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Abstract

Whereas battery electric vehicles (BEV) are on their path to maturity in the light duty segment, their viability in medium and heavy-duty applications faces greater skepticism. Furthermore, their higher upfront cost relative to diesel trucks is perceived as even more challenging for less wealthy nations such as India. Here we undertake a total cost of ownership (TCO) assessment of BETs for four different classes of freight trucks in India using a bottom-up vehicle subsystem level cost estimation. We estimate that in a scenario in which the incremental upfront cost of BET relative to a diesel truck is simply the extra cost of the battery pack procured at close to current average international battery pack prices, BETs could have lower TCO, less than 5-year payback and deliver substantial life cycle cost savings even without accounting for their environmental benefits. In addition to eliminating tailpipe pollution, they already deliver lower life cycle greenhouse gas emissions based on the current average electricity mix in India. Achieving a scale of production that yields lower TCO will, however, require public support over a potentially long-maturation phase marked by learning-by-doing externalities and absence of economies of scale that render BETs costlier without subsidies or regulations. Currently, while there exist multiple types of incentives for light duty BEVs as well as for battery manufacturing in India, targeted policies for zero emissions trucks are absent, a gap that needs to be filled if BETs are to emerge as serious alternative to diesel trucks in a decade or so.

1. Introduction

Globally, the transportation sector was responsible for 24% of direct CO_2 emissions from fuel combustion in 2019 (1). 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 (1). HDVs are also significant sources of criteria air contaminants – such as Particulate Matter (both PM10 and PM2.5), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x), Carbon Monoxide (CO), and Volatile Organic Compounds (VOC) – which adversely affect air quality and human health (2). Globally, vehicle tailpipe emissions were responsible for an estimated 361,000 premature deaths in 2010 and 385,000 premature deaths in 2015 (3). 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 (3).

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 (4); given highway infrastructure improvements, it is likely this figure is higher today and will increase. 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 (5). 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 (6).

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. Indian regulations consist of 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 (7).

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 (8). 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 freight 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.

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 everything else, to zero-emissions technology. In 2021, Indian policymakers stated intention 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 (9). 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 (10) (11) (12).

However, in recent years, energy densities of batteries have increased significantly and the prices have decreased about 80% compared with a decade ago (13) (14). Battery prices are expected to continue decreasing due to economies of scale, more efficient production processes and greater competition (14) (15). Therefore, there is a growing literature on pathways to decarbonizing road freight through electrification and there are a growing number of studies suggesting the barriers to electrification of long-haul heavy-duty trucking are surmountable (14) (15) (5) (16).

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 (17). 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 (18). 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) (16). 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.

Ledna, et al., at NREL, project that zero-emission trucks are expected to reach cost parity with their diesel counterparts for short-haul applications as early as 2026, and for long-haul applications in 2035. Islam, et al., at ANL, project that for the class-8 long-haul sleeper trucks, fuel-cell trucks reach cost parity with conventional models by 2050, but that battery-electric trucks remain more expensive than conventional models, albeit slightly. (19)

Table 1: Summary of selected studies of electric truck TCO

Author names	Year published	Region	Diesel TCO ($/km)	BET TCO ($/km)	ΔTCO	Battery price ($/kWh)	Range (km)	Battery capacity (kWh)	GVW (metric ton (t))	Efficiency (kWh/km)
Sripad, Viswanathan (CMU) (21)	2018	USA	0.37	0.12	-67%	150	805	1000	Class 8 (~36t)	1.24
Earl et al (22)	2018	Europe	0.99	0.9	-9%	77	800	1000	40t	1.25
Mareev, Becker, Sauer (16)	2018	Germany	0.8	0.87	8%	330	723	825	40t	1.14
RMI NITI (6)	2019	India	0.34	0.51	50%				31t	
Hunter et al. (NREL) (18)	2021	USA	0.28	0.25	-9%	100	483	682	Class 8 (~36t)	1.41
Hunter et al. (NREL) (18)	2021	USA	0.36	0.55	52%	100	805	1173	Class 8 (~36t)	1.46
Burnham, et al. (ANL) (20)	2021	USA	0.66	1.15	74%	150	805		Class 8 (~36t)	NA
PManifold (23)	2021	India	1.13	1.27	13%	236		225	40t	
Phadke (25)	2021	USA	0.6	0.47	-23%	135	600	797	Class 8 (~36t)	1.33

Islam, Vijayagopal, Rosseau (24)	2022	USA	1.06	1.32	25%	140	800	1369	Class 8 (~36t)	1.71
Ledna, et al. (19)	2022	USA	0.86	1.7	98%	80	800	1369	Class 8 (~36t)	1.71

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; estimates reported in Indian currency was converted to USD using a conversion rate of 70 INR = 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. The Hunter and Burnham papers assess vehicles for model year 2025, while the Ledna paper assesses vehicles for model year 2035. All others assess the same year they were published.

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 (26). Regenerative braking enables electric delivery vehicles to recover kinetic energy that would otherwise be lost with every braking event, short distances within cities eliminate range anxiety as a concern, and the centralized nature of delivery hubs enable chargers to be positioned strategically (27). Over the course of the coming decade, BETs are projected by some researchers to 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 are projected by some researchers to reach unsubsidized TCO parity later this decade (26). The same could possibly happen for tractor-trailers (28).

Another common concern in the literature relates to a significant increase in curb weight as electric trucks require much larger batteries (16) (22) (2). 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 (29). Islam, et al., project that the payload penalty will be almost eliminated by 2050 as battery technology improves. (24) Hunter, et al., find that the penalty will be reduced significantly but not eliminated for vehicles with a 750-mile range; but that the payload capacity of battery-electric trucks with a 500-mile range could reach parity with diesel trucks due to the 2000-pound credit given by U.S. law. (18)

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 (22). This is a major reason that Islam, et al., found that the penalty from the battery weight can all but disappear. (24) This is still an area of uncertainty as there are a variety of views found within the literature on this topic. For example, Hunter, et al., found that the penalty from the battery weight depends on the desired range of the truck, as electric trucks with longer ranges will require bigger batteries, and so the battery-electric trucks with longer ranges may still have a payload penalty for many years into the future when compared to comparable diesel trucks (18). 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 (16). 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.

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 paper in the Journal of the Transportation Research Board found that electric two-wheelers are economically viable as compared to their combustion-powered counterparts, due to their lower operating costs (30). A recent study by CEEW, which considered passenger vehicles only, 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 (31). Another example is a 2022 journal article which found that electrification of the app-taxi fleet of New Delhi would be feasible with 23000 BEVs with 200 km range and 3000 50-kW chargers. This would reduce levelized cost per km by 37% compared to a diesel fleet, and reduce life-cycle GHG emissions by 27% per km (32).

A study by Rocky Mountain Institute (RMI) India assessed the possibility of using electric vehicles for urban delivery in Delhi (33). 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 concluded that there existed a strong case for new public transport buses to be purely battery electric (34).

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 (6).

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. However, they do not yet outcompete combustion-powered models on a TCO basis, unless subsidies are applied. 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 decades (23).

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 similar approach and finding significant net benefits along both dimensions (25). Figure 4 shows the modeling workflow used in this analysis.

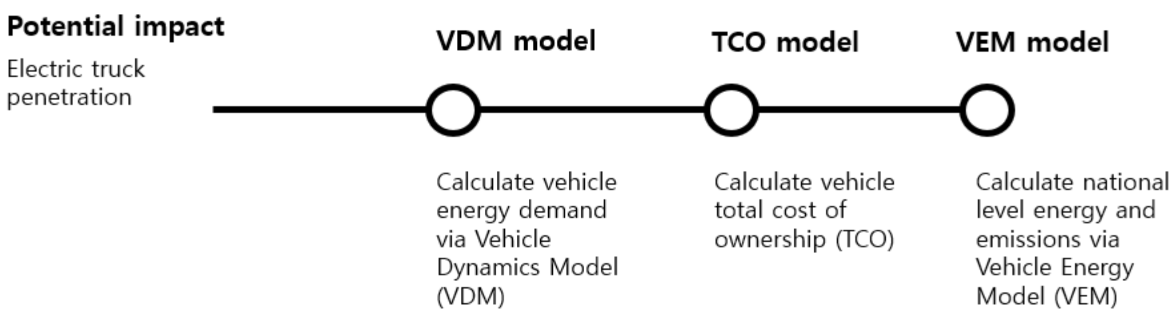

Figure 1: Overall methodology and modeling workflow

The Vehicle Dynamic Model (VDM) outputs were used to develop bottom-up capital cost estimates for the four electric truck categories. The VDM was developed by Sripad and Viswanathan (35). It 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:

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

The variables in Equation 1 are:

- E_p - The size of the battery pack required in kWh
- C_d -The coefficient of drag
- v -Average velocity
- v_{rms} -Root-mean-square of the velocity
- C_{rr} - The coefficient of rolling resistance
- W_T - The gross on-road vehicle weight (GVW), includes the payload and battery pack)
- Z - The road gradient (Z), which represents the slope as a decimal.
- D - The driving distance
- t_f - The fraction of time that the truck would be driven on a road grade of r%.
- ρ - the density of air
- g - the acceleration due to gravity
- A - the frontal area of the truck
- a -the mean acceleration or deceleration of the truck,
- η_{bw} is the battery-to-wheels efficiency
- H_{brk} is the braking efficiency of the vehicle.

The VDM uses the Autonomie model 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. Autonomie is a vehicle performance evaluation software that was developed by the U.S. Department of Energy's Argonne National Laboratory. The WHVC is the basis for the development of the World Harmonized Transient Cycle (WHTC), an engine dynamometer cycle that is used as a certification test for regulated pollutants (36). The WHVC covers a wide range of driving situations for commercial vehicles, including 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). 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, which correspond to lower highway speeds for commercial vehicles in India compared to the United States. 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) (8).

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.

In 2022, per BNEF, the average pack price for light-duty vehicle lithium-ion batteries was $151/kWh; however, pack prices per kilowatt-hour of capacity are often higher for medium and heavy-duty vehicles compared to those unlocked by light duty vehicles (37). To make a conservative assumption, this analysis assumes a battery cost of $200 per kilowatt-hour of battery capacity, 32% higher than the average price achieved in 2022. Despite this conservative assumption, this analysis finds that electric trucks deliver a lower TCO than their combustion-powered counterparts for any vehicle class, because TCO is primarily driven by operating costs.

Table 2: Classification of HDVs and baseline fuel economy.

Vehicle type	Class	Weight	Fuel economy (km/L)
Rigid truck	Light-duty truck (LDT)	7.5 tonnes ≤ GVW < 12 tonnes	8.00
	Medium-duty truck (MDT)	GVW ≥ 12 tonnes	5.05
	Heavy-duty truck (HDT)	GVW 25 tonnes	2.45
Tractor trailer	Heavy-duty tractor trailer (HDTT)	GVW 40 tonnes	2.20

Table 3: Other model inputs and parameters. The technical parameters for the VDM are derived from Sripad and Viswanathan (2017) (38). The other parameters are based on expert judgment.

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	7.50

Final drive ratio	3.86	5.29	5.57	6.83
Power Rating (kW)	90	100	160	160
Drivetrain efficiency (38)	0.90	0.90	0.90	0.90
Braking efficiency (38)	0.97	0.97	0.97	0.97
Battery discharge efficiency (38)	0.95	0.95	0.95	0.95
Battery to Wheels efficiency (38)	0.83	0.83	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
Base case battery cost (USD/kWh)	200	200	200	200
Cheap scenario battery cost (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
Annual distance	45,000	90,000	120,000	120,000
Exchange rate (INR/USD)	70	70	70	70
Nominal interest rate	10%	10%	10%	10%
Real interest rate	8%	8%	8%	8%
Cost of diesel (INR/L)	75	75	75	75
Levelized cost of charging (INR/kWh)	10	10	10	10

Total Cost of Ownership

TCO is estimated by summing the capital, maintenance, fuel, and operation costs (Equation 2). The capital costs assume that the chargers are installed in a depot where the trucks are based, and do not rely on public charging infrastructure. The net present of the capital and fuel costs was discounted using a nominal discount rate of 10% and a real discount rate of 8%. 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).

TCO = capital cost + fuel cost + maintenance cost + operations cost (2)

TCO per km = (capital cost + fuel cost + maintenance cost + operations cost) / lifetime VKT (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, including the cost of installing chargers at a depot) (Equation 4).

Capital cost (electric truck) = capital cost (diesel truck) +

battery cost + incremental powertrain cost (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 ₹10 per kilowatt-hour. This is based on an electricity price of ₹7 per kWh and a levelized infrastructure cost of ₹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. This is within the range of maintenance cost multipliers found by Argonne National Laboratory (20).

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. (25)

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 (39).

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 hare 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.

Battery costs from two scenarios, one for a base case with a cost of $200/kWh and another for a scenario with cheaper batteries, if the goal of $100/kWh is achieved, were used to develop capital cost estimates. The resulting capital cost of a 12-ton electric truck is 169% higher than an equivalent diesel truck while a 25-ton electric truck is 206% more expensive than the comparable diesel truck, if battery costs remain at $135/kWh. Figures 6 and 7 show the results for the 12-ton truck and 25-ton truck. Results for the other truck categories are present in the detailed spreadsheet available alongside this report**.**

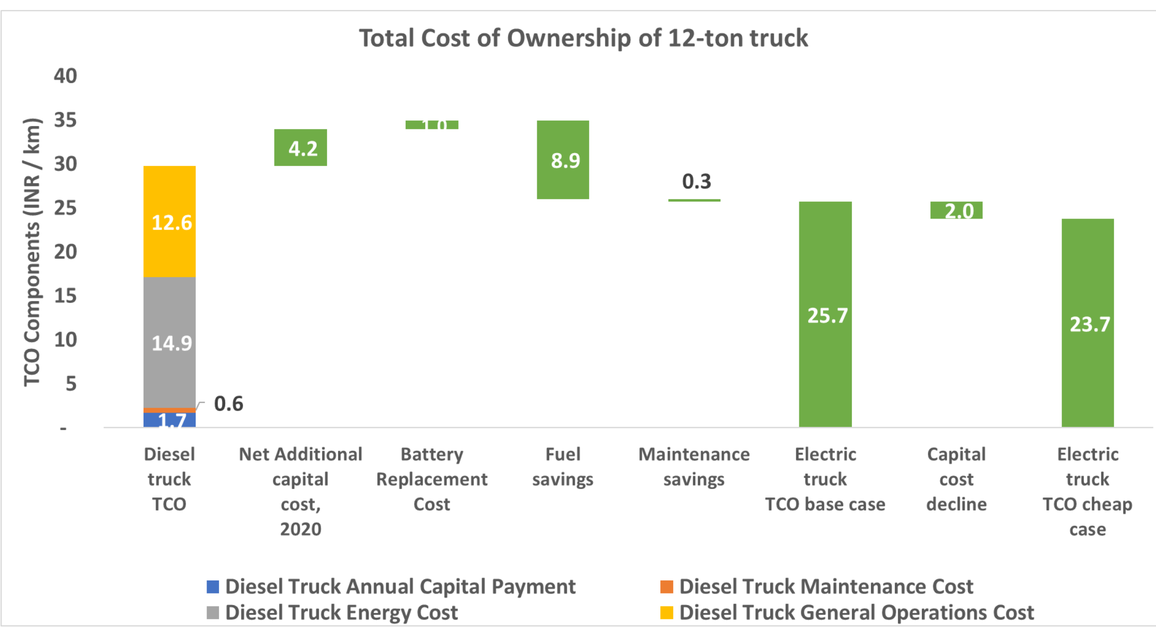

Figure 2: Total cost of ownership for a 12-ton truck

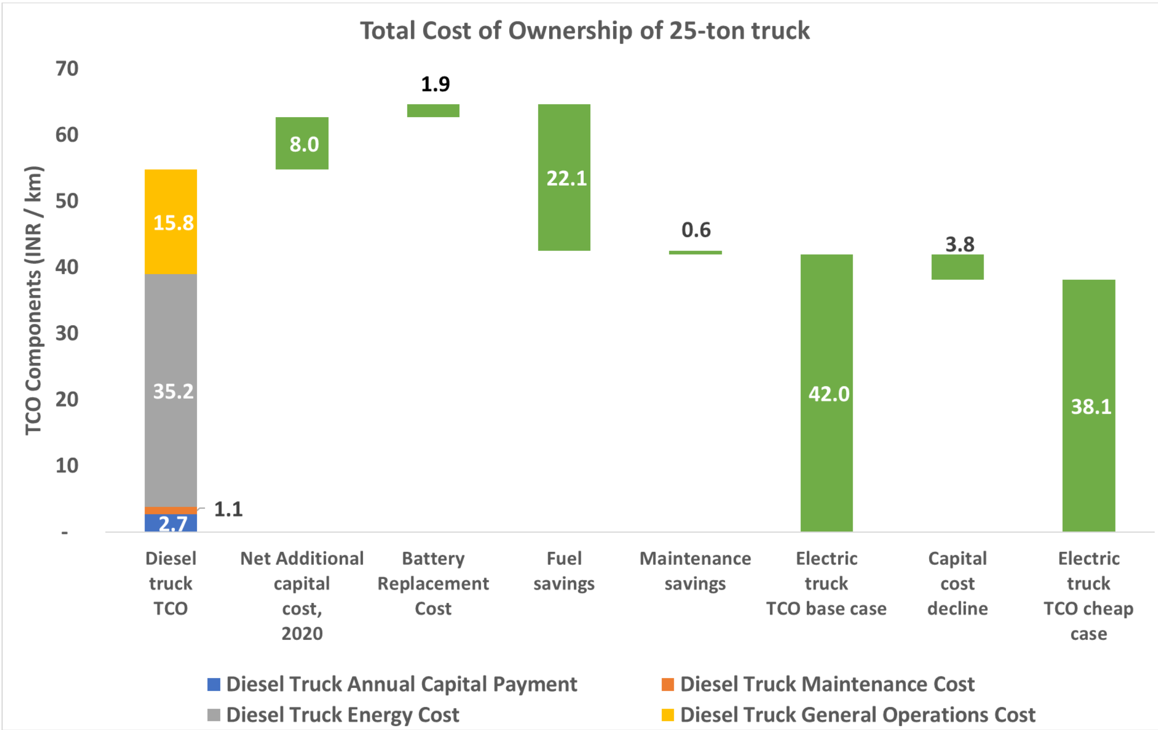

Figure 3: Total cost of ownership for a 25-ton truck

For both a 12-ton and 25-ton truck, if the battery price is assumed to be $200 /kWh, the upfront cost of the electric truck is 244% and 300% more expensive than a comparable diesel truck respectively. 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 25.7 INR/km, 13% lower than a comparable diesel truck TCO of 29.7 INR/km, assuming battery prices at $200/kWh. As Figure 7 shows, if battery costs are assumed to be $100/kWh, the estimated TCO of a 12-ton electric truck is 23.7 INR/km, 20% lower than the comparable diesel truck.

Similarly, for a 25-ton truck, with battery price at $200/kWh, we estimate that the TCO for an electric truck is 42.0 INR/km, 23% lower than the diesel truck TCO of 54.7 INR/km (Figure 8). If battery costs are $100/kWh, the TCO of the 25-ton electric truck is 38.1 INR/km and the difference in TCO of the diesel and electric truck becomes 30%. Across all four truck classes, a capital cost comparison between diesel and electric trucks shows that while electric trucks are more expensive (by 97% to 313%), their per-km TCO cost is lower (by 6% to 23%). In addition, their payback period is between 3.3 years and 5.9 years, well below the expected 15-year life of the respective 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 (%)	97%	244%	300%	313%
Difference in TCO (%)	6%	13%	23%	16%
Payback Period (years)	5.9	4.4	3.3	4.4

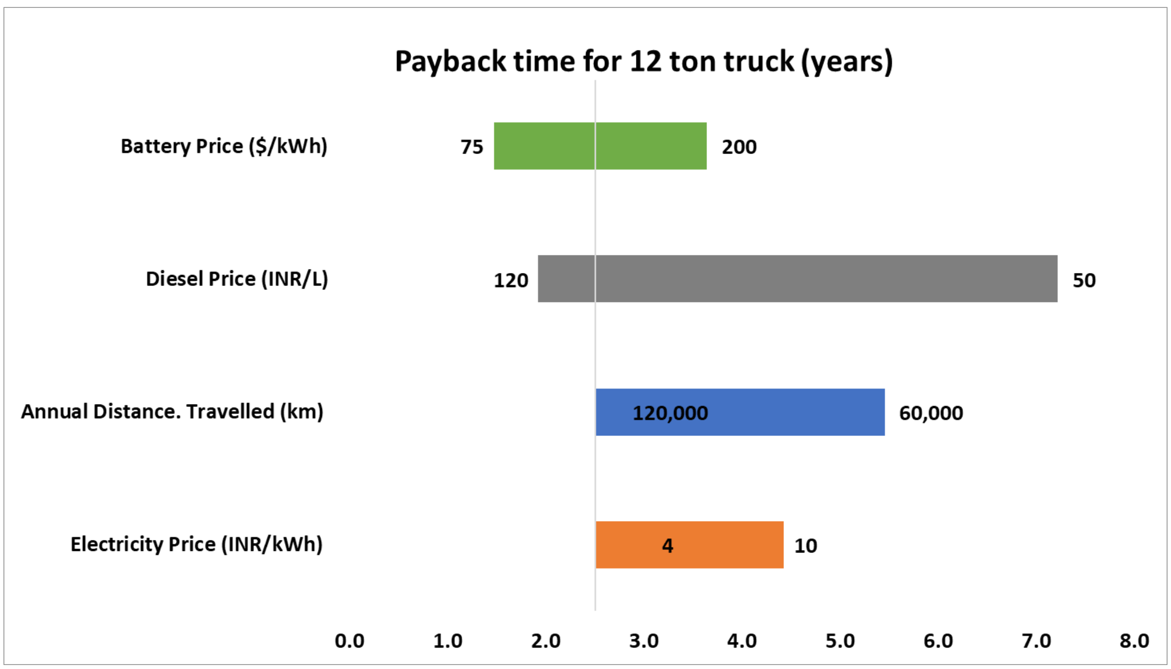

Figure 4: Sensitivity analysis for payback period for a 12-ton truck

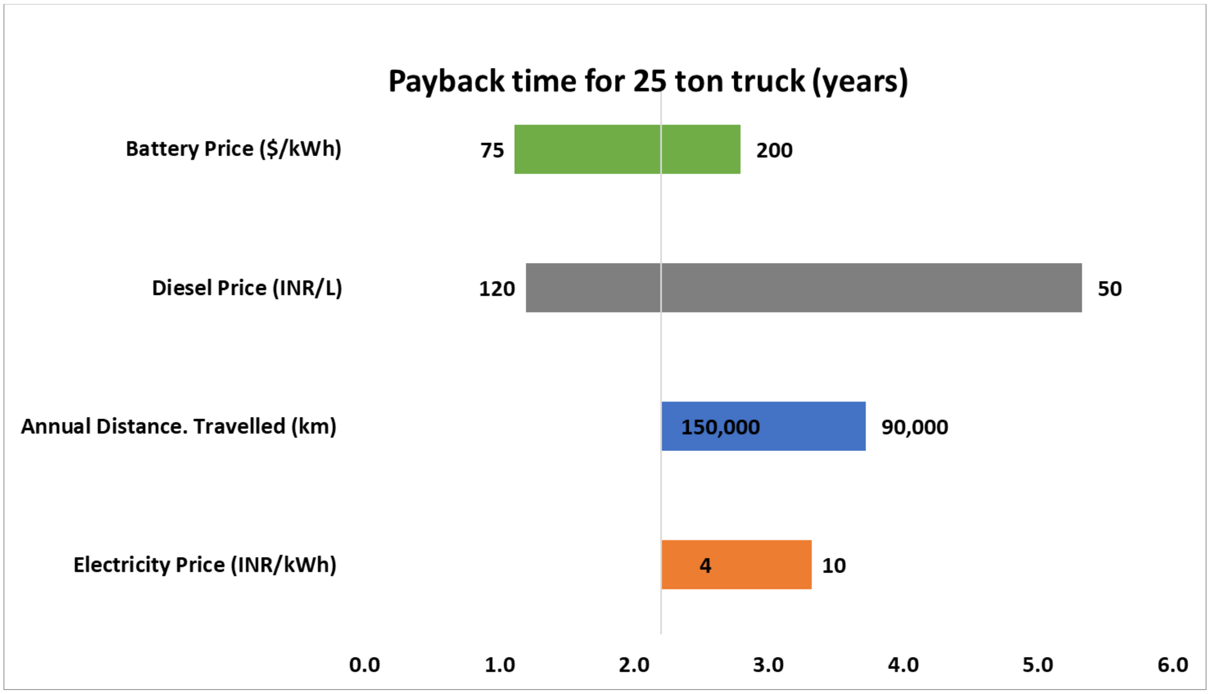

Figure 5: Sensitivity analysis for payback period for a 25-ton truck

Figure 9 shows the sensitivity of payback period to various factors for the 12-ton and 25-ton truck categories. 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 3.6 years, with the battery cost at $200/kWh. 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.

If the cost of a battery is $135/kWh, then the lifetime savings from electrification are 2.2, 6.3, 8.0, and 32 million rupees for 7.5-, 12-, 25-, and 40-ton vehicles respectively. If the cost of a battery declines to $100/kWh, which is projected to happen, then the lifetime savings from electrification increase to 2.5, 7.0, 9.9, and 35.9 million rupees, for the same respective categories of trucks.

Charging Infrastructure Needs and Costs for Truck Fleets

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. This simulation assumes that the endpoint are on the order of 400 km apart, and that the journey takes around 7.5 hours including break time. Each truck starts from its origin, Point A or Point B, with a full charge, and discharges its battery over the course of the journey. It will stop to charge 25 km short of its destination to conduct fast charging,

This analysis assumed a 24-hour schedule with a fleet of 44 trucks to estimate charging needs. This analysis assumed, in addition to other assumptions that were previously mentioned, that the first truck departs from its origin at 5 a.m. and had an average speed of 48 km/h; that a single truck departs each end-node at 30 minute intervals; and that each truck will return to the rest-stop nearest to its destination after completing its pick-up or drop-off of goods and will not depart until it's fully charged; that a single truck can undertake multiple trips during a 24-hour period. Personnel management is not considered for this simulation.

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 11). To provide the same level of service[1] 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.

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

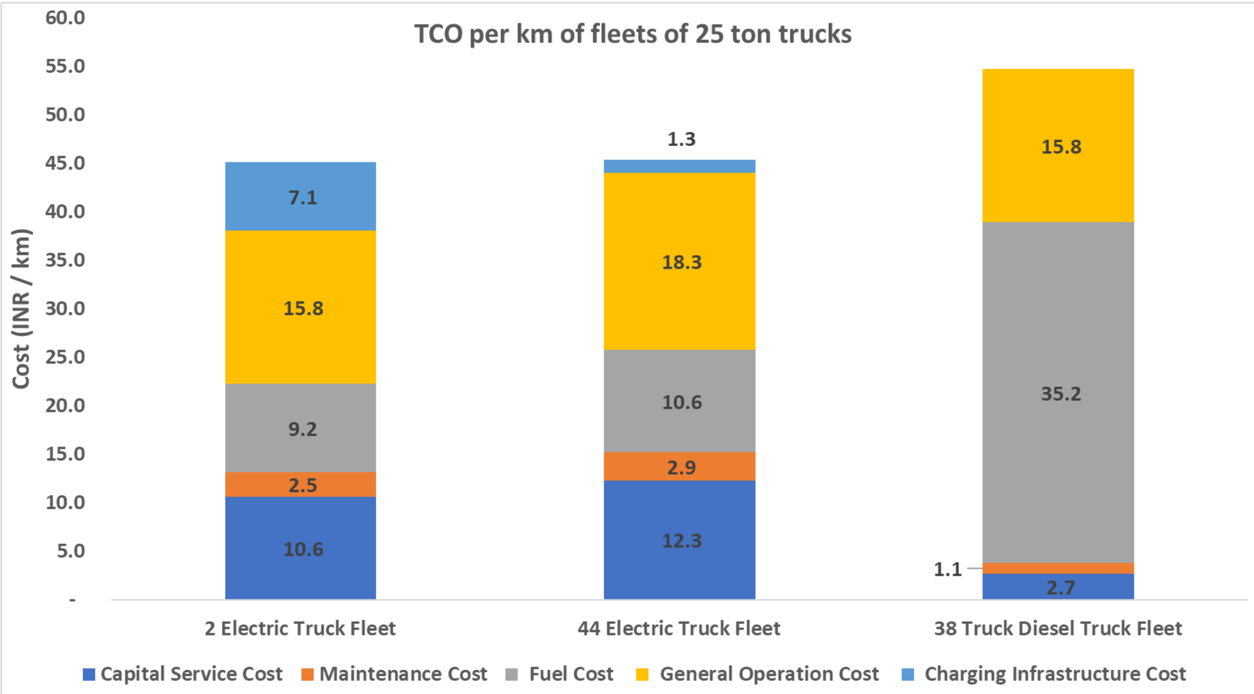

Figure 6: Total cost of ownership for truck fleets

To summarize the results, battery electric trucks in India can deliver lower total cost of ownership for electric trucks relative to diesel trucks at a battery cost of $200/kWh and taking into consideration cost of building charging infrastructure. Furthermore, TCO is relatively insensitive to the battery price, as the operating costs dominate the total cost of ownership of battery trucks. Our modeling suggests electric trucks can break even at a battery prices of $400/kWh holding all other assumed cost and performance parameters fixed.

5. Conclusion

Countries with population density and traffic congestion which face a high burden of air pollution, and are also large importers of oil such as India stand benefit more alternatives to diesel such as battery electric vehicles compared to countries. But whereas battery electric vehicles (BEV) are on their path to maturity in the light duty segment, their viability in medium and heavy-duty applications faces greater skepticism. This study suggests that that in a scenario in which the incremental upfront cost of BET relative to a diesel truck is simply the extra cost of the battery pack procured at close to current average international battery pack prices, BETs could have lower TCO, less than 5-year payback and deliver substantial life cycle cost savings even without accounting for their environmental benefits. Achieving a scale production that yields lower TCO will, however, require public support over a long-maturation phase marked by learning-by-doing externalities and lack of economies of scale when BETs will be costlier.

Currently, while there exist multiple types of incentives for light duty BEVs as well as for cell manufacturing in India, targeted policies for zero emissions trucks are absent, a gap that needs to be filled if BETs are to emerge as serious alternative to diesel trucks in a decade or so.

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Author contribution statement

DR contributed to study design, model development and testing, and lead the writing of the manuscript.

NG contributed to model testing and debugging, literature review and writing the manuscript.

NA contributed to design of the study.

NK contributed to model development.

AK contributed to data collection, model development and summarize the results.

AP contributed to design of the study.

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