricardo estimated the number of HD hydrogen refueling stations required to meet the 2032 target based on the projected hydrogen demand by 2032.

8.2 Hydrogen Infrastructure Needs by 2032

Ricardo estimates that 1192 HD hydrogen refueling stations will need to be developed to meet the 2032 FCEV and H2-ICE targets. Approximately 380 stations will need to be deployed in Texas and California. The estimated hydrogen refueling infrastructure needs by state are summarized in Table 13.

Table 13: Hydrogen Refueling Station Needs by 2032 by State

State	# Of Stations Needs by 2032	State	# Of Stations Needs by 2032
Texas	201	Washington	14
California	180	Maryland	14
Pennsylvania	78	Alabama	14
Florida	74	Louisiana	14
Georgia	55	Oregon	13
New York	54	South Carolina	10
Illinois	45	Nebraska	9
Indiana	36	Iowa	7
Arizona	32	New Hampshire	6
Ohio	30	Kansas	5
Oklahoma	27	Nevada	5
Missouri	26	Connecticut	5
North Carolina	24	New Mexico	5
Michigan	24	Maine	5
Tennessee	20	Kentucky	5
Massachusetts	20	Arkansas	5
Wisconsin	18	Idaho	4
New Jersey	17	Mississippi	4
Utah	17	Montana	4
Minnesota	17	Hawaii	3
Colorado	16	Vermont	3
Virginia	15	South Dakota	2

High-capacity hydrogen refueling stations (with an estimated ~4,000 kg daily capacity) are expected to be developed for HD FCEVs and H2-ICEs in our study between 2030 to 2032. The annual capacity per refueling station is estimated to be 1.04 M tons (4000 kg/day X 260 days/year).

An example of the calculation procedures for determining California's hydrogen station needs is shown in Table 14.

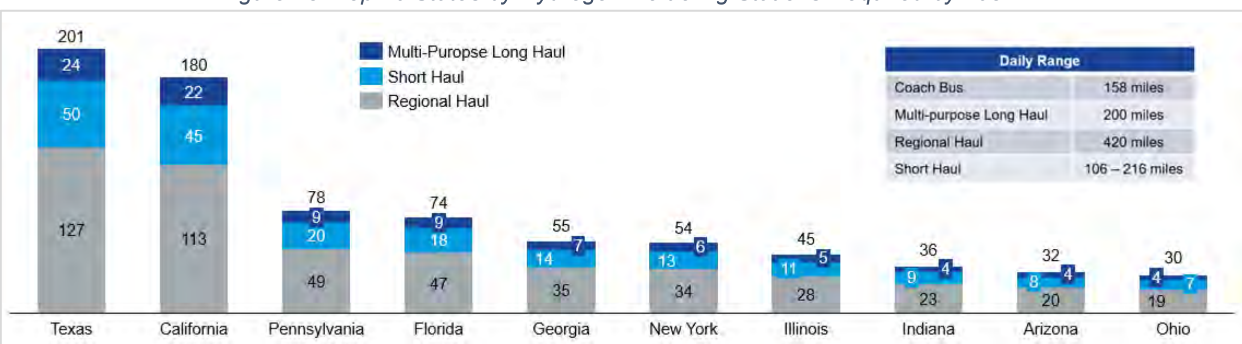
Table 14: Example of Hydrogen Infrastructure Needs Analysis

Annual gaps between hydrogen demand and capacity - California	140 M tons
Daily station capacity	4,000 kg
Annual hydrogen refueling station capacity per station	1.04 M tons
Utilization rate	75%
# Of stations needed	180

Over 60% of hydrogen refueling stations are expected to be deployed for regional-haul applications. Due to their duty cycle (420 miles daily mileage), regional haul applications may be heavily reliant on public hydrogen refueling networks. Across the U.S., California and Texas are expected to lead the infrastructure deployment for hydrogen refueling. Approximately 404 stations will need to be installed in the hydrogen refueling network in or connected to California or Texas (stations in California, Texas, Oregon, Nevada, and New Mexico).

Approximately 40% of the hydrogen refueling stations will need to be installed for return-to-base applications. With daily operations ranging from 106 miles (heavy haul) to 216 miles, those HD applications may require a mix of depot refueling and public refueling networks.

Figure 23: Top 10 States by Hydrogen Refueling Stations Required by 2032



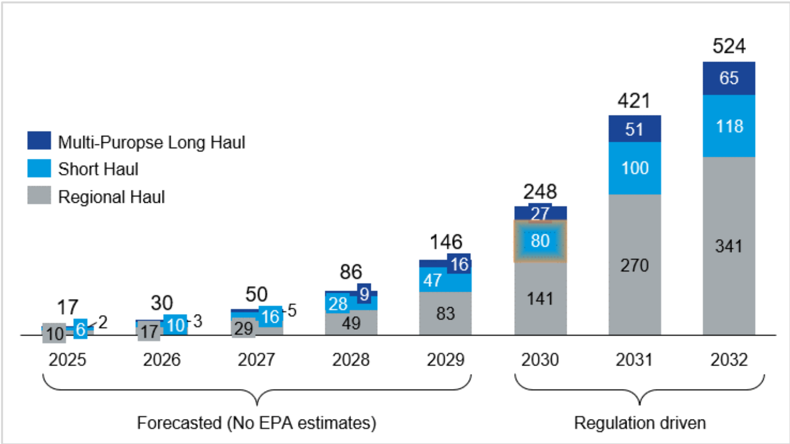
8.3 Hydrogen Infrastructure Deployment Timeline

To meet the hydrogen demand calculated in section 7, we estimated the required timeline for refueling station deployment.

Approximately 421 and 524 hydrogen refueling stations are expected to be deployed in 2031 and 2032, respectively. Roughly 65% of those stations will be deployed for regional haul applications, meaning that 270 and 341 public refueling stations along interstate highways, intrastate highways, and in truck clusters will need to be deployed in 2031 and 2032, respectively (see Figure 33).

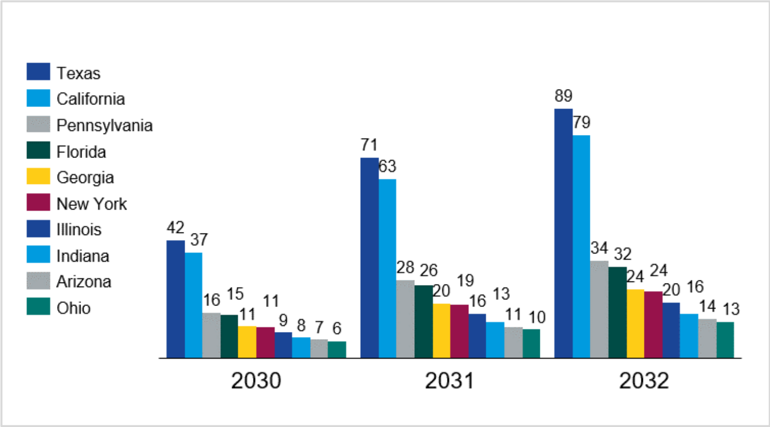
As no FCEV adoption was forecasted by EPA before 2030, the refueling station deployment between 2027 and 2029 was back-calculated using 1) the total number of refueling stations required by 2030, and 2) the estimated growth rate between 2030 and 2031.

Figure 24: Annual Hydrogen Refueling Stations Deployment Required by Applications



Most of the top 10 states are expected to deploy their first heavy-duty long-haul hydrogen refueling station by 2028. That said, the development of hydrogen fueling stations is a time-intensive exercise. Thus, the stations' funding, design, and planning must be scheduled at least 1-2 years earlier than the deployment timeline. California is leading the development efforts and has several refueling station projects funded, but without a clear timeline from publicly available sources. We estimate that only 16 refueling stations will have been installed in California by 2027 based on 1) California's current and projected refueling capacity, and 2) the capacity per station (annual capacity of 1.04 M tons). The refueling station deployment timeline by each state is listed in Appendix C in Table 38.

Figure 25: Top 10 States by Annual Hydrogen Refueling Stations Deployment



8.4 Hydrogen Infrastructure Investment Requirements by 2032

8.4.1 Methodology

In this study, Ricardo estimated the total hydrogen infrastructure investment needs based on capital cost per station and the number of stations required. The capital costs are derived from the recent Technical Report from NREL titled "Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles", which were also compared to the published costs of HD refueling stations. Capital costs include equipment costs and installation and commissioning. The costs for the hydrogen transportation infrastructure (e.g. pipelines) are not included in the capital costs.

The typical station for this study was defined as having a total daily hydrogen capacity of 4,000 kg/day and 2 dispensers. For this typical station, the capital cost per installed capacity is $2,730 per kg. The station assumptions for this study are summarized below in Table 15. Available capital cost data from deployed stations can be found in Table 21.

Table 15: Typical MDHD Hydrogen Refueling Station Assumptions

Metric	
Daily Capacity [MTPD]	4
Daily Capacity [kg/day]	4,000[39]
Dispensers	2
CAPEX [$M]	10.92
Levelized CAPEX [$/kg]	10.92

Table 16: Hydrogen Refueling Station Costs per Capacity

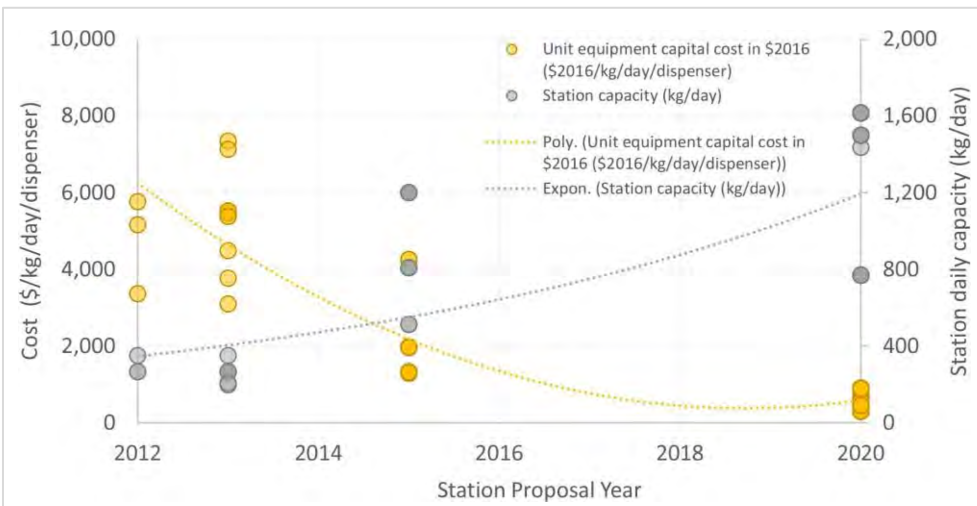
Project	Daily Capacity	Refueling Station Specs	Liquid or Gaseous	Estimated Costs (Total funding)
Shell[40]	5000 kg	3X350 bar and 3X750 bar fueling positions	Gaseous fuel delivery	$6.8M
Orange County Transportation Authority	4,536 kg	350 bar	Not Available	$6M
First Energy's NorCal Zero station	1,610 kg	700 bar	Liquid hydrogen delivery	$8.2M

[39]NREL, 2024, https://www.nrel.gov/docs/fy24osti/88818.pdf

Alameda-Contra Costa Transit -Emeryville Facility[41]	1,750 kg	Not Available	Not Available	$4.4M
Average cost per dispensed capacity (daily capacity)				**~$2600/kg**

HD hydrogen refueling station costs are expected to follow the cost reduction path of LDV hydrogen refueling stations due to anticipated economies of scale. The cost of LDV stations decreased by approximately 80% from 2012 to 2020 and by approximately 45% from 2016 to 2020 (Figure 35). As the current HD hydrogen market seems to be at a similar stage (early commercialization) as the LD FCEV market was in 2016 based on the comparison of cumulative sales, the HD hydrogen refueling station costs are expected to reduce by approximately 45% as of 2032. With a 45% cost reduction, the capital cost per dispensed capacity (daily capacity) is estimated to be approximately $1,775/kg. As a result, the estimated capital cost is approximately $7.1 million for each hydrogen refueling station with a dispensed capacity of 4,000kg/day.

Figure 26: Capital Cost of LDV Hydrogen Refueling Station[43]



[40] Oregon Department of Transportation, 2022, Hydrogen Pathway Study
[41] AC Transit, 2021, https://www.actransit.org/sites/default/files/2021-06/0604-20%20Report-ZEB%20Perf_FNL_062321.pdf

8.4.2 Results

Based on the estimated infrastructure costs and number of hydrogen stations needed to meet the EPA's ZE-truck target by 2032, the necessary upfront investment in hydrogen refueling station infrastructure is approximately $7.2 billion, as shown in Table 17. Approximately $4.5 billion of that investment is needed to serve the longer-range regional haul applications in the refueling network.

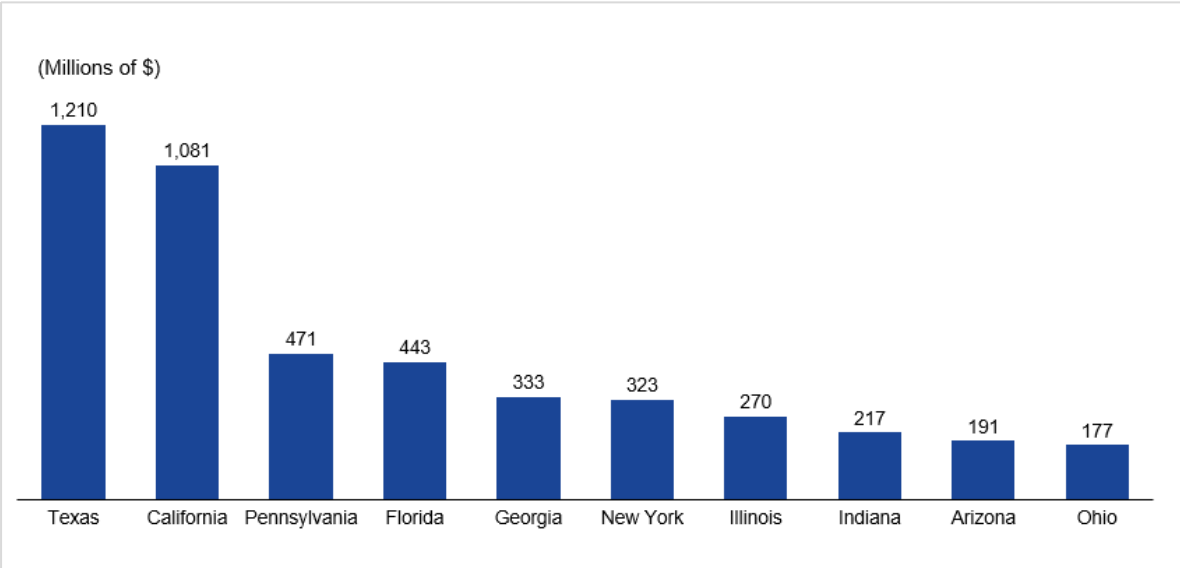
Table 17: Estimated Hydrogen Refueling Station Investment Requirements

Use Case	# Stations	Total Capital Cost
Multi-purpose Long-Haul	143	$0.9 B
Regional Haul	752	$4.5 B
Short Haul	298	$1.8 B
Total Investment	**1192**	**$ 7.2 B**

Approximately $2.3 billion in investments will be required to serve FCEV and H2-ICE in California and Texas, as shown in Figure 36.

[43] DOE, 2020, https://www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf

Figure 27: Top 10 States by Investments Required for Hydrogen Refueling Stations by 2032



8.5 Federal and State Hydrogen Infrastructure Incentives and Funding

With an estimated total of $0.54 billion in available incentive funding, the required additional investment for the necessary hydrogen infrastructure is $6.7 billion (Table 18). Estimated funding or incentives for hydrogen refueling stations are shown in Table 18. For incentives and funding not dedicated to hydrogen technology, it is assumed that 30% of the funding could be allocated to hydrogen refueling station projects, except for IIJA where funding dedicated to hydrogen refueling was calculated based on how past awards were used and H2HUBS.

The key available funding or incentives are shown in Table 36 in Appendix C.

Table 18: Estimated Funding for Hydrogen Refueling Station

Federal / State	Program	Estimated Funding for Hydrogen Refueling Station
Federal	H2HUBS	$350 M (out of ~50B expected to be leveraged from $7 B DOE investment)
	IIJA Charging and Fueling Infrastructure	$120 M (out of $800 M)
California	EnergIIZE	$20 M
Texas	Governmental Alternative Fuel Fleet (GAFF); Alternative Fueling Facilities Program (AFFP)	$3 M
New York	ZEV Rebate and ZEV Fueling Infrastructure Grant for Municipalities	$17 M
Pennsylvania	EV Charging Station and Hydrogen Fuel Cell Infrastructure Grants	$15 M

8.6 Summary of Key Insights

The required additional investment for HD refueling stations is estimated to be $6.7 billion. That estimate is based on the forecast and estimate of HD refueling stations' needs, the capital cost of HD refueling stations, and federal and state incentives and funding.

1. **HD hydrogen needs**
   1,192 HD hydrogen refueling stations will need to be developed to meet the 2032 FCEV and H2-ICE targets. 380 stations are expected to be deployed in Texas and California.
2. **Capital costs**
   The estimated capital cost is approximately $7.1 million for each MHD hydrogen refueling station with a dispensed capacity of 4,000kg/day.
3. **Federal and state funding**
   Approximately $0.5 billion in estimated incentive funding is available for MHD hydrogen refueling stations.

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[44] DOE, National Clean Hydrogen Strategy Roadmap, 2023

9 Hydrogen Infrastructure Deployment Recommendations

Accelerate deployment of hydrogen refueling corridors and hydrogen public refueling stations in truck clusters

As over 50% of FCEVs and H2-ICEs are expected to be deployed for longer mileage applications (>200 daily miles), the majority of hydrogen applications may not return to base daily. Thus, access to public hydrogen refueling network will be required to support the anticipated deployment of FCEVs and H2-ICEs. Additionally, the deployment of public refueling stations can save the upfront costs for truck fleets and support FCEV and H2-ICE adoption.

1. **Hydrogen Corridors development**
   Under the Alternative Fuels Corridors (AFC) program of the Federal Highway Administration (FHWA), several interstate highways and state highways are designated as hydrogen AFCs. However, most of the designated AFC is still pending (no refueling station or not at the right frequency).[45] Thus, investment and support are needed to build-up and accelerate HD hydrogen refueling corridors.

2. **Public refueling stations in truck clusters**
   Fuel cell trucks and H2-ICE trucks make up roughly 90% of projected hydrogen demand from vehicles. Thus, it is important to build hydrogen infrastructure in the key truck clusters, such as ports, airports, railroads, warehouses, and freight hubs.

Dedicated funding for HD hydrogen refueling stations

The upfront costs of a HD hydrogen refueling station are much higher than for a BEV charging station (both Level 2 and DC fast chargers). However, fewer incentives or funding programs are currently available for hydrogen refueling infrastructure, which is due to the earlier stage of commercialization of hydrogen technology compared to BEVs. Based on Table 36 in Appendix C, none of the key ZEV infrastructure incentives or funding programs are dedicated to hydrogen infrastructure.

Thus, we recommend the adoption of a dedicated hydrogen refueling infrastructure program to facilitate the deployment of the necessary hydrogen refueling infrastructure. The NEVI Program for EV charging infrastructure is an example of how a dedicated funding program can help to accelerate transitions to a new technology.

[45] Frequency: Public hydrogen stations no greater than 150 miles between one station and the next on the corridor, and no greater than 5 miles off the highway
[46] DOT,https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/previous_rounds/round_5/#ready

Extend incentives for HD refueling station

Since the capital cost of HD hydrogen refueling stations is higher than that of a charging station or LD refueling station, the incentives should be designed to reflect the difference. However, in the ZEV infrastructure program of some states, the technology difference is not considered. For example, a ZEV infrastructure grant of up to $0.5M is offered in NY and Pennsylvania. That amount is only 7% of the hydrogen refueling infrastructure capital cost (~$0.5M for ~$7.1M) compared to 50% of the cost for the EV fast-charging infrastructure (~$1M DC fast charger capital cost). Similarly, Hydrogen Refueling Infrastructure (HRI) credits in California can only be awarded up to 1,200 kg per day at maximum capacity. Since a HD refueling station is estimated to have an approximately 4,000 kg daily capacity, that creates a limit on the amount of HRI credits that HD stations can earn.

HD FCEV and H2-ICE demonstration and pilot projects in California and Texas

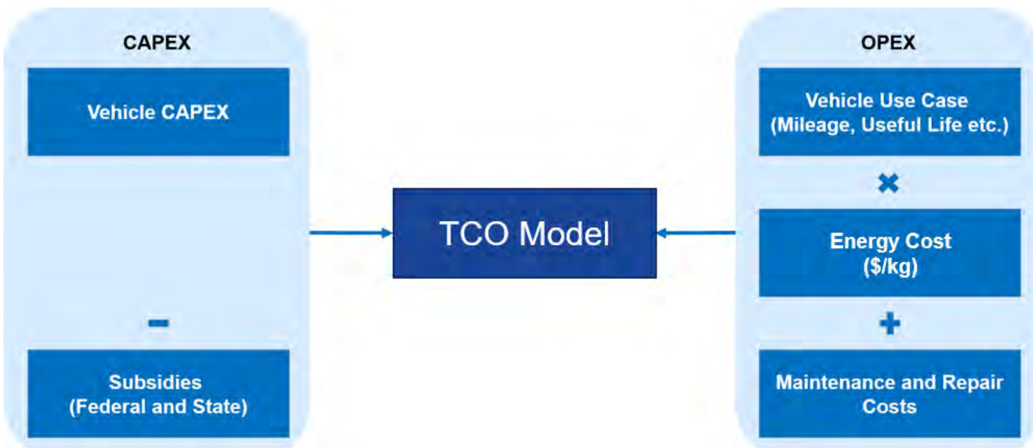
It is beneficial for refueling infrastructure providers to deploy their products for fleet applications and to monitor performance, concerns, and successes at the fleet level. Pilot and demonstration projects can lead to an improved generation of FCEV, H2-ICE, and hydrogen refueling stations that are well-accepted by the fleets. Pilot and demonstration projects also provide fleets an opportunity to gain experience with deploying and operating a new technology and provide valuable feedback. The benefits extend beyond the participating entities and provide valuable information to state agencies and the industry.

The priority for demonstration and pilot projects should be in California and Texas due to their forecasted high hydrogen demand. California is already accelerating efforts to develop its hydrogen refueling infrastructure. Compared to California, Texas has more hydrogen resources but is at an earlier stage in facilitating the deployment of FCEV and H2-ICEs. Pilot and demonstration deployment projects in Texas are recommended for providing insights and feedback to accelerate adoption based on lessons learned from real-world experiences.

10 FCEV and H2-ICE TCO Analysis

This section assesses the total cost of ownership (TCO) of a Class 8 fuel-cell electric truck and an H2-ICE truck versus a diesel baseline truck. This report analyzes the key cost components that differ between those technology types, including vehicle upfront cost, fuel, maintenance, and subsidies (see Figure 38). This analysis does not include the time value of discounted costs over the vehicle's useful life or insurance costs.

Figure 28: Key Cost Components of TCO



10.1 TCO Calculation Methodology

This analysis divides TCO into two major components (CAPEX and OPEX), as presented in Figure 38. The key assumptions of each key component are stated below. The TCO analysis is based on the forecast for FCEV development starting in 2030.

10.1.1 Vehicle CAPEX

Vehicle Cost

The vehicle cost includes the cost of purchase (see Table 24) less the residual value of the sale of the vehicle at the end of the vehicle's useful life.

As regional-haul applications comprise over 50% of total hydrogen demand (see Figure 27), Class 8 drayage trucks in regional haul operations were modeled in this analysis. The average daily operational VMT for regional haul applications is 420 miles/day (Table 16). To meet the duty cycle requirements, we have selected a Class 8 sleeper cab tractor truck as the comparative baseline for the HD FCEV.

FCEV and H2-ICE vehicles are expected to cost more upfront than the diesel baseline truck. The vehicle cost of a fuel cell truck is based on a "virtual teardown" analysis Ricardo conducted from a bottom-up methodology,[47] and on estimates of vehicle costs from various system and subsystem costs. As the range (540 miles) of the FCEV in the Ricardo study is able to meet the duty cycle requirements of regional haul applications (420 miles per day), the vehicle price forecast for MY 2030 was used in this TCO study. The specifications of the modeled fuel-cell truck type are summarized in Table 19.

Table 19: Key Assumptions of FCEV and H2-ICE Vehicles

Parameter	Value	Key assumptions/details
Approximate range (miles)	540 miles	□ >Daily operational VMT for regional haul applications of 420 miles □ Estimated based on 0.11kg/mile
Fuel cell propulsion system (kW)	~390	Average of limited models • Hyundai Xcient 350 kW • Hyzon Hymax 450 kW
Hydrogen storage system (kg)	60	□ Based on Toyota/Kenworth fuel cell truck specification □ Range >420 miles

The FCEV price was estimated between $352,000 and $430,000 in this study. We also reviewed the literature on the retail prices for other Class 8 fuel cell electric trucks, which ranged between $226,000 and $295,000 in various other studies.[48] Thus, the lower Ricardo estimate of $352,000 is used in this study.

The price of an H2-ICE vehicle was estimated based on the price of the diesel baseline and the added hydrogen storage system cost (60 kg at $800/kg from the HD TRUCS Model). Table 20 displays vehicle prices for different technology types.

Table 20: Price Assumptions of FCEV and H2-ICE Vehicles

Vehicle	2030 MY
Class 8 Fuel Cell Electric Truck	$352,000
Class 8 H2-ICE Truck	$206,000
Class 8 Sleeper Cab – Diesel	$158,000

For all three types of trucks, a useful life of 10 years is assumed. In addition, we assumed that 20% of the initial retail price would remain as residual value at the end of 10 years (CARB, 2021). By comparison, CARB estimated a residual value of 20% based on aggregated used vehicle prices from online truck marketplaces.

[47] Anculle, E., Bubna, P., and Kuhn, M. (2021). “E-truck virtual teardown study: Final Report.” https://theicct.org/wp-content/uploads/2022/01/Final-Report-eTruck-Virtual-Teardown-Public-Version.pdf
[48] Powertrain Performance and Total Cost of Ownership Analysis for Class 8 Yard Tractors and Refuse Trucks, National Renewable Energy Laboratory, 2022
Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document, CARB, 2021
Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains, Argonne National Laboratory, 2021

Subsidies to Vehicle Upfront Cost

Due to the higher upfront cost of FCEVs and H2-ICEs compared to the baseline truck, we also assessed how subsidies could support FCEV and H2-ICE adoption.

Table 21: Subsidy Assumptions

Vehicle	Subsidy	Key assumptions/details
Class 8 Fuel Cell Electric Truck	$240,000	Estimated based on HVIP for class 8 FCET[49] Hyundai XCIENT: $240,000 Hyzon HyHD8: $240,000
Class 8 H2-ICE Truck	$60,000	Due to limited commercially available models for H2-ICE, estimated based on 1)H2-ICE forecast price and 2)subsidies offered to different technology types

10.1.2 Vehicle OPEX

We analyzed operating costs by focusing on two key components: fuel and maintenance and repairs.

Fuel Costs

Fuel costs are calculated using the total fuel used per year and the cost of fuel per unit. Total fuel consumption per year is estimated based on annual VMT and fuel efficiency inputs EPA's from HD TRUCS Model.

Table 22: Fuel Cost Calculation Assumptions

Vehicle	Annual VMT	Fuel Efficiency	Key assumptions/details
Fuel Cell Electric Truck	260 days * 420 miles = 109,200 miles	0.10 kg/mile (9.6 miles/kg)	See *Table 15*
H2-ICE Truck	260 days * 420 miles = 109,200 miles	0.13 kg/mile (7.8 miles/kg)	The fuel efficiency of H2-ICE is estimated to be ~19% less than FCEVs, as discussed in section 7.1
Diesel Truck	260 days * 420 miles = 109,200 miles	8.3 miles / DGE	HD TRUCs: 8.5 miles/DGE 2030 forecast: 8.1 miles/DGE (CARB,2020,50)

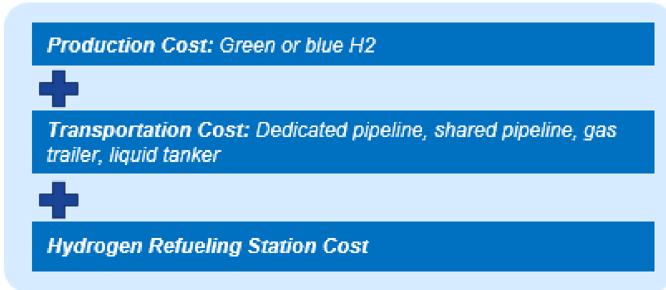
A literature review and data analysis were performed to forecast the hydrogen and diesel prices in 2030.

Hydrogen Price

In this study, hydrogen price is estimated based on the key price components, as presented in Figure 39 in Appendix C.

[49] California HVIP
[50] CARB, Cost Data and Methodology Discussion, 2020

Figure 29: Hydrogen Price Methodology



We obtained ranges of hydrogen costs from various cost studies and roadmaps, including those deployed by the International Energy Agency (IEA),[51] International Renewable Energy Agency (IRENA),[52] BloombergNEF,[53] DOE Hydrogen and Fuel Cell Technologies Office (HFTO) targets,[54] Energy Futures Initiative (EFI), Hydrogen Council,[55] International Council on Clean Transportation (ICCT),[56] Chemical Engineering Journal (CEJ)[57] and Columbia University.[58]

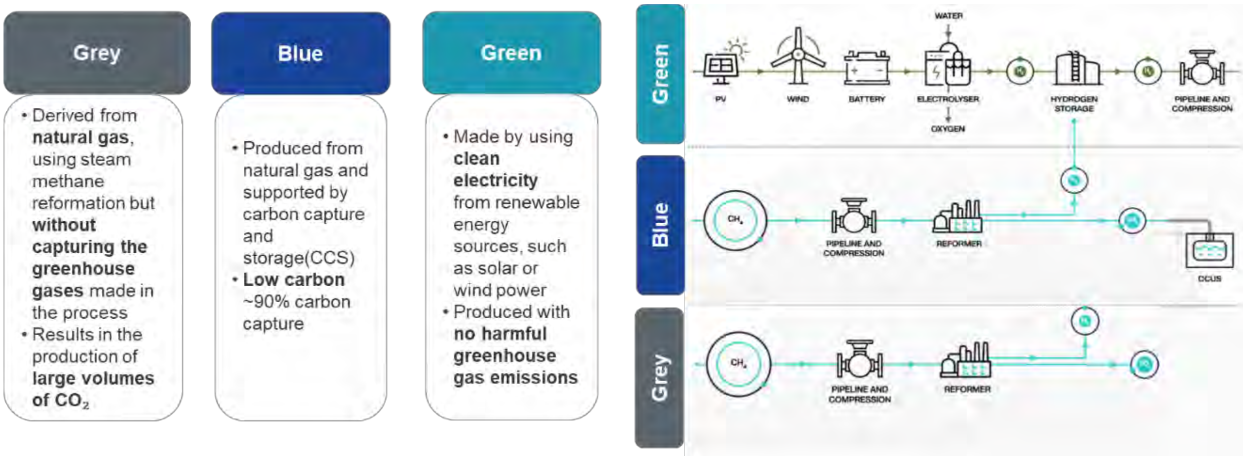
The total hydrogen price (production + transportation + dispensing) is expected to decline due to the economies of scale, and, as a result, we applied an annual reduction rate of 3%.

1. Production Cost

Due to the cost differences between blue hydrogen and green hydrogen, we reviewed recent studies on both hydrogen types. The key differences between blue and green hydrogen are summarized in *Figure 40*.

[51] IEA, 2022
[52] IRENA, Green Hydrogen Cost Reduction, 2020
[53] Bloomberg, Hydrogen Economy Outlook, 2020
[54] DOE, 2020
[55] Hydrogen Council, 2020
[56] ICCT, Assessment of Hydrogen Production Costs from Electrolysis, 2020
[57] Chemical Engineering Journal, 2021
[58] Columbia, 2021
[59] Petrofac

Figure 30: Difference between Blue and Green Hydrogen[59]



The hydrogen price in Table 23 below is based on the price projections from the various sources noted above and from Ricardo analysis.

Table 23: Hydrogen Price Assumptions

Hydrogen Type	Production Cost ($/kg) in 2030
Green Hydrogen	$3.8/kg
Blue Hydrogen	$1.5/kg

Green hydrogen is expected to decline to a production cost of approximately $2-6/kg in 2030. Accordingly, production cost of $3.8/kg is used in the model. Blue hydrogen is expected to decline to a production cost of $1-2/kg in 2030. A production cost of $1.5/kg is used in the model.

2. Transportation Cost

This study analyzed the top three hydrogen transportation methods in Figure 43: gaseous tube trailer, liquid tanker, and pipeline. The key differences in the delivery options are summarized in Figure 43.

Figure 31: Key Methods of Hydrogen Delivery[60]

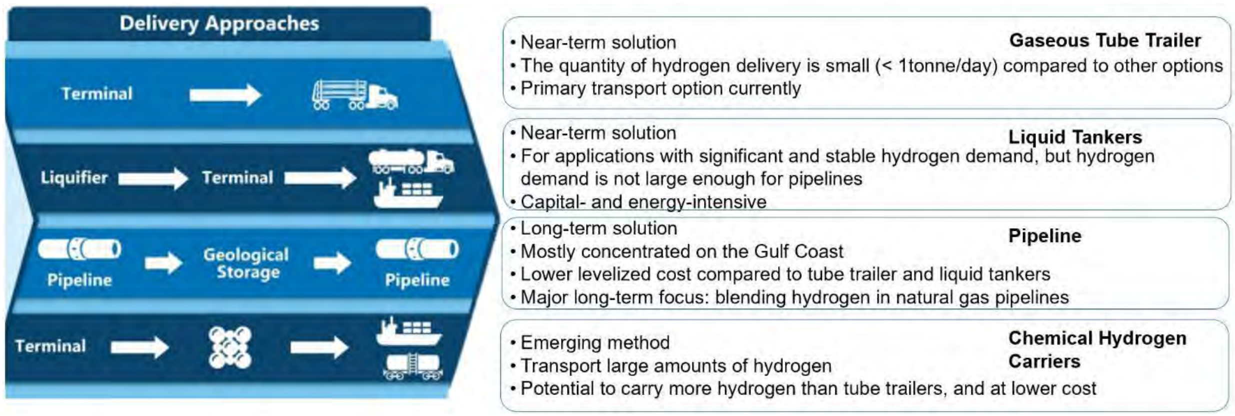


Table 24: Hydrogen Transportation Costs Assumptions

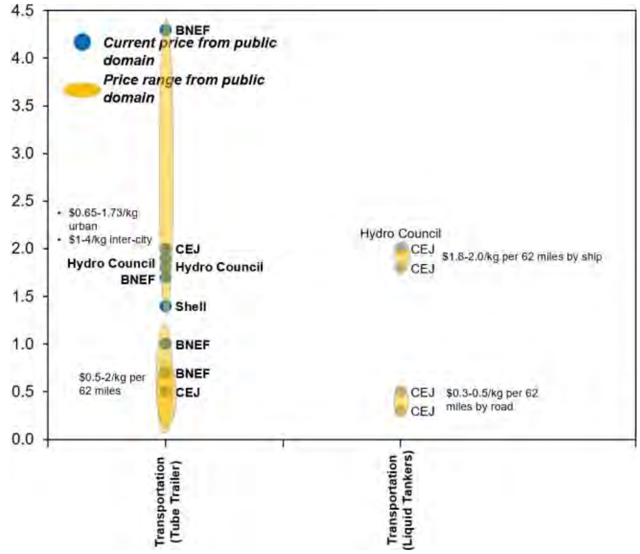
Delivery Option	Transportation Cost ($/kg) in 2030
Gas Tube Trailer	$1.5/kg
Liquid Tankers	$1.2/kg
Dedicated Pipeline	$0.5/kg
Repurposed Pipeline	$0.3/kg

The current transportation costs of the gas tube trailers is scattered (as depicted in Figure 32), but there are several data points at $2/kg. A 25% cost reduction is assumed for gas tube trailer transportation by 2030, as the production costs are expected to drop approximately 25%-30% from 2020 to 2030. BloombergNEF estimated the cost delivered by liquid tanker to be 10%-40% lower compared to the cost of transport by gas tube trailer for a use case of the same distance. Ricardo estimated the transportation cost of the liquid tanker to be 20% lower than the gas tube trailer (see Table 27).

Transportation costs by pipeline are estimated to be the lowest among the three main hydrogen delivery options. The dedicated pipeline cost from IEA ranged between $0.1/kg -$0.9/kg, and averaged at $0.5/kg. Transportation through repurposed pipelines blended with small amounts of natural gas could save costs through the utilization of existing infrastructure.

[60] DOE, 2020

Figure 32: Hydrogen transportation costs



3. Dispensing Cost

Limited public data is available for the levelized cost of hydrogen at refueling stations. Based on the 2020 cost averaged at approximately $5/kg in Table 28 and the projection of production costs, a 30% cost decrease is estimated to reach a $3.5/kg dispensing cost in 2030.

Table 25: Dispensing Cost Assumptions

Current or Projected Dispensing Cost	Timeline	Key assumptions/details
$3.5/kg	2030	Estimated based on: - 2022 levelized refueling station cost - ~25%-30% cost reduction in green hydrogen production cost
$4.4-5.3/kg	2020	Levelized cost of refueling station estimated by McKinsey Supply Model[61]
$3/kg - $7/kg	2020	Estimated based on the delivery and dispensing cost by DOE[62] $5-$11/kg, and the delivery cost ranged from $2-4/kg in *Figure 44*. The high spread of the dispensing costs due to the various capacity of the dispenser and gaseous or liquid hydrogen

In this study, FCEV and H2-ICE are expected to have the same hydrogen dispensing cost. Although FCEV requires higher hydrogen purity compared to H2-ICE, the purity standards of the refueling station are the same for different hydrogen technologies. SAE J-2919 and ISO 14687 specify the minimum purity level shall be higher than 99.97%, which could meet the requirements for both vehicle types. In this analysis, we did not assume different standards of purity in refueling stations for FCEV and H2-ICE.

Diesel Price

We collected current projections for diesel prices from Energy Information Agency's 2020

Annual Energy Outlook (AEO). Due to the volatility of diesel prices in recent years, we adjusted the 2030 forecast based on EIA's estimated average diesel prices of $3.7/gal (2024) and applied the same growth rate as in the 2020 Annual Energy Outlook to calculate the diesel price from 2030 to 2040.

Table 26: Diesel Price Assumptions

Year	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Diesel Price ($/DGE)	3.97	4.02	4.05	4.11	4.15	4.18	4.23	4.26	4.29	4.33	4.33

Maintenance Cost

We calculated the maintenance costs for 2022 at $0.196/mile from data available through American Transportation Research Institute for baseline trucks.[63] The 2030 maintenance costs for the baseline truck are estimated at $0.27/mile based on 1) the 2022 value, and 2) an estimated annual growth rate of 4% based on 2012-2022 data.

FCEVs are assumed to have 25% lower vehicle maintenance costs than diesels.[64] Due to their engine-based configuration, H2-ICEs are estimated to have 10% lower maintenance costs than diesels.

Table 27: Diesel Maintenance Cost Assumptions

Vehicle	Maintenance Cost in 2030 ($/mile)
Fuel Cell Electric Truck	0.20
H2-ICE Truck	0.24
Diesel Truck	0.27

Subsidies

Due to the higher fuel price for hydrogen compared with diesel, we assessed the impact of incentives on fuel costs, such as revenue from California's LCFS program. We used a value of $0.283/kg (CARB LCFS) in this study.

[61] McKinsey Hydrogen Supply Model, Hydrogen Council, 2020
[62] DOE, Hydrogen and Fuel Cell Activities, 2022
[63] ATRI, An Analysis of the Operational Costs of Trucking, 2023
[64] CARB, Total Cost of Ownership Discussion Document, 2021

10.2 TCO Analysis

Based on the inputs listed above, the total cost of ownership (TCO) is analyzed for FCEV, H2-ICE, and baseline trucks in 2030.

The TCO has been calculated for four scenarios with different fuel types and delivery options, as set forth in Table 29. As blue hydrogen production and pipelines are primarily concentrated in the gulf coast,[65] scenarios A and B are defined as blue hydrogen transported by pipeline. Compared to blue hydrogen, green hydrogen production is more fragmented. Thus, liquid tanker and gas tube trailers are modeled for a shorter delivery distance for green hydrogen.

Table 28: TCO Scenarios

Scenario	Fuel Type	Delivery Option	Fuel Cost
A	Blue Hydrogen	Repurposed Pipeline	• Production: $1.5/kg • Transportation: $0.3/kg • Dispensing: $3.5/kg
B	Blue Hydrogen	Dedicated Pipeline	• Production: $1.5/kg • Transportation: $0.5/kg • Dispensing: $3.5/kg
C	Green Hydrogen	Liquid Tanker	• Production: $5/kg • Transportation: $1.2/kg • Dispensing: $3.5/kg
D	Green Hydrogen	Gas Tube Trailer	• Production: $5/kg • Transportation: $1.5/kg • Dispensing: $3.5/kg

The TCO analyses of the four scenarios have been plotted for FCEV, H2-ICE, and diesel baseline trucks in Figures 47 through 50.

As a result of lower maintenance and repair costs, and available subsidies to mitigate upfront costs and operational costs, FCEVs achieve a lower TCO compared to the diesel baseline under scenarios A and B. H2-ICEs approach TCO parity with the diesel baseline under scenario A but are still 2% higher.

Fuel costs are the most critical TCO component in all scenarios, accounting for more than 50% of the TCO under all four scenarios among the three vehicle types. Due to the higher fuel costs of green hydrogen, fuel costs comprise more than 75% of TCO under scenarios C and D (approximately 76% for H2-ICE and approximately 79% for FCEV).

In scenario A, due to the higher fuel efficiency and relatively lower blue hydrogen cost (compared to scenario C and D), the fuel costs of FCEV is approximately 3% lower than that of the diesel baseline.

Driven by the increased green hydrogen production costs and transportation costs, the TCO of FCEV and H2-ICE under scenarios C and D are approximately 40%-50% higher than the TCO in scenarios A and B.

Figure 33: TCO – Scenario A

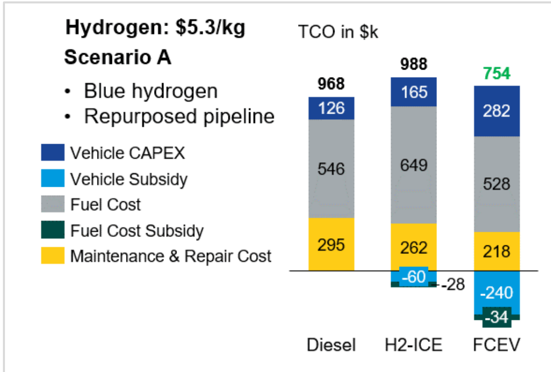


Figure 34: TCO – Scenario B

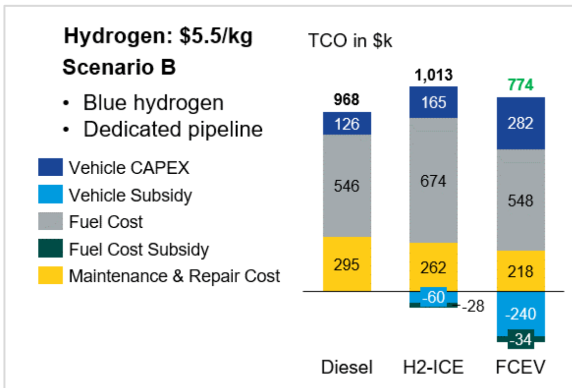


Figure 35: TCO – Scenario C

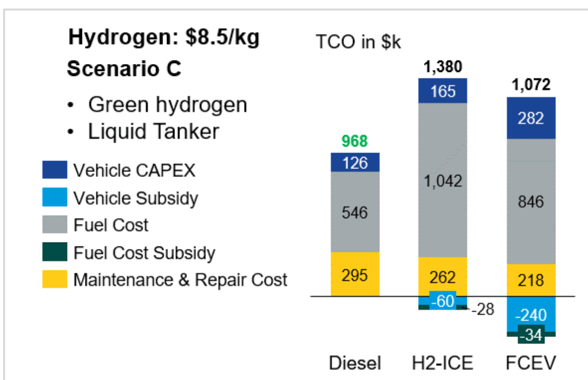
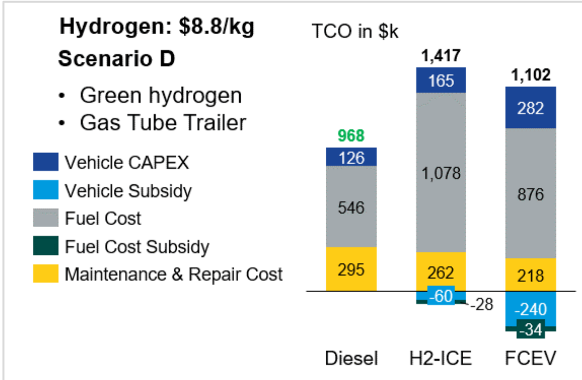


Figure 36: TCO – Scenario D



10.3 Sensitivity Analysis

Although the TCO analysis for the base cases in section 10.2 is based on the best available value of the core cost components, many of the inputs are still uncertain and vary significantly from the various sources. Thus, we assessed the influence of key drivers on upfront costs and operation costs.

10.3.1 CAPEX Sensitivity Analysis

The CAPEX sensitivity analysis was completed using scenario B. In the base cases of all four scenarios, the assumed subsidies for FCEV and H2-ICE are $240,000 and $60,000, respectively. As illustrated in Figure 37 and 38, every $10,000 in vehicle subsidy translates into a 1% TCO reduction compared to the diesel baseline for both FCEVs and H2-ICEs. As a result, H2-ICEs (with their lower relative fuel efficiency) could reach cost parity with an upfront subsidy of $80,000, while FCEVs could reach cost parity with a subsidy of just $30,000.

Figure 37: Sensitivity on CAPEX Subsidies – FCEV

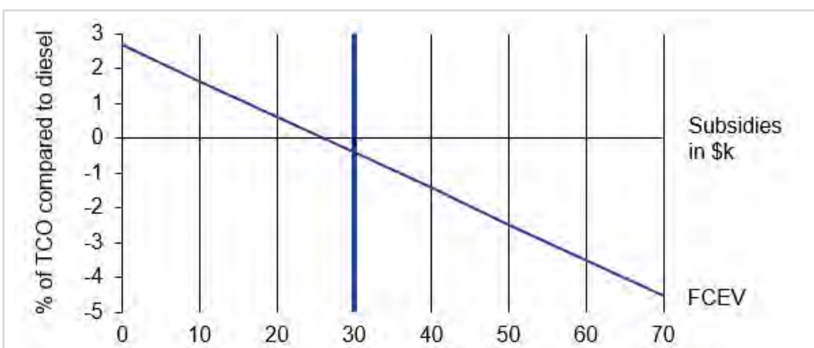
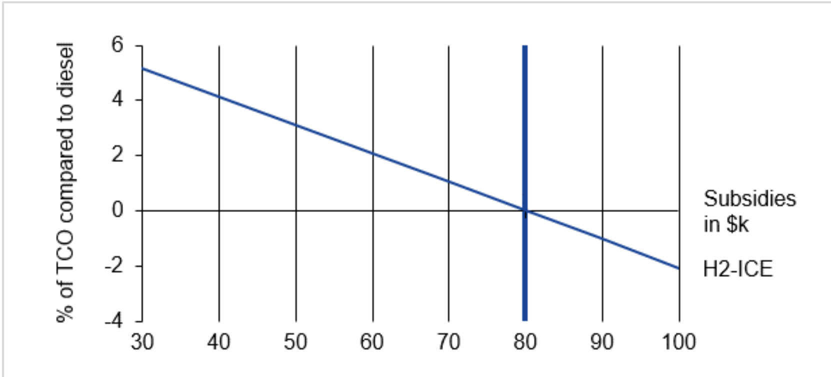


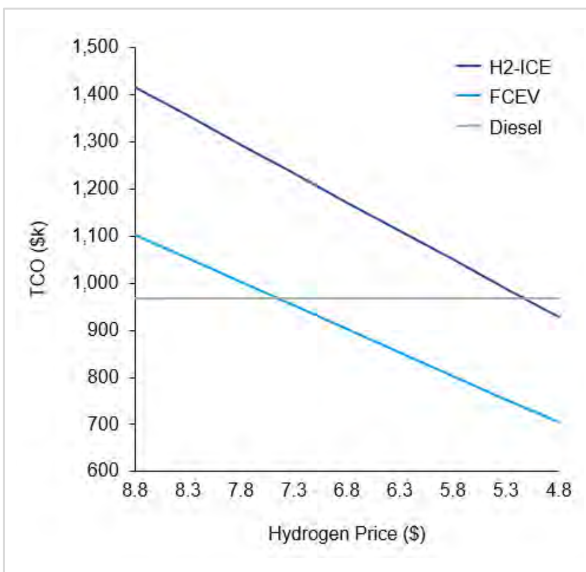
Figure 38: Sensitivity on CAPEX Subsidies – H2-ICE



10.3.2 OPEX Sensitivity Analysis

In order to assess the impact of hydrogen price, scenario D was used due to the highest fuel price among all options (Figure 49). Figure 53 shows the impact of hydrogen price on TCO using prices ranging from $4.8/kg to $8.8/kg. Every $0.5/kg in hydrogen price translated into a 5-7% (FCEV) or 4-6% (H2-ICE) TCO reduction. FCEV trucks could achieve the same TCO as the baseline truck at a retail hydrogen price of approximately $7.4/kg and H2-ICE trucks could achieve the same TCO as the baseline truck at a retail price of approximately $5.1/kg. To achieve a total cost reduction of $3.7/kg($8.8/kg minus $5.1/kg), it isimperative to drive cost reductions at every step of the H2 supply chain.

Figure 39: Sensitivity on Hydrogen Price



10.4 Summary of Key Insights

In this section, we have analyzed the total cost of ownership of a Class 8 fuel cell truck, a hydrogen ICE truck, and their diesel truck counterpart. A summary of our key findings from this TCO study is presented below.

With a subsidy sufficient to offset higher upfront costs, FCEVs and H2-ICEs are modeled to be cost-competitive in 2030 under the low hydrogen price scenario (i.e., where blue hydrogen is used and transported by pipeline). FCEVs are highly competitive with a TCO 22% below the baseline diesel vehicle for scenario A. H2-ICE vehicles approach parity (still 2% higher) with the baseline vehicle under scenario A. FCEV adoption could ramp up faster if the subsidies were to continue. With high up-front costs, purchase price subsidies will remain critical to support the adoption of FCEVs and, to a lower extent, H2-ICE until the vehicle cost and refueling costs decrease.

Under the scenario of FCEVs and H2-ICEs fueled with high-priced hydrogen (green hydrogen and delivered by gas tube trailer), the fuel costs increased by over 50% for both FCEVs and H2-ICE vehicles compared to the TCO under the low-price scenarios. Thus, even with the subsidy to offset the high upfront cost, FCEVs and H2-ICEs cannot reach cost parity with diesels using green hydrogen transported by trailers. The TCO of FCEVs and H2-ICEs are approximately 10%-45% higher than diesel baselines under that scenario.

There are limited cost savings from repurposed pipelines versus dedicated pipelines (2%-3%), driven by the low portion of transportation costs in the total fuel costs. Similarly, liquid tankers could only save 2-3% of TCO compared with gas tube trailers.

Although FCEVs and H2-ICEs are not cost-competitive with the diesel baseline under the latter two green hydrogen scenarios, the TCO of FCEVs and H2-ICEs are generally forecast to drop. In that regard, diesel trucks are expected to increase in cost due to additional NO_x and GHG regulatory requirements. The key drivers of the forecasted cost reduction in TCO of FCEVs and H2-ICEs are illustrated below.

1. **Fuel Costs**

    a. Production costs

    Production costs of green hydrogen are expected to drop, driven by electricity costs and capital costs. The growth in renewable energy supply, economies of scale for electrolyzers, improvement in efficiency, and extended equipment lifetime are expected to drive cost reduction.

    b. Transportation and dispensing cost

    With the scaling-up of the demand from FCEVs and H2-ICEs, the hydrogen transportation costs and dispensing costs could reduce due to improved utilization. The economies of scale would drive down the capital cost of the major components in the refueling station (e.g., compressor).

    As the capacity of refueling stations is expected to increase – e.g., the capacity of refueling stations for heavy-duty vehicles versus the refueling capacity for light-duty vehicles – the higher capacity also will lead to reduced unit costs.

2. **Vehicle Costs**

    Vehicle capital costs are expected to decline, mainly driven by improvements to the fuel cell and hydrogen storage systems. Key cost reduction opportunities include 1) improvement in manufacturing costs as volumes increase, 2) improvement of tank design layouts that can minimize the amount of composite fiber, and 3) standardization of components that can accelerate cost reduction by increasing volume.[66]

3. **Subsidies**

    In the scenarios that have hydrogen fuel prices significantly higher than diesel prices (scenarios C and D), the subsidy of upfront costs under current programs cannot completely offset the higher TCO. Thus, in order to improve the adoption of FCEVs and H2-ICEs, subsidy programs need to be designed to reflect the changing relative costs of hydrogen fuel and upfront vehicle purchase prices.

[66] Fuel Cell Roadmap 2020, Narrative Report, Advanced Propulsion Centre APC – UK

Conclusion

Economies of scale are one of the key drivers in reducing TCO. Vehicle capital costs could decrease substantially due to standardized components and manufacturing processes. The scaling-up of volumes also could reduce hydrogen production prices (electrolyzer capital cost), dispensing costs (compressor and hydrogen storage tanks costs), and transportation costs (improved utilization).

To scale up the adoption rates for FCEVs and H2-ICE vehicles, an effort to reduce vehicle capital costs and hydrogen fuel prices is needed. Such an effort should utilize:

1. Funding for demonstration and financing programs to reduce the upfront costs for fleets to adopt the technologies early.
2. Available federal funding (e.g., Hydrogen Hubs under the Infrastructure Investment and Jobs Act)[67] and increased state funding for low-carbon hydrogen production projects to scale-up more cost-effective hydrogen production.
3. Grants to accelerate the deployment of the hydrogen refueling and transportation infrastructure, as stated in section 9, to improve hydrogen availability and reduce unit costs.
4. Funding for research across the supply chain to explore new or improved technologies to make hydrogen prices more economically viable.

[67] Infrastructure Investment and Jobs Act

11 Acronyms and Abbreviations

ACF	Advanced Clean Fleet
ACT	Advanced Clean Trucks
ICT	Innovative Clean Transit
BEV	Battery electric vehicle
CALeVIP	California Electric Vehicle Infrastructure Project
CAPEX	Capital expenditures
CARB	California Air Resources Board
CEC	California Energy Commission
CORE	Clean Off-Road Equipment Voucher Incentive Project
CUPC	California Public Utilities Commission
DCFC	Direct current fast charger
EnergIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles
EPA	Environmental Protection Agency
FCEV	Fuel cell electric vehicle
FHWA	Federal Highway Administration
GHG	Greenhouse gas emissions
H2-ICE	Hydrogen ICE vehicle
HD	Heavy-duty
HVIP	Hybrid and Zero Emission Truck and Bus Voucher Incentive
LCFS	Low Carbon Fuel Standard
LD	Light-duty
MD	Medium-duty
MHD	Medium- and heavy-duty
MHDVs	Medium- and heavy-duty vehicles
NERC	North American Electric Reliability Corporation
NEVI	National Electric Vehicle Infrastructure
OPEX	Operating expenses
SOC	State of charge
TCO	Total cost of ownership
ZET	Zero-emission truck
ZEV	Zero-emission vehicle

Appendix A

Table 29: BEVs On the Road by 2032 – Buses and Refuse Trucks

MOVES Source Use Types	Other Buses	Other Buses	Transit Buses	Transit Buses	Transit Buses	School Buses	School Buses	School Buses	Refuse Trucks	Refuse Trucks
MOVES Regulatory Classes	LHD45	MHD67	LHD45	MHD67	HHD8	LHD45	MHD67	HHD8	MHD67	HHD8
California	4,931	160	712	11	771	819	10,215	677	76	345
Texas	1,522	51	222	3	255	261	3,229	217	25	114
New York	1,110	37	161	3	180	187	2,329	156	18	81
Illinois	800	27	117	2	133	137	1,694	114	13	60
Florida	795	26	115	2	129	134	1,667	111	13	58
North Carolina	724	24	106	2	124	126	1,551	105	12	56
Pennsylvania	669	22	97	2	111	114	1,413	95	11	49
Washington	610	20	89	1	101	104	1,291	87	10	45
Ohio	589	20	86	1	98	101	1,249	84	10	44
New Jersey	528	17	77	1	86	89	1,110	74	9	39
Indiana	520	17	76	1	87	89	1,106	74	9	39
Colorado	507	17	74	1	84	87	1,072	72	8	38
Virginia	490	17	72	1	85	85	1,052	71	8	38
Arizona	493	16	72	1	83	85	1,046	70	8	37
Georgia	460	15	67	1	76	78	973	65	8	34
Michigan	463	15	67	1	74	78	967	64	7	33
Oregon	396	13	58	1	68	69	849	57	7	30
Missouri	390	13	57	1	65	67	826	56	6	29
Tennessee	342	12	50	1	61	60	741	50	6	27
Wisconsin	346	11	50	1	57	59	732	49	6	26
Oklahoma	318	11	47	1	57	56	690	47	6	25
Minnesota	324	11	47	1	55	56	691	47	5	25
Iowa	254	9	37	1	44	44	546	37	4	20
Alabama	241	8	35	1	41	41	513	35	4	18
Maryland	234	8	34	1	41	41	507	35	4	19
Connecticut	231	8	34	1	38	39	485	32	4	17
Kansas	218	7	32	1	38	38	472	32	4	17
Utah	227	7	33	1	36	38	474	32	4	16
Louisiana	211	7	31	0	37	37	455	31	4	17
South Carolina	214	7	31	0	36	37	457	31	4	16
Idaho	184	6	27	0	32	32	395	27	3	14
Nebraska	165	6	24	0	29	29	357	24	3	13
Arkansas	163	6	24	0	29	29	353	24	3	13
Montana	147	5	22	0	26	26	318	22	3	12
New Mexico	144	5	21	0	25	25	308	21	2	11
Nevada	123	4	18	0	20	21	260	17	2	9

MOVES Source Use Types	Other Buses	Other Buses	Transit Buses	Transit Buses	Transit Buses	School Buses	School Buses	School Buses	Refuse Trucks	Refuse Trucks
MOVES Regulatory Classes	LHD45	MHD67	LHD45	MHD67	HHD8	LHD45	MHD67	HHD8	MHD67	HHD8
Kentucky	116	4	17	0	20	20	247	17	2	9
North Dakota	97	3	14	0	17	17	209	14	2	8
Maine	90	3	13	0	15	15	191	13	1	7
Mississippi	79	3	12	0	13	14	168	11	1	6
South Dakota	61	2	9	0	8	9	119	8	1	4
New Hampshire	51	2	7	0	9	9	109	7	1	4
Massachusetts	52	2	8	0	8	9	108	7	1	4
West Virginia	47	2	7	0	8	8	100	7	1	4
Wyoming	46	2	7	0	8	8	98	7	1	3
Hawaii	39	1	6	0	7	7	83	6	1	3
Vermont	38	1	6	0	7	7	82	6	1	3
Alaska	33	1	5	0	5	6	69	5	1	2
Rhode Island	32	1	5	0	5	5	68	5	1	2
Delaware	21	1	3	0	3	4	44	3	0	2

Table 30: BEVs On the Road by 2032 – Short-haul and Long-haul Trucks

MOVES Source Use Types	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	LHD2b3	LHD45	MHD67	HHD8	LHD2b3	LHD45	MHD67	HHD8	MHD67	HHD8
California	159,411	92,982	30,294	9,134	5,697	3,089	680	502	3,661	6,961
Texas	50,505	29,746	9,682	3,013	1,801	981	224	166	1,209	2,298
New York	36,387	21,334	6,947	2,131	1,299	706	159	117	854	1,624
Illinois	26,497	15,598	5,077	1,577	945	515	117	87	633	1,203
Florida	26,042	15,265	4,971	1,523	930	505	113	84	611	1,161
North Carolina	24,283	14,355	4,670	1,471	865	472	110	81	590	1,122
Pennsylvania	22,097	12,993	4,230	1,309	788	429	97	72	525	998
Washington	20,182	11,877	3,866	1,200	720	392	89	66	481	915
Ohio	19,529	11,496	3,742	1,163	696	379	87	64	466	887
New Jersey	17,348	10,183	3,315	1,021	619	337	76	56	409	778
Indiana	17,304	10,199	3,319	1,036	617	336	77	57	415	790
Colorado	16,766	9,862	3,210	995	598	326	74	55	399	759
Virginia	16,474	9,748	3,171	1,002	587	320	75	55	402	764
Arizona	16,366	9,643	3,139	978	584	318	73	54	392	746
Georgia	15,208	8,943	2,911	901	542	295	67	50	362	687
Michigan	15,103	8,838	2,878	877	539	293	65	48	352	669

MOVES Source Use Types	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	LHD2b3	LHD45	MHD67	HHD8	LHD2b3	LHD45	MHD67	HHD8	MHD67	HHD8
Oregon	13,284	7,852	2,555	804	473	258	60	44	323	613
Missouri	12,920	7,606	2,476	769	461	251	57	42	309	587
Tennessee	11,612	6,897	2,243	716	413	226	53	39	288	547
Wisconsin	11,442	6,733	2,192	680	408	222	51	37	273	519
Oklahoma	10,815	6,430	2,091	670	385	211	50	37	269	511
Minnesota	10,814	6,386	2,078	652	385	210	49	36	262	497
Iowa	8,544	5,055	1,644	519	304	166	39	29	208	396
Maryland	8,027	4,736	1,541	482	286	156	36	27	193	368
Alabama	7,943	4,719	1,535	491	283	155	37	27	197	374
Kansas	7,577	4,445	1,447	445	270	147	33	24	178	339
Connecticut	7,393	4,389	1,427	455	263	144	34	25	183	347
Utah	7,402	4,335	1,412	431	264	144	32	24	173	329
Louisiana	7,130	4,228	1,375	437	254	139	33	24	175	333
South Carolina	7,146	4,220	1,373	431	255	139	32	24	173	329
Idaho	6,184	3,659	1,190	376	220	120	28	21	151	287
Nebraska	5,593	3,320	1,080	344	199	109	26	19	138	263
Arkansas	5,535	3,285	1,068	341	197	108	25	19	137	260
Montana	4,985	2,958	962	306	177	97	23	17	123	234
New Mexico	4,819	2,849	927	292	172	94	22	16	117	223
Nevada	4,062	2,388	778	241	145	79	18	13	97	183
Kentucky	3,860	2,276	741	231	138	75	17	13	93	176
North Dakota	3,275	1,941	631	200	117	64	15	11	80	153
Maine	2,992	1,765	574	180	107	58	13	10	72	137
Mississippi	2,631	1,554	506	159	94	51	12	9	64	121
New Hampshire	1,844	1,047	342	94	66	35	7	5	37	71
South Dakota	1,705	1,008	328	103	61	33	8	6	41	79
Massachusetts	1,679	977	318	95	60	33	7	5	38	73
West Virginia	1,566	925	301	95	56	30	7	5	38	72
Wyoming	1,526	902	293	92	54	30	7	5	37	70
Hawaii	1,298	766	249	78	46	25	6	4	31	60
Vermont	1,278	754	245	77	46	25	6	4	31	59
Alaska	1,085	637	208	64	39	21	5	4	26	49
Rhode Island	1,059	624	203	63	38	21	5	3	25	48
Delaware	689	405	132	41	25	13	3	2	16	31

Table 31: Cumulative BEV Charger Deployments by year for the top 10 states

	2025	2026	2027	2028	2029	2030	2031	2032
California	18,625	31,149	51,573	83,349	126,476	181,615	248,022	324,222
Texas	3,205	6,528	13,271	23,760	37,998	56,808	79,663	104,642
New York	3,238	5,877	10,644	18,059	28,124	41,034	56,609	74,378
Illinois	1,773	3,539	7,069	12,560	20,014	29,597	41,164	54,316
Florida	2,234	4,130	7,539	12,841	20,037	29,423	40,792	53,453
North Carolina	1,125	2,555	5,847	10,968	17,919	26,780	37,453	49,741
Pennsylvania	1,593	3,105	6,035	10,593	16,780	24,913	34,785	45,651
Washington	1,389	2,744	5,429	9,607	15,277	22,479	31,146	41,177
Ohio	1,295	2,595	5,197	9,245	14,739	21,787	30,290	39,989
New Jersey	1,449	2,680	4,963	8,516	13,338	19,484	26,888	35,555

Table 32: FCEV and H2-ICEs on the road by 2032

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Texas	0	11,792	631	1,666	4,719
California	0	10,532	564	1,488	4,215
Pennsylvania	0	4,591	246	649	1,837
Florida	0	4,321	231	610	1,729
Georgia	0	3,241	174	458	1,297
New York	0	3,151	169	445	1,261
Illinois	0	2,633	141	372	1,054
Indiana	0	2,117	113	299	847
Arizona	0	1,858	99	262	744
Ohio	0	1,728	93	244	692
Oklahoma	0	1,599	86	226	640
Missouri	0	1,512	81	214	605
North Carolina	0	1,426	76	201	571
Michigan	0	1,383	74	195	553
Tennessee	0	1,167	62	165	467
Massachusetts	0	1,148	61	162	459
Wisconsin	0	1,037	56	146	415
New Jersey	0	994	53	140	398
Utah	0	994	53	140	398
Minnesota	0	994	53	140	398
Colorado	0	951	51	134	380
Virginia	0	864	46	122	346
Washington	0	821	44	116	329
Maryland	0	821	44	116	329
Alabama	0	821	44	116	329
Louisiana	0	821	44	116	329
Oregon	0	735	39	104	294
South Carolina	0	605	32	85	242
Nebraska	0	519	28	73	207
Iowa	0	405	22	57	162
New Hampshire	0	338	18	48	135
Kansas	0	315	17	45	126
Nevada	0	302	16	43	121
Connecticut	0	302	16	43	121
New Mexico	0	302	16	43	121
Maine	0	302	16	43	121
Kentucky	0	293	16	41	117
Arkansas	0	270	14	38	108
Idaho	0	248	13	35	99

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Mississippi	0	248	13	35	99
Montana	0	225	12	32	90
Hawaii	0	173	9	24	69
Vermont	0	173	9	24	69
South Dakota	0	135	7	19	54
North Dakota	0	135	7	19	54
West Virginia	0	113	6	16	45
Alaska	0	90	5	13	36
Wyoming	0	90	5	13	36
Rhode Island	0	86	5	12	35
Delaware	0	68	4	10	27

Appendix B

Table 33: Battery size, Charger type, Charging characteristics by truck Use and Class type

Truck Use Type	Truck Class Type	Battery size (kWh)	Charging location	Charging sessions per day	No. of chargers per vehicle	Charger type	Charger capacity	Nominal charging demand (kW)	Total BEV MDHV on road 2032
Other Buses	LHD2b_3	105	Depot	1	1	L2	19.2	10.50	0
Other Buses	LHD4_5	129	Depot	1	1	L2	19.2	12.90	20,882
Other Buses	MHD6_7	160	Depot	1	1	DCFC	50	16.00	692
Other Buses	HHD8	313	Highway	6	0.16	DCFC	350	350.00	0
Transit Buses	LHD2b_3	105	Depot	1	1	L2	19.2	10.50	0
Transit Buses	LHD4_5	129	Depot	1	1	L2	19.2	12.90	3,040
Transit Buses	MHD6_7	160	Depot	1	1	DCFC	50	16.00	48
Transit Buses	HHD8	313	Depot	1	1	DCFC	150	31.30	3,445
School Buses	LHD2b_3	88	Depot	1	1	L2	19.2	8.80	5
School Buses	LHD4_5	88	Depot	1	1	L2	19.2	8.80	3,555
School Buses	MHD6_7	155	Depot	1	1	L2	19.2	15.50	44,087
School Buses	HHD8	155	Depot	1	1	L2	19.2	15.50	2,957
Refuse Trucks	MHD6_7	211	Depot	1	1	DCFC	50	21.10	340
Refuse Trucks	HHD8	281	Depot	1	1	DCFC	50	28.10	1,541
Short Haul Single Unit	LHD2b_3	68	Depot	1	1	L2	19.2	6.80	689,213
Short Haul Single Unit	LHD4_5	127	Depot	1	1	L2	19.2	12.70	405,133
Short Haul Single Unit	MHD6_7	141	Depot	1	1	DCFC	50	14.10	131,887
Short Haul Single Unit	HHD8	420	Depot	1	1	DCFC	350	42.00	40,785
Long Haul Single Unit	LHD2b_3	68	Depot	1	1	L2	19.2	6.80	24,588
Long Haul Single Unit	LHD4_5	127	Depot	1	1	L2	19.2	12.70	13,379
Long Haul Single Unit	MHD6_7	141	Depot	1	1	DCFC	50	14.10	3,037
Long Haul Single Unit	HHD8	733	Highway	6	0.16	DCFC	350	350.00	2,241

Truck Use Type	Truck Class Type	Battery size (kWh)	Charging location	Charging sessions per day	No. of chargers per vehicle	Charger type	Charger capacity	Nominal charging demand (kW)	Total BEV MDHV on road 2032
Short Haul Combination Truck	MHD6_7	264	Depot	1	1	DCFC	150	26.40	16,358
Short Haul Combination Truck	HHD8	420	Highway	6	0.16	DCFC	350	350.00	31,101

Appendix C

Table 34: Annual National Hydrogen Demand (H2 tons)

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Hydrogen Demand By 2030	0	131,027	6,516	8,141	47,462
Hydrogen Demand By 2032	0	316,460	2,860	13,109	76,420

Table 35: Annual Hydrogen Demand by 2032 by State (H2 tons)

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
California	0	47,760	432	1,978	11,533
Florida	0	19,594	177	812	4,732
Texas	0	53,475	483	2,215	12,913
Washington	0	3,723	34	154	899
New York	0	14,287	129	592	3,450
New Jersey	0	4,507	41	187	1,088
Arizona	0	8,425	76	349	2,035
Colorado	0	4,311	39	179	1,041
Illinois	0	11,940	108	495	2,883
Georgia	0	14,696	133	609	3,549
Virginia	0	3,919	35	162	946
Massachusetts	0	5,205	47	216	1,257
Oregon	0	3,331	30	138	804
Pennsylvania	0	20,819	188	862	5,027
Maryland	0	3,723	34	154	899
North Carolina	0	6,466	58	268	1,561
Ohio	0	7,838	71	325	1,893
Michigan	0	6,270	57	260	1,514
Nevada	0	1,372	12	57	331
Utah	0	4,507	41	187	1,088
Minnesota	0	4,507	41	187	1,088
Hawaii	0	784	7	32	189
Connecticut	0	1,372	12	57	331

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Tennessee	0	5,290	48	219	1,278
Indiana	0	9,601	87	398	2,319
Missouri	0	6,858	62	284	1,656
Wisconsin	0	4,703	43	195	1,136
South Carolina	0	2,743	25	114	662
Oklahoma	0	7,250	66	300	1,751
Alabama	0	3,723	34	154	899
Kansas	0	1,429	13	59	345
Kentucky	0	1,327	12	55	320
New Mexico	0	1,372	12	57	331
New Hampshire	0	1,531	14	63	370
Iowa	0	1,837	17	76	444
Idaho	0	1,123	10	47	271
Vermont	0	784	7	32	189
Louisiana	0	3,723	34	154	899
Maine	0	1,372	12	57	331
Delaware	0	306	3	13	74
Nebraska	0	2,351	21	97	568
Rhode Island	0	392	4	16	95
Arkansas	0	1,225	11	51	296
Montana	0	1,021	9	42	246
Mississippi	0	1,123	10	47	271
Alaska	0	408	4	17	99
West Virginia	0	510	5	21	123
South Dakota	0	612	6	25	148
Wyoming	0	408	4	17	99
North Dakota	0	612	6	25	148

Table 36: Major Funding Programs

Federal							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Inflation Reduction Act	Tax credit equal to 30% of capital cost						
IIJA Charging and Fueling Infrastructure	$2.5 B			X		X	X
Hydrogen Demonstration Project	$400M in 2022		X			X	X
Regional Clean Hydrogen Hubs	$7 B		X		X	X	X
ZEV Infrastructure and Advanced Vehicle Grants							
California							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Hydrogen Refueling Infrastructure (HRI) credits		Awarded up to 1,200 kg per day				X	X
EnergIIZE	$69M in 2022; 30% allocated to hydrogen			X			X
Assembly Bill 8	$20 M					X	
Texas							

Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Governmental Alternative Fuel Fleet (GAFF)	$3.9M in total		X	X		X	X
Alternative Fueling Facilities Program (AFFP)	$6M in total			X		X	X
New York							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Zero Emission Vehicle (ZEV) Rebate and ZEV Fueling Infrastructure Grant for Municipalities	Up to $0.5M per refueling station $7,500 per vehicle		X	X		X	X
Pennsylvania							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
EV Charging Station and Hydrogen Fuel Cell Infrastructure Grants	Up to $0.5M per refueling station			X		X	X

Table 37: Hydrogen Refueling Station Deployment Timeline by State

State	2032	2031	2030	2029	2028	2027
Texas	89	71	42	25	14	9
California	79	63	37	30	23	16
Pennsylvania	34	28	16	10	6	3
Florida	32	26	15	9	5	3
Georgia	24	20	11	7	4	2
New York	24	19	11	7	4	2
Illinois	20	16	9	5	3	2
Indiana	16	13	8	4	3	2
Arizona	14	11	7	4	2	1
Ohio	13	10	6	4	2	1
Oklahoma	12	10	6	3	2	1
Missouri	11	9	5	3	2	1
North Carolina	11	9	5	3	2	1
Michigan	10	8	5	3	2	1
Tennessee	9	7	4	2	1	1
Massachusetts	9	7	4	2	1	1
Wisconsin	8	6	4	2	1	1
New Jersey	7	6	4	2	1	1
Utah	7	6	4	2	1	1
Minnesota	7	6	4	2	1	1
Colorado	7	6	3	2	1	1
Virginia	6	5	3	2	1	1
Washington	6	5	3	2	1	1
Maryland	6	5	3	2	1	1
Alabama	6	5	3	2	1	1
Louisiana	6	5	3	2	1	1
Oregon	6	4	3	2	1	1
South Carolina	5	4	2	1	1	0
Nebraska	4	3	2	1	1	0
Iowa	3	2	1	1	0	0
New Hampshire	3	2	1	1	0	0
Kansas	2	2	1	1	0	0
Nevada	2	2	1	1	0	0
Connecticut	2	2	1	1	0	0
New Mexico	2	2	1	1	0	0
Maine	2	2	1	1	0	0
Kentucky	2	2	1	1	0	0
Arkansas	2	2	1	1	0	0
Idaho	2	1	1	1	0	0
Mississippi	2	1	1	1	0	0
Montana	2	1	1	0	0	0
Hawaii	1	1	1	0	0	0
Vermont	1	1	1	0	0	0
South Dakota	1	1	0	0	0	0