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Freight Trucks in India are Primed for Electrification

Nikit Abhyankar¹, Narayan Gopinathan², Aditya Khandekar¹, Nihan Karali¹,
Amol Phadke¹, Deepak Rajagopal^{1,2}

¹Lawrence Berkeley National Laboratory

²Institute of Environment and Sustainability, University of California Los Angeles

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Freight Trucks in India are Primed for Electrification

N. Abhyankar*, N. Gopinathan⁺, A. Khandekar*, N. Karali*, A. Phadke*, D. Rajagopal^{*,+,#}

Abstract

Diesel trucks account for more than seventy percent of all road freight movement in India, a share that has been steadily rising for over two decades. Diesel trucks also account for about 57% of petroleum used for transportation in India, which imports 88% of its crude oil consumption (with crude oil accounting for 16% of all imports). Diesel-based trucking is therefore a major contributor to concerns related to air pollution and greenhouse gas emissions, cost of freight, balance of trade and energy security. Recent dramatic improvements in battery costs and energy density have created opportunities for truck electrification that were seldom thought possible just a few years ago. This study analyzes the potential for truck electrification to reduce India's emissions, fuel imports, and cost of freight through an estimation of cost of production and operation based on international battery prices. We find that battery electric trucks (BET), once mature, could have lower total cost of ownership (TCO) than diesel trucks across multiple weight classes and they also mitigate fuel price volatility, an issue endemic to diesel trucking. BETs might entail a small payload penalty which can be mitigated through light weighting strategies and any revenue losses offset by fuel cost savings. Simple calculations suggest that, at the current average grid emissions intensity for India, BETs reduce the greenhouse gas intensity of freight by 9% to 35% across different classes of trucks when compared to diesel in addition to eliminating air pollution along highways and congested areas. Nevertheless, as is often the case for infant industries which promise external benefits (reduce pollution and create knowledge spillovers), sustained policy support will be needed for the BET industry if it is to attain commercial viability: achieving minimum scale will only occur after a long maturation phase, during which electric trucks may entail both higher upfront cost and total cost of ownership relative to diesel trucks. To this end, complementing the existing Production Linked Incentive (PLI) scheme with additional policies such as subsidies for early adopters, as well as binding obligations on truck manufacturers and large fleet owners to induct a certain quantity or share of BETs annually – will be critical for creating certainty for investors and the economies of scale needed to stimulate a positive feedback cycle of higher deployment and lower costs. India has already successfully leveraged renewable purchase obligations, to achieve significant deployment of low-cost renewable energy; the time is now right to consider how such an approach could help India reduce its dependence of diesel for trucking.

* Lawrence Berkeley National Laboratory

⁺ Institute of Environment and Sustainability, University of California Los Angeles

[#] Corresponding author: Email: rdeepak@ioes.ucla.edu

Executive Summary

Heavy-duty vehicles (HDVs), comprising heavy-duty trucks and buses, account for only about 10% of the global vehicle stock but are responsible for 46% of global greenhouse gas (GHG) emissions arising from road transportation. HDVs are also significant sources of criteria air pollutants - such as particulate matter (both PM₁₀ and PM_{2.5}), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), and volatile organic compounds (VOC) – which adversely affect air quality and human health (Talebian et al., 2018). In India, air pollution from transportation is estimated to have caused 74,000 premature deaths in 2015; two-thirds of this figure is attributable to diesel consumption, which is dominated by trucking (Annenberg, et al. 2019).

India's transportation-sector energy use has grown about 7% annually since 2000, with petroleum use for on-road transportation accounting for vast majority of this growth. As of 2015, more than half of freight transport occurred over roads; given highway infrastructure improvements, it is likely this figure is higher today and continue to increase. In 2020, the share of freight moved by road in India was 71% (NITI Aayog and RMI 2021). Trucks and buses together consume about 54% of the diesel used for road transportation in India (Karali and Abhyankar 2019). Though trucks comprise only 5% of the vehicle fleet, they produce 71% of the CO₂ emissions, 74% of the PM emissions, and 55% of the NO_x emissions from road vehicles in India (Apte, et al., 2017; Guttikonda and Mohan 2014; Kodjak 2015). Additionally, about 88% of India's crude oil consumption is met through imports, with crude petroleum imports accounting for about 16% of all imports.¹ Reducing fuel use for trucking therefore has substantial beneficial implications for India's balance of trade, energy and economic security, and public health and the environment.

From 2002 to 2022, vehicle sales in India experienced a continuous annual growth rate of 9.1%.² Given the projected rate of growth in vehicles and freight movement, aggregate emissions can be expected to rise sharply even under the most optimistic scenarios of improved fuel economy in the heavy-duty fleet. This means that fuel efficiency improvements alone will not be sufficient to achieve the dramatic reductions in diesel required for improving air quality or India's target for net zero emissions. Therefore, additional strategies must be pursued to reduce diesel use while enabling greater freight movement. These strategies include a modal shift to rail and water transport; electrification of the rail network; and fuel switching of trucks. Potential alternative energy and fuel technologies for trucks that require consideration include biodiesel and renewable diesel, renewable natural gas, diesel-battery hybrids, hydrogen fuel cell trucks, and pure battery electric trucks (BET).

¹ <https://oec.world/en/profile/country/ind?depthSelector2=HS4Depth>

² <https://www.ceicdata.com/en/indicator/india/motor-vehicles-sales-growth>

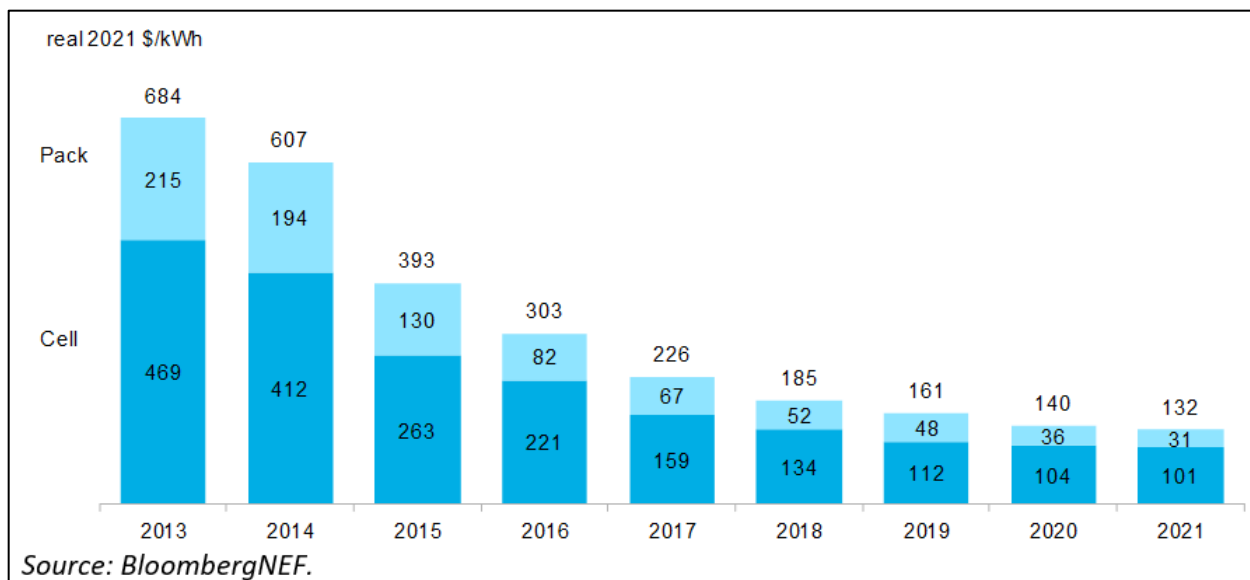


Figure E1: Trend in international battery prices (Source: BloombergNEF 2022). Recent dramatic declines in battery prices and improvement in their energy density have created opportunities for battery-electric trucking that were seldom anticipated just a few years ago.

Until recently, batteries' high costs and low energy density posed major barriers to electrification of heavy-duty and long-haul trucks. This has changed. Steep declines in battery prices (Figure E1) and improvements in battery energy density motivate a reassessment of the techno-economic feasibility of BETs, which is the main objective of this work. Our calculations suggest that if vehicle manufacturers realize the current world average price of battery packs, then across multiple vehicle classes and average daily utilization rates, the techno-economic case for BETs becomes strong even without monetizing any external benefits (e.g., public health improvements from reduced pollution). However, realizing such battery pack prices require production on a large scale until which time BETs will be costlier and unprofitable when compared to a mature industry like diesel trucking.

Electrification of truck fleets will enable fleet owners to insulate themselves against fuel price volatility. Large fleet owners can mitigate fuel price risk by purchasing fixed price contracts for renewable electricity, as utilities now do through 25-year fixed price power purchase agreements. More broadly, truck electrification can help policymakers achieve multiple objectives by simultaneously reducing oil imports, air pollution, greenhouse gas emissions and the cost of freight.

We assess the techno-economic case for electrification of different categories of freight trucks in India using the latest information on international battery pack costs and estimates of energy density. To date, ours is one of the few studies of truck electrification undertaken at this level of detail for India. We analyze trucks in four weight classes: 7.5 metric ton (MT), 12 MT, 25 MT and 40 MT. For brevity, we discuss here primarily the results for the 12 MT class for which we

assumed a 300 km range here (Figure E2) This is consistent with data showing that the average truck in India travels 200 to 400 km per day (Retailers Association of India 2013). However, more generally, we find that across each of the four classes of trucks, BETs have a lower TCO while the payload penalty increases as the weight of the truck increases or as the desired range per full charge increases all else fixed.

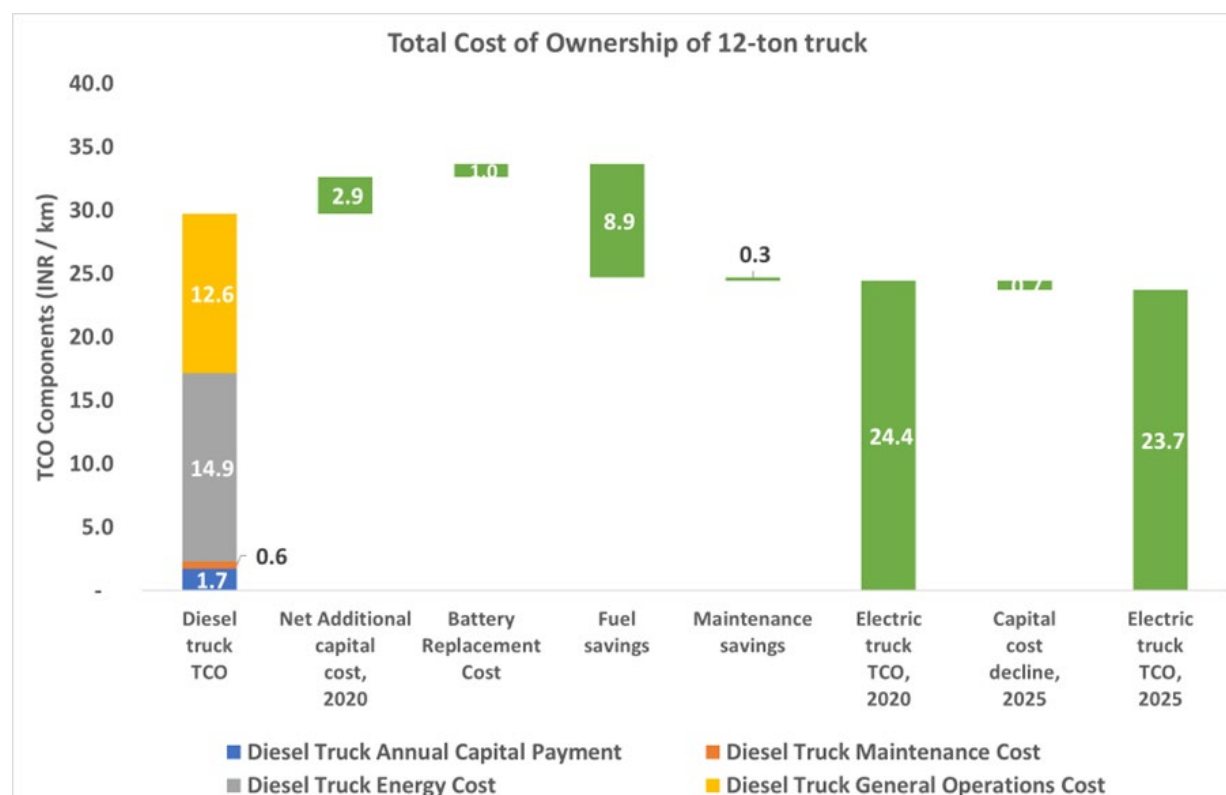


Figure E2: Total cost of ownership of diesel truck and 12-ton electric truck with 300 km range.

At a battery pack price of \$135 per kilowatt-hour (kWh), a 12-ton electric truck with a 222-kWh battery pack and 300 km range could deliver a 18% lower total cost of ownership (TCO) per kilometer relative to a diesel truck. The payback period for recouping the electric truck's higher upfront costs would be 3.1 years, while the undiscounted savings over a 15-year vehicle life amount to Rs 72 lakh. Heavier trucks require bigger batteries all else fixed. But when heavier trucks also entail greater annual vehicle kilometers driven, their payback and TCO savings could be similar to those for 12-ton trucks despite their higher upfront cost. We find that 25-ton trucks operating 400 kms per day have a payback period of about 2.2 years while 40-ton trucks operating 400 kms per day have a payback period of about 3 years.

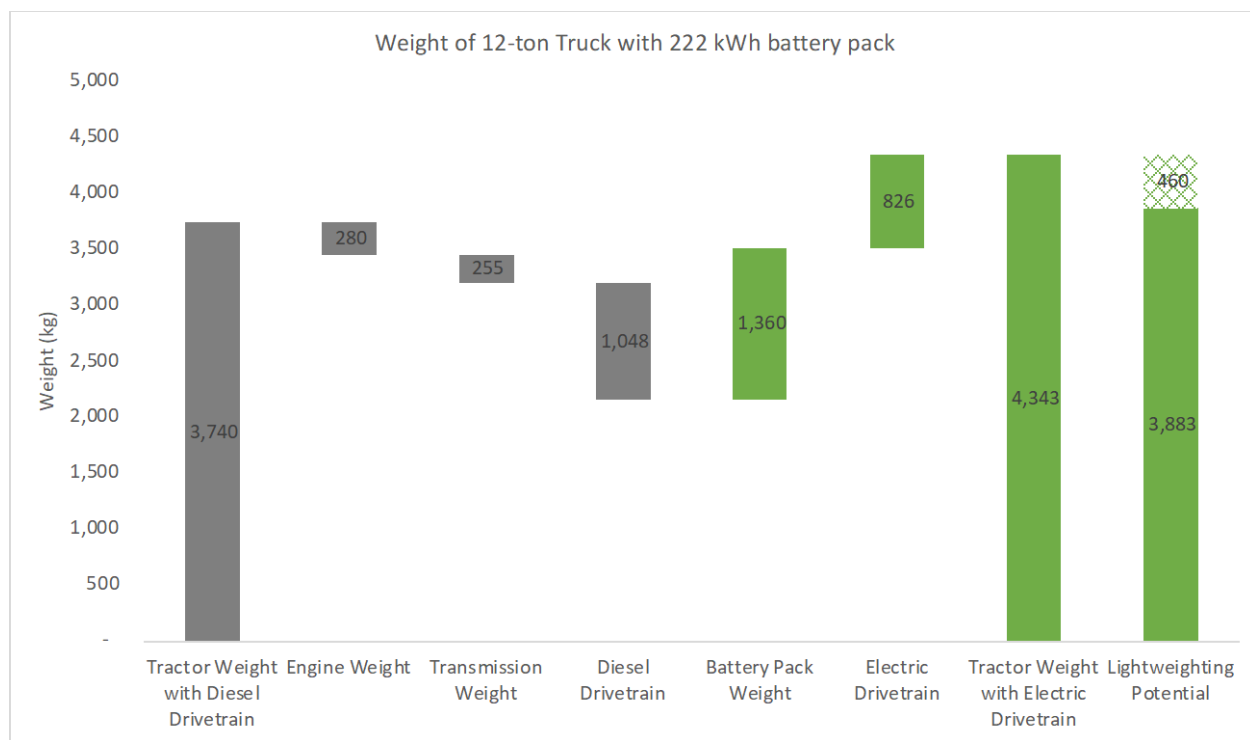


Figure E3: Weight comparison of 12-ton electric truck (with 222 kWh battery pack) to a 12-ton diesel truck.

Figure E3 compares truck weight and payload capacity. The 12-ton electric truck's curb weight, or unladen weight, is about 10% heavier, which reduces its maximum payload capacity. Lightweighting strategies could cut this penalty in half, to 5%. Under these assumptions, the vehicle is still compliant with maximum weight limits in India, but a portion of the payload is sacrificed to make room for the battery.

Simple calculations (see Table E1) unambiguously establish that at current grid average emissions greenhouse gas (GHG) intensity BETs emit 9% to 35% less GHG emissions per kilometer relative diesel trucks. Charging during times when solar production is greatest would make BETs practically carbon free (more discussion below). Even at the maximum emissions intensity observed in India, BET's result in substantially lower emissions per kilometer relative to diesel. The implications of BETs on air quality in urban areas and along congested highways are also unambiguously positive although they shift some of the burden to the power generation phase. India's renewable energy targets, which are amongst the most ambitious in the world suggest that the grid emissions are set to decline steadily in India, which would only further increase lifecycle GHG and air quality benefits. Spatially and temporally detailed environmental implications of BETs including those from battery production and disposal are topics for future work.

Table E1: Comparison of lifecycle greenhouse gas emissions intensity per kilometer for Diesel and BET for each of the four classes of trucks.

Emissions* intensity	Diesel	gCO ₂ e/Litre	3579			
(Lifecycle GHG)	Electric	gCO ₂ e/kWh	701			
		Units	7.5MT	12MT	25MT	40MT
Fuel Economy	Diesel	km/Litre	8	5.5	3.45	2.2
	BET	km/kWh	2.50	1.69	0.88	0.49
Emissions	Diesel	gCO ₂ e/km	446.9	650.0	1036.3	1625.1
	BET	gCO ₂ e/km	288.3	427.3	820.2	1485.1
GHG reduction BET			35%	34%	21%	9%

* Life cycle GHG emissions intensity of diesel is based on the reported values used in California Low Carbon Fuel Standard of 100.24-gram CO₂eq per megajoule (MJ) and energy density of 35.7 MJ per litre. The life cycle GHG emissions intensity for electric trucks is taken as the annual average GHG emissions intensity of electricity generation for 2023-24 from Abhyankar, et. al. (2021).

Several manufacturers have announced ambitious targets for zero-emission trucks, including Daimler (up to 60% sales by 2030)³, Scania (50% sales by 2030)⁴ and Volvo (>35% sales by 2030)⁵. It is not yet unclear what are the specific plans of each of these manufacturers for the Indian market if any. India – already one of the world’s largest automobile producers and exporters – has all the necessary institutional infrastructure to begin transitioning to electric trucks and become a world leader in the next decade or so. Vehicle and automotive parts account for 4% of India’s exports, and its automotive industry has successfully managed challenges such as adapting to stringent emissions limits. India has also committed to expand its renewable electricity capacity to 500 gigawatts (GW) by 2030. This goal, combined with the diurnal profile of renewable energy generation, offers opportunities for synergies with electric truck charging needs and vehicle-to-grid (V2G) integration. If these opportunities are realized, BETs could both reduce renewable integration costs and enhance grid reliability.

Figure E4 depicts the contrasting trend we can expect for fuel cost, in real terms, for a diesel truck and 12-ton electric truck with 300 km range. Diesel truck fuel cost is projected to increase beyond 2022, while electric trucks show a declining fuel cost trend beyond 2022. This analysis assumes large fleets could take advantage of nominally fixed price 25-year solar power purchase agreements (implying declining real cost of charging over time due to inflation) either at their own charging facilities or indirectly through third-party charging service providers for on-route

³ <https://www.reuters.com/business/autos-transportation/daimler-truck-all-in-green-energy-shift-targets-costs-2021-05-20/>

⁴ <https://www.scania.com/group/en/home/newsroom/news/2021/Scania's-commitment-to-battery-electric-vehicles.html>

⁵ <https://www.volvogroup.com/en/sustainability/climate-goals-strategy/reducing-carbon-emissions.html>

charging on highways for long-haul trips and would reschedule their operations so as to charge during solar generation hours.

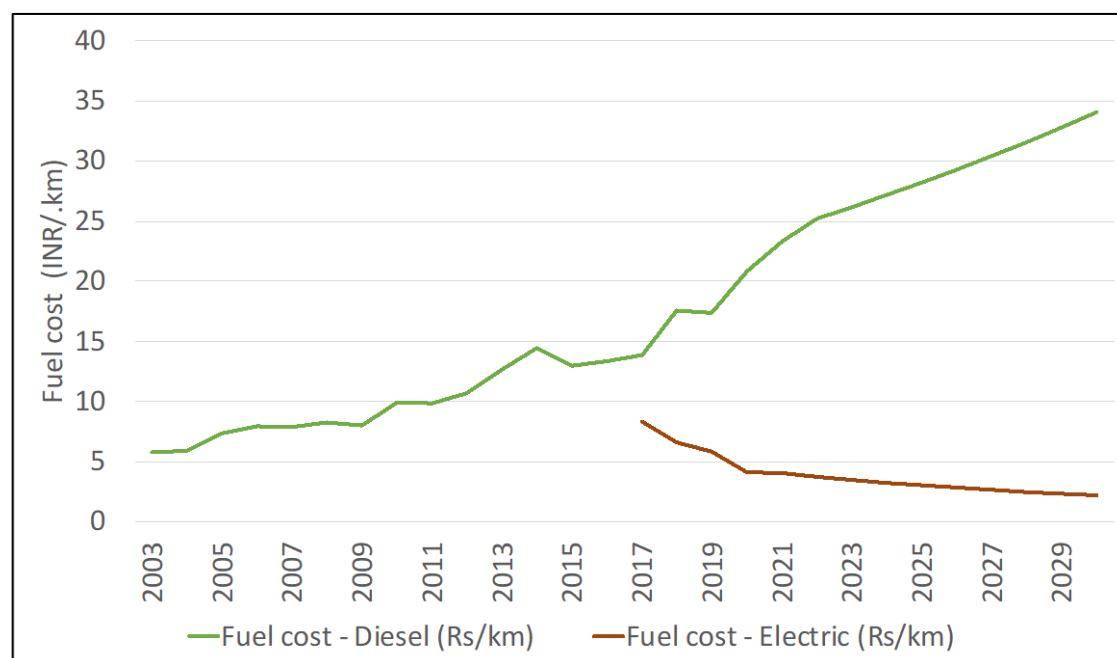


Figure E4: Comparison of fuel cost, in real terms, between a diesel truck and a 25-ton electric truck with 300 km range.

Following the trend in actual retail diesel prices from 2003 to 2022, the cost of diesel is projected to increase beyond 2022. Electric truck charging cost shows a declining trend beyond 2022, assuming trucks charge using nominally fixed price 25-year solar power purchase agreements (implying a declining real cost of electricity when adjusted for inflation).

India already has successful policies that can be leveraged to accelerate adoption of BETs. Its Production Linked Incentive (PLI)⁶ scheme, which provides subsidies for products manufactured domestically, can spur investments in domestic manufacturing of cars and battery cells. This would also generate new employment opportunities and reduce reliance on imports of electric vehicle components. India also has policies at both the national and subnational levels to foster EV adoption, including Faster Adoption and Manufacturing of Electric Vehicles (FAME), which provides funding for purchase incentives for electric vehicles. Electric vehicles are also given preferential tax treatment: they are subject to a 5% Goods and Services Tax (GST), while conventional vehicles are subject to 28%. Further, special electricity tariffs for EV charging are available. With these policies, India has taken significant steps towards electrifying its light

⁶ <https://www.india.gov.in/production-linked-incentive-pli-scheme?page=1>

vehicle segments, including 2- and 3-wheelers, cars and public transport buses. India is therefore primed to embark on truck electrification as its next logical step.

BETs do bring additional challenges, however. Freight vehicles experience harsher environmental exposure and must be both more durable and longer lasting than light-duty vehicles. Vehicle duty cycles also pose tight limits on the weight and volume of battery packs, and the ultra-fast charging (250kW or greater) capacity required for on-route charging during long-haul trips (as opposed to short-haul with charging at dedicated end-points for which lower charging speeds could suffice), will increase thermal stress on battery cells. Due to the large quantities of energy that are required by heavy trucks, battery packs can range up to 1000 kWh, and so power dispensed by chargers has to be commensurate with this need to avoid excessive dwell times at chargers. The highest power chargers available today dispense 350 kW. However, as heavier vehicle segments electrify, this may have to increase.⁷ All of this means BETs will need to undergo significant experimentation – across design, manufacturing, and deployment – with battery chemistries, pack designs, driving cycles, and charging regimes, plus different combinations of each. Since such experimentation and learning generates positive externalities that benefit society at large and are not entirely appropriable by private investors, public support is required to subsidize the associated private costs.

Ambitious targets backed by strong supportive policies, both fiscal and non-fiscal, will be required to attract private investment on a scale required to help BETs reach commercial viability. While the aforementioned PLI scheme represents one major initiative to stimulate investment, additional policies will be needed to attract complementary investments, particularly in vehicle manufacturing and the creation of a robust public charging infrastructure that meets the requirements of commercial trucking, which may require hundreds of kilowatts to be dispensed by chargers. Mandates on truck OEMs to meet a certain share of annual sales through zero-emission vehicles (ZEV) has helped drive adoption of alternative fuel vehicles worldwide, while an analogous policy has catalyzed global renewable electricity growth. A complementary mandate on large fleet owners to procure ZEVs would provide important certainty for OEMs without discriminating against other technologies (e.g., hydrogen fuel cell electric vehicles).

The time is ripe for India to pursue truck electrification with urgency and clarity of purpose. By leveraging proven policies and capitalizing on its inherent advantages, India can create a thriving domestic electric vehicle industry over the next decade or so and become a global leader in producing clean, efficient, high-quality vehicles.

⁷ <https://betterenergy.org/blog/charging-medium-and-heavy-duty-electric-vehicles-plugging-into-the-future-part-ii/>

1. Introduction

Globally, the transportation sector was responsible for 24% of direct CO₂ emissions from fuel combustion in 2019 (IEA, 2020). Heavy-duty vehicles (HDVs), comprising heavy-duty trucks and buses, account for only about 10% of the global vehicle stock but produce 46% of greenhouse gas (GHG) emissions from road transport (IEA, 2020). HDVs are also significant sources of criteria air contaminants – such as Particulate Matter (both PM₁₀ and PM_{2.5}), Nitrogen Oxides (Nox), Sulphur Oxides (Sox), Carbon Monoxide (CO), and Volatile Organic Compounds (VOC) – which adversely affect air quality and human health (Talebian et al., 2018). Globally, vehicle tailpipe emissions were responsible for an estimated 361,000 premature deaths in 2010 and 385,000 premature deaths in 2015 (Annenberg, et al., 2019). In India, air pollution from transportation is estimated to have caused 74,000 premature deaths in 2015; two-thirds of this figure attributable to diesel consumption, which is dominated by trucks (Annenberg, et al., 2019). Though trucks comprise only 5% of the vehicle fleet, they produce 71% of the CO₂ emissions, 74% of the PM emissions, and 55% of the NO_x emissions from road vehicles in India (Apte, et al., 2017; Guttikonda and Mohan 2014; Kodjak 2015).

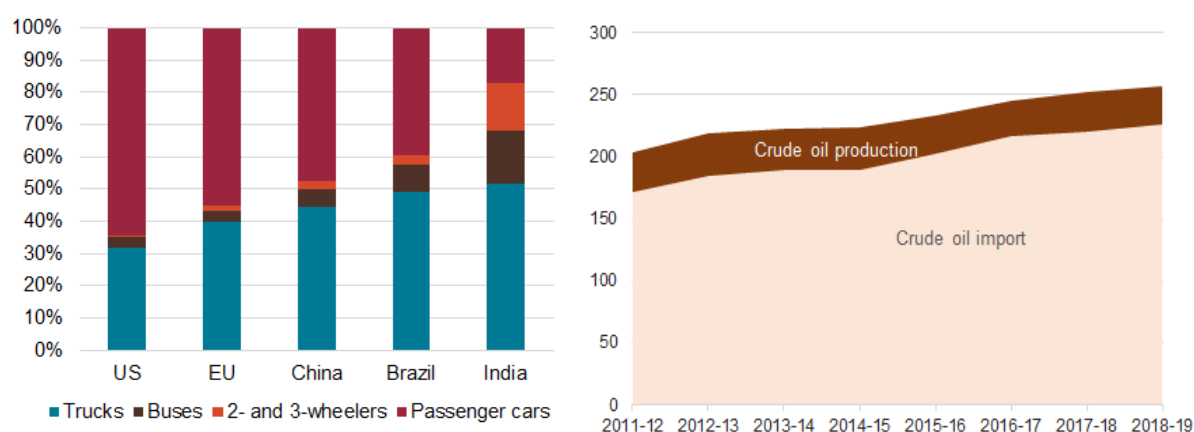


Figure 1: a) Share of fuel consumption for road transportation across select countries and regions; b) Time trend of share of imports in domestic crude oil consumption for India.

India's transportation-sector energy use has grown about 7% annually since 2000, with petroleum use for on-road transportation accounting for vast majority of this growth. As of 2019, 64% of freight transport occurred over roads (Statista 2022); given highway infrastructure improvements, it is likely this figure is higher today and will increase. Figure 1a (above) shows that India's share of trucks in national fuel consumption (~52%) exceeds all other major economies shown (ICCT, 2017). Additionally, Figure 1b shows that about 87% of India's crude oil consumption is met through imports (~249.2 MMT in 2018-19). Reducing fuel use for trucking therefore has substantial beneficial implications for balance of trade, energy and economic security, and public health and the environment.

In a business-as-usual scenario, road freight is projected to double between 2015 and 2050 globally (Moultak et al. 2017). A fast-growing economy like India's can be expected to register higher-than-average global growth. Currently, trucking and road freight transportation is the single largest oil-consuming sector in India. According to one report, India's freight transport sector is projected to consume a cumulative 5.8 billion tonnes of oil equivalent between 2020 and 2050 (NITI Aayog and RMI, 2021).

Reducing both diesel use and freight emissions while accommodating greater total freight movement (measured in tonne-kilometers) could be achieved through three broad means, which we mention here before presenting a more detailed literature overview in the next section. One obvious strategy is increasing the average fuel economy of conventional diesel trucks. A second approach is through more efficient logistics and planning to optimize freight movement, including policies to increase the modal share of freight movement by rail and marine transport. The third strategy is fuel switching from diesel to alternative powertrains such as hybrid, battery, or fuel cell electric vehicles, or catenary in the case of rail transport. These three strategies are all complementary to each other. While other reports have assessed all three strategies holistically, this report focuses on the third strategy: fuel switching trucks from diesel to electricity.

Globally, fuel economy standards have become common for light-duty vehicles over several decades; similar standards for heavy-duty vehicles have been adopted only since the mid-2000s. Since 2006, some form of fuel efficiency or GHG standards for heavy-duty commercial vehicles have been put in place in Japan, the U.S., Canada, China, EU, India, and the U.S. state of California (which has more stringent regulations than the U.S. federal government), with Brazil, Mexico, Chile, and South Korea expected to follow soon.

In India, regulations for the fuel efficiency of heavy trucks have been developed, though enforcement has been delayed several times. This regulation is a performance standard stipulating maximum fuel consumption (in liters per hundred kilometers); each vehicle must meet the standard for its category to be approved for sale in India. This differs from regulation in the U.S. and Canada, where Corporate Average Fuel Economy (CAFE) standards require sales-weighted averages of all vehicles sold by each manufacturer to meet efficiency standards, allowing some vehicles to be below the requirements (ICCT 2017).

Given the projected rate of growth in vehicles and freight movement, aggregate emissions can be expected to rise sharply even under the most optimistic future scenarios of improved fuel economy in the heavy-duty fleet. A modeling exercise found that in the most optimistic scenarios for fuel efficiency, diesel consumption rises to 68.8 million tonnes of oil equivalent (MTOE) from 27.5 MTOE in 2020, and rises to 116.8 MTOE in a business-as-usual scenario (Karali, et al., 2017). As such, fuel efficiency standards are necessary but not sufficient for achieving

absolute reductions in fuel consumption and associated emissions. For that reason, the second and third strategies, improving logistical efficiency and fuel switching, will be necessary.

This report focuses on the techno-economic feasibility of battery electric trucks (BET) in India. The objective is not to advocate for every truck to be electric, but to illustrate the potential of BETs to reduce both shipping costs and emissions relative to diesel trucks. Recent cost and performance improvements in battery technology have made electrifying heavy- and medium-duty trucks substantially more feasible from a techno-economic perspective. The rapid growth in the share of EVs in the light-duty sector worldwide is proof that the battery industry has matured even as it develops new battery chemistries. The nascent and promising market for medium- and heavy-duty electric vehicles is primed for public support – and will require it if it is to become commercially viable. This report, unlike other recent research, aims to broadly assess the techno-economics of freight truck electrification in India across four segments of heavy-duty vehicles – 7.5MT, 12MT, 25MT and 40 MT. It seeks to inform policymakers, fleet owners, truck manufacturers, charging service providers, investors, and energy system planners of the many ways in which BETs can achieve public policy goals in India, and what actions must be taken for those benefits to be realized.

Under the Global Drive to Zero⁸ umbrella (Figure 2), more than a dozen sovereign states have promised to mandate 100% sales of zero-emissions trucks and buses by 2040, and 30% sales by 2030, to enable a complete fleet of zero-emissions trucks and buses by 2050.

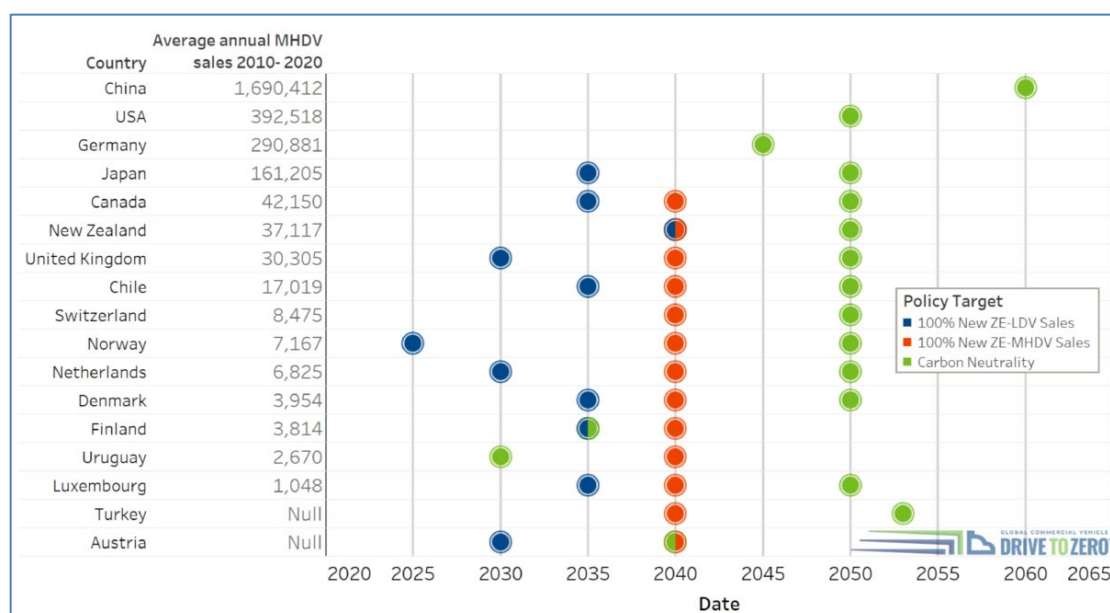


Figure 2: International targets for vehicle electrification (Source: CALSTART).

⁸ <https://globaldrivetozero.org/mou-nations/>

One of the world's most ambitious transportation sector policies is the State of California's Advanced Clean Trucks (ACT) rule, promulgated by the California Air Resources Board (CARB), requiring all truck manufacturers to sell an increasing share of zero-emissions trucks over time; by 2035, 40% of tractor trucks, 55% of pickup trucks and vans, and 75% of rigid truck sales must be zero-emissions trucks (Buysse and Sharpe). Furthermore, CARB is developing a complementary mandate, the Advanced Clean Fleets (ACF) rule, for truck fleets operating in California; under it, fleet operators must purchase increasing shares of zero-emissions trucks, with the goal of achieving a zero-emission truck and bus fleet statewide by 2045 (CARB). Beyond California, several U.S. states, including Oregon, Washington, New York, New Jersey, and Massachusetts, have adopted California's ACT regulation, while Connecticut, Maryland, and Maine are developing rules to implement ACT requirements. Several additional American states have signed a Memorandum of Understanding to achieve 30% sales of zero-emissions medium and heavy-duty vehicles by 2030 and 100% by 2050.⁹

India has committed to achieving net zero GHG emissions by 2070, which will require all but eliminating oil consumption and transitioning all modes of mobility, along with literally everything else, to zero-emissions technology. In 2021, India raised targets for specific sectors of the vehicle market to accelerate transportation decarbonization and reduce oil imports. Specifically, 70% of commercial vehicle sales, and 80% of two- and three-wheeler vehicle sales, must be electric by 2030, along with 40% of bus sales and 30% of private car sales (PTI 2021). Furthermore, at the subnational level, 25 states of India have declared their intention to develop vehicle electrification policies, of which 15 have already announced such policies.

2. Literature Review

Until the past few years, studies on the topic mostly concluded that battery electric trucks (BETs) were not yet able to replace conventional diesel trucks, especially in the heavy-duty long-distance category. This was not only due to high cost of batteries but also on performance due to the low energy density, and consequent excess weight of batteries that cut into payload capacity, and also the high share of coal in electricity. For such reasons, the literature which focused on reducing emissions from trucks focused on increasing efficiency standards, or fuel switching to either natural gas or hydrogen. (Lajevardi, et al., 2018, Kast, et al., 2017, Malik 2019).

⁹ <https://www.electrictrucksnow.com/states>

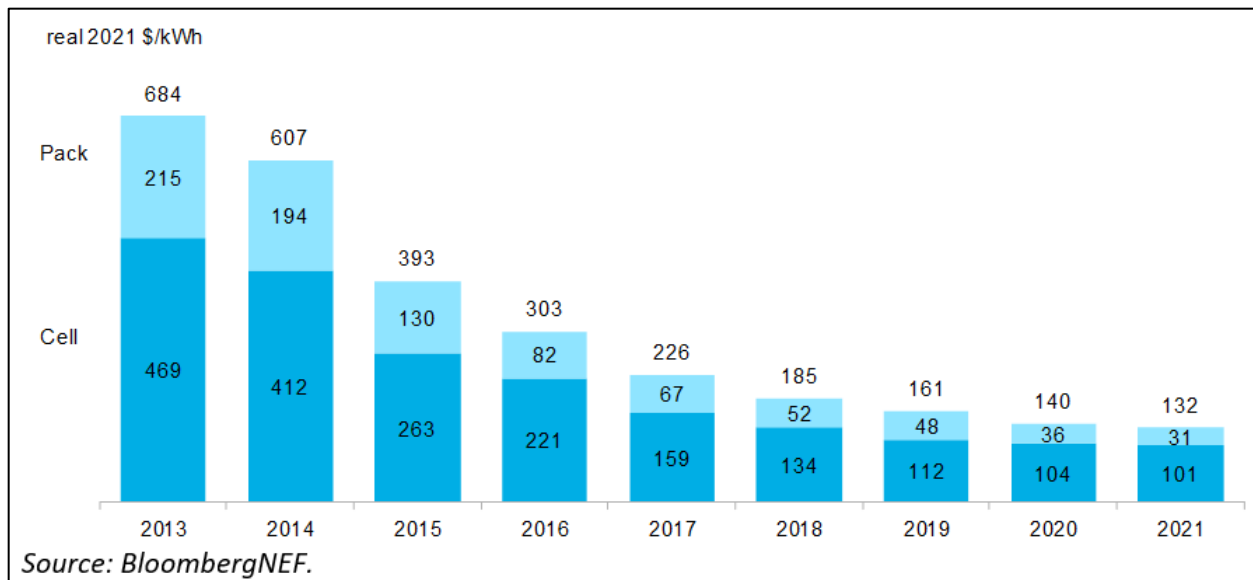


Figure 3: Trend in international battery prices (Source: BloombergNEF).

However, in recent years, energy densities of batteries have increased significantly and the prices have decreased about 80% compared with a decade ago (Bloomberg NEF, CARB 2019). Battery prices are expected to continue decreasing due to economies of scale, more efficient production processes and greater competition (CARB, 2019, and Tanco, et al., 2019). Therefore, there is a growing literature on pathways to decarbonizing road freight through electrification and there is a growing number of studies suggesting the challenges to BET for long-haul heavy-duty trucking are surmountable (CARB 2019, Tanco, et al., 2019, Mareev, et al., 2018, and Moultak, et al., 2017).

Furthermore, coal's share of electricity generation is declining steadily in India and many other countries. Though coal currently accounts for the bulk of India's electric generation, by the 2040s solar energy is projected to outproduce coal. This turnaround is due to policies such as India's target for 500 GW of renewable capacity by 2030, and the extraordinary cost competitiveness of solar energy, which is expected to outcompete even existing coal power plants, even paired with battery storage, by 2030 (IEA 2021). For this reason, concerns about electrification leading to higher power plant emissions are likely to be unfounded over the long run.

As can be seen from Table 1, most studies comparing the TCO of electric and diesel trucks found that total cost of ownership is lower for electric trucks than for diesel-powered counterparts, while some have shown the opposite. The conclusions depend on the specific scenario referenced. For example, Hunter et al, working at NREL, found that trucks with ranges of 300 mi (483 km) or less had a lower TCO than their diesel counterparts, but the cost of a long-range battery increased the TCO for the trucks with 500-mile (805 km) range. Mareev, et al., found that in most scenarios BETs have a higher TCO than diesel counterparts, but they can have a lower TCO if aerodynamic and rolling drag can be minimized and if long-life batteries are used

(despite a higher upfront battery cost). The numbers in the table from the Mareev paper show their scenarios with “average route” and “average losses”, which show a higher TCO for BETs. In calculating numbers for Table 1, the general operation costs (which include labor and other costs which are equivalent for diesel and electric trucks) have been removed to give a consistent comparison.

Table 1: Summary of selected studies of electric truck TCO.

Author names	Year published	Region	Diesel TCO (\$/km)	BET TCO (\$/km)	Δ TCO	Battery price (\$/kWh)	Range (km)	Battery capacity (kWh)	GVW
Chad Hunter et al (NREL)	2021	USA	0.28	0.25	-9%	100	483	682	Class 8 (~36t)
Chad Hunter et al (NREL)	2021	USA	0.45	0.25	-44%	100	193	155	Class 4 (~7t)
Chad Hunter et al (NREL)	2021	USA	0.36	0.55	52%	100	805	1173	Class 8 (~36t)
Andrew Burnham (ANL)	2021	USA	0.66	1.15	74%	150	805		Class 8 (~36t)
Sripad and Viswanathan (CMU)	2018	USA	0.37	0.12	-67%	150	805	1000	Class 8 (~36t)
Earl et al	2018	Europe	0.99	0.90	-9%	77	800	1000	40t
Mareev, Becker, Sauer	2018	Germany	0.80	0.87	8%	330	723	825	40t
Phadke et al. (LBL)	2021	USA	0.60	0.47	-23%	135	604	375	Class 8 (~36t)

Note: \$ refers to U.S. Dollars (USD). Estimates reported in Euro currency was converted USD using a conversion rate of 1 Euro = 1.1 USD. * -TCO refers to ‘Total Cost of Ownership’ and do not include any charging infrastructure related costs. ** - GVW refers to ‘Gross Vehicle Weight’, including cargo.

Some studies on the movement of freight have found that electrification of freight trucks used for certain urban and regional applications can be done with existing technology and need not wait for technological advancement. Due to the high rate of utilization and the stop-and-go nature of their duty cycles, urban delivery vehicles are prime targets for electrification. Regenerative braking enables electric delivery vehicles to recover kinetic energy that would otherwise be lost with every braking event, relatively short distances within cities eliminate range anxiety as a concern, and the centralized nature of delivery hubs enable chargers to be positioned strategically (Lund, et al., 2022). Over the course of the coming decade, BETs will reach TCO parity for many more applications and duty cycles of truck usage. In many European countries, BETs have already reached TCO parity for delivery vehicles when purchase subsidies are included, and will reach unsubsidized TCO parity later this decade (Basma 2022). The same is likely to happen for tractor-trailers (Basma 2021).

Another common concern in the literature relates to a significant increase in curb weight as electric trucks require much larger batteries (Mareev, et al., 2018, Earl, et al., 2018, and Talebian, et al., 2019). Nykvist and Olsson found that BETs are techno-economically viable depending on the duty cycle and that with accommodations, even the heavier categories of trucks can electrify economically. These accommodations would include high-capacity charging on the order of 1 MW, and an increase in the permissible weight limit to accommodate a heavy battery. Under these conditions, heavy battery electric trucks can be competitive with diesel trucks in absolute terms both per ton-kilometer and per kilometer (Nykvist and Olsson 2021).

However, the elimination of components including the engine, transmission and differentials, the fuel system and exhaust hardware substantially offset the increase in weight due to the battery system which could be about 3 metric tonnes (Earl, et al). Furthermore, availability of fast recharging infrastructure could help reduce the battery size without sacrificing performance if average speeds and driving patterns are such that there is sufficient and periodic idle time for charging without excessive delay in total trip time (Mareev, et al.). Recent success in electrifying light commercial vehicles and urban buses will also provide a foundation for the building up of charging infrastructure and garnering the policy support necessary to extend the commercialization of electric vehicles to heavy-duty trucks and long-distance operations.

Sen et al. perform a life cycle analysis with different Class 8 (approx. 36t) trucks in the United States and conclude that battery electric trucks outperform other alternative fuels in terms of costs and emissions, despite their incremental costs and electricity generation related emissions. Mareev et al. also calculate life cycle costs of 40t semi-trailer trucks in Germany and show that battery electric trucks can perform at the same cost level as diesel trucks, even when batteries are dimensioned up to 825 kWh and recharging stations up to 880 kW charging power in order to enable 4.5 h trip durations and full recharge during 45 min mandatory rest periods of drivers. Table 1 summarizes some details from these studies. There are a few studies estimating the pollution impacts of electric trucks. Mulholland et al. (2018) estimate that electric trucks (medium-duty trucks partly battery electric and partly catenary electric, heavy-duty trucks catenary electric) will influence road freight emissions from 2035 onwards and account for one third of the emission reductions in 2050. Talebian et al. (2018) analyzed the role of electric trucks in achieving the GHG emission reduction targets in British Columbia, Canada, and conclude that, even with stringent regulations on fuel efficiency of diesel trucks, >65% of truck fleet need to be fully electric by 2040, which would require all new trucks to be electric from 2025 onwards. Cabukoglu et al. (2018) conclude that achieving higher levels of electric vehicles (up to 95%) and CO₂ reductions (up to 90%) is possible, but would require exemptions from maximum permissible weight regulations, coordinated smart charging with high capacity (>50 kW) grid connections at home bases and development of extensive battery swapping infrastructure. One other aspect to consider is the daily driving distances. For example, Mareev et al. (2017) showed that the daily distance covered by trucks in Germany is shorter than 350 km. Similarly, Cabukoglu et al. (2018) showed that in Switzerland the daily distance travelled with

rigid trucks is rarely >400 kms and with articulated trucks there is a peak in the frequency of daily distance around 300 km s. While this may be true for countries like Germany and Switzerland where freight transport consists of mostly short distances with semitrailers, the situation is very different in countries covering large geographies such as India.

While there is a growing literature on various aspects of battery electric trucks that focus on specific countries, such an assessment for the Indian context seems missing. Most of the studies on vehicle electrification in India focus on the light-duty sector and on public transport buses. For example, a recent study by the Council on Energy, Environment, and Water, which considered passenger vehicles only and did not include freight vehicles, found that if electric vehicles garner a 30% share of vehicle sales by 2030, the country's oil import bill would reduce by more than a trillion rupees each year (Soman, 2020). A study by Rocky Mountain Institute (RMI) India assessed the possibility of using electric vehicles for urban delivery in Delhi (Ghate, et al.). It found that for two-wheelers, electric vehicles already have a lower TCO than combustion vehicles, and for three-wheelers and four-wheelers, the electric vehicles are rapidly approaching cost parity on a TCO basis. This report found that complete electrification of all delivery vehicles in Delhi by 2030 is technically feasible and would confer both substantial air quality benefits to the city and fuel cost savings to vehicle operators. The city of Delhi already has a target for 25% of new vehicles registered in the city by 2024 to be electric. An earlier report by some of the authors concluded that there existed a strong case for new public transport buses to be purely battery electric (Khandekar et al).

A report by NITI Aayog and RMI found that the three key opportunities for reducing emissions from freight movement in India are increasing the mode share of rail transport (through building dedicated freight corridors and increasing intermodal transportation), optimizing truck use (through efficient loading and packaging, and improved warehousing), and promoting efficient and alternative fuel technologies (through both improving fuel economy of ICE vehicles and switching to electric mobility where viable). It finds that currently, in the heavy-duty use segments, electric vehicles have a higher TCO than their diesel counterparts, because of the high capital cost. However, declining battery costs, improved charging infrastructure, and economies of scale in manufacturing will reduce the cost of electric vehicles over time (NITI and RMI, 2022).

A recent comprehensive study of truck electrification in India found that many categories of truck use, including last-mile delivery and urban trash trucks, can be electrified using current technology. If adequate investments in charging equipment are made, then the techno-economic feasibility of electrification expands to include almost all use segments over the coming decade (Global Drive To Zero 2022).

3. Methodology and Main Assumptions

The present work builds on earlier work by several of the authors analyzing the economic and environmental impacts of electrification of regional and long-haul trucks in the U.S. using a related approach (See Phadke, et al. 2021). Figure 4 shows the modeling workflow used in this analysis.

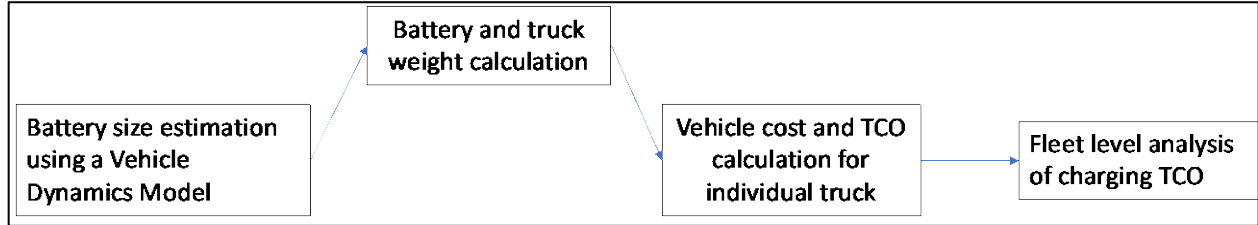


Figure 4. Schematic of the process followed in estimating TCO.

The Indian truck market spans a wide range of vehicle weight classes and vocational uses. This wide diversity in vehicle weight class and vocation makes it difficult to disaggregate the data. In this analysis, we categorize and combine the weight classes and baseline fuel economy for each class as in Table 2. Baseline diesel trucks are based on the most common technologies in the Indian HDV market. Beginning on April 1, 2020, all HDVs in India were required to achieve the BS VI emission standard. We use official reported data and statistics from government records, manufacturer reports, and other non-governmental organization (NGO) and research institution papers to establish the parameter set differentiated by weight and year of first registration. The modeling period is 2000-2050 in annual time-steps and the model of India heavy-duty trucks is calibrated against historical data between 2000 and 2018. Table 2 summarizes the input data used in this analysis. Table 3 gives other model inputs and parameters. The battery cell energy density is different from the battery pack energy density because there are other components in the battery pack, such as the protective case.

Table 2: Classification of HDVs and baseline fuel economy

Vehicle type	Class	Weight	Fuel economy (km/L)
Rigid truck	Heavy-duty truck (HDT)	$GVW \geq 12$ tonnes	8.00
	Medium-duty truck (MDT)	$7.5 \text{ tonnes} \leq GVW < 12$ tonnes	5.05
	Light-duty truck (LDT)	$GVW < 2.5$ tonnes	2.45
Tractor trailer	Heavy-duty tractor trailer (HDTT)	$GVW > 40$ tonnes	2.20

Table 3: Other model inputs and parameters

Parameter	Gross Vehicle Weight			
	7.5 t	12t	25t	40t
Total truck weight (kg)	7,490	11,950	25,000	40,000
Aerodynamic drag coefficient	0.7	0.7	0.7	0.7
Rolling resistance coefficient	0.01	0.01	0.01	0.01
Frontal area (square meters)	5.01	5.83	7.18	7.5
Final drive ratio	3.86	5.29	5.57	6.83
Power Rating (kW)	90	100	160	160
Drivetrain efficiency	0.85	0.85	0.9	0.9
Braking efficiency	0.9	0.9	0.95	0.95
Battery discharge efficiency	0.9	0.9	0.95	0.95
Battery to Wheels efficiency	0.69	0.69	0.83	0.83
Depth of discharge	80%	80%	80%	80%
Battery cell energy density (Wh/kg)	250	250	250	250
Battery pack energy density (Wh/kg)	157	164	171	169
Battery cost in 2022 (USD/kWh)	135	135	135	135
Battery cost in 2025 (USD/kWh)	100	100	100	100
Electric truck payload capacity (kg)	4657	7352	16390	23124
Diesel truck payload capacity (kg)	4775	8210	19000	27030
Life of a truck (years)	15	15	15	15
Daily vehicle km traveled (km)	150	300	400	400
Days used each year	300	300	300	300
Exchange rate (INR/USD)	70	70	70	70
Levelized cost of charging (INR/kWh)	10	10	10	10

Vehicle Dynamic Model

The battery pack size required to estimate the capital cost of our modelled electric trucks are generated independently by using a vehicle dynamic model based on standard operating conditions for each truck category (Equation 1).

The vehicle dynamic model is a parametric representation of a truck that we use to estimate the required battery pack size based on the standard performance requirements of a Class 8 diesel truck. The vehicle dynamic model is represented below in Equation 1:

$$E_p = \left[\frac{\left(\frac{1}{2} \rho * C_d * A * v_{rms}^3 + C_{rr} * W_T * g * v + t_f * W_T * g * v * Z \right)}{\eta_{bw}} + \left(\frac{1}{2} W_T * v * a \left(\frac{1}{\eta_{bw}} - \eta_{bw} * \eta_{brk} \right) \right) \right] * \frac{D}{v} \quad (1)$$

The variables in Equation 1 are: the size of the battery pack required in kWh (E_p), the coefficient of drag (C_d), average velocity (v), root-mean-square of the velocity (v_{rms}), the coefficient of rolling resistance (C_{rr}), the gross on-road vehicle weight (GVW) represented by (W_T) (includes

the payload and battery pack), the road gradient (Z) and the driving distance (D). Z represents the average road gradient determined by $(r/100)$, where r is the percent road grade. The term t_f represents the fraction of time that the truck would be driven on a road grade of $r\%$. ρ is the density of air, g is the acceleration due to gravity, A is the frontal area of the truck, a is the mean acceleration or deceleration of the truck, η_{bw} is the battery-to-wheels efficiency: the product of battery discharge efficiency and drivetrain efficiency, η_{brk} is the braking efficiency of the vehicle.

We use the Autonomie model¹⁰ to estimate some of the parameters used in Equation (1) that are specific to India using the World Harmonized Vehicle Cycle (WHVC)-India drive cycle. The WHVC is the basis for the development of the World Harmonized Transient Cycle (WHTC), which is an engine dynamometer cycle that is used as a certification test for regulated pollutants (Heinz 2001). The main purpose of the WHVC is to cover a wide range of driving situations for commercial vehicles. As such, the cycle contains distinct urban, rural, and motorway sections, which are shown in Figure 5.

The WHVC-India cycle is a chassis dynamometer test that was derived for by the International Council on Clean Transportation to account for the fact that truck speeds in India are typically much slower than in other major markets such as the U.S. and the EU (Sharpe, Garg, and Delgado, 2018). As can be seen, the WHVC-India cycle is identical to the WHVC for roughly the first 1,200 seconds of the cycles, and then afterward the speeds of the WHVC are multiplied by 0.7 to produce the speeds for the WHVC-India. During the highway portion at the end of the cycle, the maximum speed of the WHVC-India is approximately 60 km/hr, as compared to roughly 87 km/hr in the WHVC. This maximum cruising speed of 60 km/hr is reasonably representative of commercial vehicle speeds in India. While the maximum speeds have been set to approximately 60 km/hr in the WHVC-India, the acceleration and deceleration rates in the cycle are roughly identical to the WHVC. The details of the Indian Autonomie model can be found in Karali et al. (2017).

¹⁰ Autonomie is a vehicle performance evaluation software platform that was developed by the U.S. Department of Energy's Argonne National Laboratory

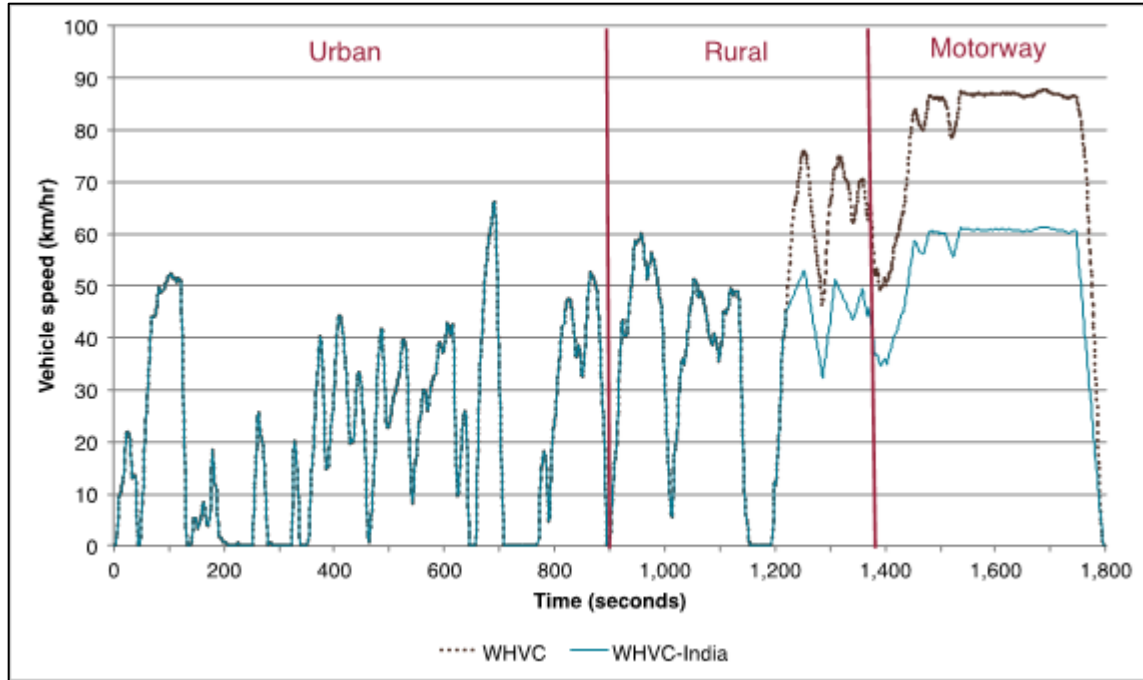


Figure 5: Vehicle speed-time trace for the WHVC and WHVC-India cycle.

Total Cost of Ownership

TCO is estimated by summing the capital, maintenance, fuel, and operation costs (Equation 2). To annualize the component costs on a per-kilometer basis, we simply use the costs from Equation 2 and amortize it over the annual km traveled (Equation 3).

$$\text{TCO} = \text{capital cost} + \text{fuel cost} + \text{maintenance cost} + \text{operations cost} \quad (2)$$

$$\text{TCO per km} = \frac{(\text{capital cost} + \text{fuel cost} + \text{maintenance cost} + \text{operations cost})}{\text{lifetime VKT}} \quad (3)$$

For each truck category, the capital cost of an electric truck is the sum of the capital cost of a diesel truck, the capital cost of the battery and the incremental powertrain cost (the cost difference between the diesel and electric powertrains) (Equation 4).

$$\text{Capital cost (electric truck)} = \text{capital cost (diesel truck)} + \text{battery cost} + \text{incremental powertrain cost} \quad (4)$$

The fuel costs for electric trucks represent the cost of electricity plus the levelized cost of building the charging infrastructure, which combined is assumed to be INR 10 per kilowatt-hour. This is based on an electricity price of Rs 7 per kWh and a levelized infrastructure cost of Rs 3 per kWh. The fuel costs for diesel trucks are estimated based on published manufacturer

estimates. The maintenance costs for electric trucks are assumed to be half of the maintenance costs of diesel trucks which are based on expert input.

At scale, the difference in the cost of diesel and electric trucks for any category should reflect the incremental cost of the battery electric drivetrain, savings from diesel drivetrain cost, savings in fuel and maintenance costs. Therefore, a bottom-up cost estimate allows us to develop an estimate of how the market will price these trucks in the future.

Class 8 Truck Battery Pack Weight Estimation

The weight of the battery packs depends on four components: 1) cells, which store energy; 2) busbars, which act as the transmission system for the battery pack; 3) cooling tubes, which maintain optimal ambient temperature within the pack; and 4) an outer case for protecting the pack against physical damage. The basis for our battery pack weight estimation is the 100 kWh battery pack used in the Tesla Model 3 whose component weights are shown Table 4 below.

Table 4: Weight estimates of Tesla Model 3 battery pack components.

Component/Variable	Value	Units
Battery pack size	100	kWh
Tesla Model 3 battery pack weight	619	kg
Tesla Model 3 battery pack dimensions	91 x 59 x 4.5	in
Specific energy of each cell	250	Wh/kg
Total number of battery modules	16	
Individual battery module weight	26.1	kg
Energy stored per module	5.2	kWh

The difference between the total module weight (418 kg) and the total cell weight (400 kg) gives the total weight of the busbars and cooling tubes (18 kg). The difference between the total pack weight (619 kg) and the total module weight (418 kg) gives the weight of the protective case (201 kg). Assuming 50% of the busbar and cooling tube weight is from busbars and 50% is from cooling tubes, we calculate the per-unit weights of individual battery pack components (Table 5).

Table 5: Per-unit weight of individual battery pack components.

Cooling tubes	0.09	kg/kWh
Busbars	0.09	kg/kWh
Battery cell	4	kg/kWh

To estimate the battery pack weights for all four truck categories, we make the following assumptions:

- Weight of battery cells is scaled by battery pack capacity
- Weight of cooling tubes is scaled by battery pack capacity with a 5% weight reduction from design changes
- Weight of busbars is scaled by battery pack capacity and then reduced by 50% to account for higher voltage
- Weight of the protective case is scaled with the ratio of battery pack surface area of the truck battery pack to Tesla Model 3 battery pack

To complete the potential of maximizing payload capacity in electric trucks to compensate for the weight of the battery pack, we estimated the potential impact of lightweighting on total truck weight. Truck lightweighting is a set of strategies that could improve the fuel efficiency of trucks by 1) reducing the rolling resistance, 2) increasing payload capacity due to reduced curb weight, and 3) allowing the adoption of other fuel efficiency technologies that may add weight to the truck.

The main lightweighting strategy that is suitable and currently available for the trucks covered in this study is to substitute existing material with a lighter one. For a given truck, some possibilities include converting the cab sheet metal from steel to aluminum or lightweight steel, or converting aerodynamic roof hoods from aluminum to plastic. Another well-developed strategy for lightweighting is to reduce the physical joining of parts through fasteners by combining the different components during manufacturing. While lightweighting may not improve individual truck efficiency dramatically, it has driven a significant improvement in operational efficiency of fleets wherein larger payload capacity per truck has led to smaller fleet sizes for delivering the same quantity of payload, according to the North American Council for Freight Efficiency (Lee et al).

Route-level Charging Infrastructure Needs

To better analyze the operational challenges of operating an electric truck fleet, we simulated a 24-hour schedule with a fleet of 44 trucks (25-ton with 580 kWh battery pack) to estimate their charging needs and their cost implications. To do so in addition to the earlier assumptions, we assumed:

- Availability of 1C opportunity charging at 25 km from each endpoint
- 30-minute charging is done at the available charging stop
- The first truck departs from its origin at 5 am and has an average speed of 48 km/hour
- A single truck departs each end-node at 30-minute intervals
- Each truck will return to a rest-stop nearest to its destination after completing its pickup/drop of goods and will not depart until it is fully charged
- A single truck can undertake multiple trips during a 24- hour period
- Personnel management is not considered for this simulation

To estimate the cost implications of building a charging station network to support an electric truck fleet, we built a cost estimate for a truck charger by assuming that the balance of system costs is similar to a utility-scale solar power plant. The cost inputs that went into this estimate are shown in Table 6 below. Fleet-level electrification could require distribution system upgrades which are not considered here. The calculations assume the installation of chargers with 320 kW capacity.

Table 6: Breakdown of charging infrastructure capital cost in India.

Charging System Component	Capital Cost \$/kW
Grid Connection (including Transformer)	74
Cabling / Wiring	81
Converter	46
Electrical installation	38
Safety and security	66
Inspection	9
Monitoring and Control	3
Total capital cost (\$/kW)	316

4. Results

Table 7 below summarizes the estimated battery pack size, pack weight and energy demand at the wheels for each truck category.

Table 7: Estimated battery pack size, pack weight and energy demand at the wheels for each truck category.

	7.5-Ton	12-Ton	25-Ton	40-Ton
Required Pack Size (kWh)	81	222	569	769
Battery Pack Weight (kg)	516	1360	3,326	4,459
Energy Demand at Wheels (kWh/km)	0.43	0.59	1.14	1.54

It is assumed that only 80% of the battery pack capacity is used during normal operation, thereby ensuring that 20% of the battery capacity is available for emergencies. Complete discharge of a lithium-ion battery causes degradation of the cell, so it is optimal to maintain a reserve.

The vehicle dynamic model outputs were used to develop bottom-up capital cost estimates for the four electric truck categories. Battery costs from two scenarios, one for 2022 (\$135/kWh) and another for 2025 (\$100/kWh) were used to develop capital cost estimates. The resulting capital cost of a 12-ton electric truck is 116% higher than an equivalent diesel truck while a 25-ton electric truck is 157% more expensive than the comparable diesel truck, if battery costs remain at \$135/kWh. Figures 6 - 9 show the results for the four truck categories.

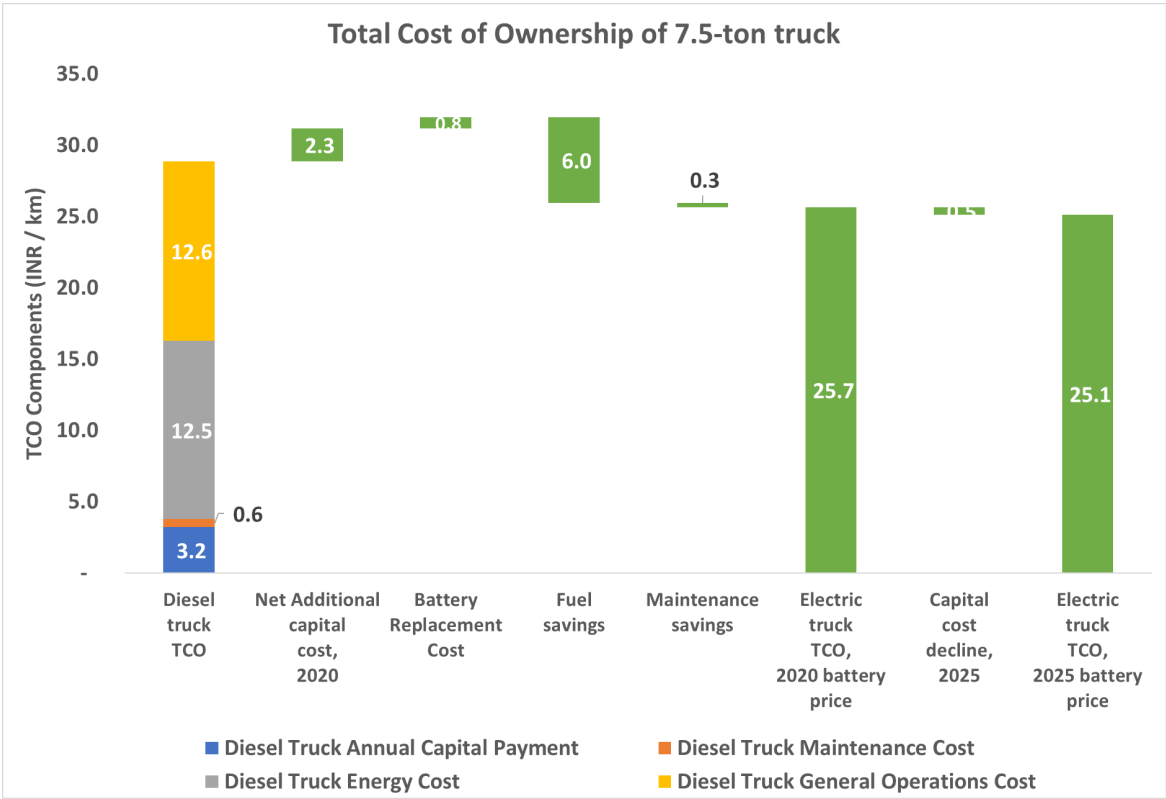


Figure 6: Total cost of ownership for a 7.5-ton truck

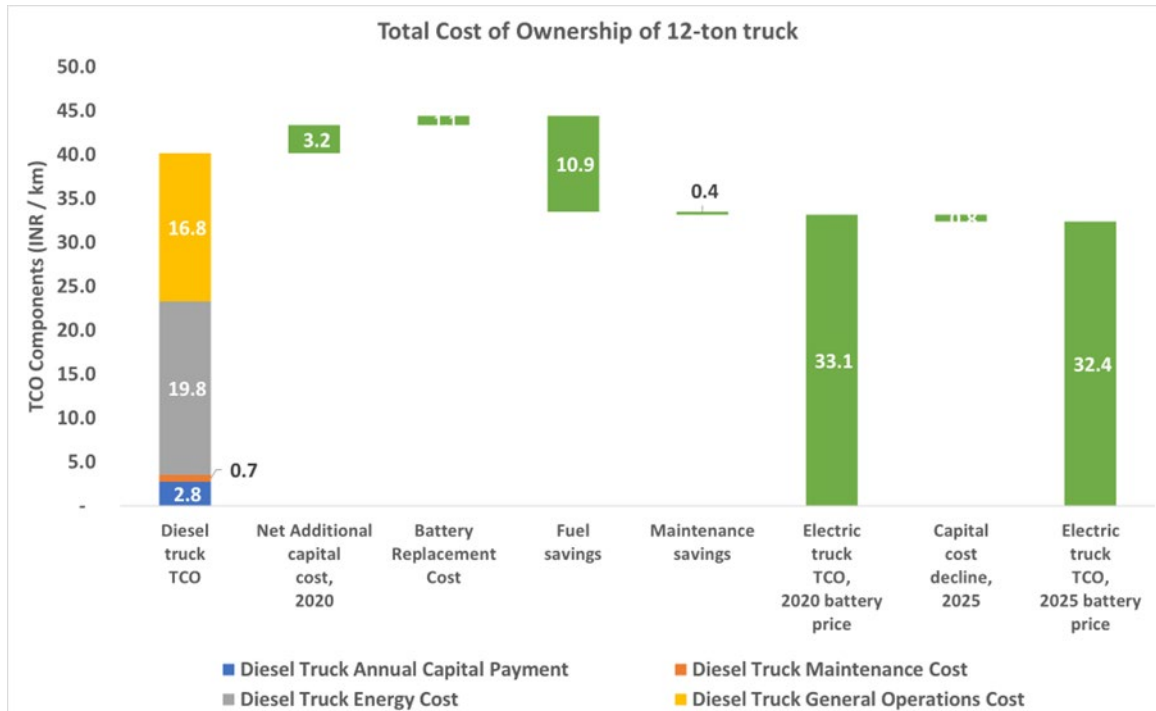


Figure 7: Total cost of ownership for a 12-ton truck

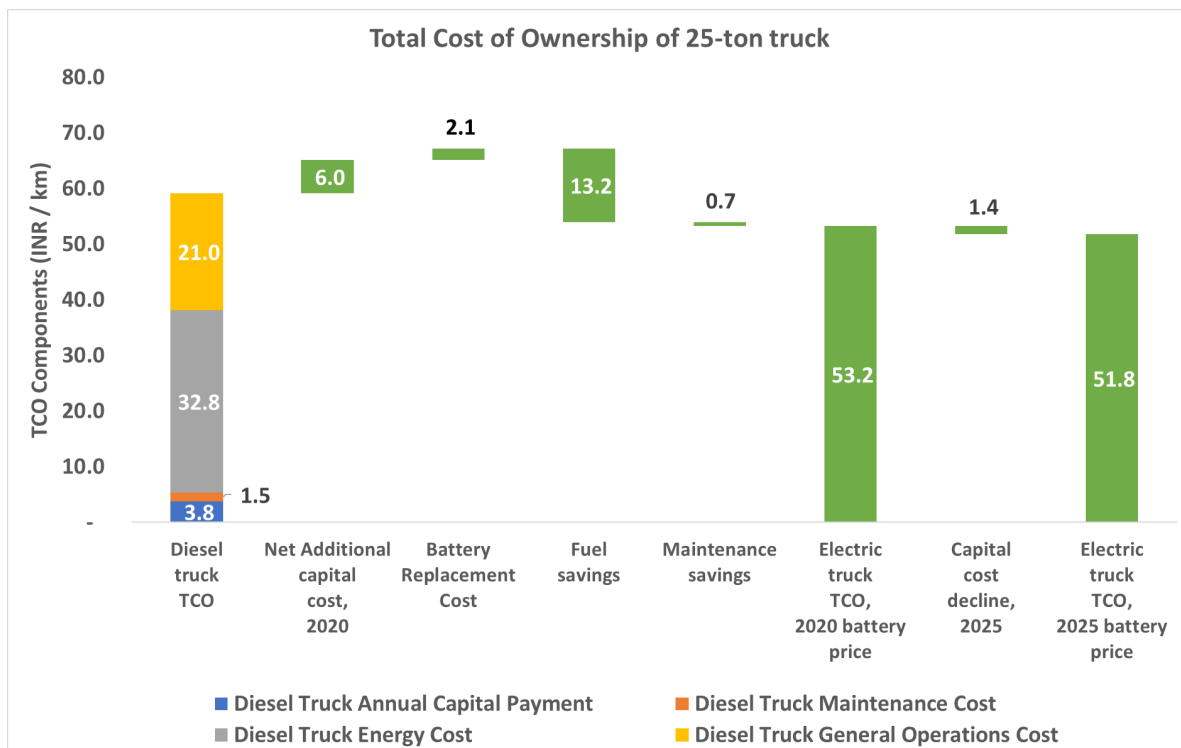


Figure 8: Total cost of ownership for a 25-ton truck

Our calculations for TCO include capital cost, fuel and maintenance cost, battery replacement every 2000 cycles and general operation cost which includes driver cost, insurance cost, permits and tolls.

Figures 7 and 8 show our estimates for 12-ton and 25-ton trucks. We estimate that the TCO for a 12-ton electric truck is 33.1 INR/km, 17% lower than a comparable diesel truck TCO of 40.1INR/km, assuming battery prices at \$135/km. As Figure 7 shows, if battery costs are assumed to be \$100/kWh, the estimated TCO is 32.4 INR/km, 19% lower than the diesel truck.

Similarly, for a 25-ton truck, with battery price at \$135/kWh, we estimate that the TCO for an electric truck is 53.2 INR/km, 10% lower than the diesel truck TCO of 59.1 INR/km (Figure 8). If battery costs are \$100/kWh, the difference in TCO of the diesel and electric truck becomes 12%.

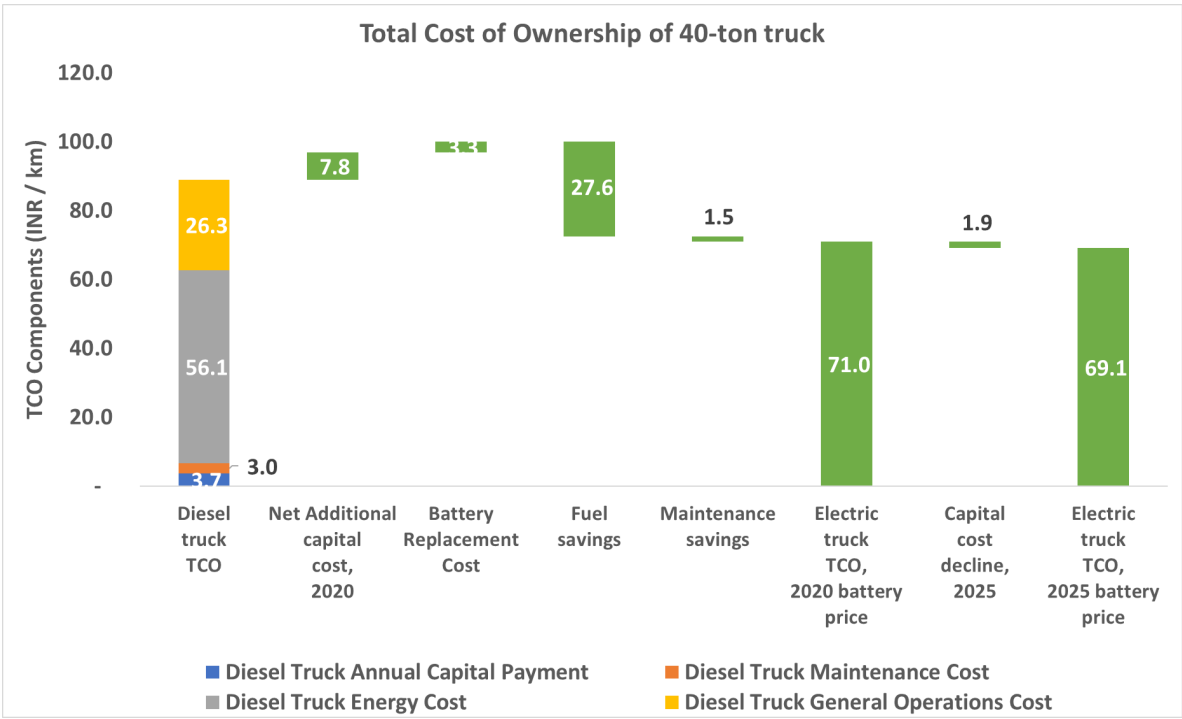


Figure 9: Total cost of ownership for a 40-ton truck

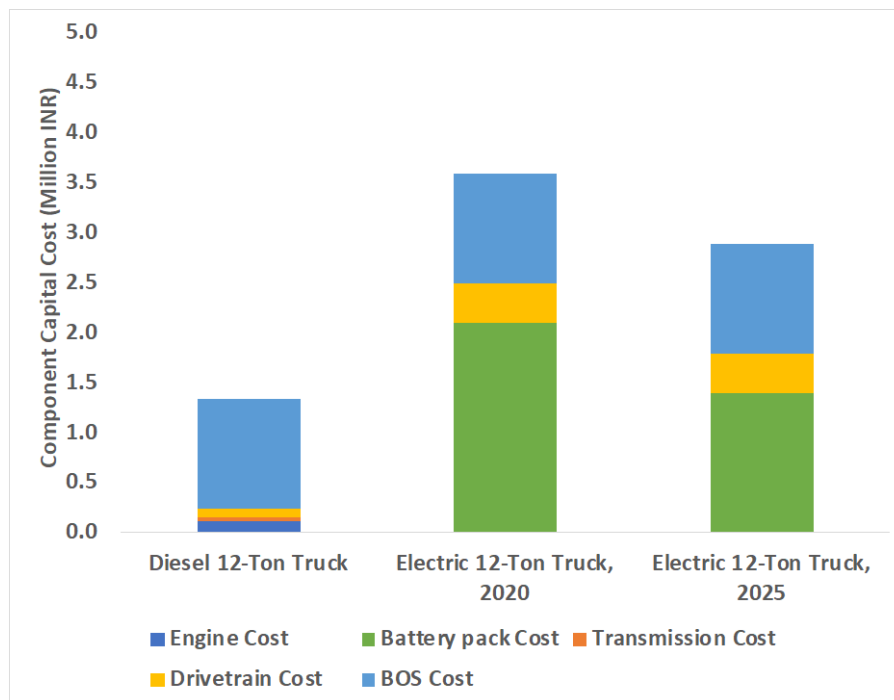


Figure 10(a): Capital cost of 12-ton truck and 200-km range with battery costs of \$135/kWh in 2020 and \$100/kWh by 2025. Drivetrain cost for an electric truck includes electric motor cost, gearbox cost and inverter cost.

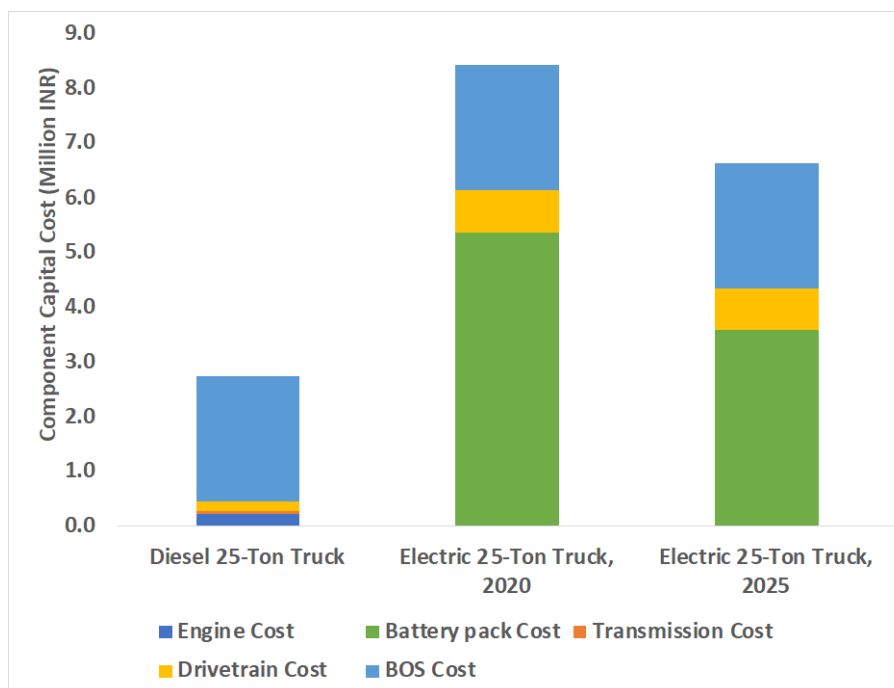


Figure 10(b): Capital cost of 25-ton truck and 300-km range with battery costs of \$135/kWh in 2020 and \$100/kWh by 2025. Drivetrain cost for an electric truck includes electric motor cost, gearbox cost and inverter cost.

For both a 12-ton and 25-ton truck, if the capital cost if battery price is assumed to be 100 \$/kWh, the electric truck is 128% and 156% more expensive than a comparable diesel truck respectively.

Across all four truck classes, a capital cost comparison between diesel and electric trucks shows that while electric trucks are more expensive (by 67% to 214%), their per-km TCO cost is lower (by 11% to 28%). In addition, their payback period is between 2.3 years and 4.1 years, well below the expected 15-year life of the respective electric truck categories. Table 8 summarizes these numbers by truck category. Each value signifies the difference between the parameter for an electric truck and corresponding parameter for a diesel truck.

Table 8: Summary of differences in capital cost, TCO and payback for all four truck classes.

	7.5-ton	12-ton	25-ton	40-ton
Difference in capital cost (%)	67%	169%	206%	214%
Difference in TCO (%)	11%	18%	28%	21%
Payback Period (years)	4.1	3.1	2.3	3.0

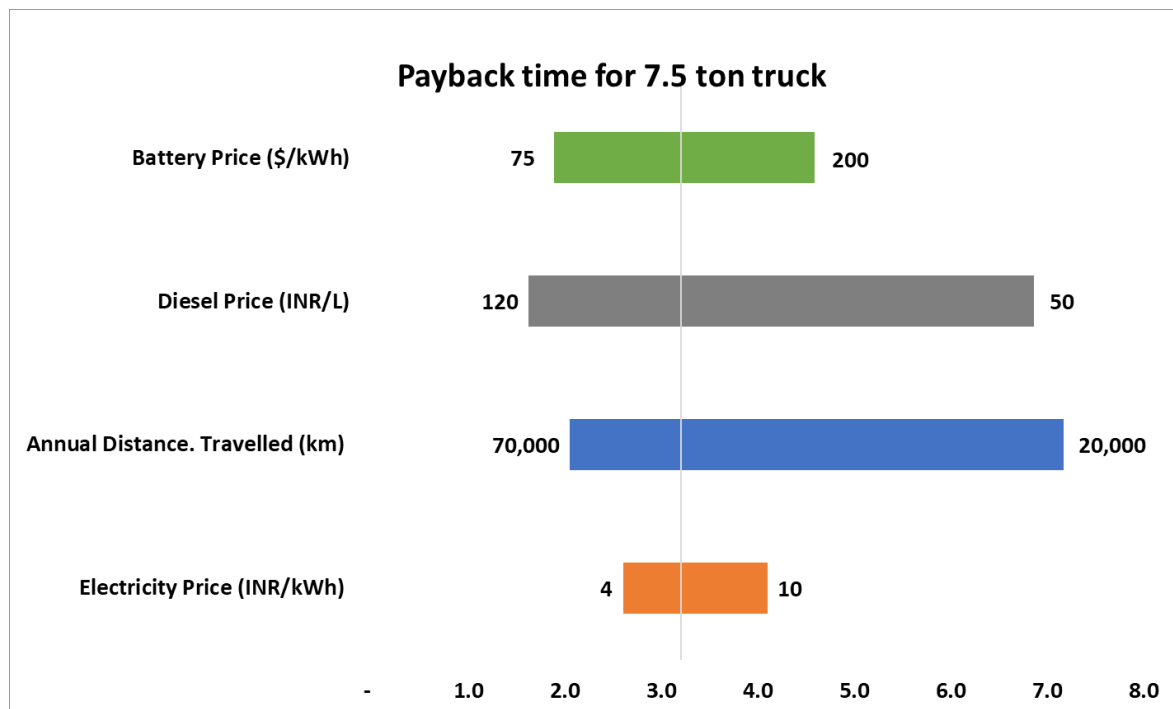


Figure 11a: Sensitivity analysis of payback for 7.5-ton BET

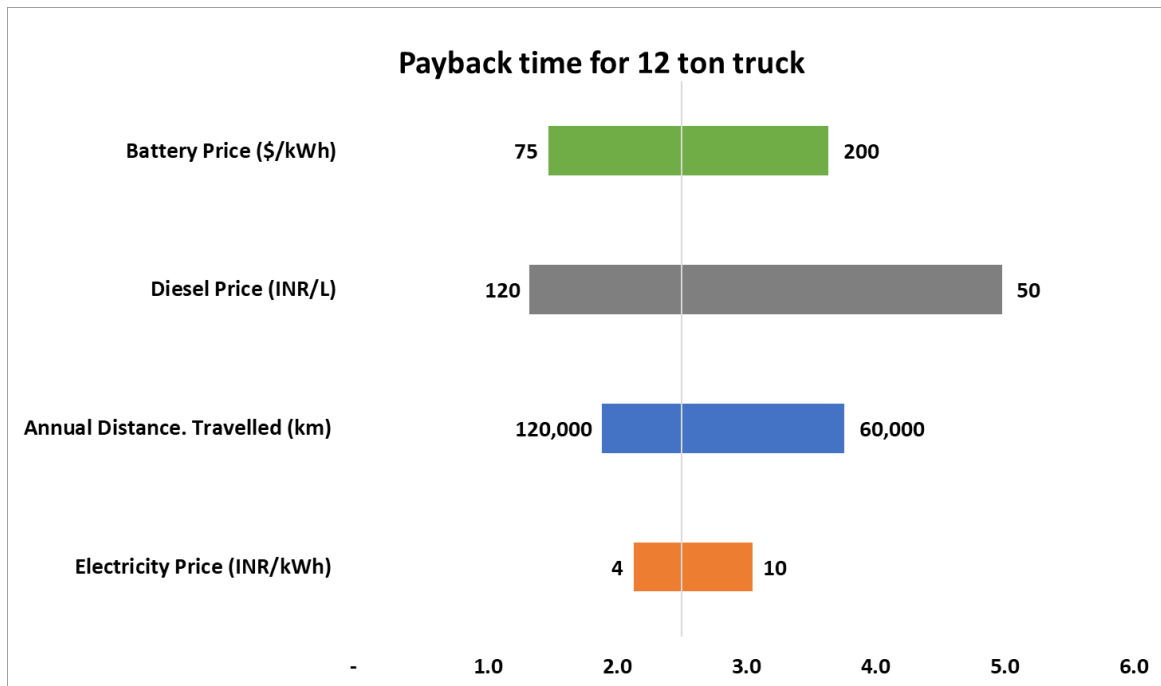


Figure 11b: Sensitivity analysis of payback for 12-ton BET

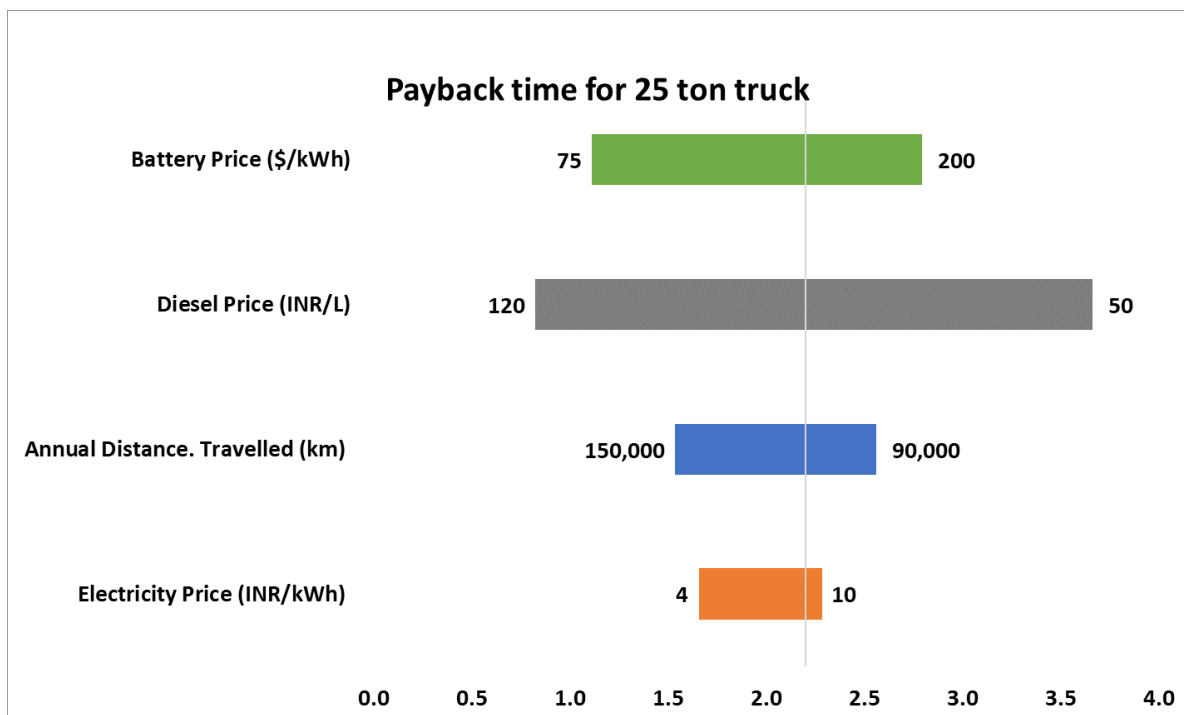


Figure 11c: Sensitivity analysis of payback for 25-ton BET

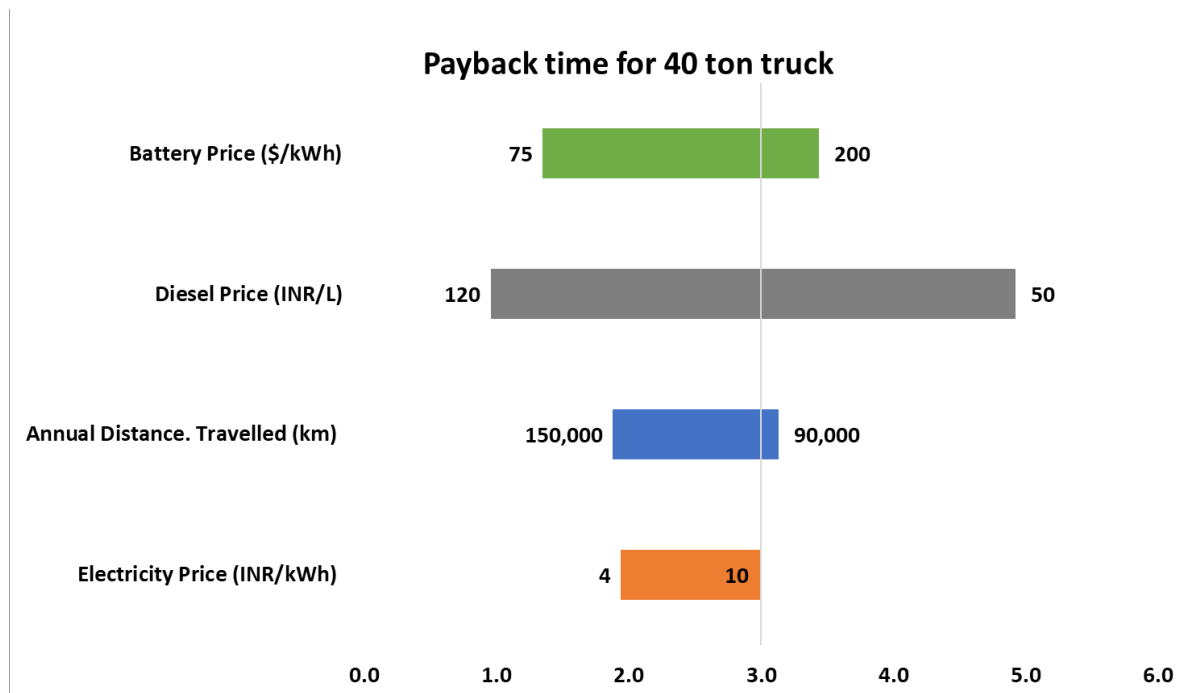


Figure 11d: Sensitivity analysis of payback for 40-ton BET.

Figure 11 shows the sensitivity of payback period to various factors for each of the four classes of trucks. The sensitivity analysis was carried out by changing one input at a time and keeping all other input at baseline values. The four inputs used for conducting the sensitivity analysis are battery price, diesel price, annual distance travelled and electricity price. The sensitivity bounds for battery price are based on battery price projections from BNEF until 2026, the bounds for diesel price and annual distance are based on expert input, and for electricity price, the lower bound is the total cost of delivered solar energy and the upper bound is based on current commercial electricity tariff.

The mean payback period for a 12-ton truck is 2.5 years. However, when battery price, annual distance, diesel price and electricity price are varied individually, the payback period ranges from 1.3 years to 5.0 years. Diesel price has the biggest impact on the payback period. A simulated increase in the price of diesel from 50 to 120 INR/L more than triples the payback period from 1.3 years to 5.0 years.

Battery Pack Weights: We estimate the impact of electrification of trucks on their payload capacity. Incremental truck weights are estimated by adding the weight of the battery and electric powertrain and subtracting the weight of the diesel powertrain components. Figure 12 shows the results of the weight estimation for the 12-ton and 25-ton truck categories. The hatched green bar segment shows the potential for reducing truck weight using lighter materials (e.g., aluminum instead of steel for the truck body). The curb weight of a 12-ton electric truck is 12% higher than a corresponding diesel truck without lightweighting, which impacts the payload capacity, but the penalty can be eliminated with the use of lightweighting strategies. For a 25-ton electric truck,

curb weight is 30% higher than that of a diesel truck without lightweighting and 13% higher with lightweighting.

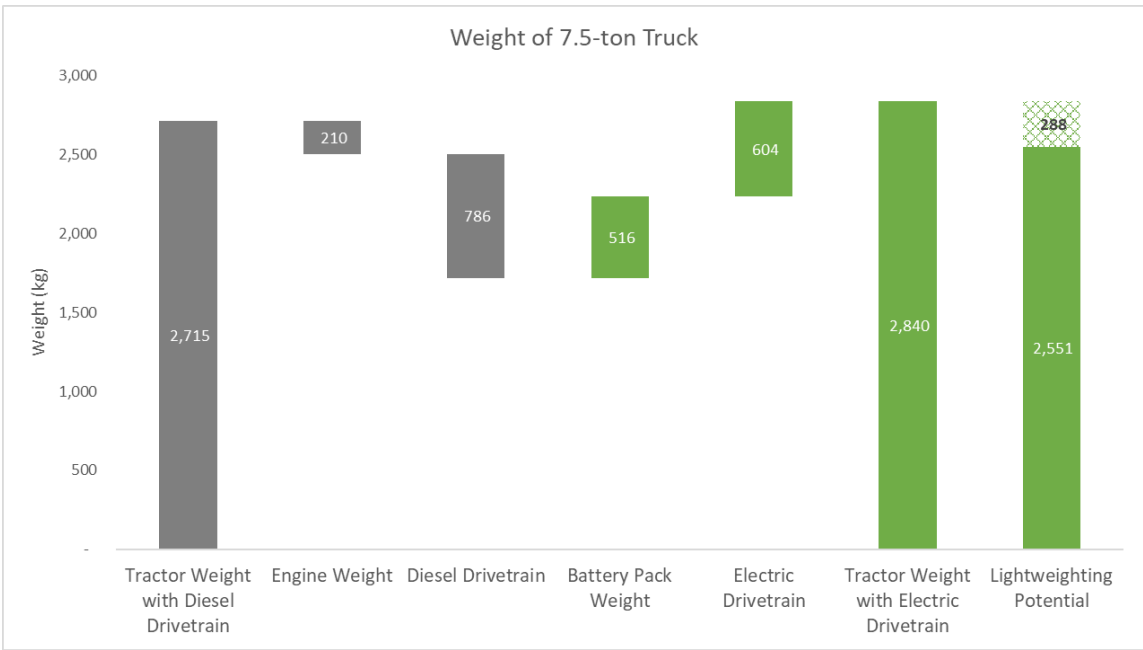


Figure 12a: Weight of a 7.5-ton diesel compared with a corresponding battery-electric truck with cell-specific energy of 250 Wh/kg

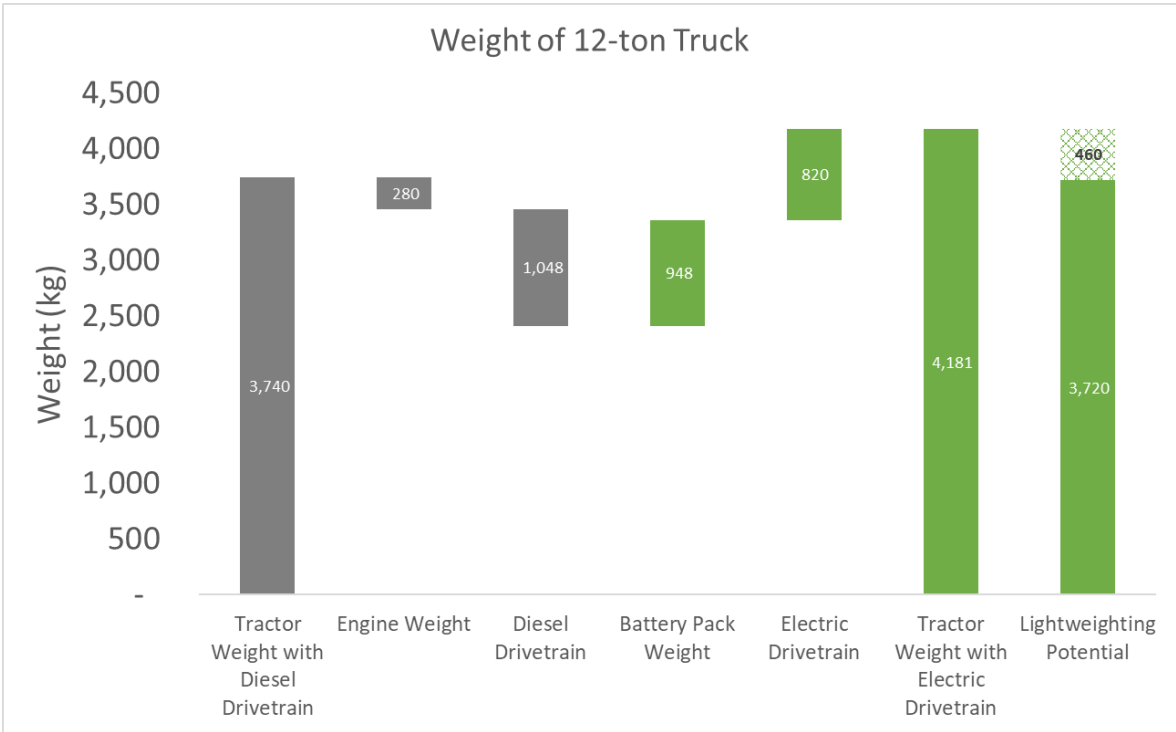


Figure 12b: Weight of a 12-ton diesel compared with a corresponding battery-electric truck with cell-specific energy of 250 Wh/kg

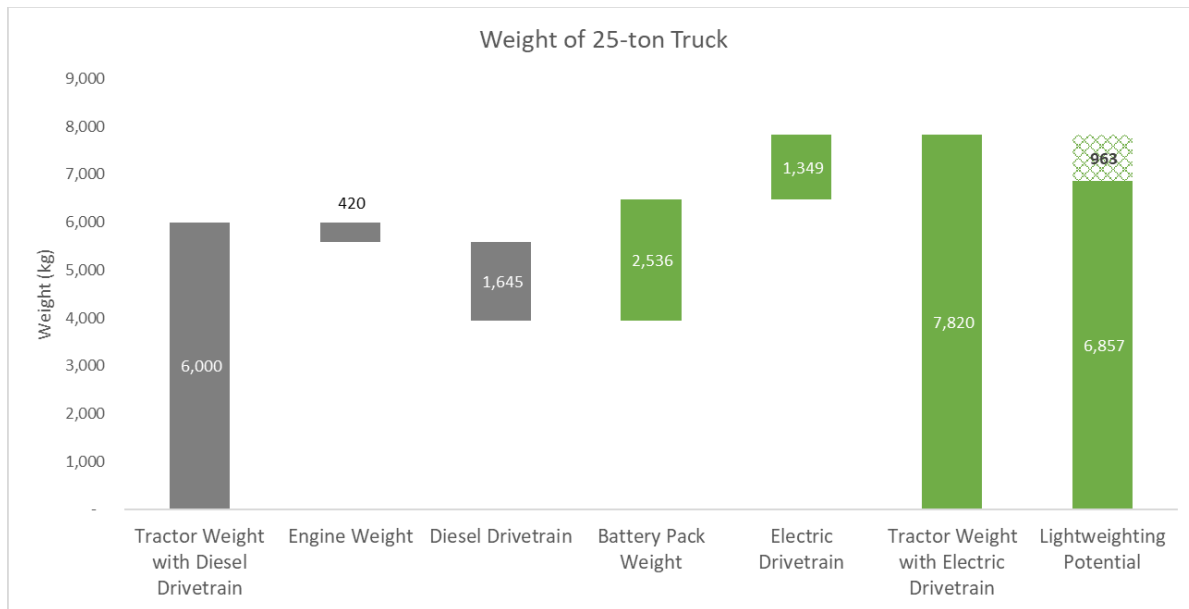


Figure 12c: Weight of a 25-ton diesel compared with a corresponding battery-electric truck with cell-specific energy of 250 Wh/kg

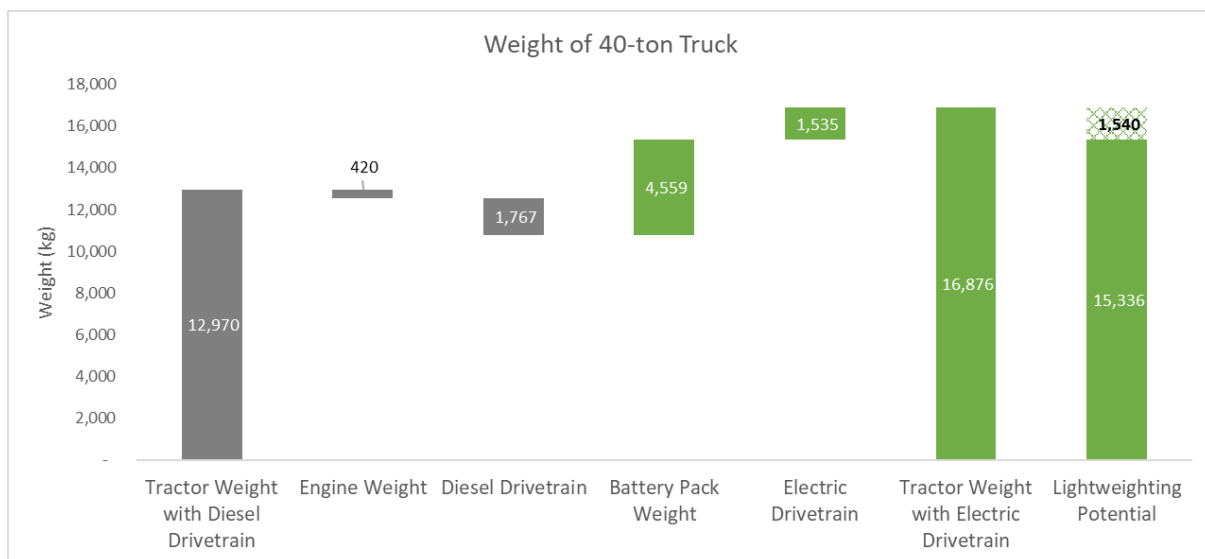


Figure 12d: Weight of a 40-ton diesel truck compared with a corresponding battery-electric truck with cell-specific energy of 250 Wh/kg

Charging Infrastructure: Based on the assumptions, a 2-electric truck fleet requires 2 charging stations, one near each end-point. But, with strategic planning and scheduling a 44 electric truck fleet could be supported with just 8 charging stations, unlocking an economy of scale. We assume three additional chargers at each endpoint to handle overflow when operations are delayed, which might result in bunching of trucks needing to be charged. In any case, the relationship between fleet size and number of chargers required is not linear. This reduces the per kilometer cost of charging per truck from 7.1 INR/km to 1.3 INR/km (See Figure 13). To

provide the same level of service¹¹ as 44 electric trucks with a departure every 30 minutes, 38 diesel trucks are needed. The resulting TCO for operating a fleet of 44 electric trucks, including the cost of charging infrastructure, is ~ 39.8 INR/km. The TCO of a truck fleet of 38 diesel trucks is ~ 49.8 INR/km. These results are shown in the figure below. Due to the economy of scale, the inherently higher efficiency of an electric drivetrain, and the lower cost of electric energy, even after accounting for the downtime while the trucks are charging, the cost to haul a truckload one kilometer is lower with an electrified fleet.

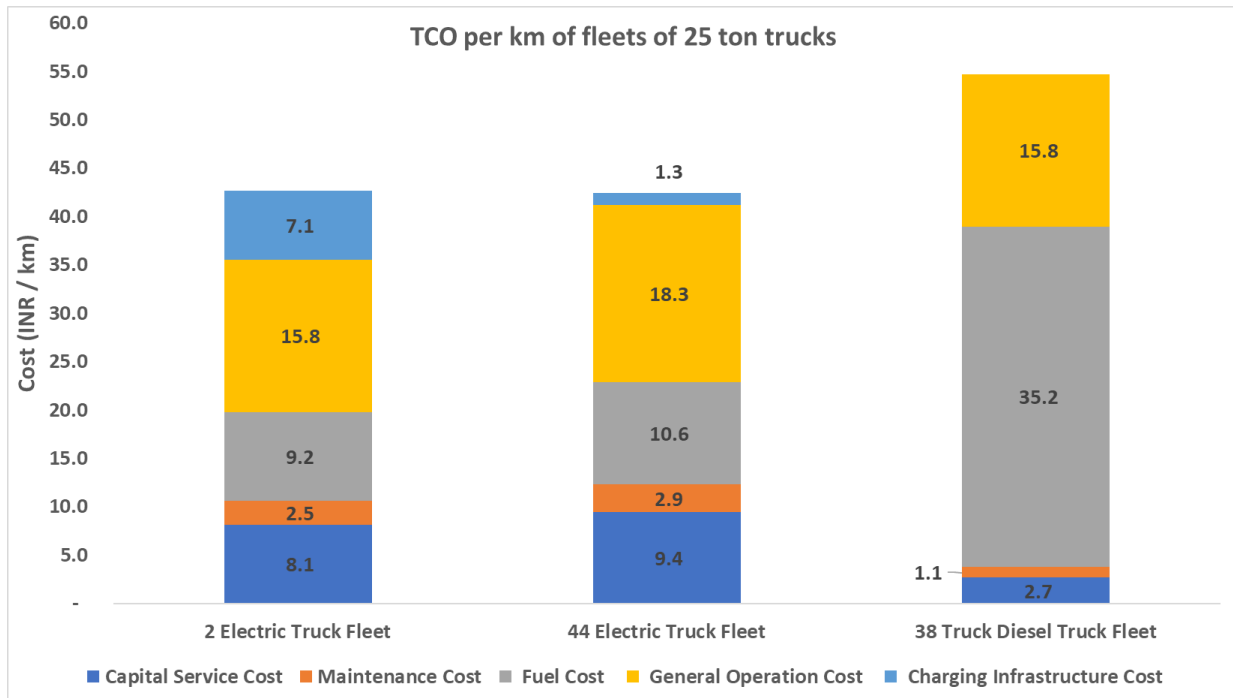


Figure 13: Total cost of ownership for truck fleets.

¹¹ Level of service is defined as the total payload capacity being carried between two termini in a 24-hour period.

Table 9: Comparison of lifecycle greenhouse gas emissions intensity per kilometer for Diesel and BET for each of the four classes of trucks.

Emissions* intensity	Diesel	gCO ₂ e/Litre	3579			
(Lifecycle GHG)	Electric	gCO ₂ e/kWh	701			
		Units	7.5MT	12MT	25MT	40MT
Fuel Economy	Diesel	km/Litre	8	5.5	3.45	2.2
	BET	km/kWh	2.50	1.69	0.88	0.49
Emissions	Diesel	gCO ₂ e/km	446.9	650.0	1036.3	1625.1
	BET	gCO ₂ e/km	288.3	427.3	820.2	1485.1
GHG reduction BET			35%	34%	21%	9%

* Life cycle GHG emissions intensity of diesel is based on the reported values used in California Low Carbon Fuel Standard of 100.24 gram CO₂eq per megajoule (MJ) and energy density of 35.7 MJ per litre. The life cycle GHG emissions intensity for electric trucks is taken as the annual average GHG emissions intensity of electricity generation for 2023-24 from Abhyankar, et. al. (2021).

We have not analyzed the environmental implications of electric trucks in any detail here which is left for future work. However, simple calculations (see Table 9) unambiguously establish that at current grid average emissions greenhouse gas (GHG) intensity BETs emit 9% to 35% less GHG emissions per kilometer relative diesel trucks. Charging during times when solar production is greatest would make BETs practically carbon free (more discussion below). Even at the maximum emissions intensity observed in India, BET's result in substantially lower emissions per kilometer relative to diesel. The impact of BETs on air quality in urban areas and along congested highways is also unambiguously positive although they increase air pollution at the point of power generation. India's renewable energy targets which are amongst the most ambitious in the world suggest that the grid emissions is set to decline steadily in India. The spatial and temporal variation created by BETs and the environmental implications of battery production and disposal are also topics for future work.

5. Conclusion

By helping to reduce oil imports, air pollution, GHG emissions and the cost of freight movement, truck electrification can achieve multiple policy objectives and deliver benefits beyond what can be achieved by raising efficiency of diesel trucks and freight operations. Significant improvements in battery cost and performance have substantially increased the economic feasibility of BETs, which now appear realistic even for long-haul operations. Our analysis shows that, if battery packs are procured at roughly the current world average price, and with well-designed electricity tariffs and ultra-fast EV charging, the techno-economic case for BETs becomes strong even without monetizing any external benefits (e.g., public health improvements from reduced pollution). It is worth reiterating that BETs offer the potential to insulate fleet owners from diesel's significant fuel price risk; this can be done by purchasing fixed price

contracts for renewable electricity, as utilities do today through 25-year fixed price power purchase agreements.

That said, achieving a lower cost of freight through BETs will require production and operation on a large scale, and sufficient accumulated experience across all aspects of the value chain. Until such a scale of production is achieved, BETs will likely be costlier and unprofitable relative to a mature industry like diesel trucking. Therefore, realizing the potential benefits of BETs requires sustained public support over a long period of infancy until they can reach full maturity and commercial viability.

While electrification of light-duty vehicles and buses, which is already underway, provides a firm foundation for embarking on truck electrification, BETs present some unique challenges. Freight trucks experience harsher environmental conditions and are put through tougher duty cycles relative to buses and light duty vehicles. They also face tighter constraints on weight and volume of battery packs so as to not compromise on payload capacity that generates revenues. Trucks will also require faster charging capacities (in the range of hundreds of kW or perhaps even in megawatt (MW) range), which increases thermal stress on batteries which will reduce battery life. For these reasons, BETs will need to undergo significant experimentation in design, manufacturing, and deployment of different battery chemistries, different pack designs, and different types of charging cycles. Public support will be needed to subsidize the private costs associated with such experimentation, which will generate positive externalities that are not completely appropriable by private investors.

India, one of the world's largest producers and exporters of automobiles, has the basic institutional infrastructure to begin the transition to electric trucking. Its automotive industry accounts for 8% of the country's exports and has successfully managed challenges such as adapting to stringent emission limits¹². Secondly, India has committed to add about 450 GW of renewable electricity capacity in the next decade, and the diurnal profile of renewable energy generation offers synergies with vehicle charging needs. Through vehicle-to-grid (V2G) integration, BETs can help reduce renewable integration costs and enhance grid reliability. India's PLI scheme, which subsidizes domestically manufactured products, can spur investments in battery cell manufacturing in India, thereby generating new employment opportunities and reducing import reliance on EV components. Lastly, with the Faster Adoption and Manufacturing of Electric Vehicles (FAME) and several other incentives – including the low 5% Goods and Services Tax (GST) as opposed to 28% on conventional vehicles, as well as special electricity tariffs for EV charging – India has already made significant strides towards electrification of light vehicles including 2- and 3-wheelers, cars and public transport buses. India is therefore primed to embark on truck electrification as the next logical step. Ambitious

¹² Automobile. Invest India. <https://www.investindia.gov.in/sector/automobile>

targets backed by strong supportive policies, both fiscal and non-fiscal, are needed to accelerate the market for electric trucks, to reduce the heavy burden of air pollution on Indian cities, and to reduce the country's financial burden from oil imports.

These targets and policies will help pull in private investments on the scale required to put BETs on a path to commercial viability within a decade or so. While the PLI scheme can be harnessed to attract investments in BETs, additional policies will be needed to catalyze investments in battery manufacturing, vehicle manufacturing, and charging infrastructure which are the most capital intensive in the BET value chain. On the demand side, a mandate on manufacturers to meet a certain share of annual sales through ZEVs has successfully driven EV adoption at both a fleet and household level, with ZEV mandates having been used in countries around the world to accelerate ZEV adoption (Axsen, et al; Rokadiya and Yang).

Emissions performance standards and fuel economy standards can also be effective in driving BET adoption, provided targets are stringent enough to force BET adoption. Basic economics also suggests that both vehicle mandates and performance standards can relieve the burden of subsidies on public finances while also increasing the effectiveness of each unit of subsidy. But targets require great political support to be strong and binding, since regulated parties will obviously prefer just subsidies over regulations.

The time is ripe for India to pursue truck electrification. By leveraging successful prior policies and with additional targeted interventions, India can create a thriving domestic electric vehicle industry over the next decade or so and become a global leader in producing clean, efficient, high-quality vehicles.

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