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Heavy-duty zero-emission vehicles

Pace and opportunities for a rapid global transition

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The Zero Emission Vehicles Transition Council is an international forum focused on enhancing political cooperation on the transition to zero emission vehicles (ZEVs).

It brings together Ministers that represent over 50% of the global car market. Council members have agreed to collectively address some of the key challenges in the transition to ZEVs, enabling the transition to be faster, cheaper, and easier for all.

The Council will convene on a regular basis to discuss how to accelerate the pace of the global transition to ZEVs, to reduce emissions and help the global economy meet our goals under the Paris Agreement.

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Executive Summary

Heavy-duty vehicles (HDVs) are the transportation sector's second largest source of greenhouse gas emissions and its largest source of air pollutant emissions globally. Given the large emissions footprint of HDVs, the Zero Emission Vehicle Transition Council (ZEVTC), whose membership represents countries accounting for about half of global vehicle sales and a quarter of global HDV sales, has identified these vehicles as a high-priority area of focus.

This paper reviews and summarizes the latest information on the pace of transition required for the HDV fleet to align with climate targets, the feasibility of such a transition given the latest data on technology availability and cost, potential pathways for adoption in various HDV segments, and high-priority policies and measures that governments would ideally adopt.

Key takeaways from this paper are as follows:

An accelerated global transition to ZEVs could reduce road transport CO_2 emissions 73% by 2050 compared to 2020 levels. Transitions to HD ZEVs represent approximately half of this emissions reduction potential. Achieving this level of ambition for the HDV sector would yield cumulative CO_2 emission reductions of 47.5 billion tonnes between 2020 and 2050.

The ZEV share of global HDV sales needs to rise to 45% by 2030, and to nearly 100% no later than 2040, if the transportation sector is to fulfil its emission reduction responsibilities in line with Paris Agreement goals. The needed pace of transition varies across individual HDV segments; greater ambition is required for segments, like buses, where zero-emission technology is commercially available and cost-effective.

A rapid transition to zero-emission HDVs will have significant global health benefits. Among G20 economies, actions to ensure that all new HDVs are either ultra-low or zero-emission could avoid 3 million premature deaths through 2050, equivalent to 5 trillion USD in health benefits. The magnitude of these benefits would be greater with an accelerated transition to HD ZEVs.

Commercial availability and cost of ownership projections demonstrate that 45% zero-emission HDV sales in 2030 and 100% sales in 2040 are feasible goals for ZEVTC countries. Urban buses, urban delivery vehicles and short-haul tractor trailers are three HDV segments poised for early HD ZEV adoption. HD ZEVs in these segments are, or are projected to become, cost-competitive and commercially mature, and can reach 100% sales as early as 2030 and no later than 2035 in ZEVTC countries.

Effective design of national policy in five key areas—target-setting, regulations, incentives, infrastructure, and fleet purchases—is needed to accelerate the transition to HD ZEVs.

Target setting. Overarching political statements should be used to set HD ZEV sales targets that align with climate goals, are legally binding, are unambiguous, and drive greater ambition for vehicle segments whose ZEV market is more advanced. For ZEVTC members, HD ZEV sales share targets of 45% by 2030 and 100% no later than 2040 would align with Paris Agreement goals.

Regulations. Legally-binding vehicle regulations should drive the adoption of zero-emission technology; require, through the use of long-term targets, that manufacturers produce an increasing number or percentage of HD ZEVs each year; recognize differences in cost, emission footprints, and technology readiness among vehicle segments; and use allowances judiciously, to minimize their dilution of a regulation's impact. HD ZEV regulations should align sales requirements for individual vehicle segments with phase-out targets.

Incentives. Fiscal incentives such as purchase subsidies and tax deductions bring forward the parity date for total cost of ownership. Incentive programs should be tailored to close segment-specific gaps in cost parity, have a revenue-neutral source of funding, and undergo regular review and revision to reflect technology development and cost changes.

Infrastructure. Governments are well-positioned to coordinate among stakeholders and to lead the development of infrastructure roadmaps, ensuring that build-outs align with vehicle electrification targets. Governments should set policies to incentivize private sector investment while targeting public sector investment strategically where it is most needed in the early stages of market development.

Fleet purchase requirements. Fleet purchase requirements create market demand for zero-emission products that can further drive the supply of HD ZEVs, and should be applied to public fleets of buses and trucks as well as large private fleets, to spur the transition to HD ZEVs. Purchase requirements should be aligned with targets and regulations for individual HDV segments.

Introduction

The purpose of this paper is to demonstrate the need for a rapid shift to HD ZEV[1] technology in markets across the world, summarize the benefits and feasibility of such a shift, and describe the enabling policies that can bring it about. Its particular focus is on the ZEVTC markets. The paper offers three guiding questions for governments seeking to transition their country's HD fleet to ZEVs:

1. What pace is required for the transition, given the urgent demands set by global climate targets?

2. Can the required technologies be deployed in the identified timeframe?

3. How can policies be effectively designed to support the needed pace of transition?

The focus of this paper is on zero-emission technologies—battery-electric and fuel cell electric powertrains—that produce no tailpipe emissions of GHGs and for which life-cycle analysis has shown the potential for deep well-to-wheel GHG emission reductions relative to vehicles powered by combustion engines burning fossil-fuels.[2]

1 See the Glossary for a definition of terms.

2 ICCT HDV life-cycle assessment report in preparation.

The pace of the HD ZEV transition needed to align with climate targets

ICCT performed a detailed modelling exercise to determine the CO_2 emission reductions of an accelerated transition of the world's vehicle fleet to ZEVs. The exercise also considered what is feasible in terms of technology deployment.[3]

Road transport CO_2 emission pathways

The results of the modelling exercise are summarized in Figure 1. It shows that in the absence of new policy action, CO_2 emissions from global road transport (including cars, vans, trucks, and buses) are projected to increase by 32% over the next three decades (red line). This outcome is far from what is needed to help stabilize the climate: If the road transport sector is to reduce its emissions to a level consistent with a temperature cap of 2°C (yellow line), emissions must stabilize by 2030, decrease by 29% by 2040, and fall further, by 60%, by 2050. Hewing to a 1.5°C compatible pathway is still tougher: Emissions must decrease by 40-60% by 2030 and by 80-90% by 2040, settling at near-zero by 2050 (green wedge).

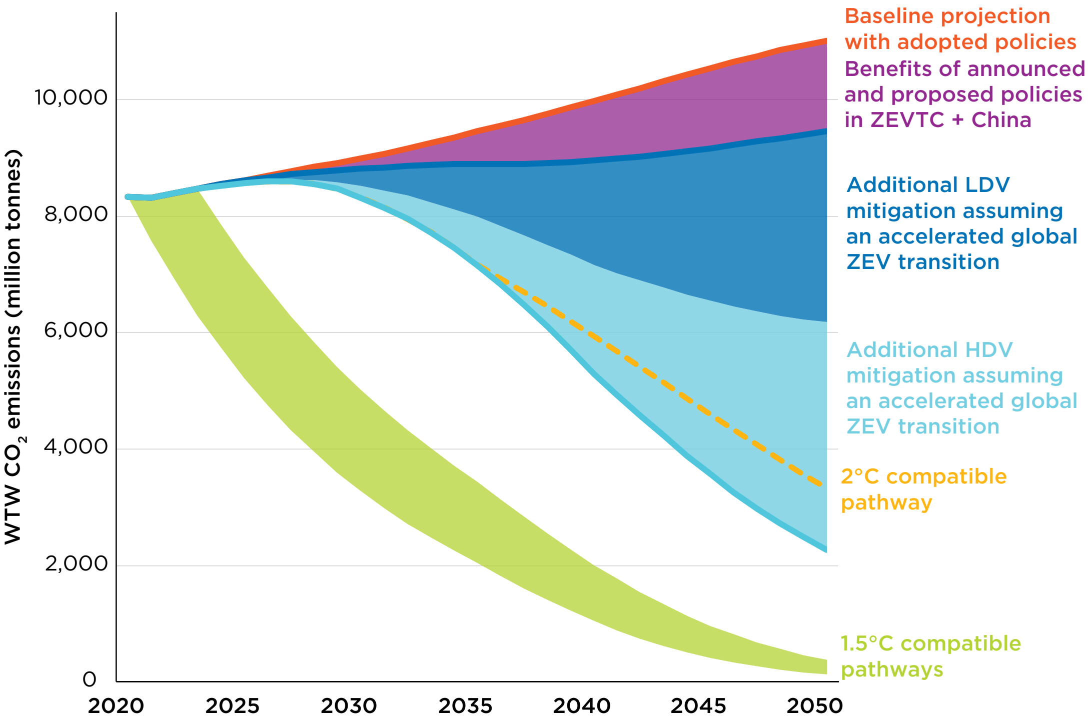

Figure 1. Global WTW CO_2 emissions from cars, vans, trucks, and buses compared to 1.5°C and 2°C compatible emissions pathways. Source: Sen and Miller (2022).

CO_2 emission benefits of an accelerated global ZEV transition

Figure 1 shows that vehicle policies announced or proposed by governments in major markets (purple wedge) leave road transport's emissions well above the levels needed

3 Arijit Sen and Josh Miller, "Emissions reduction benefits of a faster, global transition to zero-emission vehicles," (ICCT: Washington, DC, March 8, 2022) https://theicct.org/publication/zevs-global-transition-benefits-mar22/. Additional details of modeling assumptions and scenarios available in Appendix A.

to contribute to climate stabilization. In fact, emissions under the "announced and proposed" scenario are projected to *increase* over the next 3 decades, by 14%. By contrast, an accelerated transition of on-road vehicles (light and heavy alike) to ZEVs (blue wedges) could reduce CO_2 emissions 73% by 2050—slightly below a 2°C pathway, but still well short of the preferred 1.5°C pathway. HDVs account for about half of the emissions reduction (light blue wedge) in the accelerated transition scenario.

Transitioning new HDV sales to ZEVs is not, by itself, sufficient to align with a 1.5°C pathway: for this, additional measures would be required, such as maximizing fuel efficiency of any remaining internal combustion engine vehicles entering the market, and accelerating the pace of fleet renewal. However, transitioning new HDV sales to ZEVs, if pursued comprehensively and aggressively, could help to reduce transport emissions to a level consistent with a 2 °C scenario.

Pace of HD ZEV transition needed to align with Paris Agreement goals

Table 1 shows HD ZEV sales shares, segmented by vehicle type and by year, that are required for ZEVTC members to align with a below-2°C pathway. For example, by 2030, 75–90% of bus sales in ZEVTC markets should be ZEVs (the range accounts for the fact that not all ZEVTC markets are poised to transition at the same pace), and all bus sales should be ZEVs by 2040. For ZEVTC members as a whole (bottom row), alignment with Paris Agreement goals requires achieving a ZEV sales share for new HDVs of at least 45% by 2030 and nearing 100% by 2040.

ZEVTC members' ambitious HD ZEV targets would not only be a powerful signal, but would also offer policy ideas, regulatory lessons, and technological solutions to the rest of the world, including to emerging and developing markets that will also play an important role in limiting warming to well below 2 °C. ZEVTC Regional Dialogues and International Assistance Taskforce meetings will be important venues for identifying areas of collaboration to overcome barriers to accelerated ZEV transitions in developing countries, including for HDVs, and coordinating technical and financial development assistance to ensure a global transition. Such collaborative venues would also help emerging markets and developing economies (EMDEs) avoid getting locked into polluting technologies that are rapidly becoming obsolete.

Table 1. HD ZEV sales shares required, by year, for ZEVTC members to align with Paris Agreement goals

Vehicle type	2025	2030	2035	2040	2045
Bus (>3.5 tonnes)	7%-30%	75%-90%	90%-100%	100%	100%
Medium truck (3.5 to 16 tonnes)	3%-12%	40%-50%	75%-90%	100%	100%
Heavy truck (>16 tonnes)	2%-9%	30%-41%	60%-75%	90%-100%	100%
All HDVs (sales-weighted average per country)	3%-12%	40%-56%	69%-83%	94%-100%	100%
All HDVs (sales-weighted average for all ZEVTC members)	4%	45%	76%	97%	100%

Health benefits of a rapid transition to HD ZEVs

An accelerated transition to HD ZEVs would yield immediate health benefits. The majority of HDVs on the road today are diesel-fuelled vehicles. Long-term exposure to diesel exhaust has been linked to lung cancer, stroke, heart disease, pulmonary disease, chronic respiratory illnesses, asthma, bronchitis, and other adverse health effects. In 2015, transportation tailpipe emissions were associated with 385,000 premature deaths from ambient fine particulate matter ($PM_{2.5}$) and ozone pollution, equivalent to a societal cost of nearly 1 trillion USD per year.[4] On-road diesel vehicles were the greatest contributor, accounting for 47% of transportation-related premature deaths.

A recent analysis shows that among G20 economies, actions to ensure that all new HDVs are ultra-low emission or zero-emission could avoid 3 million premature deaths through 2050, equivalent to 5 trillion USD in health benefits.[5] The magnitude of these benefits would be greater still with an accelerated transition to HD ZEVs. Regional studies from the United States, European Union, and India have corroborated the large-scale air quality and health benefits of transitioning to zero-emission HDVs in ZEVTC markets.[6] Addressing HDV pollution is also vital from an environmental justice standpoint, as evidenced in the United States, where diesel HDVs are consistently one of the largest sources of social disparity in $PM_{2.5}$ exposure.[7] In EMDEs where highly polluting HDVs are used, HD ZEVs can help address the air pollution crisis affecting the health of residents.[8]

HD ZEV assessment: Technology readiness, commercial availability, cost

Heavy-duty vehicles encompass a wide variety of vehicle types and applications. The technological development, commercial readiness, and cost-effectiveness of the various HDV segments are evolving at different paces. In the discussion below, we analyze these three dimensions, with particular emphasis on "first-mover segments" where near-term policy actions could hasten HD ZEV deployment.

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4 Susan Anenberg, Joshua Miller, Daven Henze, Ray Minjares, *A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015*, (ICCT: Washington, DC, 2019), https://theicct.org/sites/default/files/publications/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf.

5 Lingzhi Jin, Caleb Braun, Joshua Miller, Claire Buysse, *Air Quality and Health Impacts of Heavy-Duty Vehicles in G20 Economies*, ICCT: Washington, DC, 2021), https://theicct.org/publication/air-quality-and-health-impacts-of-heavy-duty-vehicles-in-g20-economies/#:~:text=Air%20quality%20and%20health%20impacts%20of%20heavy%2Dduty%20vehicles%20in%20G20%20economies,-July%2022%2C%202021&text=On%2Droad%20diesel%20vehicles%20are,significant%20near%2Dterm%20climate%20warming.

6 Phadke et al., "The 2035 Report: Transportation" Goldman School of Public Policy, (UC Berkeley, 2021); Eamonn Mulholland, Josh Miller, Caleb Braun, Lingzhi Jin, Felipe Rodríguez, *Quantifying the Long-Term Air Quality and Health Benefits from Euro 7/VII Standards in Europe* (ICCT: Washington, DC, 2021; Arjit Sen, Josh Miller, Anup Bandivadekar, Mukesh Sharma, Pavan Kumar Nagar, Direndra Singh, *Understanding the Air Quality and Health Impacts of Large-Scale Vehicle Electrification in India*, (ICCT: Washington, DC, 2021), https://theicct.org/publication/understanding-the-air-quality-and-health-impacts-of-large-scale-vehicle-electrification-in-india/.

7 Christopher Tessum, David Paollela, Sarah Chambliss, Joshua Apte, Jason Hill, Julian Marshall, "PM2.5 Polluters Disproportionately and Systemically Affect People of Color in the United States," *Science Advances*, April 28, 2021, https://www.science.org/doi/10.1126/sciadv.abf4491.

8 Clive Cookson, "Almost All the World's Population Breathes Harmful Air, Says WHO," *Financial Times*, April 4, 2022, https://www.ft.com/content/eb93b458-0bb2-4e93-ae5a-4da42e7bfe8d.

First-mover HDV segments

A number of HDV segments—buses, urban delivery vehicles, and short-haul tractor trailers—share common characteristics that suit them well for ZEV deployment today. These include predictable daily range and payload, return-to-base operations, reliable and dedicated parking, and suitability for applying innovative business models.[9]

As detailed in the following sections, the relatively mature state of the ZEV market for these segments suggests that a high level of ambition for an accelerated transition to ZEVs is warranted. **In ZEVTC markets, ZEV policies should be oriented toward achieving a 100% ZEV sales share for the urban bus segment by 2030 and for the urban delivery vehicle and short-haul tractor trailer segments no later than 2035.** Accelerated electrification of these segments will be necessary to achieve overall HD ZEV sales shares for ZEVTC members of 40% to 56% by 2030, and of near-100% by 2040, shares that our modelling shows are needed to align with Paris Agreement goals. In other parts of the world, the transition to HD ZEVs in these segments has also begun, and could conceivably unfold as quickly as in ZEVTC markets.

Urban buses

The HDV bus segment includes urban buses, school buses, minibuses and coaches, and accounts for between 5% and 35% of total HDV CO_2 emissions in ZEVTC markets (Appendix A). Urban buses make up the majority of the bus fleet in ZEVTC countries and represent between 0.6% and 27.0% of HDV sales in these markets (Table 2).

Urban buses are the HDV segment with the quickest and widest adoption of zero-emission technology to date. Their operational profile is a good fit for zero-emission technology: they carry predictable loads, operate on predefined routes, travel between 100km and 250km on a single journey, and have access to en route charging and, at trip's end, dedicated depot space for refuelling and recharging. School buses and shuttle buses also share these operational characteristics.

Table 2. HDV sales shares, TCO parity year, and HD ZEV market readiness for urban buses

ZEVTC market	2020 HDV sales share	ZEV share in 2020 bus sales	TCO parity year	Market readiness
US (including California)	1.3%	0.6%	2022-2025	Mature market
Canada	0.6%	1.7%	2022-2025	Mature market
EU + UK + Norway	8.9%	6.4%	2022	Mature market
India	14.6%	0.6%	2022	Mature market
Japan	NA	NA	NA	Small-scale commercialization
Mexico	13.5%	5.3%	2030	Mature market
Republic of Korea	27.0%	1.6%	NA	Mature market

Note: Sales share for EU + UK + Norway, India, Mexico and Republic of Korea are for all bus types. Sales and TCO data for Japan not available. TCO parity year in Canada and market readiness are assumed to follow the US.

9 Further details of the characteristics of first-mover segments are included in Appendix B. Accelerated transitions to ZEV technologies in these segments offer significant CO_2 emissions reduction potential. For example, the three segments account for half of total HDV CO_2 emissions in the United States. Catherine Ledna, Catherine, Matteo Muratori, Arthur Yip, Paige Jadun, and Chris Hoehne, "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis," NREL, March 7, 2022, https://doi.org/10.2172/1854583.

The market for zero-emission urban buses in ZEVTC countries is mature. The mass adoption of zero-emission buses, which began in China in the mid-2010s, has spread to other markets, including ZEVTC members. In 2020, some 3,000 buses sold in ZEVTC markets were zero-emission, representing 2.6% of bus sales overall.[10] Zero-emission bus technologies are commercially available in all ZEVTC markets. As of 2022, a global database listed more than 40 manufacturers of zero-emission buses that collectively produced more than 100 different models.[11]

The development of the zero-emission bus market has made ZEV bus technologies a cost-effective alternative to ICE buses. For most markets where data is available, zero-emission buses are essentially cost-competitive, having achieved parity with ICE buses in terms of total cost of ownership (TCO), or being on track to achieve this by 2025 (Table 2). The high upfront costs of zero-emission buses are offset by operational savings over their lifetimes because of greater energy efficiency and lower maintenance costs; this has been demonstrated in analyses of ZEVTC member nations as different as India and the United States.[12] As battery and fuel-cell technologies evolve, the TCO of zero-emission buses is expected to continue to fall.

Zero-emission buses will be adopted more widely in the next decade across cities in ZEVTC markets as operators grow more comfortable with the technology and its operations. Kolkata, India plans to introduce 5,000 electric buses by 2030.[13] In Paris, France, operator RATP intends to procure more than 3,000 electric buses by 2025.[14] And the mayor of London has announced that all new transit buses in his city will be zero-emission, with 950 zero-emission buses already on the road or on order.[15]

Urban buses are experiencing the fastest transition to zero-emission in EMDEs as well; as of Feburary 2022, Latin American countries had deployed 2,803 zero-emission urban buses, the greatest number outside of China.[16] Learnings from ZEV Regional Dialogues and International Assistance Taskforce meetings can help identify areas in policy, technology and financing where additional support from ZEVTC members can help remove barriers, allowing more EMDEs to transition to zero-emission urban buses. Exchanges between ZEVTC members and EMDEs can also promote innovative business models and policy interventions that accelerate zero-emission public bus adoption in EMDEs, especially Latin America.

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10 Dale Hall, Yihao Xie, Ray Minjares, Nic Lutsey, and Drew Kodjak, "Decarbonizing Road Transport by 2050: Effective Policies to Accelerate the Transition to Zero-Emission Vehicles," (Washington, D.C.: ZEV Transition Council, December 27, 2021), https://theicct.org/publication/zevtc-effective-policies-dec2021/.

11 CALSTART (2022): Drive to Zero's Zero-emission Technology Inventory (ZETI) Tool Version 7.0, Available online at https://globaldrivetozero.org/tools/zero-emission-technology-inventory/.

12 Aparna Vijaykumar, Parveen Kumar, Pawan Mulukutla, and OP Agarwal, "Procurement of Electric Buses: Insights from Total Cost of Ownership (TCO) Analysis," World Resources Institute India, accessed February 16, 2022, https://wri-india.org/sites/default/files/WRI_EBus_Procurement_Commentary_FINAL.pdf; Caley Johnson, Erin Nobler, Leslie Eudy, and Matthew Jeffers, "Financial Analysis of Battery Electric Transit Buses," June 1, 2020, U.S. Department of Energy, Office of Scientific and Technical Information, https://doi.org/10.2172/1659784.

13 C40 Knowledge Hub, "Cities100: Kolkata Is Electrifying Buses and Ferries," accessed March 12, 2021, https://www.c40knowledgehub.org/s/article/Cities100-Kolkata-is-electrifying-buses-and-ferries?language=en_US.

14 "RATP on the Way to a 2025 Clean Fleet in Paris. Interview with Nicolas Cartier," *Sustainable Bus*, September 24, 2019, https://www.sustainable-bus.com/news/ratp-on-the-way-to-a-2025-clean-fleet-in-paris-interview-with-nicolas-cartier/.

15 "Mayor Announces That All New London Buses Will Be Zero-Emission," Mayor of London/London Assembly, September 17, 2021, https://www.london.gov.uk//press-releases/mayoral/mayor-host-zero-emission-bus-summit-at-city-hall.

16 LAMOB, Universidade Federal do Rio de Janeiro, C40 Cities, International Council on Clean Transportation, and Partners for Growth, "E-BUS RADAR," E-BUS RADAR, February 2022. https://www.ebusradar.org/en/.

Urban delivery vehicles

Urban delivery vehicles, including delivery vans and smaller straight trucks, make up the majority of the medium truck fleet in ZEVTC countries. We estimate that medium trucks are responsible for 3% to 46% of total HDV CO_2 emissions in ZEVTC markets. Urban delivery vehicles constitute 0.2% to 12.5% of total HDV sales in ZEVTC members, although definitions of this segment vary somewhat by country.

Table 3. HDV sales shares, TCO parity year, and HD ZEV market readiness for urban delivery vehicles

ZEVTC market	2020 HDV sales share	TCO parity year	Market readiness
US (including California)	10.7%	2022 (Class 4) - 2027 (Class 7)	Small-scale commercialization
Canada	6.4%	2022 (Class 4) - 2027 (Class 7)	Small-scale commercialization
EU + UK + Norway	12.5%	Before 2030	Small-scale commercialization
India	0.2%	NA	NA
Japan	NA	NA	Small-scale commercialization
Republic of Korea	2.2%	NA	Small-scale commercialization

Note: Sales in California/US and Canada refer to all Class 4-6 straight trucks. Sales in India and Republic of Korea refer to vans listed in the database. Mexico sales data do not contain truck segment information. TCO parity year and market readiness in Canada are assumed to follow the US. Sales data in Japan and TCO data in India, Japan, Mexico and Republic of Korea not available.

Like urban buses, urban delivery vehicles typically have predictable daily range requirements and duty cycles; urban delivery trucks and vans in the U.S. typically travel less than 200 miles (320 km) daily.[17] Urban delivery vehicles are also characterized by return-to-base operations and long overnight dwell times, features that fit well with depot-charging battery-electric technology.

The market for zero-emission delivery vehicles is advancing, with small-scale commercialization under way in several ZEVTC markets, as shown in Table 3. As many as 20 zero-emission models are now available in Europe and United States.[18] Depending on vehicle load and application, their ranges typically span 75–205 miles (120–330 km).[19] Early deployments are led by fleet owners, who are often retailers and logistics companies. Amazon ordered 100,000 electric delivery vans from Rivian in 2019, for entry into service by 2024.[20] The logistics company United Parcel Service ordered 10,000 Arrival delivery vans, for delivery between 2020 and 2024. And Pride

17 Austin L. Brown, Daniel Sperling, Bernadette Austin, J. R. DeShazo, Lew Fulton, Timothy Lipman, Colin Murphy, et al., “Driving California’s Transportation Emissions to Zero,” University of California Institute of Transportation Studies, April 1, 2021, https://doi.org/10.7922/G2MC8X9X; Kevin Walkowicz, Adam Duran, and Evan Burton, “Fleet DNA Project Data Summary Report,” National Renewable Energy Laboratory, August 1, 2014, https://www.nrel.gov/transportation/assets/pdfs/fleet_dna_delivery_vans_report.pdf.

18 Sharpe, Benjamin, Claire Buysse, Jason Mathers, and Victor Poudelet, “Race to Zero: How Manufacturers Are Positioned for Zero-Emission Commercial Trucks and Buses in North America,” (ICCT: Washington, DC, 2020): https://theicct.org/publication/race-to-zero-how-manufacturers-are-positioned-for-zero-emission-commercial-trucks-and-buses-in-north-america/; Hussein Basma and Felipe Rodríguez, “Race to Zero: How Manufacturers Are Positioned for Zero-Emission Commercial Trucks and Buses in Europe,” (ICCT: Washington, DC, 2021). https://theicct.org/publication/race-to-zero-ze-hdv-eu-dec21/.

19 Baha M. Al-Alawi, Owen MacDonnell, Ross McLane, and Kevin Walkowicz, “Zeroing in on Zero-Emission Trucks: The Advanced Technology Truck Index: A U.S. ZET Inventory Report,” CALSTART, January 2022, https://calstart.org/wp-content/uploads/2022/02/ZIO-ZETs-Report_Updated-Final-II.pdf.

20 AndrewJ. Hawkins, “Amazon will order 100,000 electric delivery vans from EV startup Rivian, Jeff Bezos says,” *The Verge*, (September 19, 2019), https://www.theverge.com/2019/9/19/20873947/amazon-electric-delivery-van-rivian-jeff-bezos-order.

Group Enterprises' order of more than 6,320 Workhorse C-Series electric delivery trucks is expected to be delivered between 2021 and 2026.[21]

The economics of operating zero-emission urban delivery trucks and vans is promising, although the TCO estimates vary by level of utilization; greater daily driving distance for some delivery applications leads to greater cost savings and more favorable comparisons. (See Table A4 in Appendix B.)

Short-haul tractor trailers

Short-haul tractor trailers are the third segment with great potential for an accelerated transition to zero-emission technologies. These tractor trailers have higher payloads than urban delivery vehicles but similar daily driving ranges, which make them suitable for electrification using today's technologies.

Short-haul tractor trailers and equivalent straight trucks generally weigh more than 40 tonnes (gross vehicle weight), typically travel fewer than 300 km (180 miles) per day, and have day cabs instead of the sleeper cabs found on long-haul tractor trucks. This segment includes vehicles used in diverse applications, including beverage trucks and drayage trucks. In our modelling, short-haul tractor trailers are grouped with long-haul tractor trailers in the heavy truck category, which accounts for between 24% and 93% of HDV CO_2 emissions in ZEVTC markets. Across ZEVTC markets where sales data are available, short-haul tractor trailers accounted for between 2.3% and 8.6% of total HDV sales in 2020.

Table 4. HDV sales shares, TCO parity year, and HD ZEV market readiness for short-haul tractor trailers

ZEVTC market	2020 HDV sales share	TCO parity year	Market readiness
US (including California)	8.6%	2025-2033	Approaching commercialization
Canada	6.1%	2025-2033	Approaching commercialization
EU + UK + Norway	5.0%	2028	Approaching commercialization
India	4.0%	NA	Approaching range-limited commercialization
Republic of Korea	2.3%	NA	NA

Note: Original sales data in Canada are for all tractor trailers; the ratio of short- to long-haul trucks is assumed to follow the US. Original sales data in EU + UK + Norway refer to all tractor trailers, and the breakdown is 88.5% long-haul and 11.5% short-haul, consistent with 2019 data. Original sales share for India and Republic of Korea are for all tractor trailers and the breakdown assumes 50% long-haul and 50% short-haul. Mexico sales data does not contain truck segment information. Sales data in Japan and TCO data in India, Japan, Mexico and Republic of Korea not available.

The market for zero-emission short-haul tractor trailers in ZEVTC countries is at a relatively early stage of development. In North America and Europe, zero-emission short-haul tractor trailers are approaching commercialization, while in markets such as India, technology demonstrations and pilots are underway.

Today, commercially available models of zero-emission short-haul tractor trailers are primarily battery-electric. The list of available products is growing quickly: In North

21 "Workhorse Receives Purchase Order from Pride Group Enterprises for 6,320 C-Series All-Electric Delivery Vehicles," Workhorse Group, Inc., January 4, 2021, https://ir.workhorse.com/news-events/press-releases/detail/162/workhorse-receives-purchase-order-from-pride-group; Victoria Tomlinson, "UPS Invests in Arrival and Orders 10,000 Generation 2 Electric Vehicles," Arrival.com, April 24, 2020, https://www.arrival.com/us/en/news/ups-invests-in-arrival-and-orders-10000-generation-2-electric-vehicles.

America, battery-electric tractor truck models in production, or nearly so, include the eCascadia from Freightliner (Daimler), the second generation VNR Electric from Volvo, the Peterbilt 579EV from Paccar, and the Nikola Tre. Volvo recently received its first major order for the electric VNR model and has plans to deliver more than 100 to fleets in California in the next few years.[22] In Europe, Mercedes-Benz (Daimler) released the eActros with a 6*2 tractor configuration, DAF has a zero-emission variant of its CF tractor, and Scania has also announced its first battery-electric tractor truck model.[23] Volvo will begin series production of the FH Electric truck in Europe, which has a tractor version.[24] In India, Tata Steel plans to deploy 27 electric tractors with a minimum payload of 35 tonnes to transport finished steel between its plants and stockyard.[25] Other available models include the Kenworth T680E, the Lion 8 tractor, and the BYD 8TT.[26] Besides battery-electric powertrains, Toyota and Kenworth successfully deployed five hydrogen fuel cell tractor trucks in the Port of Los Angeles.[27]

Zero-emission short-haul tractor trailers are expected to achieve TCO parity with ICE vehicles within the decade in the North American and European markets, and as early as 2025 if purchase incentives, inexpensive energy, and other facilitating conditions are in place. Although the purchase price of a battery-electric short-haul tractor truck is much higher than that of a diesel truck, the cost of battery-electric trucks is projected to fall. [28]

Long-haul tractor trailers

Long-haul tractor trailers face additional barriers to ZEV deployment, including range and payload limitations, and are at the earliest stages in the transition to zero-emission technologies.

Long-haul tractor trailers and equivalent straight trucks make up between 2.3% and 28.1% of HDV sales in ZEVTC markets with available sales data. Long-haul tractor trailers are used for long-distance hauling of the heaviest goods and have sleeper cabs to maximize operation time. Our global model groups short-haul tractor-trailers with long-haul tractor trailers into a single 'heavy truck' category. To align with a 2°C emissions pathway, sales of zero-emission heavy trucks should reach 30% to 41% by 2030 and 90% to 100% by 2040 in ZEVTC markets.

22 Truckinginfo, "Double-Digit Order for Volvo VNR Electric Going to Last-Mile Delivery - Fuel Smarts - Trucking Info," April 13, 2021, https://www.truckinginfo.com/10141147/qcd-commits-to-largest-commercial-volvo-vnr-electric-order-to-date.

23 Mercedes Benz Trucks, "EMobility: The EActros and Its Services," accessed February 21, 2022, https://www.mercedes-benz-trucks.com/en_GB/emobility/world/our-offer/eactros-and-services.html; "Scania Launches Fully Electric Truck with 250 Km Range," Scania Group, September 15, 2020, https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/3768729-scania-launches-fully-electric-truck-with-250-km-range; "DAF LF AND CF Electric Zero-Emission Transport Solutions," DAF, accessed March 24, 2022, https://paccarinnovation.com/media/1384/533201-daf_brochure_lf-cf_electric_en_v17_lr.pdf.

24 Volvo Trucks Global, "Volvo FH Electric," accessed March 24, 2022, https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fh/volvo-fh-electric.html.

25 "Tata Steel Pioneers the Deployment of Electric Vehicles for Transportation of Finished Steel in the Country," Tata Steel, July 30, 2021, http://www.tatasteel.com/media/newsroom/press-releases/india/2021/tata-steel-pioneers-the-deployment-of-electric-vehicles-for-transportation-of-finished-steel-in-the-country/.

26 Kenworth Trucks, "T680E," accessed March 24, 2022, https://www.kenworth.com/trucks/t680e/; Lion Electric, "All-Electric Lion8 Tractor Truck," accessed March 1, 2022, https://pages.thelionelectric.com/all-electric-lion8-tractor-truck-lion-electric/; BYD, "Class 8 Day Cab - BYD USA," accessed March 1, 2022, https://en.byd.com/truck/class-8-day-cab/.

27 "Port of Los Angeles Rolls Out Hydrogen Fuel Cell Electric Freight Demonstration," The Port of Los Angeles, June 7, 2021, https://www.portoflosangeles.org/references/2021-news-releases/news_060721_zanzeff.

28 Ben Sharpe and Hussein Basma, *A meta-study of purchase costs for zero-emission trucks*, (ICCT: Washington, DC, 2022) https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf.

Table 5. HDV sales shares, TCO parity year, and HD ZEV market readiness for long-haul tractor trailers

ZEVTC market	2020 HDV sales share	TCO parity year	Market readiness
US (including California)	15.0%	2030-2045	Approaching range-limited commercialization
Canada	10.8%	2030-2045	Approaching range-limited commercialization
EU + UK + Norway	28.1%	2024-2029	Approaching range-limited commercialization
India	4.0%	After 2030	Prototypes
Republic of Korea	2.3%	NA	NA

Note: Original sales data in Canada are for all tractor trailers and the ratio of short- to long-haul trucks is assumed to follow the US. Original sales data in EU + UK + Norway refer to all tractor trailers, and the breakdown assumes 88.5% long-haul and 12.5% short-haul, consistent with 2019 data. Mexico sales data does not contain truck segment information. Original sales share for India and Republic of Korea are for all tractor trailers and the breakdown assume 50% long-haul and 50% short-haul. Outlier TCO parity results removed to show consensus among studies. TCO parity year and market readiness in Canada are assumed to follow the US. Sales data in Japan and TCO data in India, Japan, Mexico and Republic of Korea not available.

Zero-emission technology use in the long-haul tractor trailer HDV segment depends on range and load requirements, and on operating conditions. High rates of daily utilization and large payload requirements create challenges for battery-electric powertrains: longer driving distances means a need for larger battery packs, more frequent recharging stops, and high-power recharging infrastructure, while heavy payloads require more powerful powertrains and larger energy storage systems, which add weight and cost and reduce the vehicles' effective payloads. HDVs that cannot return to base after each trip will need accessible public refuelling and recharging points, especially if the vehicles operate around the clock and have low or no dwell times.

Planning and investing in charging and refueling infrastructure will be critical to enable the use of zero-emission long-haul tractor trailers. ICCT estimates that the total installed power of public charging infrastructure in the EU needs to be 13.0 Gigawatts by 2030 to support projected zero-emission long-haul freight activities.[29] In the US, the fleet of zero-emission long-haul tractor trailers will require 127,000 charging points and more than 220 hydrogen refueling stations by 2030.[30]-

When heavy payloads, long distances, and short overnight dwell times are the norm, hydrogen fuel cell powertrains and electric road systems offer alternative solutions. Korean manufacturer Hyundai has expanded its fuel-cell tractor truck demonstration from Europe to North America, with 32 Xcient fuel cell trucks delivered to customers in northern and southern California.[31] U.S.-based hydrogen fuel-cell manufacturer Hyzon Motors has completed the delivery of 29 49-tonne trucks to a Chinese steel conglomerate.[32] These hydrogen fuel-cell tractor trailers belong to the heaviest weight category and are capable of long-distance driving greater than 400 km (250 miles).

29 Pierre-Louis, Ragon, Eamonn Mulholland, Hussein Basma, and Felipe Rodríguez, "A Review of the AFIR Proposal: Public Infrastructure Needs to Support the Transition to a Zero-Emission Truck Fleet in the European Union," (ICCT: Washington, DC, 2022. https://theicct.org/publication/afir-eu-hdv-infrastructure-mar22/.

30 Ray Minjares, Felipe Rodríguez, Arijit Sen, and Caleb Braun, "Infrastructure to Support a 100% Zero-Emission Tractor-Trailer Fleet in the United States by 2040," (ICCT: Washington, DC, 2021, https://theicct.org/publication/infrastructure-to-support-a-100-zero-emission-tractor-trailer-fleet-in-the-united-states-by-2040/.

31 "Hyundai's XCIENT Fuel Cell Hitting the Road in California," Hyundai Motors, July 27, 2021, https://www.hyundai.com/worldwide/en/company/newsroom/-0000016695.

32 "Hyzon Motors Delivers 29 Hydrogen Fuel Cell Electric Heavy Duty Trucks to Reduce Carbon Emissions in the Steel Industry," Yahoo Finance, December 8, 2021, https://finance.yahoo.com/news/hyzon-motors-delivers-29-hydrogen-133000065.html.

Relative to other segments, estimates of TCO for long-haul tractor trailers show more variation. Results depend on modelling assumptions regarding energy costs and capital costs, including vehicle price and infrastructure costs. One common and encouraging finding is that even the heaviest HD ZEVs can be viable from a TCO perspective if governments help to create the right conditions, including ZEV regulations to ensure product availability, purchase subsidies, in-use incentives to extend operating advantages of HD ZEVs, and investments in charging and refuelling infrastructure. The gap in the upfront purchase price between diesel and electric vehicles is narrowing too, as cell and battery pack performance improves, and as production volumes increase.

Designing effective policies to accelerate the HD ZEV transition

An accelerated transition of the HDV fleet to ZEVs, in line with the requirements to maintain a Paris Agreement-aligned CO_2 emissions pathway, is feasible only with strong government support. A recent ZEVTC paper analyzed the five most effective policies for accelerating the shift to ZEVs—target setting, regulations, incentives, infrastructure, and fleet purchase requirements.[33] In this section we provide key policy design considerations that best support an accelerated HD ZEV transition, along with examples of good policy designs.

Target setting. Overarching political statements that set targets for ZEV sales should be aligned with climate goals. Targets should include clear and specific language to avoid ambiguity and ideally should be made legally binding. For HDVs, targets can be set for individual vehicle segments to drive greater ambition for those segments where ZEV technology is available and cost-effective. For ZEVTC members, HD ZEV sales share targets of 45% by 2030 and 100% no later than 2040 would align with Paris Agreement goals.[34] Table 1 provides HD ZEV sales shares, by year, and by vehicle category (buses, medium trucks and heavy trucks) for ZEVTC members to align with this pathway. More ambitious targets should be considered for individual first-mover market segments where the ZEV market is more advanced in terms of technology readiness and cost parity: 100% ZEV sales share for the urban bus segment by 2030, and for the urban delivery vehicle and short-haul tractor-trailer segments by 2035.

Regulations. Legally-binding vehicle regulations can accompany political phase-out targets to cement manufacturers' shifts to HD ZEV production and ensure sufficient vehicle supply. Such regulations should be technology forcing—meaning they should be designed to drive zero-emission technologies to market faster than market forces would alone. Allowances, flexibilities, or credits, which can significantly weaken regulations, should be considered carefully. ZEV regulations, which require that a certain share of a manufacturer's HDVs be zero-emission, are the most straightforward policy to guarantee market availability of ZEV models. HD ZEV regulations should align sales requirements for individual vehicle segments with phase-out targets, while setting long-term targets to provide to manufacturers certainty and time to invest. California's Advanced Clean Trucks regulation, to be implemented in 2024, is a good

33 Hall et al., *Decarbonizing Road Transport by 2050: Effective Policies to Accelerate the Transition to Zero-Emission Vehicles*.

34 The Global MOU on ZE MHDVs, to which 5 ZEVTC members are signatories, provides a framework for setting national ambitions for accelerating deployment of HD ZEVs and reaching net-zero by 2050. Targets laid out in the Global MOU are 30% HD ZEV sales by 2030 and 100% HD ZEV sales by 2040. Our modelling has shown that while 100% sales by 2040 is in line with a below-2oC scenario, 30% sales by 2030 is not. HD ZEV sales of 45% by 2030 is more aligned with a below-2oC scenario.

example of effective regulatory design.[35] It has a broad regulatory scope, sets sales requirements that recognize differences among segments, and is in line with the state's transportation decarbonization target.

Incentives. Fiscal incentives such as purchase rebates and tax deductions supplement existing policies to shift market behavior, particularly in the early stages of the transition to HD ZEVs. Most HD ZEVs have a higher upfront capital cost than comparable ICE vehicles; subsidies that are tailored, by vehicle category, to close the gap in cost are among the most effective fiscal incentives. Revenue-neutral incentive programs (such as bonus-malus programs, or CO_2-based tolls) that increase the cost of higher emitting vehicles help accelerate the arrival of cost parity and help pay for incentive programs. Because the cost of ZEV technologies is changing rapidly, incentive programs should be reviewed regularly and revised to ensure that incentive amounts reflect technology and cost developments over time.[36]

Infrastructure. Governments have an important role to play in ensuring the availability of charging and fuelling infrastructure to support electrification targets. Governments are well-positioned to develop infrastructure roadmaps that satisfy current and future energy needs, and to coordinate planning among stakeholders to ensure that infrastructure build-outs align with the pace of technology transition set by ZEV sales targets and regulations.[37] Further government actions in the form of policies and incentives should drive private sector investment while ensuring that sufficient charging and refueling capacity is available in the early stages of market development.

Fleet Purchases. Fleet purchase requirements create market demand for HD ZEVs by mandating a minimum share of zero-emission vehicles in fleet purchases. Such purchase requirements, should, at minimum, create a market effect as great as that of supply-side polices such as ZEV regulations, and ideally generate even greater demand, especially for vehicle segments well suited for electrification today. An example is the 2029 100% zero-emission purchase requirement of the California Innovative Clean Transit regulation, whichs aligns with the recommended pace of transition for the urban bus segment, and which creates near- and medium-term demand for zero-emission bus products. Further, ZEV purchase requirements for public fleets, especially urban buses in some ZEVTC jurisdictions, could be broadened to cover other HDV segments as well as private owners, as has been proposed in the California Advanced Clean Fleets Regulation.[38] Putting a greater onus on larger fleets to transition more rapidly will avoid over-burdening small owner-operator fleets who have less ability to absorb the higher upfront costs of electric vehicles.

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35 Claire Buysse and Benjamin Sharpe, "California's Advanced Clean Trucks Regulation: Sales Requirements for Zero-Emission Heavy-Duty Trucks," (ICCT: Washington, DC, 2020, https://theicct.org/publication/californias-advanced-clean-trucks-regulation-sales-requirements-for-zero-emission-heavy-duty-trucks/.

36 A good example of HD ZEV purchase incentives is the California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), which provides purchase subsidies to HD ZEV consumers of up to $315,000 per vehicle. HVIP funding comes from revenues of California's Cap and Trade emissions trading scheme. For in-use incentives, the EU's proposed revision to the *Eurovignette* Directive will have a CO_2 provision that increases the road toll for internal combustion engine vehicles while reducing tolls for HD ZEVs by up to 75%.

37 Regulation can play an important role in driving the rapid deployment of publicly accessible charging infrastructure and hydrogen refueling stations. For example, the EU's proposed Alternative Fuels Infrastructure Regulation mandates a minimum amount of charging and hydrogen refueling capacity along major corridors.

38 California Air Resources Board, "Advanced Clean Fleets Regulation Workshop," March 2, 2021, https://ww2.arb.ca.gov/sites/default/files/2021-02/210302acfpres_ADA.pdf.

Glossary

Battery electric vehicles (BEVs)	Vehicles that run exclusively on electricity derived from on-board batteries, which are charged from an external charging station or Electric Vehicle Supply Equipment (EVSE).
Baseline scenario	The reference scenario in modeling exercises that all other scenarios compare against.
Black carbon	A product of incomplete combustion in pre-Euro VI standard diesel engines. It is a major component of particulate matter (PM) pollution and a potent short-lived climate pollutant. Also known as soot.
Bonus/malus system	A set of incentives and disincentives used to persuade consumers to give up internal combustion engine vehicles in favour of zero-emission vehicles. Incentives often take the form of rebates or subsidies (bonus). Disincentives can be taxes or fees (malus).
Bus segment	A category of heavy-duty vehicles weighing more than 3.5 tonnes and used to transport passengers. Key sub-segments are urban buses, coaches, school buses, and minibuses weighing more than 3.5 tonnes.
CO_2 standards	Government regulations that set minimum levels of vehicle fuel efficiency and maximum emissions of vehicle carbon dioxide or other greenhouse gases.
Depot charging	Electric vehicle charging that takes place at depots and facilities owned or leased by heavy-duty fleet owners. Depot charging enables vehicles parked overnight to recharge at relatively low power levels (~100 kilowatts, kW).
Duty cycle	The operational characteristics of a vehicle, such as daily range, average speed, number of stops per trip, and payload.
Drayage truck	Heavy trucks that transport containers to and from ports and railyards and other distribution centers. They travel short distances but have large payloads. In North America, most drayage trucks are tractor trailers; other markets use straight trucks for similar applications.
Dwell time	The time a vehicle is stationary and not in operation.
Fleet purchase requirements	A regulation requiring that a minimum share of a fleet be zero-emission, as a stimulant to market demand. Most fleet purchase requirements today apply to transit buses and to fleets owned by governments.
Fine particulate matter/ $PM_{2.5}$	Air pollutant whose diameter is smaller than 2.5 micrometres. Older diesel heavy-duty vehicles are a major source of $PM_{2.5}$ emissions.
Fiscal incentives	Government financial support to reduce the cost of zero-emission vehicles. These can be divided into purchase subsidies (such as tax credits, rebates), in-use incentives (exemptions from tolls and fees), and tax reductions (which can be one-time or recurring).
Heavy-duty vehicles (HDVs)	Medium and heavy commercial vehicles including buses and trucks whose maximum gross vehicle weight rating is greater than 3500 kg (3856 kg in the US and Canada). Interchangeable with the term medium- and heavy-duty vehicles (MHDVs) in some markets.
Heavy truck segment	A category of heavy-duty vehicles used in this paper's emissions modelling. Heavy trucks include vehicles greater than 16 tonnes in weight that are used to transport freight. Key segments in this category include short-haul tractor trailers (e.g. beverage or drayage trucks), long-haul tractor trailers, and heavy rigid trucks used for a variety of applications.

Hydrogen fuel cell electric vehicles (FCEVs)	Vehicles powered by hydrogen, which is converted to electricity by an onboard fuel cell.
Light-duty vehicles (LDVs)	Cars or trucks whose maximum gross vehicle weight rating is less than 3500 kg (3856 kg in the US and Canada). These are typically passenger cars, vans, and light trucks.
Medium truck segment	Trucks weighing between 3.5 and 16 tonnes that are used to transport freight. Urban delivery vehicles make up the majority of the medium truck fleet; other key segments include utility vehicles and rigid trucks used for regional and long-haul delivery.
Nitrogen oxides (NO_x)	Nitrogen oxides (NO_x) are poisonous, highly reactive gases emitted by internal combustion vehicles. NO_x are a criteria air pollutant and a precursor to ground-level ozone pollution.
'Return to base' operations	Activity of commercial or municipal vehicles whose daily operations start and end in the same depot/facility.
Straight trucks	A type of truck of various sizes used for a wide range of freight applications. In contrast to tractor trailers, the cab and body of straight trucks cannot be separated.
Targets	The aspirational visions set by a government to signal future policy directions. In this document targets refer to goals set to ensure that the stock of electric vehicles, as a share of all vehicles, is increasing. Targets assist manufacturers of zero-emission vehicles and related infrastructure in planning their products and investments.
Technological readiness	The level of testing and proving of electric vehicles. Technological readiness is often expressed in terms of laboratory, pilot, and commercial levels of readiness.
Technology forcing	Technology-forcing regulations and standards are those that cannot be met with existing technology, at an acceptable cost.
Total cost of ownership (TCO)	A measure of the cumulative costs incurred across a vehicle's lifetime, including upfront purchase cost, fuel and energy expenditures, vehicle maintenance, battery replacement, and infrastructure costs. TCO provides an understanding of the cost of a vehicle over the long term and is of particular interest to heavy-duty vehicle consumers such as companies and fleets.
Tractor trailers	Trucks with a gross vehicle weight greater than 40 tonnes and having the highest payloads among all freight-carrying heavy duty vehicles. Short and regional-haul tractor trailers typically travel fewer than 300 km per day with return-to-base operations. Long-haul tractor trailers transport the heaviest goods over long distances and have sleeper cabs to maximize operation time.
Turnkey solutions	Zero-emission heavy-duty fleet services, including vehicle design, production, financing, operational, and infrastructure, provided to consumers as a package.
Urban buses	Buses of 3.5 tonnes or greater that operate in cities.
Urban delivery vehicles	Delivery vans and smaller straight trucks that make up the majority of the medium truck fleet in ZEVTC countries.
Zero-emission vehicles (ZEVs)	Vehicles, such as BEVs and FCEVs, that produce zero exhaust emissions. PHEVs, which are considered a bridge technology because they produce no exhaust emissions when operating in electric mode, are also counted as ZEVs in this paper.
Zero-emission zones (ZEZs)	A geographic area, often in an urban center, where no internal combustion engine vehicles are permitted, some or all of the time. These zones can encompass areas ranging from a single street to an entire city.
ZEV regulations	Regulations requiring that ZEVs account for a certain share of new vehicle sales by each automaker, with the share increasing over time.

Appendix A. Modelling assumptions

Emissions modelling in this paper is based on our previous work, described in detail in Sen & Miller (2022).

In our analysis the **Baseline** scenario reflects global ZEV uptake through 2020 and accounts for the projected CO_2 emission effects of adopted policies and anticipated market developments. Table A1 below provides global minimum HD ZEV sales shares by year in the baseline scenario.

Table A1. Assumptions of HD ZEV sales shares by vehicle segment, region, and year under the Baseline scenario

Vehicle segment	Region	2025	2030	2035	2040	2045	2050
Bus	ZEVTC and China	7%	10%	15%	25%	35%	50%
MDT	ZEVTC and China	3%	5%	7%	10%	15%	20%
HDT	ZEVTC and China	2%	3%	4%	5%	7%	10%
Bus	Rest of World	3%	5%	10%	15%	25%	40%
MDT	Rest of World	1%	2%	3%	4%	6%	10%
HDT	Rest of World	1%	1%	2%	3%	4%	5%

The combined mitigation potential of accelerated ZE LDV and HDV adoption is in line with the 2 °C pathway, shown as the blue wedges in Figure 1. In the accelerated global ZEV transition scenario for LDVs (dark blue wedge), we assume that all countries follow one of three pathways in Table A2 in terms of their ZEV share of total LDV sales. By 2045 all LDV sales worldwide will be 100% zero-emission under this scenario.

Table A2. Assumptions of ZE LDV sales shares under the Ambitious scenario for three groups of countries. Group A: EU countries, Canada, China, Iceland, Norway, United Kingdom, United States (states with ambitious policies); Group B: India, Japan, Mexico, Republic of Korea, United States (states without ambitious policies); Group C: All other countries. Values in 2025 are exponentially interpolated from 2020 sales shares and 2030 targets.

Pathway	Vehicle segment	2025	2030	2035	2040	2045
A	Car	30%	75%	100%	100%	100%
	Van	30%	75%	100%	100%	100%
B	Car	12%	60%	90%	100%	100%
	Van	6%	60%	90%	100%	100%
C	Car	3%	30%	60%	90%	100%
	Van	2%	30%	60%	90%	100%

Table A3. Share of HDV WTW CO_2 emissions in ZEVTC markets, by segment (2020)

Region	HDV 2020 WTW CO_2 emissions (Mt)	Bus	MDT	HDT
Canada	82.2	5%	28%	67%
Denmark	5.46	11%	4%	85%
EU-27	297	8%	7%	85%
France	45.71	12%	6%	82%
Germany	63.1	9%	12%	80%
India	206.2	15%	16%	69%
Italy	23.87	9%	8%	83%
Japan	82.7	6%	46%	48%
Mexico	51.3	19%	26%	55%
Netherlands	10.48	4%	3%	93%
Norway	7.3	19%	9%	72%
Spain	32.88	5%	6%	89%
Sweden	6.54	10%	4%	87%
South Korea	55.7	35%	41%	24%
United Kingdom	53.5	7%	10%	83%
United States	580.4	6%	25%	69%

Appendix B. HDV segment data

HDV sales share data in Tables 2, 3, 4 and 5 for all ZEVTC members are from 2020 and are based on data published by Hall et al. (2021). No HDV sales information is available for Japan. Because of inconsistencies in segment definition and gaps in data availability, we made the following assumptions and simplifications for this analysis:

For urban buses, the sales shares for EU + UK + Norway, India, Mexico, and Republic of Korea are for all bus types. Sales data for Japan is not available.

For urban delivery vehicles, sales in California/US and Canada refer to all Class 4-6 straight trucks. Sales in India and Republic of Korea refer to vans in our database. Mexico sales data does not contain truck segment information. The sales data for Mexico does not contain information on truck segments.

For short- and long-haul tractor trailers, the original sales data in Canada are for all tractor-trailers and the ratio of short- to long-haul trucks is assumed to be the same as in the US. Original sales data in EU + UK + Norway refers to all tractor-trailers (vehicle groups 5, 8, 10, 12, 14), and those account for 33.1% of all HDV sales. The split between long- and short-haul is based on reference values for regulated vehicle groups (4,5,9,10) in the EU HDV CO_2 standards, and our own estimates for the unregulated classes. Class 5-LH, 8, and 10-LH each have a 90% share of long-haul operations while the remaining 10% is regional/urban. Classes 5-RD, 10-RD, 12, and 14 have 10% of their operations long-haul, and 90% urban/regional/construction. The breakdown works out as 88.5% of long-haul and 11.5% of short/regional-haul. Sales in India and Republic of Korea refer to all tractor-trailers, without specifying short versus long haul. Long-haul and short-haul tractor trailers are assumed to have equal shares in these two countries. The sales data for Mexico does not contain any information on different truck segments.

Characteristics of first-mover segments

Several HDV segments share enabling characteristics that make them well suited for electrification today:

Duty Cycle. Buses and other first-mover segments have predictable duty cycles, meaning they feature predefined routes and schedules that do not change from time to time. High predictability and low variation in duty cycle allow manufacturers to design products with vehicle energy storage capacity and powertrain systems tailored to the specific needs of an application.

Return-to-base operations. For HDVs that follow predefined routes and schedules, with return-to-base operations and long overnight dwell times, it is easier to facilitate planning for HD-specific infrastructure at fixed locations. Fleets that own facilities like depots and yards are in an advantageous position to set up their own HD ZEV recharging and refuelling equipment as public refuelling and recharging infrastructures unfold. A longer dwell time means vehicles will likely not need high-power recharging infrastructure and high capital investments across the established electricity system. The utility sector will be a key partner, through the design of electricity rates and by building physical infrastructure for HD ZEV fleets and balancing the utility system's own reliability, performance, and costs with those of HD ZEV fleet consumers.[39] In the interim, battery-electric HDVs whose recharging needs can be met without additional upgrades to the electric power system will be able to deploy even faster.

Reliable and dedicated parking. Fleet owners who have access to reliable and designated parking spaces for their vehicles can install, plan, and operate recharging/refueling more easily. This is related to the advantages of having return-to-base operations. Dedicated spaces like depots enable deployment of reliable, and even guaranteed, charging and fueling equipment. This in turn reduces financial costs and operational uncertainties for fleet owners and operators who can build and plan infrastructure in fixed locations. Urban buses enjoy the benefits of having depots for recharging and refueling; California's trials of tractor trailer drayage trucks in several ports revealed that depots there were also a benefit.

Another enabling factor for HD ZEV adoption is **innovative business models** from the private sector. A notable example of successful public-private partnership is found in Santiago, Chile, which operates the second-largest fleet of zero-emission buses in the world, after China.[40] Its success is largely attributed to a novel business model and tendering process that separates bus ownership from operations.[41] A fleet company owns and maintains the assets, while assuming the risks related to vehicle performance. Concessionaires provide drivers, operate vehicles, and manage day-to-day activities. Meanwhile, the public transit authority provides the guarantees needed to attract investors. The separation of ownership from operations gives rise to leasing, in which asset owners, utility companies and even vehicle manufacturers, which have substantial financing power, acquire the vehicles or their high-cost components, then lease them to vehicle operators.[42] Leasing reduces the burden of high upfront capital costs on vehicle operators.

An emerging business practice is third-party provision of vehicle fleets and recharging solutions, termed "vehicle-as-a-service" or "charging-as-a-service." These business models can help fleet owners bypass high access barriers to capital and infrastructure. Some HD ZEV manufacturers including Proterra, Scania, and Orange EV have taken a further step, providing a suite of vehicle design, production, financing, operational, and infrastructure services—a so-called "turnkey" solution.[43,44] Turnkey solutions and other innovative private sector practices can make HD ZEV deployment possible even in the absence of government mandates, regulations or large fiscal subsidies. HDV segments that take advantage of the private sector's strengths can unlock barriers to financing and introduce business models that accelerate HD ZEV adoption.

39 Yihao Xie and Felipe Rodríguez, "Zero-Emission Integration in Heavy-Duty Vehicle Regulations: A Global Review and Lessons for China," (ICCT: Washington, DC, August 31, 2021) https://theicct.org/publication/zero-emission-integration-in-heavy-duty-vehicle-regulations-a-global-review-and-lessons-for-china/.

40 Sebastián Galarza, "E-Mobility and Mass Transit Systems: The Experience of Santiago de Chile," presentation at the Workshop E-Mobility and Mass Transit: Global Case Studies & Indonesian Policy Review, June 3, 2021.

41 Dalberg, C40 Cities, and International Council on Clean Transportation, "Investing in Electric Bus Deployment in Latin America: Overview of Opportunity and Market Readiness," July 2020, https://theicct.org/sites/default/files/publications/ZEBRA-market-readiness-pitch-sept2020.pdf.

42 Joshua Miller, Ray Minjares, Tim Dallmann, and Lingzhi Jin, *Financing the Transition to Soot-Free Urban Bus Fleets in 20 Megacities*, (ICCT: Washington, DC, 2017), https://theicct.org/sites/default/files/publications/Soot-Free-Bus-Financing_ICCT-Report_11102017_vF.pdf.

43 Scania Group, "Battery Electric Truck," accessed February 16, 2022, https://www.scania.com/group/en/home/products-and-services/trucks/battery-electric-truck.html.

44 Truckinginfo, "Proterra Offers Turnkey Management for Battery-Electric Vehicles," May 16, 2019, https://www.truckinginfo.com/331988/proterra-introduces-fleet-management-ecosystem-for-battery-electric-vehicles.

Total cost of ownership

The data on total cost of ownership parity assessment comes from a wide literature review of published TCO studies in ZEVTC members. We synthesize the major findings of these studies and identify board consensus regarding when TCO parity is achieved. Generally, there is a dearth of literature on HDV TCO analysis outside of the US, Europe, and China, especially for trucks. It is important to note that each study has its own set of assumptions on vehicle upfront cost, energy and infrastructure cost, vehicle kilometers/miles travelled, and other variables that are important factors for the final TCO outcome, and they should be interpreted carefully. In this paper the TCO parity years for Canada are assumed to be identical to results of US studies due to the shared market and geographical proximity.

Table A4. Published HDV TCO studies in ZEVTC members for cost parity assessment

Region	Link to study	Segments covered	Main findings
US/ California	https://vms.es.anl.gov/tools/bean/	Urban buses, urban delivery vehicles, short-haul tractor trailers, long-haul tractor trailers	Transit buses can achieve TCO parity with diesel before 2024. Class 4-7 short-haul rigid trucks can achieve TCO parity with diesel between 2022 and 2026. Class 8 short-haul tractor trailers achieve TCO with diesel between 2028 and 2033. Class 8 long-haul tractor trailers achieve TCO with diesel between 2040 and 2045.
	https://www.nrel.gov/docs/fy21osti/71796.pdf	Urban delivery vehicles, short-haul tractor trailers, long-haul tractor trailers	Class 4 delivery trucks can already achieve TCO parity with diesel in 2020, and Class 8 short-haul tractor trailers can achieve TCO parity with diesel by 2023. Class 8 long-haul tractor trailers can only achieve TCO parity with diesel after 2050.
	https://publications.anl.gov/anlpubs/2021/05/167399.pdf	Urban delivery vehicles, short-haul tractor trailers, long-haul tractor trailers	Class 4 Delivery vans can achieve TCO parity with diesel by 2023. Class 8 day cab short-haul tractor trailers can achieve TCO parity with diesel by 2027. Class 8 sleeper cab long-haul tractor trailers can achieve TCO parity with diesel by 2031.
	https://www.edf.org/sites/default/files/documents/EDFMHDVEVFeasibilityReport22jul21.pdf	Short-haul tractor trailers, long-haul tractor trailers	Delivery vans and trucks and service vans can achieve TCO parity with diesel before 2025. Class 8 short-haul and long-haul tractor trailers can both achieve TCO parity with diesel before 2025.
	http://www.zevalliance.org/zero-emission-freight-2020/	Urban delivery vehicles, short-haul tractor trailers	Battery-electric cargo vans will reach TCO parity with diesel by 2026. Battery-electric 19t trucks will reach TCO parity with diesel by 2028. Battery-electric yard tractors will reach TCO parity with diesel by 2027Battery-electric long-haul trucks will reach TCO parity with diesel by 2029.
	https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf	Urban delivery vehicles, short-haul tractor trailers	Battery-electric cargo vans can already reach cost parity with diesel in 2025, and fuel cell electric will be TCO competitive by 2030. Battery-electric walk-in vans have lower TCO than diesel in 2025, and fuel cell electric is almost TCO competitive in 2025. Both battery-electric and fuel cell electric day cab tractors have lower TCO than diesel in 2025. Fuel cell electric sleeper cab tractors have lower TCO than diesel in 2025. Battery-electric sleeper cab tractors will achieve TCO parity in 2030.
	https://www.edf.org/media/new-study-finds-rapidly-declining-costs-zero-emitting-freight-trucks-and-buses	Urban buses, urban delivery vehicles	Both zero-emission urban buses and Class 4-7 short-haul rigid trucks can achieve TCO parity with diesel before 2027
	https://theicct.org/publication/cost-ev-vans-pickups-us-2040-jan22/	Urban delivery vehicles	TCO of electric vans and pickup trucks weighing 3.9 to 6.4 tonnes, and with a 200-mile range, is already lower than a diesel version today, and will be lower than a gasoline version by 2025.
	https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf	Short-haul tractor trailers	Battery-electric short-haul tractor-trailers meet TCO parity with diesel tractor-trailers by 2030
	https://www.nrel.gov/docs/fy22osti/82081.pdf	Urban delivery vehicles, short-haul tractor trailers, long-haul tractor trailers	Battery-electric HDVs tend to become cost-competitive for smaller trucks before 2030 and for short-haul (500-mile) heavy trucks by 2035.

Region	Link to study	Segments covered	Main findings
Europe	https://www.transportenvironment.org/wp-content/uploads/2021/07/Electric-buses-arrive-on-time-1.pdf	Urban buses	The 8-year TCO of battery-electric buses utilizing both depot charging and opportunity charging is lower than a diesel bus in 2018.
	https://d-nb.info/1216637784/34	Urban buses	Battery-electric bus utilizing overnight charging with no battery replacement has a lower TCO than a diesel bus in 2019.
	https://www.strategyand.pwc.com/de/en/industries/transport/green-trucking-2020/truck-study-2020.pdf	Urban delivery vehicles, short-haul tractor trailers, long-haul tractor trailers	Battery-electric last-mile delivery and last-mile goods distribution vehicles with daily ranges below 200 km achieve TCO parity with diesel by 2030.
	https://www.ing.nl/zakelijk/kennis-over-de-economie/uw-sector/transport-en-logistiek/electric-heavy-duty-trucks.html	Short-haul tractor trailers	Battery-electric short-haul tractor trailers with annual mileage of 60,000 km become financially attractive with diesel by 2030, without subsidies.
	https://theicct.org/sites/default/files/publications/TCO-BETs-Europe-white-paper-v4-nov21.pdf	Long-haul tractor trailers	Battery-electric tractor-trailers can achieve cost parity with diesel tractor-trailers in the next 10 years in Germany, Italy, Poland, Spain, UK, France and the Netherlands without new policy interventions.
India	https://escholarship.org/uc/item/7d64m1cd	Urban buses	Across a broad range of average daily utilization rates from 150 to 250 kilometers, and at the current unsubsidized cost of electricity supply, electric buses have a lower TCO relative to diesel buses not only in the absence of EV subsidies but even after factoring in the 30% tariff on import of EV batteries into India.
	https://www.teriin.org/sites/default/files/2021-07/Report_on_The_Potential_Role_of_%20Hydrogen_in_India.pdf	Urban buses, long-haul tractor trailers	Battery-electric buses are modelled to be cost-competitive on a TCO basis with both the high-end and low-end diesel bus at 2020 costs. Even under the worstcase scenarios of high electricity tariff, low mileage and high discount rates, electric city buses should be competitive with ICE variants by 2030. By 2030, 25-tonne long-haul battery-electric trucks are neck and neck with diesel trucks, with hydrogen fuel-cell trucks have even more favorable TCO comparisons.
Mexico	https://www.energypartnership.mx/fileadmin/user_upload/mexico/media_elements/reports/Hidro%CC%81geno_AE_Tomo_V.pdf	Urban buses	For diesel, battery-electric and hydrogen fuel cell electric transit buses with a useful life of 10 years and an average annual distance of 65,000 km, both BEVs and FCEVs achieve TCO parity with diesel in 2030.