Route Towards Road Freight Electrification in India: Examining Battery Electric Truck Powertrain and Energy Consumption

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Abstract : Medium-duty/heavy-duty trucks (MD/HDTs) are yet to be included in India's electric mobility plans. With the improvement of electric vehicle (EV) technologies, there is a growing interest in battery-electric trucks (BETs) from original equipment manufacturers (OEMs). The time is opportune to consider electrification as a future direction for road freight in India. Accordingly, this article presents the results of an energy consumption simulation study of a BET under Indian conditions. This study specifically considered an MDBET over a domestic drive cycle. These energy consumption figures can facilitate future studies that analyze the technical and practical feasibility of BETs in the country. In addition, the article provides the requisite groundwork for BET modeling for a simulation study by reviewing available EV powertrain systems and components. Appropriate powertrain considerations are thereby obtained for a typical medium-duty/heavy-duty battery-electric truck (MD/HDBET) in the Indian context.

Keywords : Electric truck, heavy-duty battery electric truck, medium-duty battery electric truck, energy consumption, vehicle powertrain

1 Introduction

There is a growing awareness of the underlying health, environmental, and energy security concerns associated with conventional transportation [1-3]. These factors have driven India to follow the global trend of promoting electric mobility solutions as a substitute for conventional road transportation [4]. In line with global interest, numerous studies have been conducted to gain an understanding of electric vehicles (EVs) in the Indian scenario.

However, it is notable that this body of literature is geared toward passenger EVs. Hitherto, the subject of electrification of road freight in India has not been addressed from a scientific viewpoint. As pointed out in Ref. [5], to meet emission commitments, trucks must be included in nationwide efforts to decarbonize transport. Hence, keeping the research focus on EVs in India, it is prudent to evaluate electric trucks as an option for road freight transportation in the country.

Currently, little data is available regarding battery-electric trucks (BETs) in India. Determining the energy consumption of these vehicles is an ideal starting point to address this issue. Energy consumption figures can help facilitate a variety of further studies on BETs. A few examples of BET research that rely on kW • h/km figures include total cost of ownership (TCO) studies [6], life cycle assessment (LCA) studies [7], fleet substitution feasibility studies [8], and grid planning studies [9]. The results of such studies offer crucial insights into electric trucks in the country.

It is insufficient to consider previously published

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kW •h/km or kW •h/(kg •km) values of EVs in the Indian context [10]. Hence, there is a need to conduct a simulation study that models a typical medium-duty/heavy-duty battery-electric truck (MD/HDBET) in the Indian scenario; specifically, a BET simulation that considers Indian drive cycles as well as local ambient temperatures and road conditions is required. Before conducting the simulation, relevant literature must be examined to select and model a typical BET powertrain because there is limited technical information available on commercial MD/HDBET models[11]. Furthermore, to the authors' knowledge, original equipment manufacturers (OEMs) are not yet to commence MD/HDBET operations on a build-for-sale basis in India.

Numerous powertrain solutions are available for electric vehicles; the selection of a vehicle powertrain depends on the precise size and application of the vehicle [12]. In reality, vehicle powertrain selection is further governed by decisions concerning the cost and performance of the vehicle in question. In addition, it is worth noting that the Indian commercial vehicle industry is highly cost-sensitive [13-14]. Hence, when modeling a typical MD/HDBET, the prime guiding design philosophy for powertrain examination is focused on BET performance while paying heed to industry standards.

This article extends and contributes to the body of literature in two ways. First, EV powertrain components and related systems are examined to model a typical MD/HDBET. As seen in Fig. 1, the specific powertrain components and systems that are scrutinized in this study are in conjunction with those deemed necessary for accurate EV modeling and simulation in Ref. [15]. Second, the energy consumption results of a BET simulated in the Matlab®/Simulink® environment are presented. The truck model emulates a typical MDBET with the modified Indian drive cycle (MIDC) [16]. The article is structured such that Sections 2-4 examine BET powertrain components and systems, and Section 5 is devoted to the BET simulation study.

The remainder of this article is divided into the following sections: Section 2 reviews the classification of trucks in India and reviews different BET powertrain topologies. Section 3 examines and compares technologies for various EV powertrain components. The components examined include ① battery and battery thermal management, ② traction motors, and ③ power electronics. Section 4 analyzes the charging levels and standards of EVs in India, as well as EV charging protocols and efficiencies. Section 5 presents a BET energy consumption study. Finally, Section 6 presents the conclusions of this study.

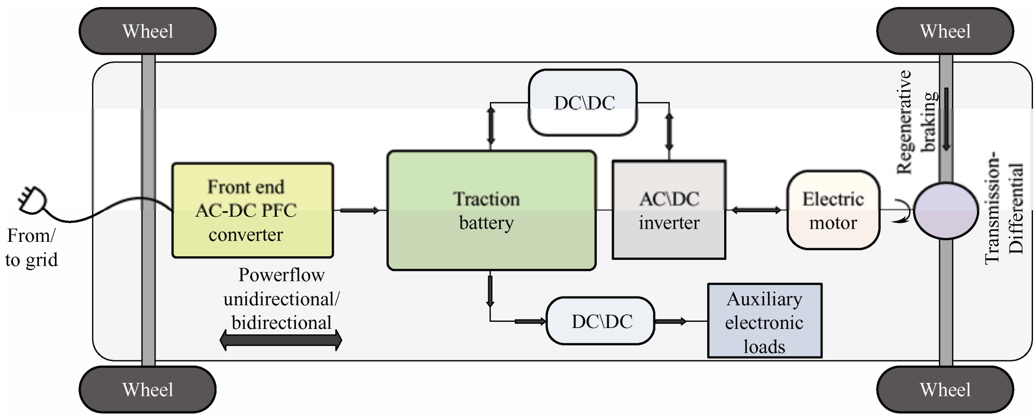


Fig. 1 Plug-in electric vehicle

2 BET classification and topology

2.1 BET classification

Before the powertrain analysis, the specific type of freight vehicle to be studied must be determined. The label freight vehicle is an indiscriminate term that covers a variety of commercial vehicles. Freight vehicle classification can be based on numerous criteria that generally involve terms of vehicle dimensions and utility. In India, as per the Automotive Research Association of India (ARAI), freight vehicles are classified into three basic groups: light commercial vehicles (LCV/N1), medium commercial vehicles (MCV/N2), and heavy commercial vehicles (HCV/N3) [17].

As shown in Tab. 1, these categories broadly divide commercial vehicles (CVs) based on their gross vehicle weight (GVW) [17]. These broad groups do not provide much insight into the characteristics of vehicles in each category. Hence, a slightly more detailed breakdown of the Indian truck classifications, as shown in Tab. 2, was suggested in Ref. [18].

Tab. 1 Classification of commercial vehicles in India

ARAI terminology	CV category	GVW/t
N1 category	LCV (light commercial vehicle)	< 3.5
N2 category	MCV (medium commercial vehicle)	3.5-12
N3 category	HCV (heavy commercial vehicle)	< 12

Tab. 2 Parameters of various vehicle sizes

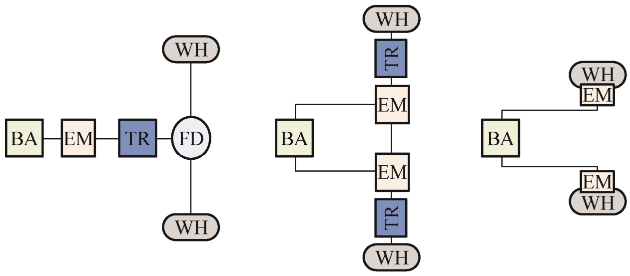
Vehicle category	Van	Light duty vehicle	Medium sized truck	Heavy duty truck	Truck and trailer
GVW/kg	3 500	7 500	15 000	24 000	40 000
Payload/kg	1 600	4 400	10 000	17 500	30 400
Load capacity/m^3	7.34	32.84	51.93	60.44	98.83
Road space occupation/m^3	47.51	78.68	103.71	115.89	168
Diesel per 100 km /L	9.8	14.5	25	32	44

When referring to electrification of trucks, studies on light-duty electric trucks (LDET) have already established uniform promising technical and economic feasibility results across multiple scenarios and regions [7, 19-20]. In contrast, the results of MD/HDET studies show widely varying electrification potentials from region to region [8, 21-22]. MD/HDTs are also the largest contributor to the total $PM_{2.5}$, SO_2, and NO_x emissions from road transportation in India [5, 23]. Hence, this review focuses on powertrain solutions for MD/HDBET modeling.

2.2 BET powertrain topology

The powertrain topology/architecture of a vehicle describes the path of power transfer from the energy source to the driven wheels [24]. The selection of the powertrain configuration depends largely on the weight and intended application of a specific vehicle [12]. An efficient powertrain topology is desired, as it can minimize the energy usage of the vehicle [25]. The BET powertrain topology must also be robust and durable to minimize vehicle TCO [26].

Compared with internal combustion engine (ICE) vehicles, EV powertrain topology options are significantly more flexible. This is in part due to the fewer mechanical connections required between the components [12]. This flexibility in the EV powertrain configuration has led OEMs to adopt various solutions. Three basic EV powertrain topologies are shown in Fig. 2: the central drive layout and two distributed drive layouts, i.e., near-wheel drive and in-wheel drive [27]. The primary advantages and disadvantages of these EV powertrain concepts are presented in Tab. 3 [27]. To arrive at an EV powertrain topology, design decisions must be made regarding the various drive configurations.



(a) Distributed drive (b) Near-wheel drive (c) In-wheel drive

Fig. 2 Basic drivetrain topologies (BA=battery, EM=electric motor, TR=transmission, FD=differential, WH=wheel)

Tab. 3 Powertrain topologies

	Distributed drive	Near wheel drive	In-wheel drive
Pros	Cost effective; Proven reliability; Flexible for different use cases	Good tradeoff between efficiency and size; Wide operation range	Most compact and efficient
Cons	Not very Efficient; Not compact	Presently not most cost effective; Not most compact	Costliest; Unproven reliability; Limited operation window

2.2.1 Central drive configuration

The central drive system typically involves substituting the EV motor and mechanical transmission in place of the engine and transmission of a traditional ICE vehicle, as shown in Fig. 2a. This solution has the appeal of being a more cost-effective approach, as conventional vehicle architecture may be recycled. However, the central drive system is not space-efficient because it does not utilize the compactness of electric axle topologies [28]. The central drive system is also linked to lower energy systems [25]. Space and efficiency are important factors when referring to MD/HDTs. Hence, it is evident that a centralized system is not an ideal solution for MD/HDBETs. However, considering the cost-sensitive nature of the MD/HDT industry, the central drive topology cannot be disregarded in the near-term development of BETs [27].

2.2.2 Distributed drive configuration

In contrast with the central drive topology, as shown in Fig. 2, the distributed drive layouts are powered by multiple electric motors. The distributed drive architecture also negates the requirement for differential systems. Two basic transmission topologies exist within distributed driven systems: in-wheel drive and near-wheel drive, as shown in Figs. 2c and 2b, respectively.

As the name suggests, the in-wheel drive is connected directly to the driven wheel. A direct drive is a unique capability of electric motors. This powertrain topology is extremely compact and avoids transmission losses. However, at present, in-wheel drive systems are not yet able to sufficiently match the operation window requirements of MD/HDTs [25]. This concern is compounded by the rise in the vehicle unsprung mass with the in-wheel drive topology [29]. As the motors are more exposed to dirt and temperature fluctuations from the surrounding environment and brakes, there are also reliability concerns linked with the in-wheel drive [27]. Additionally, at the moment, the in-wheel drive represents a costly powertrain topology because of the associated design, development, and control costs [27].

A near-wheel drive can be seen as a suitable solution for the MD/HDBET powertrain topology. As shown in Fig. 2, in this system, the individual motors are fed through a gear reduction before reaching the specific wheel it is propelling. The near-wheel drive topology has higher associated costs than the central drive configuration [27]. However, this architecture is more efficient than the central drive topology in terms of space and transmission losses, while still maintaining a wide operation window [25].

With a near-wheel drive configuration, an important consideration is the number of gear speed reductions that power from each motor has to pass through before reaching the wheels [28]. The energy losses of the near-wheel drive topology for a BET decrease with an increase in the number of gears in the transmission [30]. However, this increases the vehicle purchase and maintenance costs [25]. The torque-speed curve of electric motors is ideal for automotive traction purposes [24]. Hence, a single/dual-speed gear reduction could be sufficient to provide a suitable consideration of vehicle performance requirements and vehicle costs. In Ref. [25], the various transmission topologies were compared. Dual-speed gear reduction with a near-wheel drive layout was found to be a suitable choice for BETs. A two-speed transmission for EV applications was further supported in Ref. [31]. When considering distributed drive systems, another question to address is the number of electric motors used to propel the vehicle. With the adoption of a distributed drive system, a considerable step up in vehicle performance is observed with the transition from single to dual electric motor architecture [31]. However, when more than two motors are integrated into the BET architecture, the additional costs associated with the added motors are likely to outweigh the performance improvement [25]. From Tab. 4 [32], it is evident that the tri/quad motor layout is far from the industry standard. Hence, congruent with overall design philosophy, a dual-motor architecture with a distributed drive system is suitable for MD/HDBET applications.

Tab. 4 Characteristics of basic EV battery types

Battery type	Nominal voltage/V	Energy density /(W • h/kg)	Volumetric energy density/(W • h/L)	Specific power/(W/kg)	Life cycle	Self-discharge per month (%)	Operating temperature/℃
Lead acid (Pb-Acid)	2	35	100	180	1 000	<5	−15-50
Nickel-cadmium (Ni-Cd)	1.2	50-80	300	200	2 000	10	−20-51
Nickel-metal hydride (Ni-MH)	1.2	70-95	180-220	200-300	<3 000	20	−20-62
Lithium-ion (Li-ion)	3.6	118-250	200-400	200-430	2 000	<5	−20-60

In conjunction with these findings, the optimum transmission topology for MD/HDBET is considered to be a near-wheel transmission with a two-speed gear reduction powered by two electric motors. However, the Indian road freight industry is highly cost sensitive [13]. Hence, the overall cost reductions associated with the central drive topology indicate that this powertrain architecture cannot be ruled out for the near-term development of BET models.

3 BET powertrain components

3.1 Battery system

3.1.1 Traction battery

EV batteries are rechargeable batteries used in power traction motors and the auxiliary electronic system of vehicles. EV batteries constitute a crucial part of vehicle powertrains [32]. The range anxiety linked to battery technologies of EVs is seen as a major limiting factor to their widespread adoption. With this in mind, EV traction batteries have become an area of considerable research and development [33]. Until recently, BETs were seen as impractical because of the low energy density of batteries and the high energy requirements of freight transportation. Continuous improvements in battery prices and technologies [34-35] have played a significant role in changing this perception. An ideal MD/HDBET traction battery must possess the following characteristics [36].

(1) High energy density.

(2) High power density.

(3) Long calendar life.

(4) Low costs.

(5) Low self-discharge rate.

(6) Wide thermal range of operation.

(7) Good safety and stability parameters.

At a commercial level, the following basic rechargeable battery chemistries have been applied for vehicle traction purposes: lead-acid, Li-ion, nickel-metal hydride (NiMH), and nickel-cadmium (NiCd) [37]. Tab. 4 shows the basic technical characteristics of these principle battery types [32].

It is evident that Li-ion technologies offer the highest specific energy and power as well as a comparatively healthy life cycle [38]. Because of these factors, Li-based chemistries have been identified by academia and OEMs as the most promising near-medium-term solution as traction batteries for EVs [39].

Lithium-based batteries encompass a family of various battery chemistries. Each specific chemistry employs various combinations of cathode, anode, and electrolyte materials. The different constituent battery materials lend the battery their distinctive characteristics in terms of energy density, power density, cost, life-cycle, etc. Lithium-ion battery chemistries typically derive their name from the underlying cathode material, as they have the largest influence on battery performance [40]. For EV powertrain purposes, relevant Li-ion technologies include layered lithium cobalt oxide (LCO), spinel structure lithium manganese oxide (LMO), non-layered cathode lithium iron phosphate (LFP), advanced layered lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC) [39]. A comparison of Li-ion batteries based on cathode material is presented in Tab. 5 [41]. LCO batteries are typically used to power consumer electronics.

Tab. 5 Summary of Li-ion batteries based on cathode material

Parameter	NMC	NCA	LCO	LMO	LFP
Energy density	4	5	3	1	1
Power density	4	5	2	5	5
Safety	2	1	1	4	5
Stability	5	5	4	1	5
Cost	2	2	1	4	5

LMO is a relatively mature technology applied in the previous generation of EVs [39]. Pure LCO or LMO batteries are no longer used in traction battery applications, as can be seen in Tab. 6. Conversely, LFP chemistries have been applied in Chinese EV markets and have a reputation as the safest Li-ion battery chemistry available [42]. However, the energy density of this battery technology is still insufficient to meet long-distance MD/HDBET requirements.

Based on the above considerations, LCO, LMO, and LFP technologies may be considered unsuitable for MD/HDBET applications. This leaves NCA and NMC chemistries as suitable candidates for use in MD/HDBET powertrains.

NCA is a relatively new chemistry. NCA batteries possess a very high specific energy of 205 mA • h/g at 4.3 V, good specific power, and a reasonable life span [39]. NCA has been successfully implemented in Tesla vehicles to allow for longer-range PEVs. However, as shown in Tab. 6, this technology has not been widely adopted by OEMs. NCA batteries have a lower life cycle than those based on NMC chemistry [37]; this is an important factor from the perspective of the MD/HDBET powertrain. The NCA chemistry also poses the highest risk of thermal runaway compared with other battery technologies [42]. NMC batteries are one of the most successful Li-ion systems, combining high capacity from nickel and low internal resistance from manganese. NMC technologies have been forecasted to dominate the EV battery sector in the next decade [42].

Tab. 6 Commercial battery EVs and their characteristics as per OEM websites

OEM	Model	Battery chemistry	Battery capacity /(kW·h)	Vehicle curb weight/kg	Motor type	Motor layout	Motor peak power/Hp	Motor peak torque/lb-ft	Car type
Audi	2021 e-tron	NMC	95	2 610	Asynchronous motor	Dual motor	355	414	PV
BMW	BMW i3	NMC	42.24	1 348	PMSM	Single motor	168	110	PV
BYD	e6	LFP	82	2 420	PMSM	Single motor	121	332	PV
BYD	Qin Pro EV Standard Edition	LFP	53.1	1 490	PMSM	—	134	133	PV
Chevrolet	Chevrolet Bolt EV Standard	NMC	66	1 616	PMSM	Single motor	200	266	PV
Hyundai	Kona Electric	NMC	39.2	1 535	PMSM	Single motor	134	291	PV
Hyundai	2020 IONIQ Electric SE	NMC	38.3	1 435	PMSM	Single motor	134	218	PV
KIA	Soul EV 2018	NMC	27	1 554	PMSM	Single motor	110	210	PV
Mercedes-Benz	EQC 400 4MATIC	NMC	80	2 485	Asynchronous motor	Dual motor	408	516	PV
MG	ZS EV	NMC	44.5	1 518	PMSM	Single motor	140	260	PV
NIO	2019 SE6 Standard	NMC	70	2 345	PM motor	Dual motor	428	450	PV
Nissan	2021 Leaf SL Plus	NMC	62	1 646	PMSM	Single motor	214	250	PV
Porsche	Taycan Performance	NMC	79.2	2 050	PMSM	Dual motor	402	255	PV
Renault	ZOE Play	NMC	52	1 577	PMSM	Single motor	108	166	PV
Tata	Nexon EV	NMC	30.2	1 400	PMSM	Single motor	127	180	PV
Tesla	Model 3 Standard Plus	NCA	54	1 624	PMSM	Single motor	283	330	PV
Tesla	Model S Long Range	NCA	100	2 068	IM/PMSM	Dual motor	670	560	PV
Volkswagen	2020 e-Golf	NMC	35.8	1 615	PMSM	Single motor	134	214	PV
Mahindra	e20 p2	LFP	280 A • h	973	IM	Single motor	25	51	Low-speed PV
Mahindra	MAHINDRA TREO-HRT	—	7.37	377	PMSM	Single motor	10.7	31	3-wheeler
Piaggio	Apé E-City	Swappable batteries	4.5	389	PM motor	Single motor	7.2	21.4	3-wheeler
Omega Seiki Mobility	Range+	—	7.5	480	PM motor	Single motor	6.4	59	3-wheeler
Hero Electric	Optima LA	Lead Acid	0.96	86	BLDC hub motor	Single motor	0.33	—	2-wheeler
Hero Electric	Flash LX	—	1.536	69	BLDC hub motor	Single motor	0.33	—	2-wheeler
Okinawa	Praisepro	—	2	150	BLDC hub motor	Single motor	3.3	—	2-wheeler
Ultraviolette	F77	—	4.2	158	PMSM	Single motor	33.5	330	2-wheeler
BYD	C9	LFP	324	14 000	PMSM	Dual motor	483	2 213	Bus

（Continued）

OEM	Model	Battery chemistry	Battery capacity /(kW·h)	Vehicle curb weight/kg	Motor type	Motor layout	Motor peak power/Hp	Motor peak torque/lb-ft	Car type
Volvo	7900 Electric	—	330	19 500 (GVW)	—	—	269	14 013	Bus
E-force	EF18	NMC	170-360	18 000	Hybrid synchronous motor	—	590-737	2 987	Truck
BYD	8TT	LFP	435	11 500	PMSM	—	483	1 770	Truck
BYD	T9SJ	LFP	217	9 726	PMSM	Dual motor	402	811	Truck
Cummins	Aeos	—	140	8 200	Asynchronous motor	Dual motor	—	—	Truck
Freightliner	eCascadia	—	475	37 194 (GVW)	—	—	360-525	—	Truck
Emoss	EMS 1820	—	200	7 300	—	—	308	—	Truck
Volvo	FL Electric	—	300	16 000 (GVW)	—	—	268	781	Truck
Renault Truck	D Z.E.	—	200-300	16 000 (GVW)	—	—	248	313	Truck
Tesla	Semi	—	~1 000	36 000 (GVW)	—	Quad motor	~1 000	~2 000	Truck
Lange Aviation	Antares 21E	—	21 A • h	480	BLDC motor	—	57	160	Glider aircraft
Electric Aircraft Corporation	ElectraFlyer-U LS	—	3.3-6.6	111	—	—	20	—	Glider aircraft

By incorporating more nickel and altering the metal ratios of the cathode, higher-capacity NMC batteries can be created. Previous NMC batteries have lower energy densities than do NCA batteries. With an operating voltage of 4.3 V, the specific capacity can vary from 160 mA • h/g for NMC111 to 170 mA • h/g for NMC532 to 180 mA • h/g for NMC622. The new generation of NMC batteries has an energy density that is comparable to that of NCA; the specific capacity of NMC811 is 200 mA • h/g at the same operating voltage of 4.3 V [39]. Although the energy density of the NMC batteries is slightly lower than that of the NCA type, as shown in Tab. 6, it is apparent that the former chemistry is the industry standard. Further, when weighed against NCA chemistry, NMC batteries provide further benefits of better thermal safety [39] and higher life cycles [42]. These characteristics are particularly desirable for MD/HDBETs.

From the above literature, it is evident that the NMC chemistry offers the best solution for the MD/HDBET powertrain system in congruence with the underlying design philosophy of this article.

3.1.2 Battery management

After the battery pack is selected for the vehicle, it is necessary to have systems to ensure safe and reliable functioning of the battery [43]. This is the task of a battery management system (BMS). The BMS is an integral part of the overall battery system [44]. Undesirable conditions, such as overcurrent, overvoltage, overcharging/discharging, and high/low temperatures, can lead to significant safety and performance issues for batteries [45]. The BMS manages battery operations to prevent and tackle these conditions [46]. The primary functions of the BMS are as follows: cell monitoring, battery safety and protection, SOC estimation, SOH estimation, charging control, and thermal management [43].

Thermal considerations are crucial for vehicles that utilize large battery packs [47]. Furthermore, India experiences relatively high ambient temperatures [48]. Hence, it is prudent to specifically examine the thermal management system (TMS) aspect of BMS systems when considering BETs in the country. Optimized TMS is required to ensure battery safety and efficiency [47]. The Li-ion battery performance is significantly influenced by the temperature. For practical applications, Li batteries must not be allowed to stray beyond an upper limit of 40 ℃ and a lower limit of −15 ℃ [47]. Beyond these temperatures, Li batteries are exposed to risks of thermal runaway or sub-zero temperature operating performance [47].

TMS employs battery models to accurately measure the thermal behavior [46]. Based on the feedback from this model, TMS applies mechanisms that react to the thermal dynamics of the battery [46]. Battery thermal management strategies can be either internal or external, and they are further classified as active or passive [49]. Because of the high thermal management demands of BETs [50], only external cooling strategies are relevant.

External thermal management strategies can be categorized based on their respective cooling mediums, namely, air cooling/heating, liquid cooling/heating, and phase change material (PCM) cooling/heating [47]. Strategies utilizing air may be ruled out for BETs from the outset because of the poor cooling capabilities of air [49]. PCM cooling is a passive cooling strategy. This system has the potential to minimize parasitic energy usage [49]. However, passive systems are not robust enough to meet the cooling requirements of BETs in India [50].

This leaves liquid cooling as a suitable strategy for BET thermal management in India. Liquid cooling allows for a high rate of heat transfer while maintaining a uniform battery temperature. The relative compactness of the system is an added benefit to liquid cooling [47]. These characteristics are essential for large battery packs. A drawback of liquid cooling is its associated cost [47]. However, as indicated in Ref. [50], to facilitate the electrification of trucks in India, they must be equipped with a highly robust TMS. Hence, liquid cooling is the best TMS for MD/HDBET.

3.2 Traction motor

The electric motor (EM) is a crucial component of an EV powertrain; it provides the tractive force that propels the vehicle. Compared with ICEs, EMs are highly efficient for a wide operational window, emit no tailpipe pollutants, provide faster acceleration, and have a quieter operation [51]. To fulfill EV traction requirements, an ideal EM must possess the following characteristics [52].

(1) High torque and power density.

(2) Wide-speed range.

(3) Good maximum speed-to-base speed ratio.

(4) High efficiency over wide speed and torque ranges.

(5) Good overload capability.

(6) High reliability and robustness.

(7) Acceptable cost.

(8) Low acoustic noise.

(9) Low torque ripple.

The ideal torque/power-speed curve of an electric propulsion motor is shown in Fig. 3.

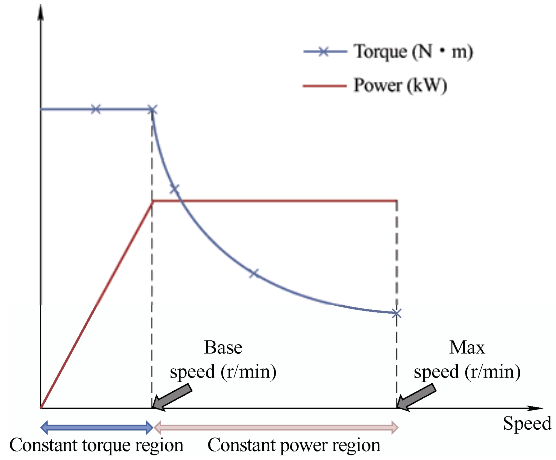


Fig. 3 Typical characteristics of an electric motor

MD/HDTs differ in their driving behavior from passenger vehicles [53]. For the specific application of MD/HDBETs, EM solutions are required to have good performance in the low-speed, high-torque region of operation.

For automotive traction purposes, the major types of EMs include brushed DC motors, induction motors, permanent magnet (PM) motors, and switched reluctance motors (SRM). Because of the low efficiencies and torque/power densities associated with brushed DC motors [54], feasible EM candidates are limited to induction motors, PM motors, and SRM [55]. A comparison of the various motor technologies is presented in Tab. 7 [55].

Tab. 7 Comparison of EMs in EVs

Parameter	DCM	IM	BLDC	PMSM	SRM
Torque/power density	-	0	++	++	0
Efficiency	-	+	++	++	+
Cost	0	++	-	-	+
Reliability	-	++	+	+	++
Size/weight/volume	-	+	++	++	+
Overload capability	-	+	+	+	+
Field weakening	++	++	-	+	++
Fault tolerance	+	++	-	-	++
Thermal limitation	0	+	-	-	++
Noise/vibration/torque ripple	-	++	0	++	-
Lifetime	-	++	+	+	++
Future potential	-	++	0	++	++

3.2.1 Induction motor and SRM

The induction motor (IM) is a mature technology. The IM is known for its simplicity, low cost, ruggedness, and high reliability [56]. However, the energy efficiency, power density, and power factor of IM motors are lower than those of PM motors as a result of inherent rotor losses. Furthermore, the IM achieves peak efficiency at higher speeds and low-torque conditions [55]. This operation window is not suitable for freight vehicles.

SRMs offer a torque-speed curve that is better suited for automotive traction purposes [57]. SRM technology is characterized by its robust mechanical construction, reliability, low cost, and torque/power density comparable to EM. A major drawback of SRM technology is that it suffers from high acoustic noise, vibration, and torque ripple. The efficiency and torque/power density of the SRM are not on par with those of the PM motors [55]. Another important point considering the overall design outline of this article is that this technology is yet to be applied in the commercial EV market [54].

In accordance with the above literature, SRMs and induction motors may be discounted as ideal EM solutions for the MD/HDBET powertrain. As a result, PM motors are left as the remaining option for BET applications.

3.2.2 PM motors

The minimal size and weight of an EM are typically achieved with permanent magnetization. PMs in the rotor induce magnetic fields in the air gap without excitation currents. This leads to a high power density [58]. The primary drawback of PM machines is the high cost of rare-earth magnets. PM machines are suitable candidates for EVs and today dominate the market [55].

PMs can be further classified as brushless DC (BLDC) or permanent magnet synchronous motors (PMSMs). BLDC motors work with trapezoid back-current waves, whereas PMSMs use sinusoidal current waves [57]. Comparatively, PMSMs offer better efficiency parameters [54]. Although PMSMs lack a wide power region, MD/HDT applications are acceptable because they have a limited operation window [53]. Additionally, from Tab. 6, it is evident that PMSMs are the most popular choice of EM among OEMs. As shown in Fig. 4, PMSMs can be further classified as surface or interior PMSM machines. This classification depends on the placement of PMs, either inside or on the surface of the rotor. Compared with surface permanent magnet (SPM) machines, interior permanent magnet (IPM) machines offer better mechanical robustness and overload capability. In addition, IPM motors provide an extended flux-weakening region because of the reluctance torque component, which increases the torque density [55].

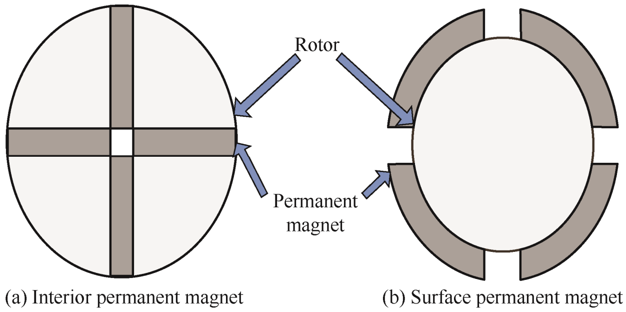


Fig. 4 PMSM classification

In further support of BET applications, internal permanent magnet synchronous motors (IPMSMs) operate at maximum efficiency in the low-speed high-torque range [59]. In Ref. [60], IPMSM was suggested as a suitable candidate for MD/HDBETs. Hence, because of its superior efficiencies and torque/power densities, the IPMSM is considered a suitable EM choice for the MD/HDBET powertrain.

3.3 Power electronics

Power conversion and control functions form the basis of power electronics (PE) in EVs [61]. The PE apparatus is responsible for handling a significant portion of the energy usage of EVs. Hence, PE represents the key enabling technologies in the EV powertrain [62]. The characteristics that are sought after in PE systems are as follows.

(1) High efficiency.
(2) Good dynamic performance.
(3) High power factor.
(4) Lightweight.
(5) Compact design.

An outline of EV design and modeling is presented in Ref. [15]. In accordance with Ref. [15], the following PE components are examined for EV powertrain modeling: ① bi-directional inverter, ② bi-directional DC/DC converter, and ③ front-end AC/DC converter. The primary PE component requirements of the MD/HDBET powertrain are the same as those of all EVs, i.e., efficiency and performance. Hence, this study only focuses on examining the efficiencies of these components for powertrain modeling. The efficiency values examined for the PE components are compared with the values for the respective PE components in Ref. [15].

3.3.1 Inverter

The inverter is a bi-directional converter that accepts the DC voltage from the traction battery and converts it into the three-phase AC voltage suitable for the EM. During the regenerative breaking period, the energy produced by the motor/generator is transferred to the battery through the inverter [31].

A comprehensive analysis of inverter topologies with various semiconductor materials was conducted in Ref. [63]. The performance of the SiC-based inverter over various drive cycles was examined. The study showed that the inverter setup with a SiC MOSFET is more efficient than an IGBT in the entire operating region. The efficiency of a SiC MOSFET-based inverter ranges from 97%-98% [63]. Note that the efficiency value of the SiC-based inverter in Ref. [63] is consistent with the values used in Ref. [15] (η_i=0.98), where η_i is the inverter efficiency.

3.3.2 DC-DC bi-directional converter

A DC-DC converter is a bi-directional device used to control the voltage of the battery and motor systems. Other functions of the DC-DC converter include optimizing the operation of the powertrain system, reducing the ripple current in the battery, and regulating the DC-link voltage to the inverter [64]. The efficiencies of an electric powertrain with and without a DC-DC converter were compared in Ref. [65]. The results showed that incorporating a DC-DC converter can significantly improve the global powertrain efficiency. Subsequently, the DC-DC converter topology requires less battery output. As with the inverter, DC-DC converter semiconductor switches are shifting toward SiC-based MOSFETs. The efficiencies of SiC MOSFET, hybrid, and IGBT DC-DC bi-directional boost converters were analyzed in Ref. [64]. The study demonstrated that SiC MOSFET-based DC-DC converters are the most efficient solution. The all-SiC design had overall efficiencies of 98.96%, 99.15%, and 99.34% for full, 75%, and 50% loads, respectively [64]. These efficiency values for the DC-DC converter are slightly higher than those presented in Ref. [15] (η_d =0.98), where η_d is the DC-DC converter efficiency.

3.3.3 Front-end AC-DC converter

The front-end AC-DC converter is a crucial component of the EV charging architecture [66]. The vehicle charging time is influenced by the charger characteristics [67]. The front-end AC-DC converter in an EV converts the AC current from the grid to the DC current to charge the traction battery. A boost circuit is added to this converter to improve power quality, which is known as a power factor correction (PFC) converter [68]. A two-stage PFC is relevant for Li-ion battery charging. In this system, the AC-DC and PFC stages of the PFC converter rectify the input AC voltage and transfer it to a regulated intermediate DC-link bus. In addition, a PFC is achieved [69].

Different two-stage PFC topologies can be found in Ref. [68]. Principle topologies include the conventional boost converter, interleaved boost converter, semi-bridgeless boost converter, and bridgeless interleaved boost converter. PFC converter topologies were evaluated in Ref. [69], while PFC converter topologies were compared in Ref. [68]. Both studies found the bridgeless interleaved boost converter to have the highest efficiency and input power factor. The peak efficiency of the Bridgeless interleaved boost converter studied in Ref. [69] was determined to be 98.7%. This efficiency value for the PFC converter is on par with the values utilized in Ref. [15] (η_r=0.98), where η_c is the front-end charger efficiency.

4 Types of charging infrastructure

In addition to battery technology and vehicle pricing, charging infrastructure is seen as a significant barrier for EV penetration into automobile markets [70]. To make the transition to MD/HDBETs from a fleet operators' perspective, confidence in national/regional charging infrastructure is a prerequisite. Improvements in EV charging technologies can offset the requirements of large traction batteries. The following characteristics are desired in ideal EV charging system technologies.

(1) High efficiency.

(2) High power density.

(3) Excellent safety parameters.

(4) Wide and uniform thermal operation window.

(5) Low distortion.

(6) Fast charging times appropriate to charging power levels.

EV charging is classified based on power levels. An overview of the EV charging levels is presented in Tab. 8 [67, 71].

Tab. 8 EV charging levels

Charging type	Charger location	Voltage/V	Current/A	Power level/kW
Level I	Onboard	120	16	1.92
Level II	Onboard	240	80	19.2
DC fast charge	Off-board	⩾200	⩾400	⩾240

EV charging can be categorized into levels 1, 2, and 3 for AC or DC charging. Considering the limitations of the present EV charging times, it is possible that BETs would require separate dedicated charging infrastructure capable of rapid charging of large battery packs [26]. However, examining such novel charging setups and equipment is beyond the scope of this study, which analyzes BET charging considering the present EV charging infrastructure and power levels.

Level 1 charging is unsuitable for commercial vehicles because of the long charging times. With this in mind, it was suggested in Ref. [8] that BETs could utilize level 2 charging for overnight charging, and level 3 charging could support mid-trip charging. However, this prevents the option of overnight BET operation. The inability to operate BETs through the night under such a charging scheme might not always be practical in the Indian scenario. This is because the average speed of MD/HDTs in India is relatively low [71]. As a result, to cover the required daily distances, these vehicles are often operated at night [71]. Furthermore, India does not enforce regulations on driving hours for truck drivers, leading them to drive frequently during the night [71]. Hence, while not all trucks in the country are required to be operated overnight, to keep this option open, charging for these vehicles in India could rely on DC level 3 fast charging, with level 2 charging being utilized primarily during long dwell periods. Therefore, DC fast charging for EVs is further examined. Efficiency values for levels 2 and 3 charging are also obtained.

4.1 Charging protocols

The next consideration regarding DC fast- charging systems for EV charging is the specific charge connectors and protocols that are utilized. From the selection of EV charging connectors available globally, as shown in Tab. 9, the Indian Ministry of Power recommends the following DC fast charge connectors for the Indian EV charging infrastructure: combined charging system (CCS) and CHArge de Move (CHAdeMO) [72-74]. Either of these DC quick charge (DCQC) protocols can be utilized by MD/HDBETs.

Tab. 9 Recommended charging infrastructure for India, MoP

Charger type	Charge connector	Rated output voltage/V
Fast	Combined charging system (CCS) (min 50 kW)	200-750 or higher
Fast	CHArge de Move (CHAdeMO) (min 50 kW)	200-500 or higher
Fast	Type-2 AC (min 22 kW)	380-415
Slow/Moderate	Bharat DC-001 (15 kW)	48
Slow/Moderate	Bharat DC-001 (15 kW)	72 or higher
Slow/Moderate	Bharat AC-001 (10 kW)	230

4.1.1 CHArge de Move

CHAdeMO is a DCQC protocol developed in Japan. The CHAdeMO protocol is currently capable of charging EVs with power from 6-400 kW [73]. The CHAdeMO protocol uses a CAN communication system for communications through the charger and vehicle. The charge sequence of the CHAdeMO protocol is as follows: at the commencement of the charging routine, the CAN communicator conducts initialization tests. After these tests are successfully cleared, charging can commence. Charging power may repeatedly vary according to protocol checks run through the CAN communicator. After the charging is finalized, the unlocking sequence is executed. Finally, the vehicle may unlock from the charger [75]. Throughout vehicle charging, the CHAdeMO protocol addresses these primary technical considerations: ① battery protection, ② protection from electrical shock,③ fail-safe charging control, and ④ connector interlock [73]. The CHAdeMO protocol has the added benefit of being future-proof by supporting bi-directional charging [73]. Large-scale adoption of the CHAdeMO infrastructure could provide a much-needed boost for the viability of long-distance MD/HDBET transportation.

4.1.2 Combined charging system

CCS is another charging protocol implemented by the Society of Automotive Engineers (SAE) and maintained by the CharIN group, which represents a consortium of European vehicle manufacturers [72]. Two types of CCS connectors are available: types 1 and 2. Type 2 chargers have been standardized as CCS connectors for India. Similar to the CHAdeMO standard, CCS is capable of charging EVs at power levels up to 350 kW. Unlike CHAdeMO, CCS uses Homeplug Green PHY protocols for charger and vehicle communication. Homeplug Green PHY is a type of powerline communication (PLC) protocol. The charging sequence of the CCS protocol was described in Ref. [76]. A unique characteristic of the CCS standard is that it is capable of facilitating AC charging, as well as DCQC, with the same connector [77]. This negates the need for multiple connector ports in EVs. The combination of AC charging and DCQC is beneficial for simplifying the MD/HDBET powertrain and trip planning.

4.2 Charging efficiency

EV charging efficiency values are required to conduct BET feasibility studies. It is useful to examine the percentage of power drawn from the electric grid that is actually taken up by the vehicle battery. These values can help estimate BET charging times. The literature regarding level 2 and level 3 charging efficiency is examined, as they are relevant to MD/HDBET feasibility studies.

The efficiency of level 2 AC charging (240 V) was evaluated in Ref. [78]. The study concluded that, on average, without considering the influence of temperature, the efficiency of level 2 AC charging was 89.4%. The efficiency of level 2 charging was also found to be higher than that of level 1 charging [78]. This further supports the assumption that level 1 charging is not suitable for BETs. The DCQC efficiency is even greater than that of level 2 charging. DCQC with a CHAdeMO connector was found to attain an efficiency of 92.6% in Ref. [79]. However, this finding did not incorporate the effect of temperature on the DCQC. At ambient temperature (25 ℃), the efficiency of DCQC was established to be approximately 90% in Ref. [80].

From the above literature, an average value of 90% may be assumed as the efficiency of EV levels 2 and 3 charging at ambient temperature. It should be noted that the charging efficiency values selected for the MD/HDBET feasibility study are comparable to the values used in prior BET studies [20, 22].

5 Energy consumption study

Simulations have been established as a cost- and time-effective solution for calculating vehicle energy consumption and performance. To determine the energy consumption of a vehicle, an accurate model must be designed [81]. The vehicle model presented in this article was developed in the Matlab®/ Simulink® environment. Matlab® and its derived software are powerful computing tools that have become the de facto standard for research and industry-level simulation work. The vehicle model used in this study is shown in Fig. 5. The model was adapted from Ref. [82] with input from the vehicle model presented in Ref. [83]. For this study, a simulation study was designed to model a typical MDBET tracking standard drive cycle. The electrical energy consumption of the BET following the input speed trace was calculated. The information presented in Sections 2-4 of this article was utilized to parameterize and develop the BET model.

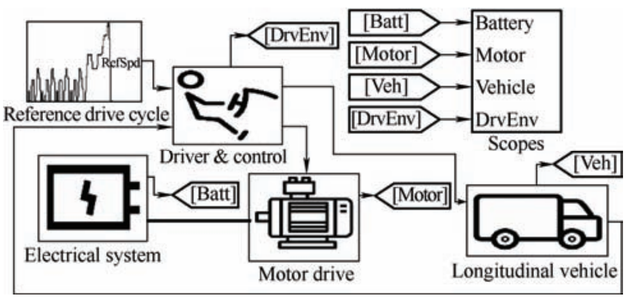


Fig. 5 BET model

5.1 BET model

As explained in Section 2, this study focuses on MD/HDBETs. The TATA LPT 1109 was the highest-selling rigid truck model in India in 2013—2014 [84]; this model falls into the group of an MCV. Hence, the vehicle class considered in the simulation study is the MCV category. Likewise, the specific vehicle body and chassis of the simulated BET were parameterized to b similar to the TATA LPT 1109 model [85-86].

There would be changes in truck curb weight because of the substitution of the ICE and related equipment with battery-electric powertrain systems.

The resulting weight change was estimated based on component assumptions proposed in Ref. [87]. In the baseline case, the BET model was assumed to operate under the maximum payload condition.

The BET model was designed with a single motor and differential layout. As pointed out in Section 2, the central drive system is not the most efficient approach [11]. However, this is the most cost-effective solution [27]. Road freight is a very cost-sensitive industry in India [13]. Hence, the central drive system could be more relevant to the country.

The powertrain examination sections of this article were used to guide the selection of the electrical components for the BET model. The model was simulated with a 250-kW PMSM machine [88], which was in turn powered by a 197.17-kW·h NMC [89] battery pack through a DC-DC converter. The modeled truck also made use of an ultracapacitor to account for the temperature extremities experienced in different parts of the country.

The salient BET parameters employed in the simulation study are listed in Tab. 10.

Tab. 10 BET model parameters

Vehicle parameter	Value
Gross vehicle weight/kg	12 000
Vehicle curb weight/kg	5 700
Max vehicle speed/(km/h)	100
Drag coefficient C_d	0.65
Frontal area/m^2	5.5
Wheel radius/m	0.5
Final drive ratio	8.5
Coefficient of rolling resistance	0.008 8
Battery storage/(kW·h)	197
Max motor torque/(N·m)	900
Max motor power/kW	250
Transmission efficiency (%)	97
Motor efficiency (%)	95

5.2 Drive cycle

Standard drive cycles represent speed versus time data that are utilized for vehicle emission and energy consumption testing. Driving patterns have a significant impact on the vehicle energy consumption [90]. Hence, it is important to select a driving schedule that represents Indian conditions. For the purpose of this simulation study, the MIDC, a drive cycle that is stipulated by ARAI, was selected [16], as shown in Fig. 6. In addition, results from other international heavy-duty drive cycles, including WHVC, HUDDS, NREL 6 EV cycle, and HHDDT, are also presented. The BET model completed the above speed traces assuming zero road-grade conditions.

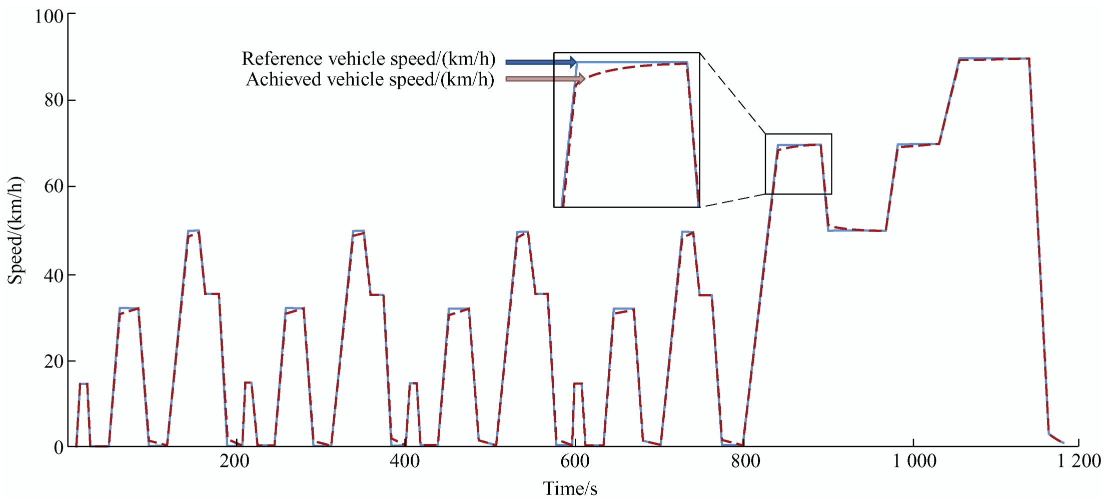


Fig. 6 BET tracking MIDC

5.3 Results

The energy consumption of the BET is represented in terms of kW • h/km. Fig. 7 shows the energy consumption of the BET under full-load conditions over the various drive cycles.

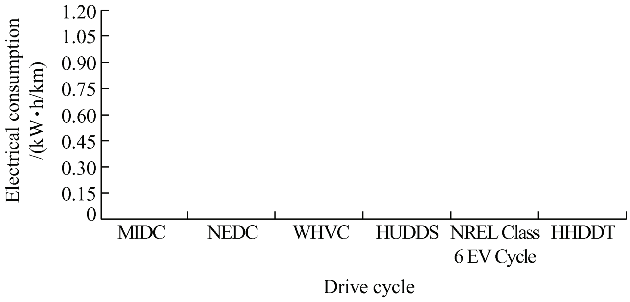


Fig. 7 BET energy consumption over various drive cycles

Across the MIDC, the BET showed a consumption of 0.884 3 kW • h/km.

Indian driving conditions are characterized by low speeds combined with frequent start-stop scenarios [10]. EVs can recover energy during deceleration. Hence, such conditions are conducive to reducing energy consumption per km. Accordingly, it is apparent in Fig. 6 that the MIDC has the least energy consumption compared with the other drive cycles.

The consumption values in Fig. 7 represent BET under full-load conditions. Of course, in real life, this is not always the case. Hence, Fig. 8 displays the impact of the payload weight on the BET energy consumption over the MIDC. As expected, there is a linear relationship between the two, whereby energy consumption steadily increases with payload.

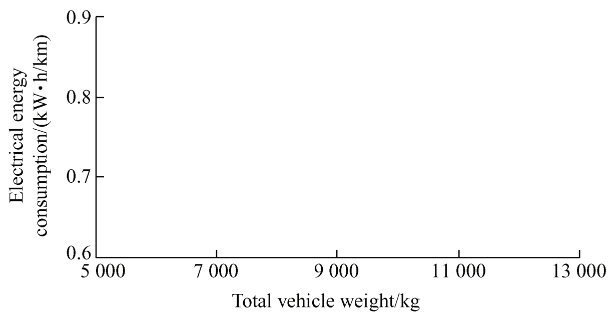


Fig. 8 Variation of BET energy consumption with increasing payload weight

Where E is the energy consumption, m is the mass of the vehicle, v is the velocity of the vehicle, and g is the gravity constant. It is worth noting that the BET consumption figures presented in this article are in conjunction with those estimated in Ref. [91]. A potential limitation of this simulation is that it only considers the results of a single BET model. Different BET classes or powertrain layouts/technologies were not considered. This could be addressed in future studies.

6 Conclusions

Significant research is required to evaluate the potential of electrification as an option for road freight in India, which has outlined ambitious plans to secure the future for EVs in the country. Accordingly, this article addresses BET technology and its operation in India; the article discussed BET powertrain considerations as well as vehicle energy consumption.

As a precursor to the energy consumption study, Sections 2-4 of this article examined available powertrain systems and components for selecting and modeling a BET powertrain. EVs offer flexibility in terms of powertrain configuration and component selection. This article scrutinized the EV powertrain systems and the considerations outlined in Ref. [15]. The optimal powertrain topology for a BET was found to be a distributed drive system coupled with two EMs and a two-speed gear reduction for each EM. Various EV traction batteries and motor technologies were also compared for BET applications. The Li-ion NMC battery and IPMSM were determined to be the optimal technologies, considering the performance requirements of the BETs. The battery and motor pairing represents the EV industry standard. The efficiencies of the relevant PE systems were also reviewed for the BET powertrain. This study additionally examined EV charging systems and infrastructure guidelines in India. Level 2 and level 3 charging efficiencies were considered for MD/HDBET applications.

Currently, there is limited technical information available on BETs [11]. Considering this, the powertrain system information presented in this article could assist component selection decisions for future BET modeling studies. The simulation study presented in this article determined the energy consumption of an MDBET under an Indian drive cycle. The BET model for the simulation was designed utilizing the information available in the previous sections of the article. The BET simulation determined an electrical energy consumption of 0.884 3 kW • h/km over the MIDC.

BET energy consumption data are required for a variety of vehicle analysis studies. Future studies could utilize the results of this study to provide valuable insights into the economic and environmental feasibility and practicality of electric trucks in the country. These insights could empower drive fleet managers, policymakers, and other industry stakeholders to arrive at informed decisions when considering BETs as a future direction for road freight transportation in the country.

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