A Pathway to Zero-Emission Trucking in India

Setting the Framework

Case-Specific Policy Analysis

UCDAVIS
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Abbreviations and acronyms

AMC	Annual maintenance cost
BET	Battery-electric truck
CAFE	Corporate average fuel economy
CAGR	Compound annual growth rate
ERSV	Electric road system vehicle
EV	Electric vehicle
FCET	Fuel-cell electric truck (hydrogen)
FY	Financial year
GHG	Greenhouse gas
GVW	Gross vehicle weight
HD	Heavy-duty
HDTs	Heavy-duty trucks
HVIP	Heavy Vehicle Incentive Program
ICE	Internal combustion engine
INR	Indian rupee
IRA	Inflation Reduction Act
MDT	Medium-duty truck
MHDT	Medium- and heavy-duty truck
MHDV	Medium- and heavy-duty vehicle
MoRTH	Ministry of Road Transport and Highways
MY	Model year
OEM	Original equipment manufacturer
PM	Particulate matter
PPP	Purchasing power parity
SEZ	Special economic zone
T	Tonne
TCO	Total cost-of-ownership
VKT	Vehicle-kilometres travelled
ZET	Zero-emission truck
ZEV	Zero-emission vehicle

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Key messages

The total cost-of-ownership of electric trucks is falling

Battery cost reductions and efficiency improvements are significantly reducing battery-electric trucks' total cost-of-ownership (TCO). Heavy-duty battery-electric trucks are projected to achieve TCO parity with internal combustion engine trucks sooner than hydrogen and fuel-cell electric trucks.

Maximise the early mover advantage

Prioritising battery-electric trucks – especially for the 18-tonne and 55-tonne segments – could help India begin the market transformation to heavy-duty zero-emission trucks (ZETs) in the coming decade.

Policy levers are critical to zero-emission truck uptake

Transitioning to ZETs in India will rely on important policy levers such as target setting, purchase incentives, greenhouse gas emissions regulations, and fleet and infrastructure development.

Main findings

This report assesses the potential of decarbonising heavy-duty trucks in India with zero-emission technologies, focusing on battery-electric technology. It presents a four-pillared roadmap for a transition to ZETs that addresses technology, infrastructure and operations, financing, and policy interventions for India. It achieves this by identifying economically feasible truck segments (based on weight classification) for the transition, along with strategies for developing support infrastructure and innovative financing models.

Based on the meta-review of global TCO studies, this report finds that heavy-duty battery-electric trucks are projected to achieve TCO parity with internal combustion engine (ICE) trucks much sooner than combustion-engine hydrogen truck (H2-ICE) and fuel-cell electric truck (FCETs) technologies across Europe and the United States. The battery-electric tractor-trailer in China is expected to achieve TCO parity with ICE in 2030. The TCO was found to improve by 60% for battery-electric trucks from 2020 to 2030, led by a reduction in battery costs and energy efficiency improvements in Europe.

The report also investigates the economic viability of heavy-duty zero-emission truck (ZET) segments in India using a techno-economic analysis tool to determine the TCO for different tonnage segments (defined by gross vehicle weight, GVW). The TCO is calculated for model years (MY) 2023 and 2030 for different truck segments. It also analyses the effect of various parameters – including financing cost, distance, electricity cost and road tolls – on the TCO for MY 2023 for the different truck segments.

The TCO analysis highlights the early mover advantage in electrifying the 55T and 18T truck segments, depending on the use case. The TCO for battery-electric 55T trucks becomes 9% cheaper than its diesel counterpart in 2030. The TCO for battery-electric 18T truck in 2030 remains only 18% higher than its ICE counterpart, signifying the need for a clear policy and regulatory pathway for electrifying the heavy-duty truck segments in India.

In addition, the report examines international policy developments at both the national and sub-national levels that have informed the proposed roadmap in terms of building the foundation for India's policy and regulatory framework for zero-emission trucking.

Based on the examinations of economic viability and international policy developments, this study finds four potential policy levers – target setting, greenhouse gas (GHG) emissions regulations, fleet and infrastructure development, and purchase incentives – that can catalyse the transition to ZETs in India.

Recommendations

Prioritise electrification for early-mover truck segments in India

Battery-electric technology has emerged as the dominant choice globally, driven by economic feasibility, battery technology maturity and cost reduction. Given the nascent stage of development of a hydrogen ecosystem in India and the challenges associated with the cost and availability of green hydrogen overall, prioritising battery-electric trucks – especially for the 18T and 55T segments for specific use cases with a competitive cost of ownership in the near future – could help India begin the market transformation to ZETs in the coming decade.

Strengthen the CO_2 regulations for medium- and heavy-duty trucks in India along with a shift to corporate average fuel economy (CAFE) norms

India's current carbon dioxide (CO_2) regulations for medium- and heavy-duty trucks, effective 1 April 2023, are essentially fuel consumption (litres/100km) requirements per vehicle as opposed to CAFE standards. The new standards could consider a 30% reduction in CO_2 emissions for the medium- and heavy-duty truck segment by 2035 from 2022 levels. India could also shift to CAFE norms, allowing technological flexibility for truck manufacturers and enabling a market-based credit trading mechanism for compliance.

Set ambitious manufacturer and fleet sales targets

Supply-side regulations have proven successful in accelerating the transition to zero-emission cars across the EU, United Kingdom, California and China. This has led to a diverse supply of products, greater investor confidence in infrastructure providers, manufacturers, and financiers, and enabled industry self-financing through market-based credit mechanisms. Given the recent announcements by leading truck manufacturers in India on investments in electric trucks, an annual manufacturer sales requirement beginning with 10% new sales share by 2030, along with a fleet purchase requirement for large corporations, could spur the ZET market.

Plan, invest, and involve industry in developing charging infrastructure

The infrastructure costs in the medium- and heavy-duty truck segment could have the potential to delay the TCO parity-time horizon by 5 to 10 years. Judging from the meta-review of TCO studies in Europe and the United States, depot charging has the potential to account for about 80% and 35-77% of charging needs, respectively, for urban and regional applications with a range of about 500 km. There exist opportunities for collective efforts between industry players to create common infrastructure along major routes, increasing utilisation rates and lowering costs. India can also create zero-emission freight corridor strategies, drawing lessons from similar efforts by the European Union and the United States.

Encourage sub-national policy and regulatory action

State governments in India impose a road tax on the purchase of trucks in their jurisdiction in addition to a goods and services tax (GST), which provides a potential policy lever for instituting differentiated road tax rates based on powertrain or GHG emission portfolio. Further, most states in India have their own electric vehicle (EV) policies, which can be expanded to include a comprehensive package for ZETs. States and cities can also create zero-emission zones or priority entry for ZETs into cities to encourage adoption. This could also be an opportunity for states to cooperate to facilitate zero-emission freight corridors, toll-free movement for ZETs, and so on.

Consider an interest subvention programme to lower electric truck financing cost

Following the example of reduced interest rates for light-duty vehicles in India, there is a potential to consider an interest subvention programme for electric trucks to offset the high upfront purchase cost barriers. Since trucks are an expensive asset involved in an operational system with thin revenue margins, sending a market signal by lowering effective interest rates would help alleviate the uncertainty for electric truck deployment.

Involve shippers and public fleet operators in a scaled adoption of zero-emission trucks

Given the fragmented nature of India’s truck market (about 80% of the fleet is owned by small fleet operators), an early move by large shippers and logistics service providers toward ZET adoption and longer-term contracts could build confidence in the market. India could also leverage the lessons learnt from electric bus aggregation to transition the public fleets, such as municipal and drayage trucks, and trucks operating in public sector units across heavy industries, such as cement, steel and mining.

The case for road freight decarbonisation

Road freight plays a critical role in India's economy and is expected to remain the dominant mode for freight movement both in India and globally. Moreover, considering India's robust GDP growth rate, growing consumption expenditure, and significant public investment in infrastructure, freight demand in the country is expected to grow rapidly, especially given current policy ambitions that focus on passenger transport. This growth will likely result in a corresponding increase in road freight emissions in India. This is a global trend: The *ITF Transport Outlook 2023* estimates that global freight emissions are expected to be about 61% of transport emissions by 2050, increasing from a share of 46% in 2019, thus contributing more than passenger transport (ITF, 2023a).

This introductory chapter provides an overview of the road freight sector with a focus on India, detailing its significant growth in recent decades. It discusses the imperative for transitioning to zero-emission trucks (ZETs) to mitigate the environmental impact, reduce emissions and achieve India's net-zero goals. The chapter presents the current state of ZET deployment globally – including initiatives by governments, manufacturers and fleet operators – and highlights the economic and environmental benefits associated with ZET adoption. However, it also acknowledges the challenges hindering widespread adoption, such as technology limitations, infrastructure requirements and financing constraints.

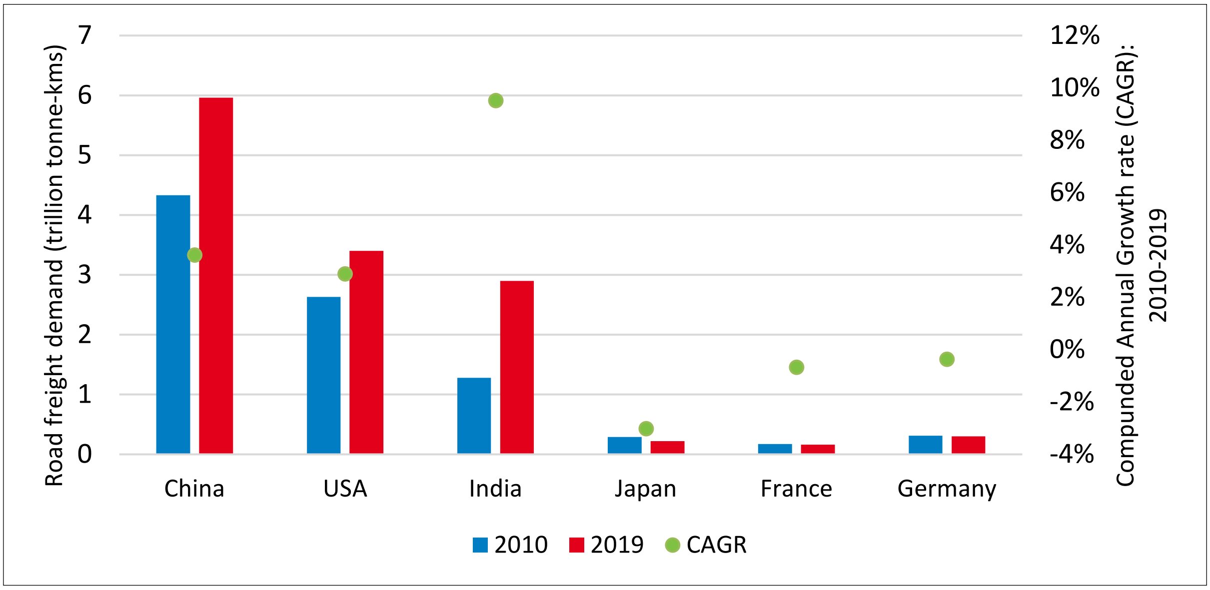
Given the remaining challenges, how can the road freight sector decarbonise? This chapter sets the stage for the subsequent sections of the report, which delve into the global policy developments enabling a ZET transition, highlight the economic viability of ZETs (through the findings of a total-cost-of-ownership analysis), and present a comprehensive policy roadmap for decarbonizing road freight through the adoption of ZETs in India.

The growing environmental impact of the road freight sector

Nine markets – Brazil, Canada, China, the European Union (EU), India, Japan, Mexico, South Korea and the United States currently constitute about 80% of global road freight demand and are expected to continue contributing more than 75% in 2050 (Ng, 2022). These markets are also significant in terms of their commercial vehicle fleet sizes, contributing about 72% and 57% of the global fleet of medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs), respectively (Ng, 2022). The United States, followed by China and India (two of the fastest-growing economies), make up over two-thirds of the total road freight demand annually (OECD, 2024). As developing countries continue to see increased capital spending from governments and higher consumer incomes, demand for commodities and finished goods is expected to increase.

In terms of road freight demand, China, the United States and India (in that order) have the highest demand (see Figure 1), and the demand is growing at an average annual rate of 5%. Road freight demand saw the highest growth between 2010 and 2019 in India, at an annual average growth rate of 10%, as compared to about 4% in China and the United States for the same period (OECD, 2024).

Figure 1. Road freight demand in major economies (trillion tonne-kilometres)



Source: OECD (2024).

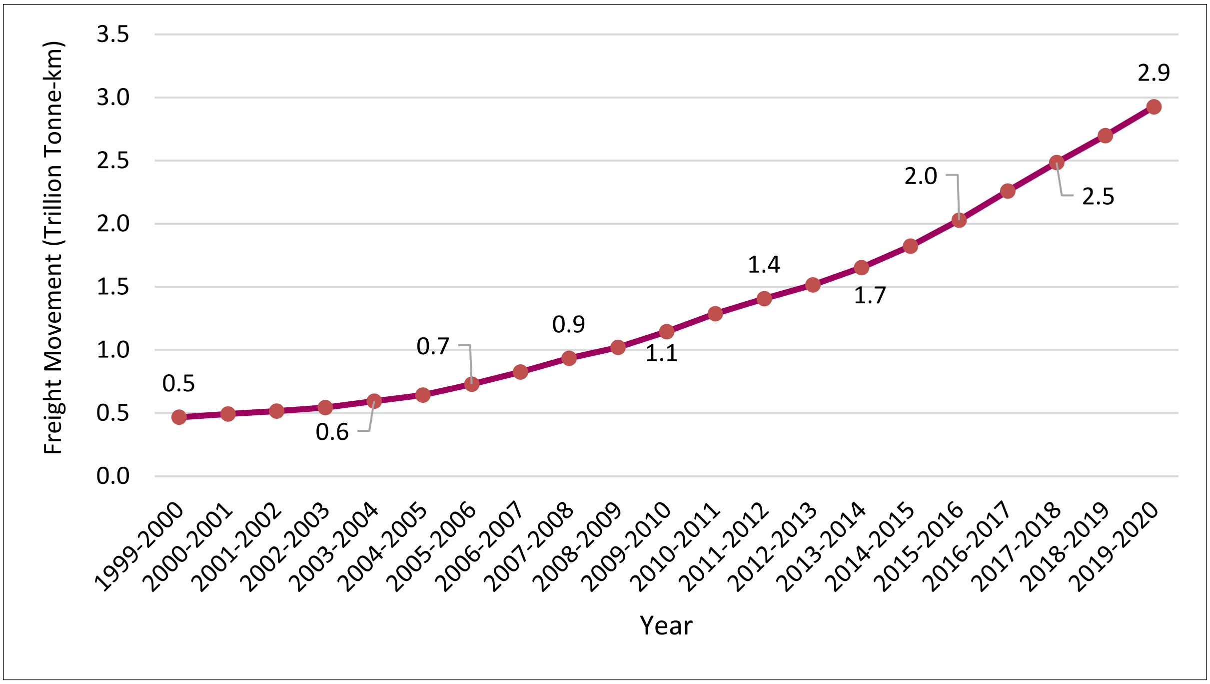
With road transport representing the largest share of freight activity globally, it also makes up over two-thirds of global freight emissions (Ng, 2022). Globally, medium- and heavy-duty vehicles (MHDVs), which include both trucks and buses, constitute about 4% of the on-road fleet but contribute over 36% of on-road fuel consumption and respective greenhouse gas (GHG) emissions. They also contribute to 73% of on-road nitrogen oxide (NO_x) emissions and 60% of particulate matter (PM2.5) emissions, with significant impacts on local air quality and human health (MacDonnell and Façanha, 2021; Borlaug et al., 2023).

Road transport is expected to remain the dominant mode of freight movement in the world, as compared to rail (which has challenges such as carrying capacity, the trade-off between passenger and freight movement), waterways (which are constrained by geography), or air (which are constrained by costs and limited connectivity to final demand centres). Further, in India, the relatively fragmented nature of truck ownership (largely made up of smaller fleet owners), the high cost of trucking assets, the strong relationship with macro-economic trends, limited regulatory measures and low-emission technology development make the MHDV segment – specifically, trucks – a hard-to-abate segment, with considerations around affordability and equity.

Overview of road freight in India

The freight sector is a crucial component of India’s economy, playing a vital role in the transportation of goods across the country’s vast and diverse landscape. India’s total freight demand has increased six-fold in the last two decades (see Figure 2), going from 0.5 trillion tonne-kilometres in financial year (FY) 2000 to about 3 trillion tonne-kilometres by FY 2020. This growth has been driven largely by robust economic and infrastructure growth in the country. Most freight is handled by road transport, which was responsible for over 70% of the total freight movement as of 2022 (Ravuri and KP, 2022). Road freight demand is expected to triple to 9.6 trillion tonne-kilometres by 2050 from 2020 levels (Sinha and Teja, 2022).

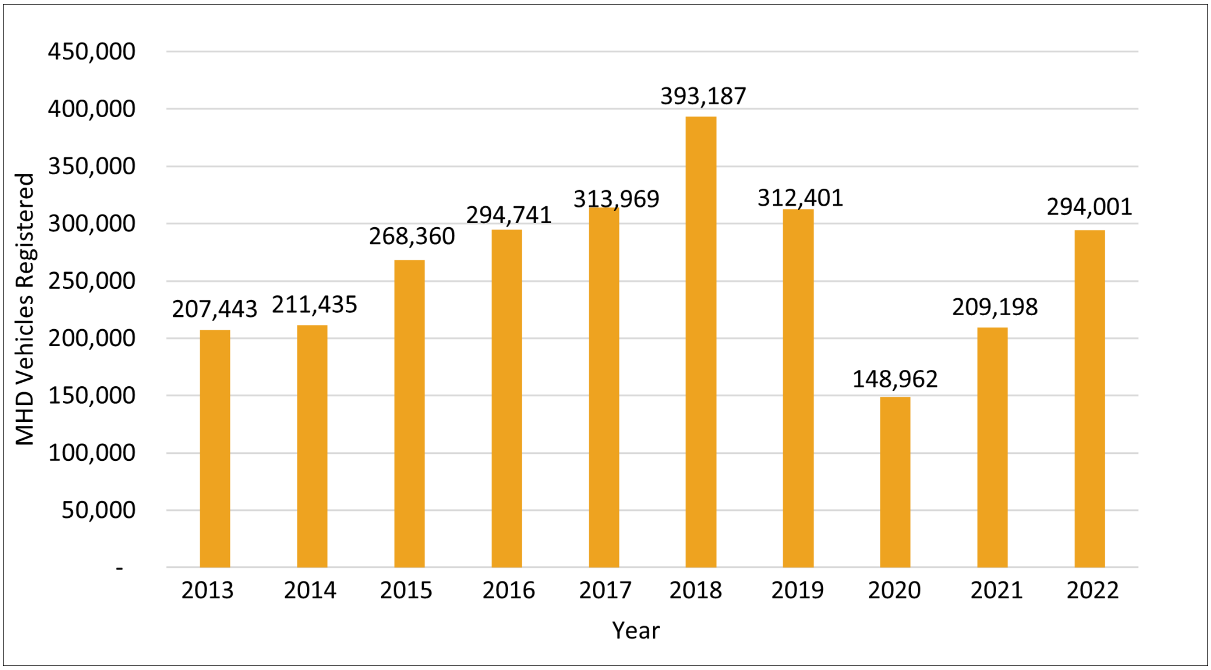
Figure 2. Freight movement by road transport in India, 1999-2020



Source: Ministry of Road Transport and Highways Transport Research Wing (2023).

In 2022, India was the fourth-largest market in terms of total commercial vehicle sales and the sixth-largest market globally in terms of MHDV sales, accounting for over 2% of the total vehicle sales in the country (Bagdia et al., 2021). Figure 3 shows the number of medium- and heavy-duty trucks (MHDTs) registered in India from 2013 to 2022, with average sales of around 0.3 million annually. Some major manufacturers by market share include Tata Motors, Ashok Leyland, Bharat Benz, Mahindra & Mahindra, and Volvo-Eicher.

Figure 3. Total medium- and heavy-duty vehicles registered in India, 2013-22



Source: VAHAN Dashboard (n.d).

The Ministry of Road Transport and Highways (MoRTH) categorises commercial vehicles in India based on gross vehicle weight (GVW), as shown in Table 1. The medium-duty trucks (MDTs) fall under the category of N2 with a GVW between 3.5 and 12 tonnes. The heavy-duty trucks (HDTs) fall under the category of N3 with a GVW of 12 tonnes and above.

According to the VAHAN database provided by the Ministry of Road Transport and Highways, over 90% of the registered MHDTs operate on diesel fuel. This segment accounts for more than one-third of the country's transport-related carbon dioxide (CO_2) emissions (Sinha and Teja, 2022).

Significant efforts will be needed to bring India's road freight sector on track to meet its 2070 net zero goal. India would need at least one-quarter of its truck fleet to have zero emissions by 2050. It would also need the fuel efficiency of diesel trucks to improve by at least 35% from 2021 levels to be on the net zero pathway (IEA and NITI Aayog, 2022). At the current fuel efficiency levels of the truck fleet, fuel consumption and CO_2 emissions will be about 10% higher by 2030 (IEA and NITI Aayog, 2022).

Table 1. Regulatory definition of commercial goods vehicles in India

Category	Definition/Homologation
N1	Motor vehicles used for carriage of goods with GVW not exceeding 3.5 tonnes.
N2	Motor vehicles used for carriage of goods with GVW exceeding 3.5 tonnes but not exceeding 12 tonnes.
N3	Motor vehicles used for carriage of goods with GVW exceeding 12 tonnes.

Source: MoRTH (2024b).

Currently, India's regulatory framework for MHDTs is driven by fuel economy and emission control requirements. India had defined fuel economy regulations for heavy trucks (GVW > 12T) in 2017 and for medium trucks (GVW 3.5-12T) in 2019. These standards were adopted as per vehicle standards as compared to the corporate average fuel economy (CAFE) standards (for the fleet of new sales) adopted by other countries including European Union member countries and the United States. Accordingly, each vehicle model is tested and certified for compliance based on a constant-speed test cycle, with thresholds defined for different vehicle weights.

While the standards for heavy trucks were to be implemented in two phases, the first phase was implemented only in April 2023. The standards proposed a fuel consumption threshold ranging from 0.147 to 0.505 l/km for N2 and N3 vehicle categories (Yadav et al., 2023). This translates into a CO_2 emissions standard ranging from 333.9 to 1147.4 g/km for the vehicle categories using a conversion factor of 2 272g of CO_2/l emissions (India GHG Program Secretariat, 2015). In terms of emissions control requirements, India has already transitioned to Bharat Stage VI, which is equivalent to Euro VI norms for all vehicles since 2020 (MoRTH, 2024a).

In addition to vehicle regulations, India has set in motion its National Logistics Policy and a national multimodal master plan, also known as the *Prime Minister Gati Shakti Yojana*, which would help in interlinking highways, ports, and railway lines with the aim of improving logistics efficiency in terms of costs, fuel consumption and time.

Defining a zero-emission truck transition

From a technology perspective, the global MHDT industry is largely a single-fuel ecosystem, i.e., diesel fuel. Historically, countries have regulated both CO_2 and other types of emissions. Other policy interventions have focused on improving logistics efficiency through better road infrastructure and electronic tolling to improve operational efficiency, raise speeds, lower stoppage time and maximize fuel efficiency. Given the significant contribution to road transport emissions and the need for rapid decarbonisation in the coming decade, the transition to ZETs is inevitable. A comprehensive policy framework, along with robust enforcement of regulatory compliance, will be needed to enable this transition.

Today, ZET technologies typically include battery-electric trucks (BETs) and hydrogen fuel-cell electric trucks (FCETs). Other innovations include electric road system vehicles (ERSV), which can recharge via overhead cables or ground conductive/inductive solutions. These technologies are considered zero-emission based on the fact that there are no tailpipe emissions from vehicles. A clean energy source for charging infrastructure and green hydrogen essentially comprise a zero-emission ecosystem. There is also considerable discussion among global ZET policy makers about allowing hydrogen internal combustion engine (H_2-ICE) trucks (using green hydrogen) to be defined as ZETs as long as their CO_2 emissions remain almost zero. With no tail-pipe climate pollutants, H_2-ICE trucks can be designed to have lower levels of nitrogen oxide (NO_x) emissions (Wright and Lewis, 2022). The EU, in its 2023 CO_2 regulations for heavy-duty vehicles, considers H_2-ICE trucks as ZETs if they emit less than 1 gCO_2/km (Council of the EU, 2024a). In contrast, California, which has a target of transitioning a majority of the truck fleet to zero-emission by 2040, does not recognize H_2-ICE as a ZET.

The transition towards ZETs is also expected to reap economic benefits with the creation of about 30 000 jobs in Europe and the contribution of up to EUR 32 billion in GDP by 2035 relative to 2022 (Boston Consulting Group, 2023). In the United States, the transition has created more than 330 000 jobs across the ZET supply chain in manufacturing, infrastructure, and research and development (Environmental Defense Fund, 2024). Additionally, the transition is projected to significantly reduce NO_x and PM2.5

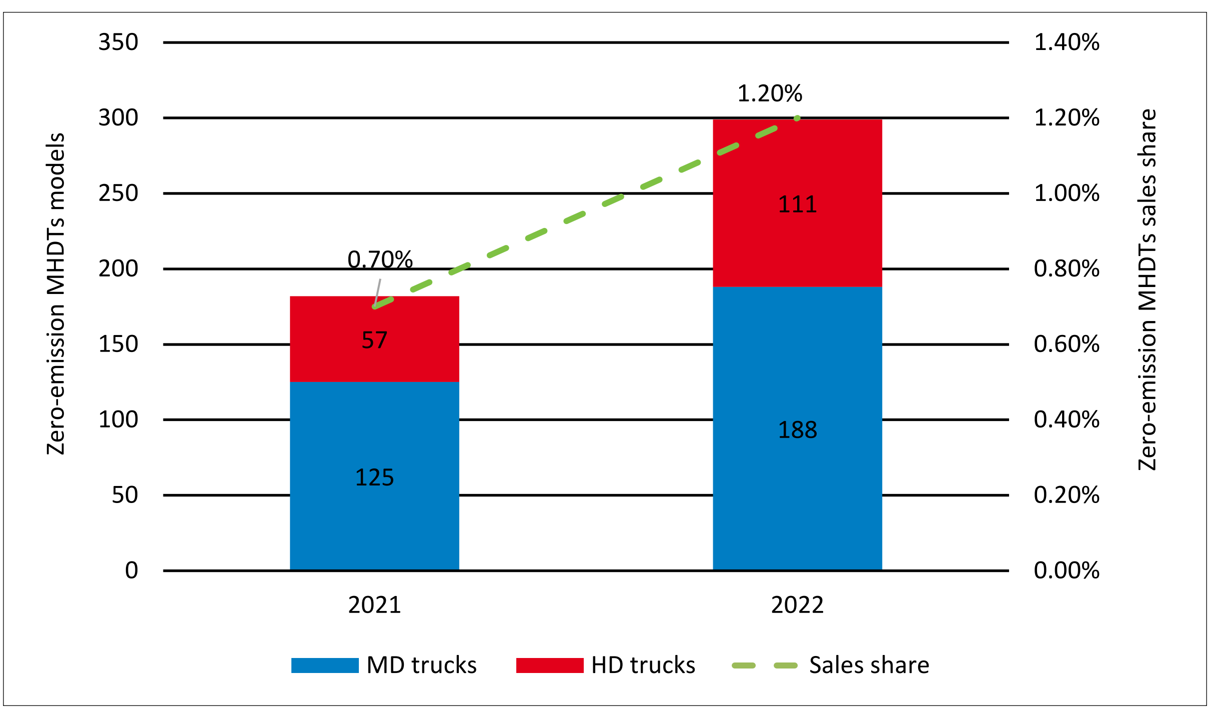
emissions, which disproportionately impact lower-income neighbourhoods, and prevent up to 57 000 premature deaths through 2050 in the United States (American Lung Association, 2022). Thus, there is a need for greater attention to facilitating a transition towards ZETs. It will require a careful analysis to develop an enabling and effective policy and regulatory framework, especially in the context of a call to enhanced climate action, based on the Global Stocktake outcomes at COP28 (UNFCCC Secretariat, 2023).

The state of global zero-emission truck deployment

The adoption of ZETs is still in nascent stages globally, with almost 80% of global sales occurring in China, followed by the EU and the United States. At the same time, there have been an increasing number of commitments and announcements by truck manufacturers (e.g. Volvo, Daimler and Traton) and fleet operators/e-commerce companies (e.g. Amazon and DHL) to transition to zero-emission fleets in the coming decade (Mathieu, 2021).

Global ZET sales in 2022 registered an approximately 50% increase from 2021, reaching 60 000 zero-emission MHDTs worldwide, dominated by sales in China. The sales share of zero-emission MHDTs remains well under 1% in all markets, given the ongoing stage of pilot demonstrations by shippers and logistics operators, except in China, where there is increasing adoption beyond pilot projects (IEA, 2023). However, the number of models available worldwide increased by about 65% in 2022 compared to 2021 in the zero-emission MHDT segment (Al-Alawi et al., 2023), as shown in Figure 4.

Figure 4. Model availability and sales share of zero-emission medium- and heavy-duty vehicles, 2021-22

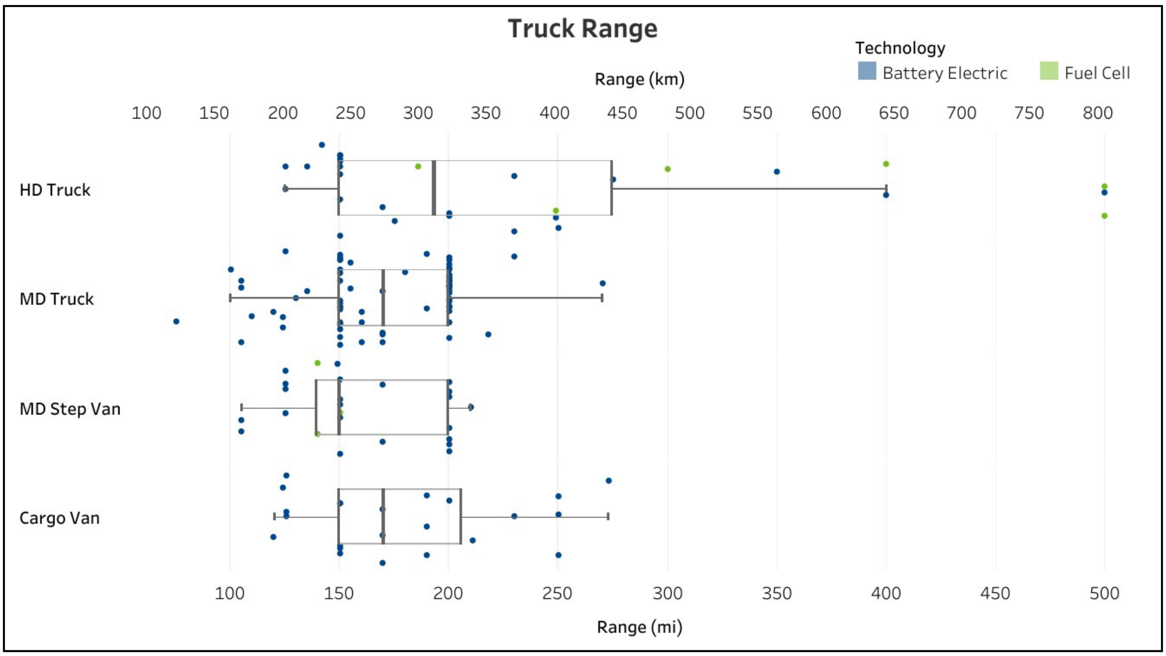


Note: MD = medium-duty; HD = heavy-duty.

Source: CALSTART (2021).

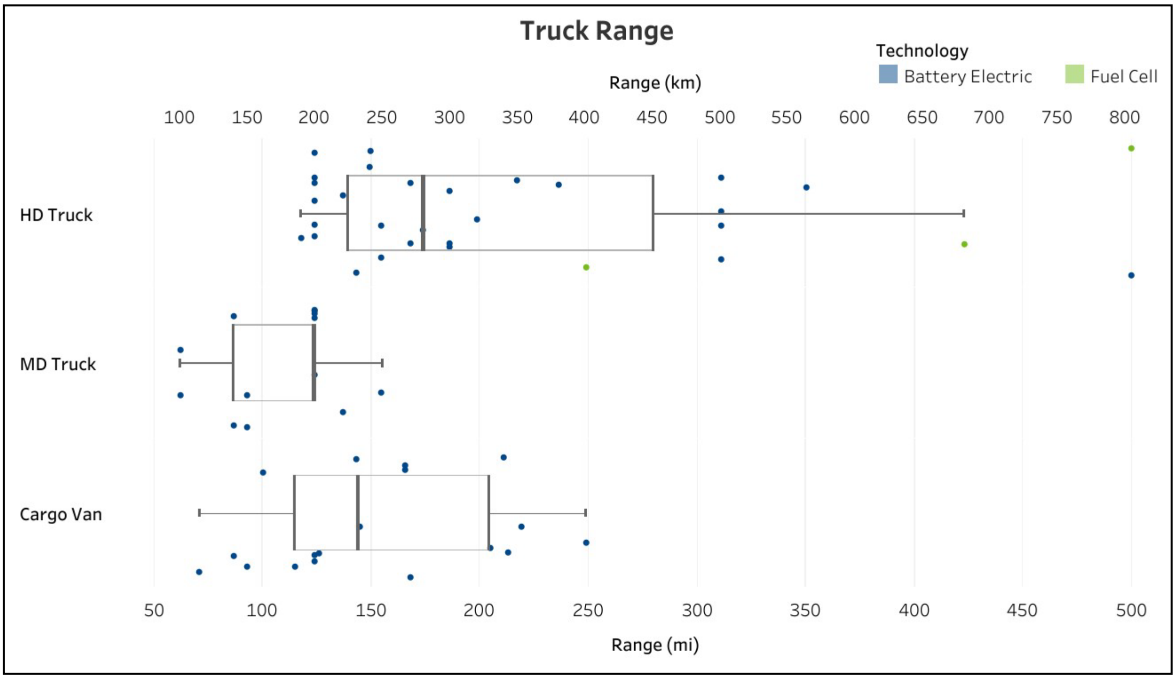
In terms of the typical range of ZETs, heavy-duty trucks in the United States have a median range of about 311 km (193 miles), with most models clustering around 241 km (150 miles). For medium-duty trucks, the median range is around 274 km (170 miles), with most models clustering around either the 241 km (150-mile) range threshold or the 322 km (200-mile) range threshold. Step-vans in the medium-duty segment (see Figure 5) also have a median range of about 241 km (150 miles). In comparison, heavy-duty ZETs in Europe (see Figure 6) have a median range of about 282 km (175 miles), and medium-duty trucks have a median range of 200 km (124 miles)

Figure 5. Zero-emission truck model range by segment in the United States



Source: CALSTART (2021).

Figure 6. Zero-emission truck model range by segment in Europe



Source: CALSTART (2021).

Major truck manufacturers globally have committed to increasing the sales share of ZETs. Daimler Trucks plans to have a full zero-emission product line-up by 2027 and 100% carbon-neutral sales in the European Union, Japan and North America by 2039. Traton Group, the owner of brands such as MAN and Scania, has committed 40% and 50% of sales share to zero-emission MAN long-haul trucks and Scania trucks by 2030, respectively (Unterlohner, 2021). Further fleet operators such as Walmart aim to transition its entire fleet to ZETs by 2040, DHL by 2050 and so on (DHL, 2017; Unterlohner, 2021). The signatories of the EV100+ campaign, including IKEA and Unilever, have committed to transitioning their fleet of MHDVs (above 7.5 tonnes) to zero-emission by 2040 in OECD countries and China and India (IEA, 2023).

In India, e-commerce giants such as Amazon have committed to deploying 10 000 electric delivery fleets by 2025, along with the deployment of electric trucks and development of charging infrastructure. They have also extended similar ambitions to other developing countries, including Colombia, Ecuador and Mexico, under the Laneshift programme (World Business Council for Sustainable Development, 2023). JSW Group in India has begun an electric-truck pilot programme, deploying an initial fleet of five trucks to move cargo, with plans to scale up to 100 trucks by 2024 (World Business Council for Sustainable Development, 2023). The ongoing pilots should provide key lessons for scaling up ZET deployment in the coming years. More recently, at the 14th Clean Energy Ministerial hosted by India, the national Electric Freight Accelerator Program (E-FAST) saw commitments for about 7 700 electric trucks (across light-, medium- and heavy-duty categories) to be deployed in India over the next three to five years by major shippers and logistics service providers (Smart Freight Centre, 2023).

Other key international efforts include the Global Memorandum of Understanding (MoU) on zero-emission MHDVs that was signed at COP26 in Glasgow by 27 countries to achieve a 30% share of zero-emission MHDV sales by 2030 and 100% by 2040 (CALSTART, 2023). Six more countries (Cape Verde, Colombia, Ghana, Iceland, Israel and Papua New Guinea) joined the Global MoU at the COP28 in Dubai, representing approximately 21% of the global MHDV sales market. Notably, the Global MoU has been endorsed by various sub-national governments, including the State of California in the United States and the states of Telangana and Goa in India. The ZEVWISE initiative, launched in 2023, aims to act as a collaborative forum for technical support and expertise on MHDVs and charging infrastructure. The ZEV Transition Council (ZEVTC), led by the UK Government, also aims to bring together government bodies and automotive manufacturers to enable a faster, cheaper and easier transition to clean mobility (ZEVTC, 2023).

The deployment of ZETs in India is currently restricted to small pilots and demonstrations involving a few dozen vehicles, enabled by partnerships between startups and large corporations such as cement companies (testing electric trucks for closed-loop operations). Given India's significant automotive manufacturing base and capability, it is expected that the relevant technical know-how will exist to enable the production and model availability of ZETs. However, a comprehensive policy ecosystem will be needed to provide market certainty and scale of deployment.

Achieving scaled deployment of ZETs still faces considerable challenges in terms of vehicle technology, infrastructure development, operational characteristics, and financing. The diverse range of segments and end-use applications of trucks limits technological and policy standardisation. The high upfront purchase costs of ZETs relative to diesel trucks are among the foremost adoption barriers (Konstantinou and Gkritza, 2023).

Technology barriers include the trade-off between battery size and payload capacity. Higher range requirements lead to heavier battery packs, reducing the energy efficiency of BETs and thus lowering effective range (Plötz et al., 2023). This will have implications for infrastructure development. At the same time, public infrastructure creation often lags behind zero-emission vehicle (ZEV) deployment, especially in developing countries (Khan et al., 2022). The deployment of fast and ultra-fast charging to minimize the shift time lost during charging en route might require power grid upgrades for the enhanced load at specific locations (Deng et al., 2023). In the case of FCETs, there are challenges associated with the cost of green hydrogen, the availability of refuelling stations, and the availability of low-carbon hydrogen production overall (Hassan et al., 2023). The nascent ZET market – with its low technology maturity and limited residual value (as compared to diesel trucks) – results in higher costs of financing the purchase of ZETs (Sharpe, 2017).

This report presents a broad policy roadmap for decarbonising road freight by adopting zero-emission trucking in India, focusing on MHDTs and drawing on global lessons. Separate chapters provide:

- a meta-review of existing studies on the economic viability of ZETs and a new total-cost-of-ownership (TCO) assessment for India
- a summary of major international policy developments with regard to ZETs based on a global review
- a roadmap for India to achieve a ZET transition, which presents considerations for India's acceleration of ZET adoption.

Understanding the economic viability of zero-emission trucks

Total cost of ownership (TCO) has been a key tool in assessing the economic viability of EVs compared to their ICE counterparts. TCO analysis has limitations, especially in the case of light-duty vehicles where consumers purchasing for personal ownership often do not think from a TCO perspective. However, in the case of MHDTs (typically commercial vehicles used for freight operations), the TCO approach is similar to the business-case approach used by fleet operators and truck manufacturers to assess market and product strategies. It thus assumes significance in the context of this study.

This chapter presents a meta-analysis of global TCO studies, followed by an analysis carried out for India based on an Excel tool developed by WRI India with support from the University of California Davis.

Meta-review of global total cost-of-ownership studies

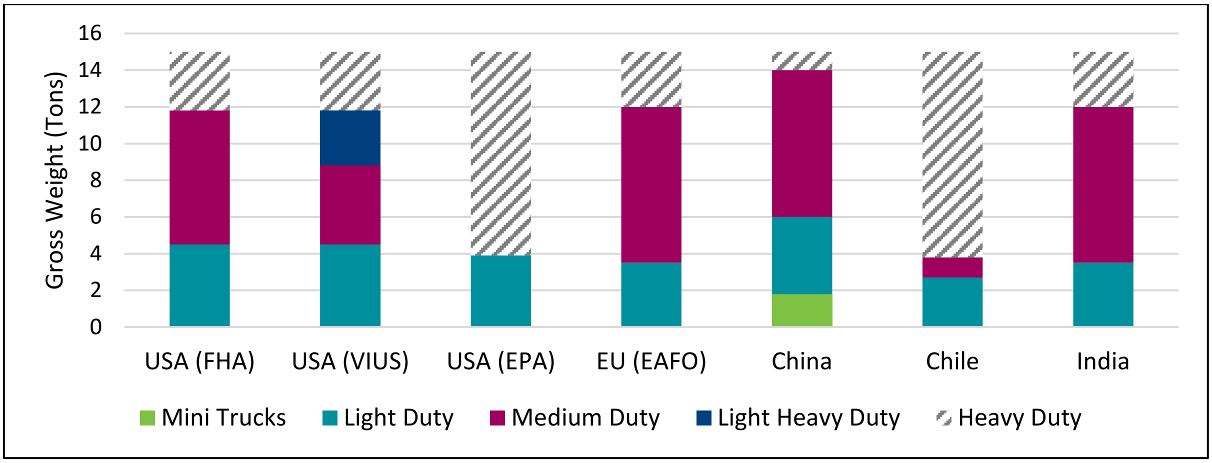
The objective of the meta-review is to create a better understanding of where ZETs stand relative to their diesel counterparts and when TCO parity is expected. The scope of the review is summarised in Table 2. A total of 12 publications were reviewed for the meta-analysis and are listed in Annex F. Analysis of their methodological variations is available in Annex E. The TCO analysis varies significantly depending on the types of use cases and assumptions considered for individual component costs. These include:

- **Vehicle parameters**: Gross vehicle weight (GVW), payload capacity (metric tonne), nominal electric range (km), battery capacity (kWh), battery density (Wh/kg), energy efficiency (kWh/km), fuel cell power (kW), hydrogen storage capacity (kg) and fuel efficiency (litre/km).
- **Operational parameters**: Type of use case considered, average distance covered per day, number of driving hours per day, stoppage time, average speed, and toll charges per trip.
- **Cost parameters**: Unit cost of electricity (USD/kWh), unit cost of fuel (USD/litre for diesel and USD/kg for hydrogen), annual maintenance cost (USD/year), and insurance premium (USD/year).

Table 2. Scope of total cost of ownership meta-review

Geography/region	Fuel type	Vehicle segments	Use cases
China European Union India United States	Diesel trucks Battery-electric trucks (BETs) Fuel-cell electric trucks (FCETs)	Heavy-duty trucks (HDT) Medium-duty trucks (MDT)	HDT: Long-haul and regional haul MDT: Regional haul and urban delivery

Figure 7. Classification of commercial vehicles per gross vehicle weight (metric tons) across regulators in different countries



Notes: GVW = gross vehicle weight. FHWA = US Federal Highway Administration. VIUS = US Vehicle Inventory and Use Survey by US Census Bureau. EPA = US Environment Protection Agency. EAFO = European Alternative Fuels Observatory.

Sources: Author analysis based on US Department of Energy (2012), European Commission (2013), Marklines (n.d.), Pettigrew (2022) and MoRTH (2024b).

As Figure 7 shows, the weight-based classification of MHDTs varies across regions. Figures 8 and 9 provide a summary of the key assumptions from the studies reviewed.

The upfront costs of heavy-duty BETs in the United States and Europe are about three times more than those of diesel trucks, and FCETs are about 3.5 times more (Sharpe and Hussein, 2022). In contrast, medium-duty BETs and FCETs cost 1.3 and 1.5 times more than diesel trucks, respectively, and are expected to be almost at par by 2030 (Burke et al., 2022; Basma et al., 2023). By 2030, the cost differential for heavy-duty trucks is expected to decline by 40% for BETs and about 25% for FCETs compared to diesel trucks (Sharpe and Basma, 2022).

In China, BETs and FCETs are about two times more expensive than their diesel counterparts (Qiu et al., 2022). By 2030, it is expected that the upfront cost of BETs will be only 20-30% more than their diesel counterparts, whereas the FCETs will lag a few years in achieving parity (Mao et al., 2021). These are presented in Figures 8 and 9. Table 3 shows the average value of the diesel cost, hydrogen production cost and electricity cost between 2020 and 2030 assumed in the studies taken for meta-review.

Table 3. Assumptions on average cost of diesel, hydrogen production and electricity, 2020-30

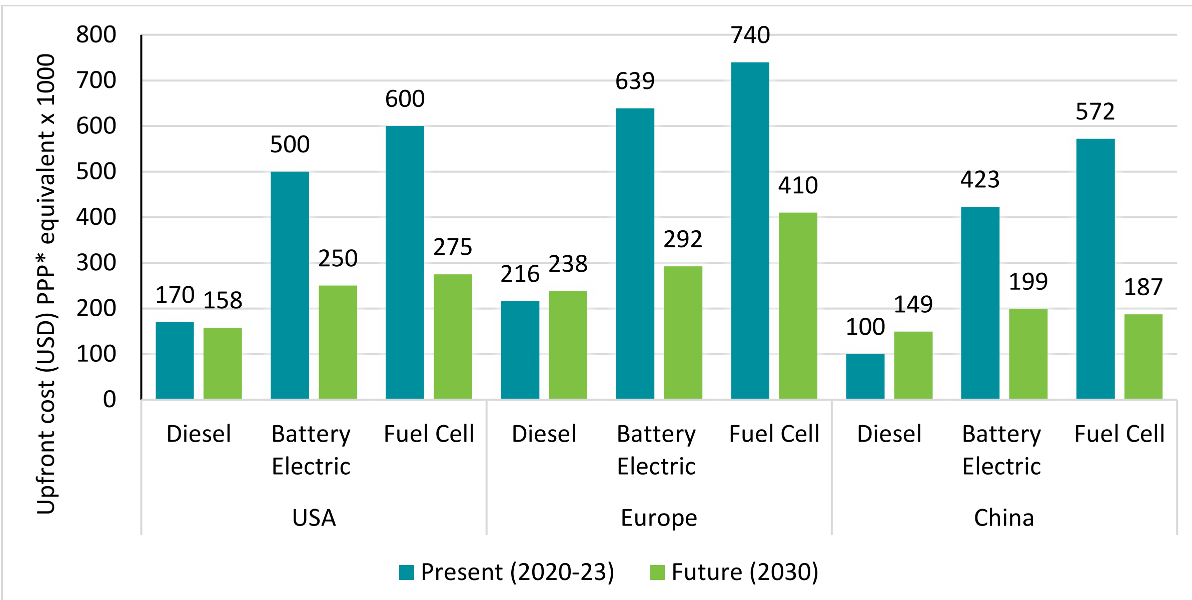
	Present costs (2020-23)	Future costs (2030)
Diesel (USD/L)	1.22	1.24
Electricity (USD/kWh)	0.19	0.20
Hydrogen* (USD/kg)	11.83	9.50

Note: *The cost of hydrogen production includes three types: grey, blue and green hydrogen.

Basma et al.(2023), Basma, Saboori and Rodríguez (2021), Basma, Zhou and Rodriguez (2022), Burke et al. (2022), ITF (2022), Mao et al. (2021), Sinha and Teja (2022), Rout et al. (2022), Rodríguez and Basma (2023) and Toll et al. (2022).

The operational costs of ZETs comprise the energy costs depending on the fuel prices, energy efficiency and the annual vehicle kilometres travelled (VKT), maintenance costs and financing costs. The assumptions of energy costs, converted to purchasing power parity (PPP) equivalent for comparison, across various regions from the studies reviewed are presented in Figure 10 (Basma et al., 2023; Borlaug et al., 2023; Burke et al., 2022; Rodríguez and Basma, 2023; Rout et al., 2022; Sinha and Teja, 2022; Toll et al., 2022; Zhao et al., 2018).

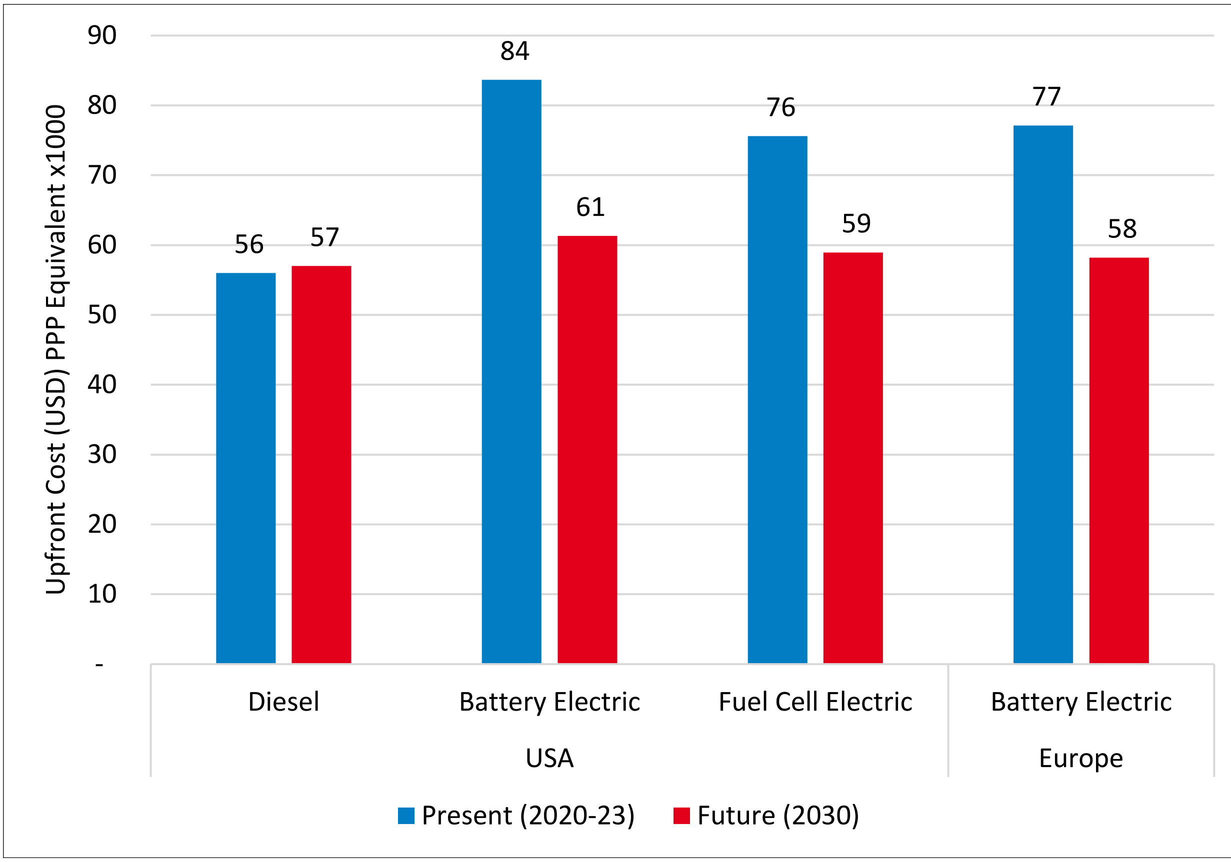
Figure 8. Upfront cost variation of heavy-duty trucks in China, Europe and the United States, 2020-30



Notes: HDTs = heavy-duty trucks. *PPP = purchasing power parity, or currency conversion rates that seek to equalise the purchasing power of different currencies by eliminating differences in price levels between countries.

Sources: Meta-analysis of total-cost-of-ownership studies, including Basma et al.(2023), Basma, Saboori and Rodríguez (2021), Basma, Zhou and Rodriguez (2022), Burke et al. (2022), ITF (2022), Mao et al. (2021), Sinha and Teja (2022), Rout et al. (2022), Rodríguez and Basma (2023) and Toll et al. (2022).

Figure 9. Upfront cost variation of medium-duty trucks across the United States and Europe, 2020-30



Note: MDTs = medium-duty trucks.

Sources: Meta-analysis of total-cost-of-ownership studies, including Basma et al.(2023), Basma, Saboori and Rodríguez (2021), Basma, Zhou and Rodriguez (2022), Burke et al. (2022), ITF (2022), Mao et al. (2021), Sinha and Teja (2022), Rout et al. (2022), Rodríguez and Basma (2023) and Toll et al. (2022).

Findings of global total cost of ownership analysis for medium- and heavy-duty trucks

Battery-electric trucks clearly emerge as the most viable technology as opposed to any other zero-emission technology intervention. For heavy-duty trucks, the general view is that BET TCO parity with ICE could be achieved as early as 2028 (or as late as 2035), depending on certain specific use cases and vehicle specifications. In the case of heavy-duty (HD) fuel-cell and H_2-ICE trucks, TCO parity is not expected even by 2040, with some exceptions. Some studies project the TCO of H_2-ICE to be higher than FCETs due to about 20% higher tank capacity for hydrogen storage and higher costs associated with the engine-transmission system in H_2-ICE trucks relative to the fuel cell-power electronics system cost in FCETs (Basma, Saboori and Rodríguez, 2021).

TCO projections are largely consistent for diesel HDTs across studies and regions. The expected TCO drop across studies in different regions considers the vehicular and operational cost-based parameters largely unchanged between 2020 and 2030. This leads to a slight change in TCO (USD/km), i.e. around 0-6% for the same period. But in the case of BETs and FCETs, the expected TCO variation is much more significant, i.e. 60% from 2020 to 2030, with the largest variation being in BETs resulting from reductions in technology cost (Burke et al., 2022). This occurs due to varying assumptions and projections of fuel cost, technology cost and operational characteristics. For FCETs, even though the TCO is expected to reduce by 30-40%, they are yet to grow at a commercial stage in terms of technological maturity and infrastructure readiness.

In China, the battery-electric tractor-trailer is expected to reach TCO parity by 2029-30, and FCE tractor-trailers do not achieve TCO parity before 2030 for any segment (Mao et al., 2021). However, a combination of policy incentives, including purchase subsidies, carbon pricing for diesel fuels, and hydrogen fuel production subsidies, have been offered as viability support to close the gap in TCO, making them cost-competitive with diesel counterparts today. They also bring forward the TCO parity year for FCETs to 2025 from a post-2030 timeline (Mao et al., 2021).

Battery costs and efficiency improvements are the main drivers of TCO reduction in Europe. The reduction in the TCO of BETs in Europe is largely based on assuming a 50% decrease in battery costs and about 30% improvement in truck efficiency from present to 2030, which results in lower truck purchase prices and lower energy costs, respectively. Additionally, the reduction in electricity overhead charges also contributes to a reduction in TCO between 2020 and 2030. The tractor-trailer segment will reach TCO parity by 2025 for BETs (Basma, Saboori, and Rodriguez, 2021), considering purchase incentives, road toll exemptions, emissions trading schemes, and constant diesel and electricity prices between 2020 and 2030 (which is an unlikely scenario).

The TCO variation for medium-duty MDTs is found to be similar to that of HDTs, with diesel-based trucks being unchanged/marginally changed between 2020 and 2030. The variation in BETs and FCETs is found to decrease by 20-30% in this decade. A study on MDTs indicates that the TCO of both BETs and FCETs will be less than diesel trucks by 2030 (Burke et al., 2022).

In terms of the sensitivity to key parameters, this analysis finds that the TCO estimates and the time to parity vary on the basis of annual mileage requirements, battery size, energy costs, upfront purchase price and charging infrastructure density.

Figures 10 and 11 show the variation in TCO between 2020 and 2030 for different MHDT technologies across various studies.

Figure 10. Total cost of ownership for heavy-duty trucks from 2020-30 across Europe and the United States

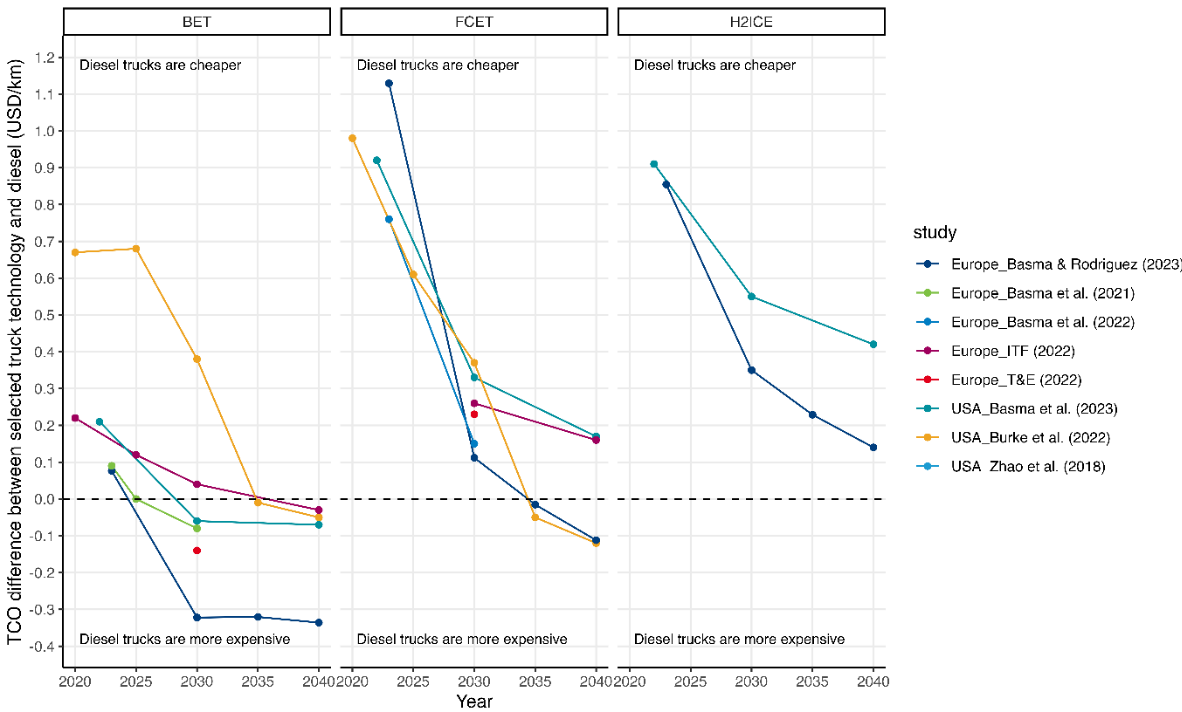
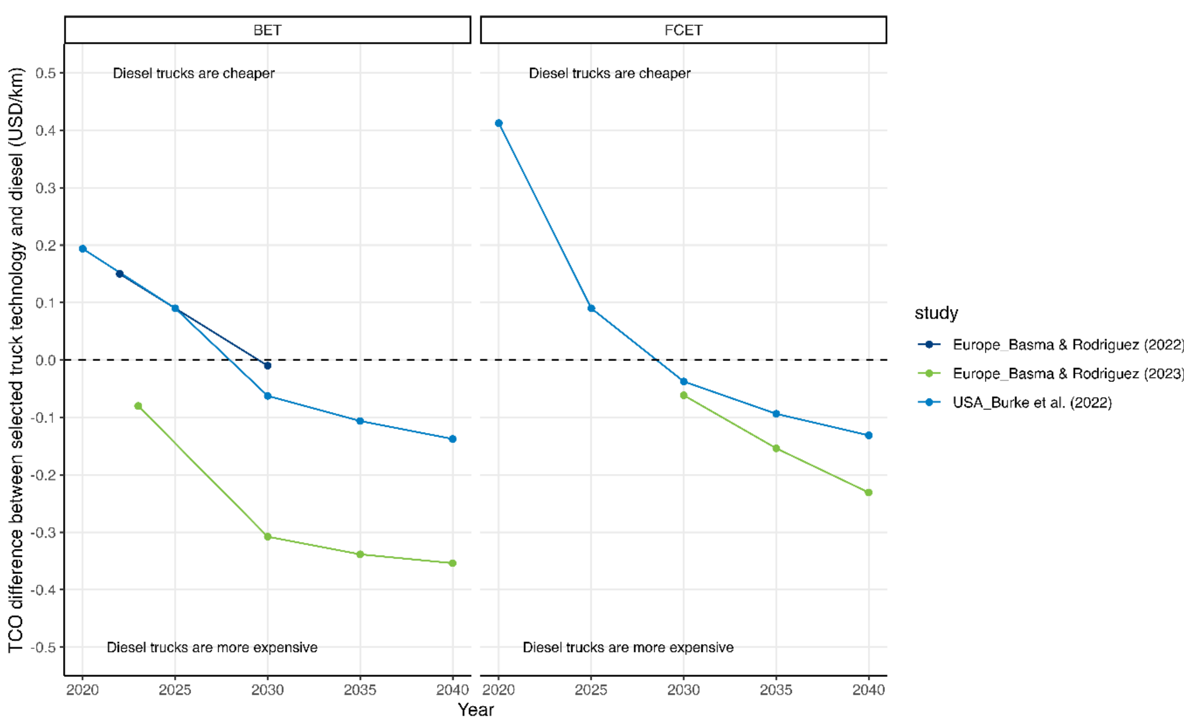


Figure 11. Total cost of ownership for medium-duty trucks from 2020-30 across Europe and the United States



Total cost-of-ownership analysis for India

This analysis estimates the TCO for four reference cases of heavy-duty trucks by weight and the use case for India (see Table 4) using the WRI India–UC Davis techno-economic analysis tool. It should be noted that in this analysis the TCO is estimated only for a battery-electric truck and a reference diesel truck and does not include hydrogen fuel cell trucks; this is in light of the evolving policy discourse on hydrogen in India and global trends indicating the dominant technology choice to be BETs as compared to trucks powered by hydrogen fuel cells (ITF, 2023b). These reference use cases have been chosen based on stakeholder consultations with logistics service providers and truck manufacturers as well as on market assessment reports from various agencies.

Table 4. Total cost-of-ownership reference cases: Battery-electric versus diesel trucks in India

	Tonnage segment	Truck type	Use Case	Reference ICE truck	Distance per trip (km) (one trip/day)
1	12 Tonnes	Rigid body	Perishable goods	Eicher Pro 3012	200
2	18 Tonnes	Rigid body	Parcel/FMCG/market	Eicher Pro 6019	500
3	28 Tonnes	Tipper	Waste handling in urban areas	TATA Prima 2830.K	100
4	55 Tonnes	Tractor-trailer	Steel sheet rolls	TATA Prima 5530.S	300

Note: FMCG = fast-moving consumer goods.

The rigid truck segment of 3.5-25T makes up about 75% of total MHDT sales in India (Climate Group, 2022). They are used to transport fast-moving consumer goods (FMCG) or market goods and perishables. Therefore, the truck models of 12T and 18T are considered for potential electrification in this TCO analysis. The use case of a tipper truck for solid waste transport provides a suitable opportunity for transitioning to ZETs for closed-loop operations, given its fixed intracity route, short-haul operating range, and negligible requirement for mid-shift charging. For the heavy-duty 55T case, this analysis assumes the use case for heavy industries, which have relatively lower distances and specific routes.

The WRI India–UC Davis techno-economic analysis tool is used to determine the TCO for different tonnage segments for India and is calculated for MY 2023 and 2030 for all the truck segments described in Table 3. The tool incorporates inputs such as payload, upfront cost, insurance premium, mileage, fuel prices, interest rate for truck financing, toll charges and annual maintenance cost to arrive at a TCO value for the life of the vehicle considered. The detailed input data parameters are described in Annexes A and B.

Some of the overarching assumptions in the TCO analysis include:

- Vehicle parameters, including tonnage, payload, axle configuration, and battery size, are considered the same for both MY 2023 and MY 2030. The parameters of tonnage, payload, battery capacity, and design range are considered equivalent to those of BET models available in Europe, as described in Table 5.
- ICE (diesel) truck upfront cost increases based on a 1.5% compound annual growth rate (CAGR) between Model Year 2023 to 2030 based on Wholesale Price Index (WPI) inflation.
- Battery costs will fall by about 40% in 2030 relative to 2023, along with a reduction of 1.5-2% CAGR in the powertrain cost for BETs (Bloomberg NEF, 2023).

- A single battery replacement is assumed over the vehicle's life of 15 years. The average battery life is assumed to be seven years.
- The operating parameters of (a) distance travelled per trip and (b) truck annual mileage are kept constant for both 2023 and 2030, given the complexities associated with incorporating fuel/energy efficiency improvements and changing routes in the future.
- Diesel fuel prices increase by 4% annually from 2023 to 2030, and the electricity price is taken at INR 10.5/kWh in 2023 and INR 16.6/kWh in 2030 (State of Maharashtra as reference case). Final electricity prices include base tariff, wheeling charges, fixed/demand charges, taxes and charging operator margin.
- Operational expenses such as the cost of debt for financing truck purchase, insurance premium and toll charges for charging are also considered equal for both MY 2023 and 2030.
- The base case TCO estimate does not incorporate any purchase incentive for BETs.
- The annual maintenance cost (AMC) for ICE trucks is 5% of the upfront costs. However, the AMC of BETs varies slightly with the tonnage segment, being 60% of the AMC for a corresponding ICE truck for the 12T and 18T segment and 65% of the corresponding diesel truck AMC for the 28T and 55T segment.
- Final TCO (INR/km) is estimated as the net present value (NPV) of cumulative costs over a 15-year life of the vehicle, assuming a discount rate of 6%.
- The charging frequency for the 12T, 28T and 55T truck segments is assumed to be once per day at the origin point and twice per day for the 18T segment. The DC fast chargers are considered in the model.

Table 5. Tonnage, payload, battery size and design range of reference battery-electric truck models in Europe

Reference model	GVW (tonnes)	Payload (tonnes)	Battery size (kWh)	Design range (km)
GINAF E2112	13	6	240	280
GINAF E2119	17	11	240	250
Volvo FE Electric	27	17	300	300
Volvo FH Electric	44	38	540	300

Findings of model year 2023 and 2030 total cost-of-ownership estimates

For 2023, with no incentives, the lifetime TCO for BETs in the 18T and 55T segments is 28% and 5% higher than their reference diesel counterparts, respectively, wherein targeted policy interventions can support the cost differential in the early stages of market transformation. Across all four segments, with no incentives, the TCO estimates for 2023 indicate that diesel trucks remain the more viable option, as expected. The highest differential in TCO for 2023 is for the 28T segment, followed by the 12T segment, wherein the BET is 75% and 47% more expensive, respectively, on a lifetime TCO basis.

For 2030, the battery electric 55T segment will be 9% cheaper than the diesel counterpart, and the 18T segment BET is only 18% costlier than the diesel case on a TCO basis. The estimates show that for both the

12T and 28T segments, the BET remains 56% and 46% more expensive than their diesel counterparts, respectively.

It is clear that BETs can be cost-competitive in key segments by 2030, which warrants a clear policy and regulatory pathway that can help accelerate this transition with limited fiscal stress.

Moreover, there is an early mover advantage to electrifying the 18T rigid truck and 55T tractor trailer segment. With a suitable combination of upfront purchase price incentives, taxation benefits and reduced toll charges, among others, the 12T and 28T segments can also achieve near TCO parity at present and complete TCO parity by 2030.

Figures 12–14 provide a graphical representation of the TCO estimates for the four reference cases for MY 2023 and 2030, as well as the TCO ratio of BET and ICE trucks across segments.

Figure 12. Total cost-of-ownership differential for different truck segments

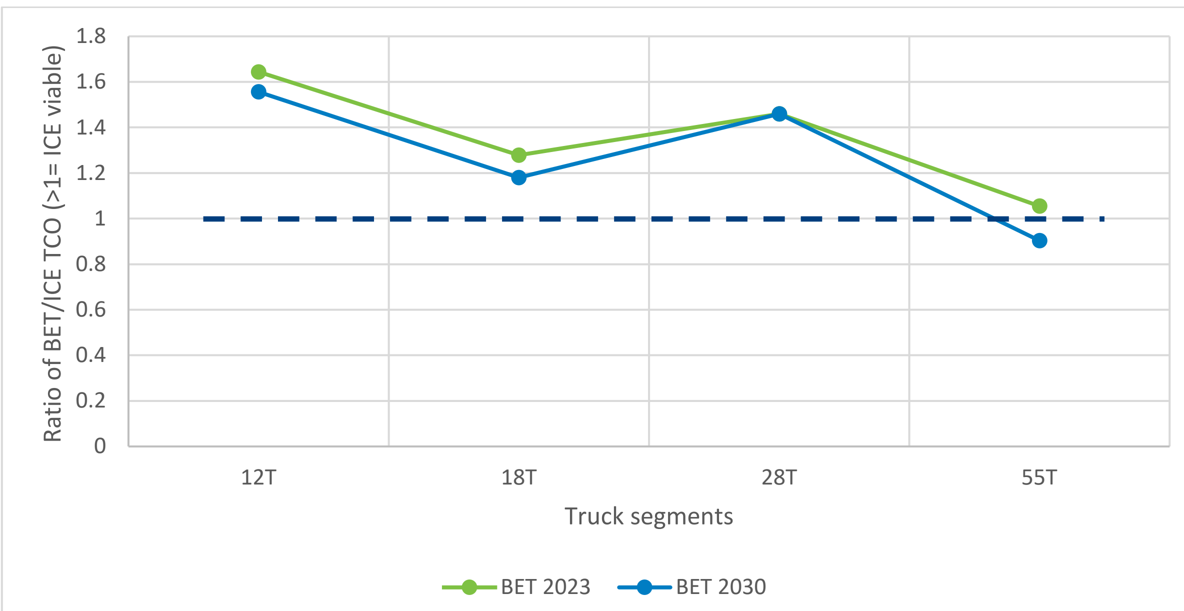


Figure 13. Model year 2023 total cost of ownership (INR/km) for different truck segments

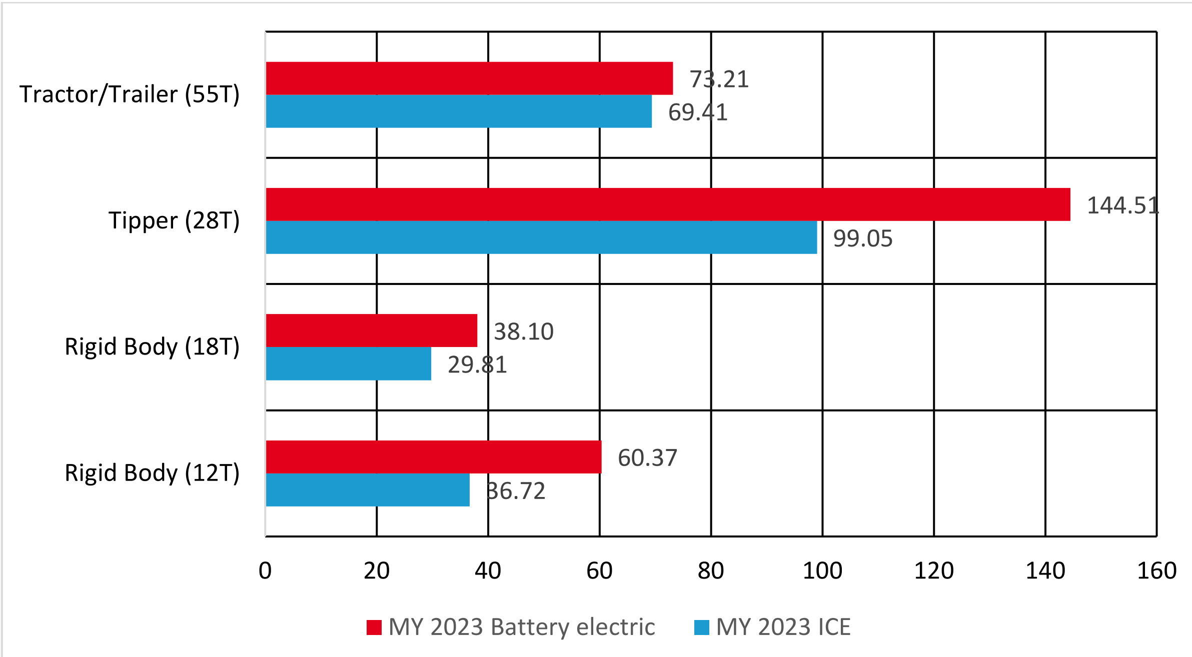
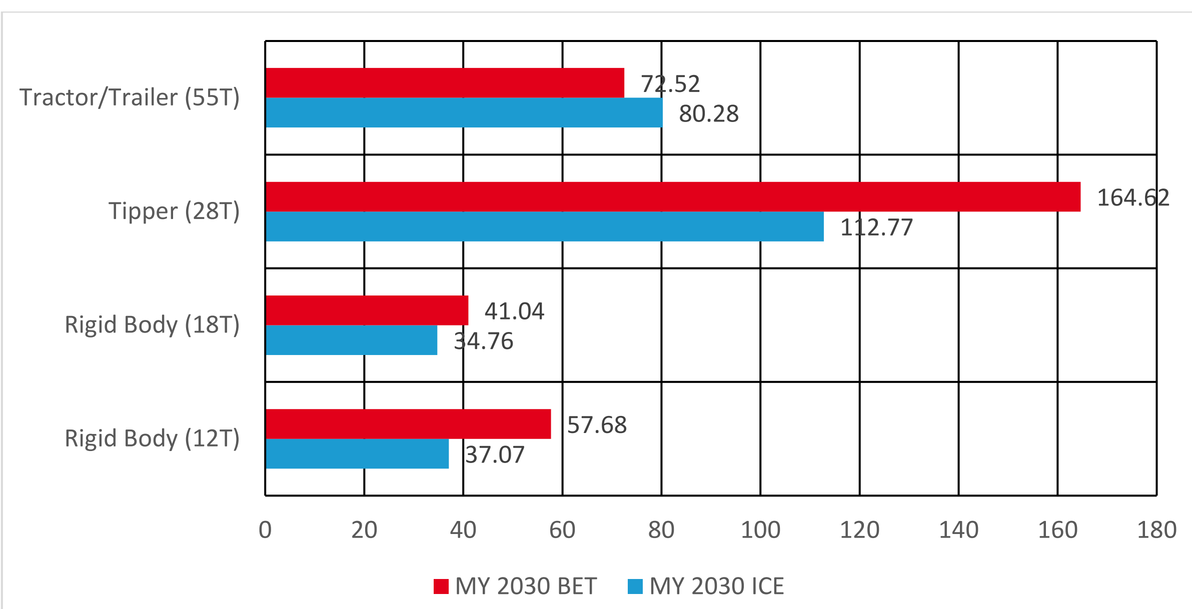


Figure 14. Model year 2030 total cost of ownership (INR/km) for different truck segments



Sensitivity analysis

This section discusses the sensitivity analysis undertaken to ascertain the impact of certain parameters on the TCO of different truck segments. This provides insights for designing the relevant policy and regulatory interventions to accelerate the transition.

The sensitivity of TCO for MY 2023 to variations in five parameters is tested (see Table 6):

1. Cost of debt or interest rate
2. Distance travelled per trip
3. Fuel efficiency for diesel truck
4. Electricity price
5. Road toll

Table 6. Scenarios for sensitivity analysis for model year 2023

Parameter	Base case	Case scenarios
Interest rate	Higher interest rate for battery-electric trucks than for diesel trucks by 200 basis points	**Case I**: The rate is the same for battery-electric and diesel trucks (15%)
		Case II: Aggregated purchase of battery-electric trucks at a reduced rate of 300 basis points below ICE rates (12%)
Distance travelled per trip	Distance per use case	**Case I**: 25% increase in the distance travelled per trip
		Case II: 25% decrease in the distance travelled per trip
Electricity price	INR 10.5/kWh	**Case I**: 25% increase in electricity cost
		Case II: 25% decrease in electricity cost
Road toll	Maharashtra road tolls considered	Road toll exemption for battery-electric trucks

Increasing or decreasing the trip distance travelled has the largest impact on the BET TCO. Decreasing the distance by 25% increases the TCO by 22% on average, whereas an increase in the distance by the same quantum decreases the TCO by 14% on average, making it more competitive.

The road toll exemption for BET lowers the TCO by 11% on average, excluding the 28T truck, which does not incur any tolls for waste handling in urban areas.

Lowering interest rates to the fleet discount rate (i.e. EV interest rates lower than ICE interest rates) has about three times the impact of bringing the interest rates to parity with existing ICE truck lending rates. Reducing interest rates by about 3% below ICE interest rates through aggregated purchases can reduce the BET TCO by about 10%.

For the 12T and 55T segments, the TCO is most sensitive to the distance travelled and the toll incurred during the trip. For the 18T segment, the largest impact on TCO is from the distance travelled and electricity price. The distance travelled and the reduction in interest rate have the greatest impact on the TCO for 28T segment.

Therefore, the distance travelled emerges as the key parameter among those considered, determining the TCO viability for the heavy-duty truck segments. The break-even distance to achieve TCO parity for 2023 ranges between 300 and 350 km for the 12T and 55T segments, which are expected to reduce for MY 2030.However, considering the real-world fuel efficiency of diesel trucks is about 25% lower than the laboratory values of fuel efficiency (Mohan et al., 2014), the TCO of diesel trucks increases by an average of 20% for the considered segments, reducing the TCO gap with the BETs.

Table 7 summarises the overall results of the sensitivity analysis.

Table 7. Results of the sensitivity analysis

Parameter	Case	12 T	18 T	28 T	55 T
Interest rate	Interest parity for EV and ICE	3%	2%	5%	3%
	EV fleet discount for interest rate	8%	6%	13%	9%
Distance travelled per trip	25% increase in distance travelled per trip	14%	11%	18%	14%
	25% decrease in distance travelled per trip	-20%	-17%	-29%	-22%
Electricity price	25% increase in electricity price	-4%	-9%	-2%	-4%
	25% decrease in electricity price	4%	8%	2%	4%
Road toll	Road toll exemption for battery-electric trucks	12%	8%	0%*	12%

Notes: EV = electric vehicle. ICE = internal combustion vehicle. T = tonne. Negative values indicate higher cost of ownership for battery-electric trucks from base case

* No toll is considered for the use case of waste handling in urban areas for a 28T tipper.

International policy developments enabling the transition to zero-emission trucks

Recent policy efforts have been made at both the national and sub-national levels in several countries to accelerate the transition to ZETs. These include setting targets, implementing emissions regulations, developing fleets and infrastructure, and providing purchase incentives. The pathway to ZETs and MHDT decarbonisation will need to include a range of interventions such as technological improvements (e.g. aerodynamic retrofits), reduced vehicle weight, reduced rolling resistance, and increased energy and operational efficiency (through higher load factors and route optimisation), in addition to the adoption of zero-emission powertrain technologies (ITF, 2021).

This chapter reviews global policy developments that have informed the policy and regulatory roadmap for the ZET transition in India presented in the final chapter. Detailed overviews of policy in California and in the European Union are available in Annexes C and D.

Goal setting

Increasingly, countries have been setting clear targets for ZEV transitions across vehicle segments, backed by legislation or executive orders that make them enforceable. European countries and sub-national governments such as California have been setting ambitious targets for ZET adoption, as summarised in Table 8. The country goals for ZET adoption are classified as "ambition" if they are announced government objectives but are not backed by any policy document or legislation. "Targets" and "legislation" are defined as those set out in official government policy or legislation and are enforceable.

Table 8. Comparison of zero-emission medium- and heavy-duty vehicle goals in Europe and California

Region/Country	Target	Policy Type	Target Year	Adoption Year
EU-27	45% CO2 emission reduction from 2019 reporting levels for MHDVs (translates to approx. 20-30% of new sales in 2030)	Legislation	2030	2024
Austria	100% of ZETs (<18T) and 60% ZET (N3)	Ambition	2030	2021
Finland	Cumulative 5 400 ZETs	Ambition	2030	2021
France	65 000 low-emission HDVs	Target	2028	2020
Germany	33% of heavy road haulage kms to be zero emission	Target	2030	2022
California	40 – 55% of new truck sales to be zero-emission in 2035 across different segments	Target	2035	2020

Source: Author analysis of various country programmes including Council of the European Union (2024a), California Air Resources Board (2021); IEA (2023) and Federal Ministry, Republic of Austria (2021).

In California, the landmark Advanced Clean Trucks (ACT) and Advanced Clean Fleets (ACF) regulations have set ambitious targets backed by clear goals for ZET adoption ranging from 40-55% across different segments by 2035. The regulation also sets targets for large fleets for ZET adoption. Some of the salient features of the ACT and ACF regulations are provided in Table 9.

Table 9. Salient features of the California Advanced Clean Trucks and Advanced Clean Fleets regulations

Sections of the Regulations	Key requirements
Manufacturer Sales Mandate	Manufacturers may sell only zero-emission medium- and heavy-duty vehicles starting in 2036.
Drayage Fleets	All drayage trucks entering seaports and intermodal railyards would be required to be zero-emission by 2035.
High Priority and Federal Fleets	Fleets must purchase only ZEVs beginning in 2024 and, starting 1 January 2025, must remove internal combustion engine vehicles at the end of their useful life as specified in the regulation. Instead of the Model Year Schedule, fleets may elect to meet ZEV targets as a percentage of the total fleet, starting with vehicle types that are most suitable for electrification.
State and Local Agencies	State and local government fleets, including city, county, special district, and State agency fleets, are required to ensure 50% of vehicle purchases are zero-emission beginning in 2024, and 100% of vehicle purchases are zero-emission by 2027.

Source: California Air Resources Board, 2021 and author analysis

Emissions regulations

Following a November 2023 vote on revised CO_2 regulations for MHDVs, the European Parliament reached a provisional agreement on 18 January 2024, introducing new targets for 2030, 2035 and 2040. The regulation covers 90% of MHDV sales, with the exception of small-volume manufacturers, agriculture, mining, and others (Council of the European Union, 2024b). Notably, the regulation requires vocational vehicles such as garbage trucks to be zero-emission from 2035; it also includes provisions for retrofitting trucks. The new targets will require a 45% reduction by 2030, 65% by 2035 and 90% by 2040, compared to 2019 levels.

The US Environmental Protection Agency (EPA) has proposed Phase 3 of GHG emissions regulations and multi-pollutant emissions standards for MHDVs applicable from the model year (MY) 2027 to MY 2032 and beyond. The standards for HDVs propose a reduction of 15-53% from MY 2027 to MY 2032 for vocational vehicles, about 26% for tractors, and 15% for heavy-haul tractors. The regulations for MDVs propose a 40% reduction in fleet-average CO_2 emissions along with a 66% reduction in fleet-average non-methane organic gases (NMOG) and NO_x emissions by MY 2032 from MY 2027 (Environmental Protection Agency, 2023).

The emissions regulation programmes in both the European Union and the United States consist of a trading mechanism (the EU Emission Trading System and the Averaging Banking and Trading programme in the United States) incentivising OEMs to increase the share of zero-emission offerings in their product line and sales share.

Overall, in addition to emission reduction benefits, these regulations are expected to provide a net positive societal benefit in terms of air quality improvements, reduced dependence on fossil fuels and operational cost savings (Environmental Protection Agency, 2023).

Fleet and infrastructure development

In the United States, two recent pieces of federal legislation, the *Infrastructure Act* (IIJA) and the *Inflation Reduction Act* (IRA), have included incentives for the production, purchase and infrastructure deployment of clean heavy-duty vehicles. Additionally, more than 15 US states have signed the Multi-state Medium and Heavy Duty Zero-Emission Vehicles (MHD-ZEV) Memorandum of Understanding, which seeks to achieve MHD ZEV sales of 30% by 2030 and 100% by 2050 (Environmental Protection Agency, 2023). More recently, the State of California passed the Advanced Clean Trucks and Advanced Clean Fleets regulations, which require a progressive sales share of ZETs by major truck manufacturers between 2024 and 2035.

In the United Kingdom, the Zero-Emission Road Freight (ZERFT) Demonstrator Program aims to invest GBP 200 million for the rollout of up to 370 ZETs and development of 57 charging and refuelling stations to build confidence among fleet operators and shippers in deploying ZETs and reducing freight emissions. It also has a separate fund of GBP 2.4 million to drive innovation in the freight and logistics sector (UK DfT, 2023).

Among emerging economies, Chile has adopted an integrated approach to move towards clean transport with policy and regulatory measures on energy efficiency, fuel economy standards and ZEV sales targets across all vehicle segments (light-, medium- and heavy-duty). The country has set different target years for different vehicle segments, beginning with 100% zero-emission sales for light and medium vehicles by 2035 and 100% zero-emission sales of freight transport by 2045 (Delgado et al., 2022).

Purchase incentives

While ZET incentive policies are still being formulated in many markets, California and the European Union have among the most advanced incentive programmes. At a federal level, the United States has allocated USD 2 billion under the IRA to support the deployment of Class 7 and Class 8 MHDVs across municipalities, schools and the postal service to facilitate a transition to ZETs, including buses. Japan plans to invest JPY 13.6 billion (USD 86 million) to introduce 5 000 electric HDVs by 2030. Canada provides incentives of up to CAD 200 000 (USD 145 000) for the purchase or lease of ZETs of various segments (IEA, 2023).

Within Europe, Germany until recently had one of the highest purchase incentives for BETs, providing a subsidy of 80% of the cost difference with respect to a diesel truck, with the price of a BET capped at EUR 450 000; this ended in December 2023. The Netherlands and Poland follow a similar subsidy model, providing subsidies at 40% and 30%, respectively, of the price difference of BETs with diesel trucks. This approach links the subsidy to the purchase price of BETs, reducing the subsidy amount with improvements in the purchase price of BETs. However, France, Italy and Spain provide a lump-sum subsidy amount varying between EUR 15 000 and 50 000 (Basma, Zhou and Rodriguez, 2022). Spain has among the highest levels of subsidy, along with France and the Netherlands. For example, for N3 vehicles (trucks with GVW over 12T), if compared to diesel trucks that typically cost USD 125 000 to USD 175 000, it would bring the share of the subsidy up to over half in countries such as Spain and France.

In California, the primary ZET incentive programme is the Heavy Vehicle Incentive Program (HVIP), which provides purchase subsidies. The incentives range from as low as USD 7 500 for Class 2B trucks to USD 240 000 for Class 8 fuel cell trucks. Table 10 provides a comparison of ZET incentives across Europe and California.

Table 10. Comparison of zero-emission truck incentives in Europe and California

Country	Power types	Vehicle class	Maximum subsidy for stated class
Germany	BEV, Hybrid, FCEV	N3	80% of additional cost
Spain	FCEV, BEV, Hybrid, CNG/LNG*	N3	EUR 130 000–190 000 depending on company size
Netherlands	FCEV, BEV- any zero-emission	N3	Up to 37% of purchase cost or EUR 131 900 for small businesses, less for large
Sweden	Biogas, FCEV, BEV	Over 3.5T	Up to 25% of total cost of the truck for small and medium-sized companies
Italy	BEV	N1 and N2	EUR 4 000–6 000 (N1) and EUR 12 000 – 14 000 (N2)
United Kingdom	BEV, Hybrid	N2 and N3	20% of purchase cost up to GBP 16 000 (N2) and up to GBP 25 000 (N3)
California	BEV, FCEV	Over 4T	USD 7 500 for Class 2B; USD 45 000 for Class 3; USD 60 000 for Class 4-5; USD 85 000 for Class 6-7; USD 120 000 for Class 8

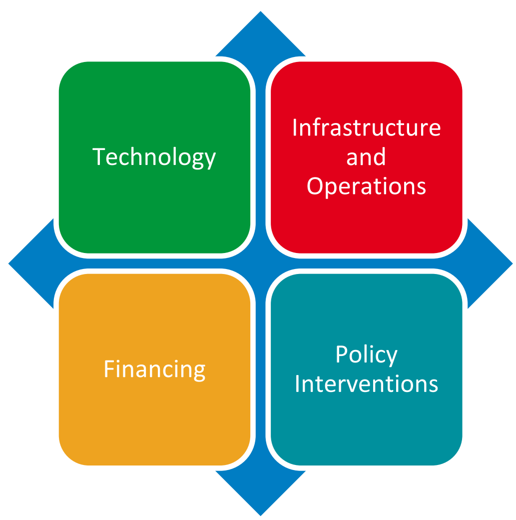
Notes: FCEV = fuel-cell electric vehicle. BEV = battery-electric vehicle. LNG = liquefied natural gas.
CNG = compressed natural gas.

Sources: Ministero delle Infrastructture e dei Transporti (2021), Government of the United Kingdom (n.d.), California HVIP (2024), Transport and Environment (2022), Ministry of Climate and Business, Government of Sweden (2024).

A roadmap for a zero-emission truck transition in India

As the TCO analysis in the previous chapter demonstrates, a transition to ZETs in India is within reach. This chapter outlines a roadmap to get there. India needs a comprehensive assessment of technology, operations, and financing, followed by a policy package that creates an enabling framework. The roadmap for India's ZET transition is structured around these four pillars (see Figure 15). The recommendations below draw from a global review of policies to enable the transition to ZETs. The EU and US policy approaches are included in Annexes C and D.

Figure 15. Four pillars of zero-emission truck adoption in India



Technology

The transition to ZETs in India will involve vehicle technology choices for different applications. The manufacturers in India have developed products based on different vehicle technologies, including BETs and FCETs. To scale up their deployment in India, a technology-agnostic approach to deploying ZETs will therefore require both regulatory clarity on ZETs and an assessment of technology readiness.

Define "zero-emission trucks"

India will need to clearly define what is considered within the scope of ZETs, including addressing the issue of near-zero-emission technologies such as H_2-ICE, which are currently being tested by some major truck manufacturers in India. Similar to the EU, India could consider H_2-ICE trucks that use only green hydrogen as falling within the scope of the definition of ZETs but have a phase-out year, after which only 100% zero-emission technologies that have no tailpipe emissions (both CO_2 and non-CO_2) will be considered (CALSTART, 2023; MPP, 2022; Toll et al., 2022).

Prioritise technology choices

While both electric and hydrogen fuel cells are considered zero-emission technologies, the role of battery-electric trucks has emerged as the dominant technology choice globally. This is also driven by the high learning curve of technology maturity for lithium-ion batteries compared to fuel cells and electric battery powertrains. Given the nascent stage of development of the hydrogen ecosystem in India, as well as uncertainty regarding hydrogen prices globally, India should consider prioritising battery-electric trucks to achieve a market transformation to ZETs in the coming decade.

Assess technology readiness

As truck manufacturers and fleet operators assess their needs and use cases to determine the right technology for their markets, developing a Technology Readiness Framework and providing a numeric score for various truck technologies each year would help India identify key gaps in technology development and identify clear interventions for both industry action and government policy. A broad framework is provided in Table 11, inspired by the indicators used in the California Air Resources Board's 2022 assessment of technology status and market-readiness (California Air Resources Board, 2022). It classifies different truck technologies under research, development, and commercialisation phases. This can then be used to score ZET technologies under different use cases and gross vehicle weights. Such an effort should be jointly undertaken with industry, government and research institutions.

Table 11. Parameters for zero-emission truck technology assessment

Phase	Definition
Research	If the technology: • Is at the early stages of invention • Requires more evidence for future innovations • Is proven to be viable through experimentation
Development	If the technology: • Is operated under specific conditions as a small/large prototype that can be used to validate real-world scenarios • Is operated in a real-world scenario / intended environment
Commercial	If the technology: • Has been successfully tested in uncontrolled environments • Is ready to support commercial activity • Can be utilized for full-scale commercial applications

Source: California Air Resources Board (2022).

Infrastructure and operations

The deployment of ZETs would require support infrastructure to address ''range anxiety'' and ensure the reliability of their operations. An integrated approach to developing slow- and fast-charging infrastructure would go a long way toward promoting their adoption. The operational planning of freight operations would also require certain modifications accounting for the charging or refuelling needs of such trucks. Infrastructure serves as a key enabler, especially in emerging economies, to scale up the adoption of ZETs.

Consider the diversity of charging infrastructure needs

Based on TCO assessments and technology costs for different use cases, the need for charging infrastructure will vary. While chargers are typically classified on the basis of their power output, they can also be categorized based on the location of chargers, enabling charging during (mid-shift) or outside (off-shift) the trucks' operational hours. This includes both depot charging (for overnight charging at the operator's depot) and destination charging (for daytime charging at distribution centres during loading and unloading, and public charging at rest areas, ports entry or parking spaces) (Mathieu et al., 2020). Typically, BETs will require higher-capacity chargers, even for off-shift charging cycles, as the average battery size is larger for MHDTs.

Identify zero-emission freight corridors

Identify freight corridors with high volume of freight traffic and prepare a strategy roadmap that can support and accelerate public and private investment in infrastructure for zero-emission trucks. This will aid in planning for both electricity infrastructure and hydrogen system planning.

Identify and plan for the costs of charging infrastructure

In the medium- and heavy-duty trucks segment, infrastructure costs account for 7-9% of lifetime operating costs for applications including long-haul, drayage and delivery. Building adequate charging infrastructure will accelerate the horizon for achieving TCO parity in case of electric trucks compared to conventional diesel trucks (Hall and Lutsey, 2019).

The cost estimates for ultra-fast chargers range from USD 0.21–0.4 million for a charger with a power output of 750 kW or above (Gogh and Hertzke, 2021) to USD 0.6 million for a power output of 1 MW (Bernard et al., 2022). The large amount of capital investment for chargers with a power output of 750 kW and above (as required for opportunity charging) is a major barrier to adopting BETs for long-haul operations.

In the European Union, depot charging (50-100 kW) is expected to account for about 80% of charging needs, followed by destination charging at about 15%, with the rest being fulfilled through public charging for urban and regional delivery applications (Mathieu et al., 2020). In the United States, off-shift charging (< 350 kW) can supply 35-77% of total energy for local and regional trucks with a range of 300 miles (480 km) and above. Overnight charging also has the benefit of reduced hardware costs for depot chargers of 50–100 kW (Bernard et al., 2022). This calls for an enhanced focus on building depot charging infrastructure for urban and regional delivery applications, which also aligns with the overall expectation as the segment reaches TCO parity faster than other use cases.

The estimated capital expenditure for a hydrogen fuel station is USD 2.1–3.2 million for a 1-tonne[2] per day output (Gogh and Hertzke, 2021). Hydrogen-based technologies also face challenges in terms of (a) lower efficiency (less than half that of an electrification pathway), (b) the high energy-intensity of producing green hydrogen through electrolysis, and (c) the opportunity costs of hydrogen as a fuel for other applications in industry and shipping (Mathieu et al., 2020).

Ensure high infrastructure utilisation rates

Given the high costs of ZET infrastructure, ensuring high utilisation rates will be critical. This will require strong regulations for ZET deployment, including identifying zero-emission freight corridors or zones. Under the PM Gati Shakti Scheme, India has identified 11 industrial corridors across the country which are being developed under the National Industrial Corridor Programme. Based on an assessment of the origin and destination of road freight across these corridors, specific routes ranging from 150 to 300 kms can be identified to deploy ZETs and associated infrastructure.

India is also estimated to have about 270 Special Economic Zones (SEZs), which are home to various industrial clusters. These SEZs can also serve as viable cases for the deployment of electric trucks for intra-zone operations. Additionally, under India's successful electric bus (e-bus) programme, various routes are operating inter-city electric bus services, wherein additional infrastructure could be added at existing e-bus charging stations, especially for medium-duty trucks (which would have similar powertrains and charging needs as e-buses), thus lowering the effective infrastructure costs and thereby, operating costs for ZETs.

Create a network of charging infrastructure

India could consider developing a regulation that is similar to the Alternative Fuel Infrastructure Regulation (AFIR) in the EU, which mandates targets for infrastructure deployment along the Trans-European Transport Network (TEN-T) for trucks by 2030. It should be noted that AFIR clearly supports BETs and FCETs and is not entirely technology agnostic (i.e. it does not support ERSVs or catenary/overhead supply, or any other alternative fuels). While current charging infrastructure guidelines in India have set a target of one public charging station per 100 km on highways with at least two public chargers of power output over 100 kW, this was done largely in the context of electric cars and buses (Ministry of Power, 2018).

To provide impetus for ZET deployment, India could consider requiring one recharging pool with an aggregated power of at least 2 MW and minimum charger ratings of 200 kW, especially along identified freight corridors. These charging stations could be built every 100 km on both sides of the highway. Lower capacity requirements and shorter distances between two charging pools could be considered for regional short-haul and urban delivery.

Involve industry in deploying charging infrastructure

The first high-power charging site in the United States was developed by Daimler Trucks and Portland General Electric in 2021, comprising eight "mega chargers" in Portland with an aggregated power output of 4.5 MW. At present, at least 12 high-power charging projects are ongoing in the United States and across Europe (Siddique, 2022), and truck manufacturers are playing a crucial role. They include Milence, a joint venture of Daimler Trucks, Volvo Group, and the Traton Group, which aims to deploy at least 1 700 fast (300-350 kW) and ultra-fast (1 MW) chargers across Europe by 2026 with a minimum power output of 1.4 MW per site and a total investment of EUR 500 million (IEA, 2023).

India is home to major truck manufacturers including Tata Motors, Mahindra Trucks and Buses, Volvo-Eicher Commercial Vehicles, Ashok Leyland and its subsidiary Switch Mobility, Daimler India Commercial Vehicles, and SML Isuzu. There is an opportunity for truck manufacturers and logistics fleet operators to form a joint venture to create a common network of charging infrastructure across major routes.

Redesign electricity tariffs and grid infrastructure

Most state electricity regulators in India currently have separate tariff rates for EV charging stations, but these are specifically in the context of charging for two- and three-wheelers as well as electric cars. Given the lack of a policy on ZETs, the current electricity tariff design does not account for high-capacity charging stations for electric trucks. Given that these could be bulk electricity consumers but with varying times of use throughout the day, it could be challenging for regulators when it comes to tariff design. While the per-unit rates of electricity could be lower, the installation of high-capacity chargers for electric trucks will likely attract high fixed costs and demand charges. This also raises the concern of developing additional grid capacity or upgrading the existing grid depending on the location.

For urban and regional delivery applications to see early ZET adoption, India could consider dynamic time-of-use electricity tariffs that favour night use, which would align with the projected reliance on off-shift charging and depot charging (ITF, 2022).

Evaluate multiple charging technologies

Battery swapping for trucks has started to emerge as an option, particularly in China. The technology may have advantages over ultra-fast charging in terms of reducing charging time by almost 90%, better grid management, and longer battery cycle life. The battery-as-a-service (BaaS) model would also reduce the upfront purchase costs by as much as 50%, and the dominant lithium iron phosphate (LFP) battery chemistry for truck batteries also provides safe and affordable options for swapping. However, barriers include the cost of building swapping stations with specialized equipment and the need for standardisation of battery packs and modules (IEA, 2023). Although countries such as Sweden and Germany have been exploring demonstration projects for electric road systems, the Swedish Transport Agency cancelled the project in August 2023 on account of higher costs (Trafikverket, 2023).

In the Indian context, with open highways that often have two-wheelers and other vehicle types operating without lane discipline, deployment of such alternatives could be challenging, and the effective costs of maintaining and operating such infrastructure could be much higher than expected. Overhead catenary networks can be explored, especially along dedicated freight corridors or within zero-emission freight zones, and they have been assessed to have cost and emission-reduction benefits (Parth Deshpande, 2023).

Financing

Road freight operations have multilayered contracting and sub-contracting through intermediaries. The stakeholders in the ecosystem include shippers who seek freight services, fleet owners who own trucks, fleet operators (or third-party logistics service providers), truck original equipment manufacturers (OEMs) and financiers. Financing, particularly debt financing, plays a key role across the trucking industry. In India, over two-thirds of loans for the purchase of trucks are through non-banking financial companies (NBFCs), which are essentially lending entities that charge higher interest rates than regular banks, as they finance entities with low credit ratings, thus taking on higher repayment risks.

Interest subventions to lower electric-truck financing premiums

Given the market uncertainty for the deployment of electric trucks, low confidence in technology maturity, and lack of infrastructure and policy support, financial institutions are hesitant to finance electric trucks;

as a result, they add a significant risk premium to conventional commercial-vehicle interest rates. India has already seen this with financing rates for electric car fleets for ride-hailing services or electric three-wheelers, where in the early years there was a premium of at least 200 basis points on EV loan interest rates as compared to those for ICE vehicles.

With electric trucks being a significantly more expensive asset and involved in a system where operational efficiency is key to revenue generation, the perceived financial risks are too high to achieve interest rate parity with diesel trucks. Other risks also include the lack of residual value estimates, battery replacement and warranty. In this context, the government could consider an interest subvention programme offering lower effective interest rates for financing ZETs. This would be expected to have significant impacts as most road-freight businesses operate on a continuous credit cycle for working capital.

Finance scaled pilot deployments of ZETs

The significance of ZET pilots across different use cases in India, which also capture data regarding battery performance, payload considerations, and charging patterns, could provide confidence to financial institutions and markets at large. The lessons from pilots will also provide insights into potential failure points in the ecosystem that can be addressed to reduce potential risks for financiers.

Involve shippers to drive ZET adoption at scale

About 80% of India's truck fleet is fragmented and owned by small fleet operators. Large logistics service providers and shippers can create positive market signals and aggregate demand to lower financial risks and costs. The market signals of longer-term contracts, paying a premium for low-carbon transport, or including emissions performance or percentage of electric trucks in the fleet as a criterion for their service procurement process by shippers could push fleet operators to adopt ZETs (Smart Freight Centre, 2023). India saw the first demand aggregation of 7 700 electric trucks announced by major shippers (including Amazon, IKEA, DHL) announced in July 2023 under the NITI Aayog E-FAST programme but is still to see a clear deployment strategy.

Transition public truck fleets to zero-emission through aggregated public procurement

Building on its experience in electric bus demand aggregation, India could leverage the lessons learnt to drive the transition to ZETs, especially for public fleets (including municipal trucks and drayage trucks) and for certain heavy industries such as cement, steel and mining, which have large public sector corporations involved.

Explore innovative business models

Various ZET financing models have emerged around leasing as opposed to direct truck ownership (Gogh and Hertzke, 2021). Given the significantly higher asset costs, leasing as a business model is expected to grow through the creation of separate leasing asset companies for ZETs, which would also lower the risk to lenders and eventually lead to a robust resale market for ZETs. Some interesting business models that could be considered include (a) a dynamic pay-per-mile leasing scheme which links the vehicle mileage to the leasing payment structure and would reduce losses for low utilisation, helping small fleet operators to transition to ZETs; and (b) a payment security mechanism to cover any payment defaults (as India has done for electric buses) or a first-loss protection scheme to guarantee a minimum residual value for first-generation ZETs (Smart Freight Centre, 2023).

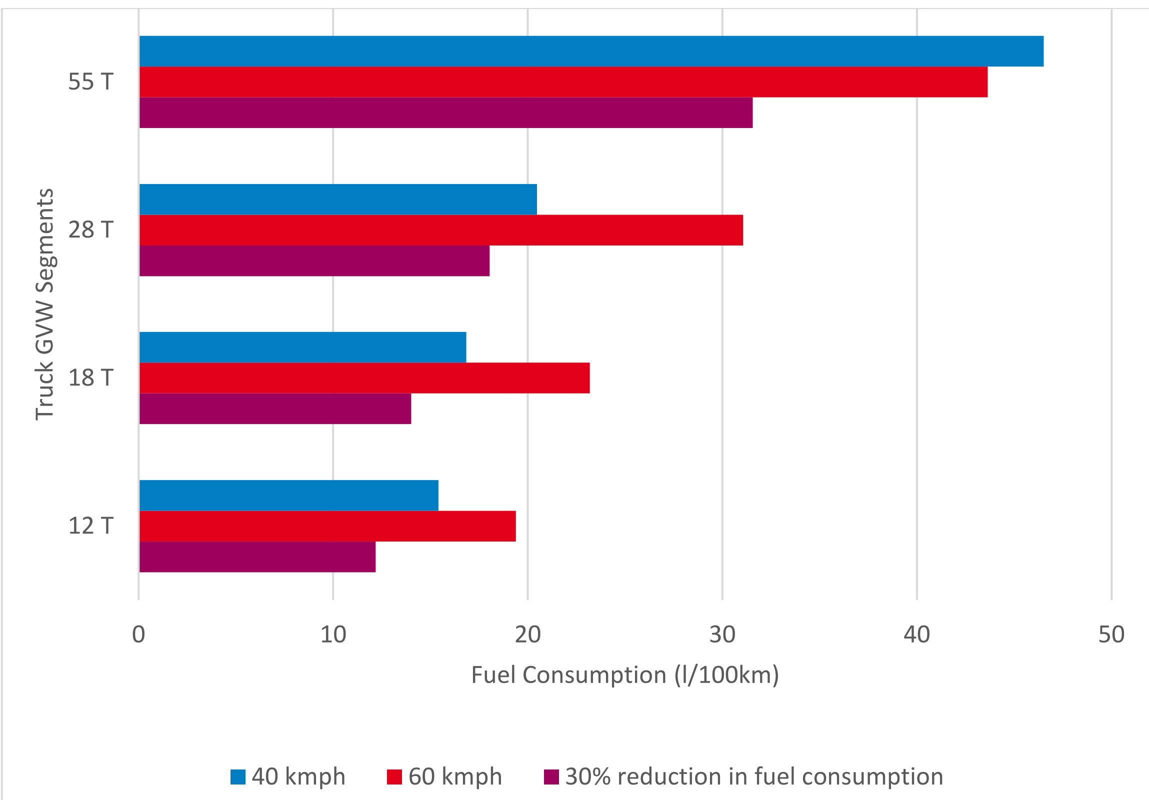
Policy and regulation framework for zero-emission trucks

Supporting the transition to ZETs by spurring technology development, deploying infrastructure, and unlocking financing will require a strong policy and regulatory framework. Based on a global review of zero-emission truck policies, India should prioritize the following five policy measures to provide the much-needed domestic policy certainty.

Implement ambitious MHDT CO_2 regulations

India's current CO_2 regulations for medium- and heavy-duty trucks, which entered into force on 1 April 2023, are essentially fuel consumption requirements (measured in litres per 100 km) and are per-vehicle norms as opposed to CAFE standards. This essentially means that each make and model is tested and certified as compliant. For the four reference cases in this TCO study, fuel consumption for different GVW segments is esttimated, as well as a 30% reduction target.

Figure 16. Fuel consumption estimates for reference truck cases



While India is currently in the process of setting new CO_2 standards for MHDTs, it will be worth considering a 30% reduction in MHDV CO_2 emissions by 2035 from a base year of 2022 levels since the last regulations were implemented.

Further, it will be important to consider shifting to CAFE standards that will allow for greater design flexibility (including engine improvements and reduction in rolling resistance) for truck manufacturers and for regulators to push technology shifts towards zero-emission trucks in priority segments. Additionally, a

CAFE regulation will allow for the imposition of penalties for non-compliance and a market-based credit trading mechanism for over-compliance (early market movers for sales of ZETs) that can be traded on the market and purchased by other manufacturers to meet any compliance deficits.

To enable better measurement, reporting and monitoring of CO_2 emissions from the MHDV segment, India is also considering the development of the Bharat Energy Efficiency Tool (BEET) modelled on the Vehicle Energy Consumption Calculation Tool (VECTO) used in the EU, which uses a computer-based simulation to assess the fuel efficiency of vehicles.

Adopt differentiated vehicle taxation policies

Commercial vehicles, including trucks and buses in India, attract a 28% goods and services tax (GST) with a relatively low additional cess (tax). India has also notified that light-duty EVs will attract a 5% GST. Since India does not have a clear ZET policy, a policy extending the 5% GST to ZETs in all segments will be a positive signal. Further, for specific truck segments (such as 18T and 55T, which are close to TCO parity), the additional cess on diesel trucks can be increased to facilitate a shift towards ZETs.

Set ambitious manufacturer and fleet sales requirements

The impact of supply-side regulations cannot be under-estimated. There is substantial evidence for this globally, especially with passenger cars in California, China, the European Union, the United Kingdom and many other contexts, wherein regulatory requirements have had the largest impact on the pace of EV adoption. They have led to a diverse and expanding supply of competitive products; greater investor confidence in infrastructure providers, manufacturers and financiers; aligned manufacturer product investments with intended goals; and enabled self-financing by the industry through market mechanisms. India's average annual MHDT sales are around 400 000 units.

Announcements made in 2021-22 regarding ZET deployment in India indicate that ZETs currently account for about 2% of new sales, even without any existing policy framework. In addition, various leading truck manufacturers in India announced early-stage investments in exploring the feasibility of electric trucks. Given this context, India could consider setting annual manufacturer sales requirements progressively reaching at least a 10% new-sales share by 2030, rising to a 15–20% new-sales share in 2030 under a high-ambition scenario. Similarly, India could also set requirements for large fleets and large corporations with a fleet demand over a certain threshold to have progressive annual requirements for adopting ZETs. This approach to sales mandates from both the supply and demand side would spur the ZET market.

Differentiated ZET purchase incentives

India's current approach to EV purchase subsidies has been linked to battery size, with an upper threshold based on a percentage of the vehicle price. While this may work well for passenger cars and two- and three-wheelers, the battery-size-linked approach may not work well for ZETs, especially given the complexity of use cases and vehicle segments. Drawing from global lessons, India may consider a purchase incentive programme for ZETs that is designed on the basis of two key criteria: (a) offering differential incentives for different vehicle weight segments (which may need additional classifications based on the market segmentation); and (b) each segment's incentive to have a percentage cap of the vehicle price and an overall vehicle price threshold.

Encourage sub-national action

States and cities, as sub-national governments, also have a strong role to play in driving ZET transitions through policy decisions. States in India impose a road tax on the purchase of trucks in their jurisdictions in addition to the GST. State governments can choose to reform the road tax mechanism to differential rates based on powertrain or emission portfolio. Further, most states in India have their own EV policies, which can be expanded to include a comprehensive package for ZETs.

States and cities can also create zero-emission zones or intra-state zero-emission corridors. Often, trucks have to wait at state borders if they arrive during the day, as there are entry restrictions due to air quality concerns; such restrictions could be lifted for ZETs. Incidentally, Telangana and Goa are the only two Indian states to endorse the Global MoU on Zero-Emission MHDVs, although India is not a signatory to the MoU. This could also be an opportunity for states to cooperate with each other to facilitate zero-emission freight corridors, toll-free movement for ZETs, and so on.

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Annex A. Total cost-of-ownership input parameters for diesel trucks

Table A.1. Total cost of ownership input parameters for diesel trucks, model years 2023 and 2030

Truck Segments		12 T	18 T	28 T	55 T	12 T	18 T	28 T	55 T
Variable	Unit	2023				2030			
GVW	Tonne	12	18	28	55	12	18	28	55
Payload	Tonne	8	13	18	43	8	13	18	43
Distance travelled/trip	km	200	500	100	300	200	500	100	300
Cost of vehicle	INR (`000)	2 400	2 900	5 400	4 500	2 663	3 218	5 993	4 994
Upfront cost financed	%	85%	85%	85%	85%	85%	85%	85%	85%
Insurance premium	INR	27 186	35 313	43 950	44 242	27 186	35 313	43 950	44 242
Mileage with 100% payload	km/l	4.9	3.9	2.1	1.8	4.9	3.9	2.1	1.8
Mileage without payload	km/l	7.0	5.5	3.0	2.5	7.0	5.5	3.0	2.5
Fuel Price	INR/L	94	94	94	94	117	117	117	117
Interest rate	%	15	15	15	15	15	15	15	15
Annual Maintenance Cost	INR (`000)	120	145	270	225	133	160	299	249

Annex B. Total cost-of-ownership input parameters for battery-electric trucks

Table B.1. Total cost of ownership input parameters for battery-electric trucks, model years 2023 and 2030

Truck Segments		12 T	18 T	28 T	55 T	12 T	18 T	28 T	55 T
Variable	Unit	2023				2030			
GVW	Ton	12	19	28	55	12	19	28	55
Payload	Ton	6	10	14	34	7	11	16	40
Cost of vehicle	INR (`000)	5 280	6 380	14 850	12 375	4 104	4 886	15 603	11 452
Cost of battery	INR/kWh	18 000	18 000	18 000	18 000	11 200	11 200	11 200	11 200
Upfront cost financed	%	85%	85%	85%	85%	85%	85%	85%	85%
Insurance premium	INR	23 108	30 016	37 357	37 606	23 108	30 016	37 357	37 606
Battery size	kWh	200	250	100	260	200	250	300	258
Battery Replacement Cost	INR/kWh	15 480	15 480	15 480	15 480	10 560	10 560	10 560	10 560
Mileage with 100% payload	km/kWh	1.00	0.70	0.70	0.77	1.00	0.70	0.70	0.77
Mileage without payload	km/kWh	1.00	2.00	1.00	1.15	1.00	2.00	1.00	1.15
Energy Charges	INR/kWh	10.5	10.5	10.5	10.5	16.6	16.6	16.6	16.6
Interest rate	%	17	17	17	17	17	17	17	17
Annual Maintenance Cost	INR (`000)	72	87	175	146	79	96	194	162

Annex C. European MHDV Decarbonisation policy

In the European Union, there already exists an established CO_2 emission reduction target for truck sales that is designed to reduce the average CO_2 of the fleet by 15%, with the current rule applying to model year 2025 (European Commission, 2019). Recently, in November 2023, the European Union adopted a general approach that sets more stringent CO_2 emission reduction targets for MHDVs. Compared to the 2019 level, this rule will require a 45% reduction by 2030, 65% by 2035 and 90% by 2040. While the current EU regulation only applies to N2 (3.5-12 tonnes) and N3 (>12 tonnes) vehicles, the new rule expands the scope to include N1 (small commercial) vehicles) as well, with exceptions for special-purpose, off-road, off-road special-purpose, and vocational vehicles.

According to the European Automotive Manufacturers Association (ACEA), the new rules will require over 400 000 ZETs on the roads, which translates to about 100 000 new ZET sales annually or about one-third of new sales. This will also require 50 000 publicly accessible chargers and 700 hydrogen refilling stations with a daily capacity of about 2 tonnes.

The European Union has also passed the Alternative Fuels Infrastructure Regulation (AFIR), which requires Member States to develop national policy frameworks for ensuring sufficient coverage of recharging and refuelling infrastructure (Council of the European Union, 2023) An updated proposal requires European Member States to ensure the construction of a minimum network of charging and refuelling stations along the TEN-T. These are expressed both in terms of maximum distance from each other (60 km) and power output per recharging pool, ranging from 1 400–3 600 kW depending on the charger type (i.e. one or more recharging stations at a specific location).

The regulation also provides guidance on the share of different charger capacities along the highway network to ensure reliable infrastructure. In the case of heavy-duty hydrogen trucks, the guidance includes minimum station capacity (1 t/day) and geographical availability, expressed in terms of maximum distances between refuelling points (Council of the European Union, 2023) For heavy-duty vehicles, the European Commission shall report by the end of 2024 on the technology and market-readiness of different options, as well as regarding technical specifications for charging and refuelling (Council of the European Union, 2023).

While CO_2 emission reduction targets are the key policy lever for the decarbonisation of MHDTs at the EU level, some member states have set their own goals, by way of either an ambition level or a specific target (see Table 8).

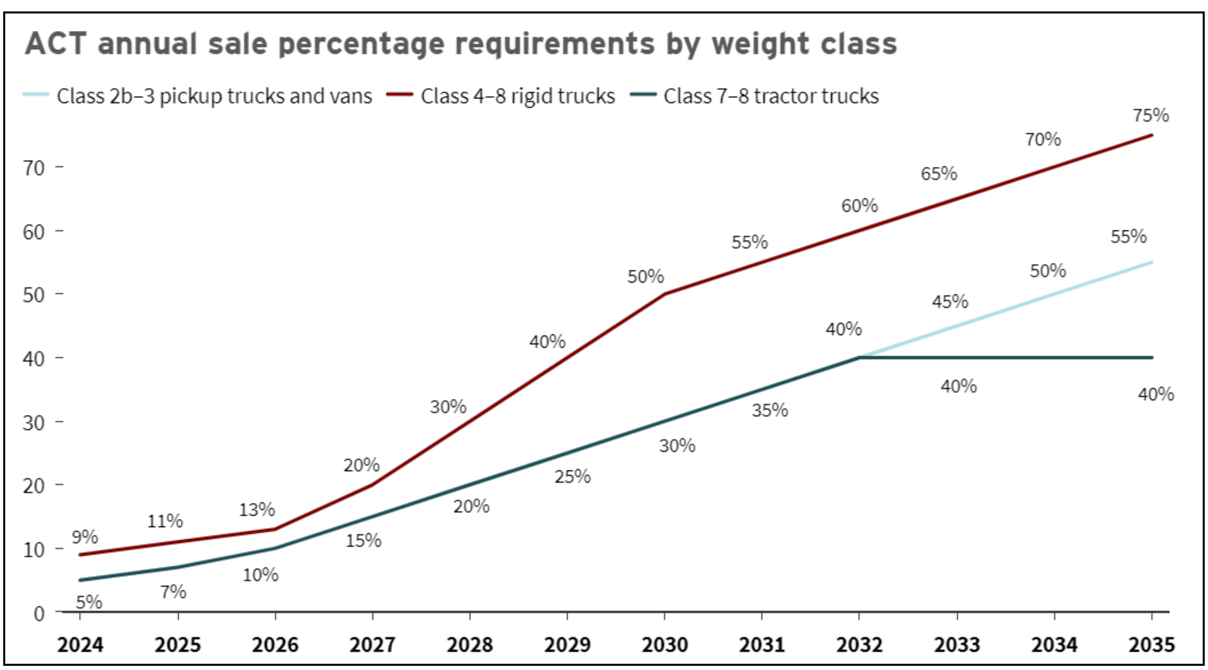
Annex D. California's Zero-Emission Trucks policy

California has taken global leadership in driving the sales of ZETs through a comprehensive set of policy measures, including the Advanced Clean Trucks (ACT) and Advanced Clean Fleets (ACF) regulations, which act as supply measures focusing on manufacturer sales requirements and fleet purchase requirements, respectively. These two regulations, combined with policies such as the Heavy Vehicle Incentive Program (HVIP), policy measures regulating criteria pollutants, and low-carbon fuels standards, provide a generally strong environment that encourages the adoption of ZETs.

Advanced Clean Trucks regulation

The ACT was approved by the California Air Resources Board (CARB) in June 2020 and established a timeline by which medium- and heavy-duty truck manufacturers must increase their sales of zero-emission vehicles (ZEVs). Its key objective was to increase the model availability and supply of ZETs available for fleets to purchase. The regulation is set to take effect in 2024, with annual sales percentages increasing through 2035, when 55% of Class 2b-3 truck sales, 75% of Class 4-8 rigid truck sales, and 40% of Class 7-8 truck sales must be zero-emission (see Figure D.1).

Figure D.1. Advanced Clean Trucks annual sales percentage requirements



Source: Adapted from McNamara (2023).

The ACT regulation also includes flexibilities for near-zero-emission vehicles, including plug-in hybrid EVs, which can generate credits until 2035. The regulation allows for a credit trading mechanism wherein manufacturers can purchase credits from others to meet compliance requirements. This also creates a revenue flow for manufacturers that generate credits, serving as a notional offset for producing higher-cost ZETs. Near-zero-emission technologies receive only a partial credit, which is estimated as 10% of the vehicle's all-electric range, with a cap of 0.75. Further, such vehicles can only be used to meet up to 50% of the credits required for compliance in any given year for each manufacturer (California Air Resources Board, 2021).

Advanced Clean Fleets regulation

The ACF regulation requires owners of large fleets (over 50 vehicles) to purchase ZETs for use in California. It is likely to also require large corporations that do not own their own fleets but depend on third-party logistics providers to require a minimum number of ZETs operating for them. In addition, to aid the deployment of zero-emission trucks, the Heavy Vehicle Incentive Program (HVIP) offers purchase subsidies to fleets (see Table D.1).

Table D.1. California's Medium- and Heavy-Duty Vehicle Incentive Schedule

Truck segment by use case	Battery-electric vehicle (USD)	Fuel-cell electric vehicle (USD)
Long haul	120 000	240 000
Short haul	120 000	240 000
Medium-duty urban	85 000	85 000
Heavy-duty vocational	120 000	240 000
Medium-duty vocational	85 000	85 000

Annex E. Methodological variations in TCO studies

The purchase cost of BETs and FCETs is estimated by adding the costs of battery/fuel cell and powertrain components to the base glider (vehicle body without powertrain) cost. The base glider cost is not only considered the same as that of diesel trucks (Basma, Saboori and Rodriguez, 2021), but also assumed to be constant between 2020 and 2030 for BETs (Mao et al., 2021), which can be reduced with the increasing scale of production. However, the cost of batteries or fuel cells depends on the scale of production, which is significantly lower than that of light-duty vehicles (LDVs). Therefore, a mark-up factor is used along with the average battery price and the required battery capacity to determine the costs for ZETs (ITF, 2022). An approach using the direct manufacturing costs (DMCs) of powertrain components (representing the cost paid by the vehicle manufacturer for the component) is also used to determine the vehicle components costs (Shiyue Mao, 2023). This approach requires an extensive data repository for the components used and their manufacturing costs for the OEMs. The high purchase price for ZETs acts as a crucial barrier to scaling their adoption, but a study suggests reducing the influence of higher purchase costs for applications with high annual average VKT (Zhao et al., 2018).

Based on a literature review of the TCO studies for various regions, the upfront costs of heavy-duty BETs in the United States and Europe are about three times higher, and FCETs are about 3.5 higher, than diesel trucks (Sharpe and Hussein, 2022). In contrast, medium-duty BETs and FCETs cost 1.3–1.5 times more than diesel trucks, respectively, and are expected to be almost at par by 2030 (Burke et al., 2022), (Hussein and Rodriguez, 2022). For heavy-duty trucks, by 2030, the differential is expected to decline by 40% for BETs and about 25% for FCETs compared to diesel trucks (Sharpe and Hussein, 2022). In China, BETs and FCETs are about two times more expensive than their diesel counterparts (Qiu et al., 2022). By 2030, it is expected that the upfront cost of BETs will achieve cost parity with its diesel counterparts, whereas the FCETs will lag a few years in achieving parity (Shiyue Mao, 2023).

The variation in the upfront costs of diesel trucks, BETs, and FCETs between 2020-23 and 2030 are shown for the United States, the European Union and China (Figures 8 and 9). There is a significant reduction in costs for heavy-duty trucks both BETs by at least 50% by 2030 for all the 3 geographies. However, the cost of medium-duty BETs and FCETs in Europe and the United States is expected to fall by 20-25% in 2030, whereas prices for diesel trucks are expected to stay the same or increase due to heavy taxation at the point of purchase.

Further, there is also a trade-off between range, battery size and payload capacity, as higher range requirements would lead to heavier battery packs and, in turn, impact the payload capacity for electric trucks. It is expected that current payload limitations for BETs will reduce over time, with payload capacity increasing by 5-15% across different segments. For example, in the ICCT study on TCO for HDTs (Basma et al., 2023), the energy density of the battery is assumed to increase from 0.14 kWh/kg to 0.25 kWh/kg in the United States and to 0.23 kWh/kg in China. In the case of FCETs, the percentage payload increase is estimated to be 2-7% (Basma et al., 2023). This includes a decrease in the hydrogen fuel tank size, improvements in energy efficiency, aerodynamic measures such as the addition of roof spoilers, a reduction in tyre rolling resistance, and a reduction of the mass of vehicles.

The operational costs of ZETs comprise the energy costs depending on the fuel prices, energy efficiency and the annual VKT, maintenance costs and financing costs. The energy costs also include the infrastructure costs associated with the fuel technology (Burke, Miller, and Sinha, 2022; Ng, 2022). The energy efficiency is estimated to improve by 23-28% from 2020 to 2030 (Mathieu, Poliscanova and Ambel, 2020; Basma, Saboori, and Rodriguez, 2021) but varies in the base value chosen. A lower energy efficiency value increases the battery size or fuel cell required for the same vehicle range and, therefore, its purchase price (Shiyue Mao, 2023).

For the review of the literature in various regions such as the United States, the European Union, the United Kingdom and China, the diesel cost, energy cost, and cost of hydrogen production were determined on the basis of parameters exclusive to the country's production data (Figure 11). The costs were converted into USD (PPP equivalent) and were averaged to find a global estimated price for each fuel. It was found that the average cost of diesel is around USD 1.22/litre at present, and studies assume it will remain constant in the future (although this study assumes an increase in diesel prices). In terms of hydrogen costs, studies assume the levelized cost of green hydrogen production at around USD 11–12 per kg and expect it to reach USD 9–10 per kg by 2030 (Borlaug et al., 2023; Rodríguez and Basma, 2023; Shiyue Mao, 2023; Zhao et al., 2018; Burke et al., 2022; Basma et al., 2023). The average price of electricity is assumed to be around USD 0.19 per kWh, and is assumed to remain around the same in the future (Basma et al., 2023; Burke et al., 2022; Zhao et al., 2018; Basma, Zhou and Rodriguez., 2022; Hussein and Rodriguez, 2022; Hussein and Rodriguez, 2022; Rout, 2022).

The electricity cost depends on the area, time of use, and end use, and includes overhead costs charged by charge point operators (CPOs) to cover hardware and installation costs along with the operational expenses of the charging station. The operational expenditure (e.g. rent, maintenance, customer support) constitutes 1.2% of the charging station capital expenditure (Basma, Saboori, and Rodriguez, 2021). The future prices of electricity will depend on the share of renewable energy and the cost of chargers, which account for 90% of the infrastructure cost associated with depot charging. There is high uncertainty regarding the costs of high-power capacity chargers, which vary from USD 0.46 million to USD 1.1 million (Ng, 2022).

Hydrogen prices depend on the cost of production, delivery of hydrogen from the production site to the fuelling station, and operation of the fuelling station. The assumptions regarding the base year (2020) values of hydrogen are around USD 15/kg in the United States and Europe (Burke, Miller, and Sinha 2022). However, the future values vary substantially from around USD 6/kg in the United States (H. Zhao, Wang, and Fulton 2018) to USD 12/kg in Europe, even while considering the lowest-cost green hydrogen production pathway (Basma and Rodríguez, 2023). If the hydrogen price is increased from USD 4/kg to USD 8/kg, the TCO for FCETs increases by 59%, denoting the considerable influence of hydrogen price on the TCO of FCETs (H. Zhao, Wang, and Fulton 2018). Even considering blue hydrogen as a fuel for FCETs, which is 39-54% cheaper than green hydrogen prices in 2020 and 28–40% in 2030 in China, does not make FCETs cost-competitive before 2030 for any ZET segment (Shiyue Mao, 2023).

Catenary and dynamic charging systems prove to be 15–22% more cost competitive than FCETs, with the high energy infrastructure cost offset by lower energy costs of electricity compared to hydrogen. Electricity price has a moderate influence on the TCOs of these technologies. However, daily truck traffic is an important parameter for determining their cost-competitiveness with diesel trucks (Zhao et al., 2018)

The annual vehicle mileage is considered a function of vehicle age, with decreasing truck mileage as the years progress. The range estimation of ZETs is based on the average daily mileage depending on the number of days of operation in a year. Therefore, annual mileage is crucial for determining the vehicle range and battery capacity and, therefore, the vehicle purchase price. A 2022 ITF study calculates the vehicle range estimations based on the first-year mileage of BETs in their use case, which might be a range overestimation, thus increasing the upfront purchase price for the segment (Ng, 2022). This might be offset to an extent by assuming a larger period of first-use ownership.

The ownership period determines the financial cost of the purchase or leasing of ZETs as well. The interest rates vary significantly from 2% for a five-year loan in Europe (Basma, Saboori, and Rodriguez, 2021) to 10% for a three-year loan in China (Shiyue Mao, 2023).

The residual value of ZETs also plays a crucial role in estimating the cost of financing. The residual value and vehicle life of new powertrain technologies could be higher compared to diesel trucks due to lower mechanical complexity and maintenance needs. However, given the early development stages of the ZET market and the lack of a second-hand ZET market, coupled with uncertainty about vehicle operational lifetimes, there will be a risk to using residual-value accounting in the case of ZETs (Ng, 2022). The residual values for ZETs are estimated to vary between 25 and 30% for 5–7 years of ownership in Europe, representing the typical first-use ownership period (Basma, Saboori, and Rodriguez, 2021).

Annex F. Studies covered in the meta-review

Table F.1. Studies covered in the meta-review

Title of study	Author	Year
Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results	Burke et al., UC Davis	2022
TCO of Alternative Powertrain Technologies for Class 8 Long-haul trucks in the United States	Basma et al., ICCT	2023
A comparison of zero-emission highway trucking technologies	Zhao et al., UC Davis	2018
Fuel-cell electric long-haul trucks in Europe: A TCO analysis	Basma, Zhou and Rodriguez, ICCT	2022
TCO for tractor-trailers in Europe: Battery-electric versus diesel	Basma, Saboori and Rodríguez, ICCT	2021
Techno-economic uptake potential of zero-emission trucks in Europe	T&E (Transport and Environment)	2022
TCO for heavy trucks in China: Fuel cell electric, battery-electric and diesel trucks	Mao et al., ICCT	2021
A comparative TCO analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel	Rout et al., Heliyon	2022
Transforming Trucking in India: Pathways to Zero-Emission Truck Deployment	NITI Aayog, RMI	2022
Decarbonising Europe's trucks: How to minimise cost uncertainty	Matteo Craglia, ITF	2022
A TCO comparison of truck decarbonisation pathways in Europe	Basma et al., ICCT	2023
Electrifying last-mile delivery: A TCO comparison of battery-electric and diesel trucks in Europe	Basma, Zhou and Rodrigeuz, ICCT	2022

Note: TCO = total cost of ownership.

A Pathway to Zero-Emission Trucking in India
Setting the Framework

This report assesses the potential of decarbonising heavy-duty trucks in India with zero-emission technologies, focusing on battery-electric technology. It presents a four-pillared roadmap for a transition to ZETs that addresses technology, infrastructure and operations, financing, and policy interventions for India. It achieves this by identifying economically feasible truck segments (based on weight classification) for the transition, along with strategies for developing support infrastructure and innovative financing models.

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