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Office of the Principal Scientific Adviser
to the Government of India

LANDSCAPE STUDY OF E-DRIVES FOR ZERO EMISSION TRUCKING (Challenges & Solution Paths)

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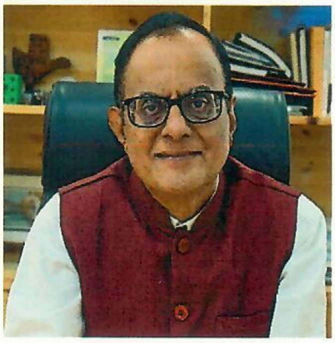
अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

सत्यमेव जयते

कर्तव्य भवन 3, जनपथ, नई दिल्ली - 110001
Kartavya Bhavan 3, Janpath, New Delhi-110001
Tel. : +91-11-24011867, 24011868
E-mail : sood.ajay@gov.in, office-psa@nic.in
Website : www.psa.gov.in



FOREWORD

India is poised at a pivotal moment in its freight transportation journey, embracing the shift towards e-mobility in alignment with our national commitment to achieving net-zero emissions by 2070. As we accelerate the adoption of Zero-Emission Vehicles (ZEVs), electrification of freight transport emerges as a key enabler for reducing greenhouse gas emissions, improving air quality, and strengthening energy independence.

Recognising this imperative, the Office of the Principal Scientific Adviser released the Technical Roadmap for Deployment of Zero-Emission Trucking in India, outlining targeted strategies for decarbonizing freight transport. A critical action point from this roadmap is the evaluation and adoption of rare earth magnet-free electric motors, which can reduce reliance on resource-constrained materials while supporting cost-effective and sustainable manufacturing.

This report, **"Landscape Study of e-Drives for Zero Emission Trucking (Challenges & Solution Paths)"**, is a product of rigorous analysis and stakeholder consultations. It provides in-depth insights into emerging motor technologies, their applicability in heavy-duty trucking, and the roadmap for reducing dependence on rare earth magnets. The findings presented herein are intended to inform policymakers, guide industry investment, and support innovation in India's e-mobility ecosystem.

I commend the teams involved for their dedicated effort and collaboration with industry, academia, and research institutions. I trust that stakeholders across government, industry, and civil society will draw on the insights of this report to support our shared goal of building a clean, resilient, and future-ready freight sector.

(Ajay K Sood)

Date: 21st October 2025

डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव
Dr. (Mrs) Parvinder Maini
Scientific Secretary

सत्यमेव जयते

भारत सरकार के
प्रमुख वैज्ञानिक सलाहकार के कार्यालय
कर्तव्य भवन 3, जनपथ, नई दिल्ली - 110001
Office of the Principal Scientific Adviser
to the Government of India
Kartavya Bhavan 3, Janpath, New Delhi-110001

MESSAGE

Electrifying road transport, especially in the freight sector, is essential for promoting environmental sustainability and strengthening energy security. The Office of the Principal Scientific Adviser to the Government of India has taken proactive steps to address this through expert-driven initiatives. One such initiative is the formation of the Consultative Group on e-Mobility (CGeM), which has played a crucial role in developing technical and policy foundations for Zero-Emission Vehicles (ZEVs). This report, **"Landscape Study of e-Drives for Zero Emission Trucking (Challenges & Solution Paths)"** is an important outcome of these ongoing efforts.

The study captures both the technical depth and potential solution paths for emerging motor technologies that reduce dependence on rare earth permanent magnets (REPMs). By incorporating detailed drive cycle analyses, drivetrain evaluations, and expert inputs from the trucking industry, this report identifies practical pathways for motor innovation and deployment suited for India's zero emission trucking needs. The analysis is based on in-depth input from experts in the truck industry who have a comprehensive understanding of the market, its use cases, and the relevant technologies.

The insights and findings presented in this report have the potential to set news direction in electric drivetrain development domain. It not only supports decarbonization goals but also strengthens the domestic manufacturing ecosystem by encouraging innovation in motor design, material substitution, and power electronics. This is especially important in the context of global supply chain uncertainties and India's aspiration to become a global leader in clean mobility technologies.

I extend my sincere thanks to all contributors, including CGeM members and technical experts, for their valuable input. I hope this report serves as a valuable guide for policymakers, manufacturers, and investors as we navigate the path toward a cleaner, more self-sufficient future for the transport sector.

PMaini

(Parvinder Maini)

Dated: 13th October, 2025

Tel. : +91-11-24011869, E-mail : parvinder.maini@gov.in Website : http://www.psa.gov.in

Executive Summary

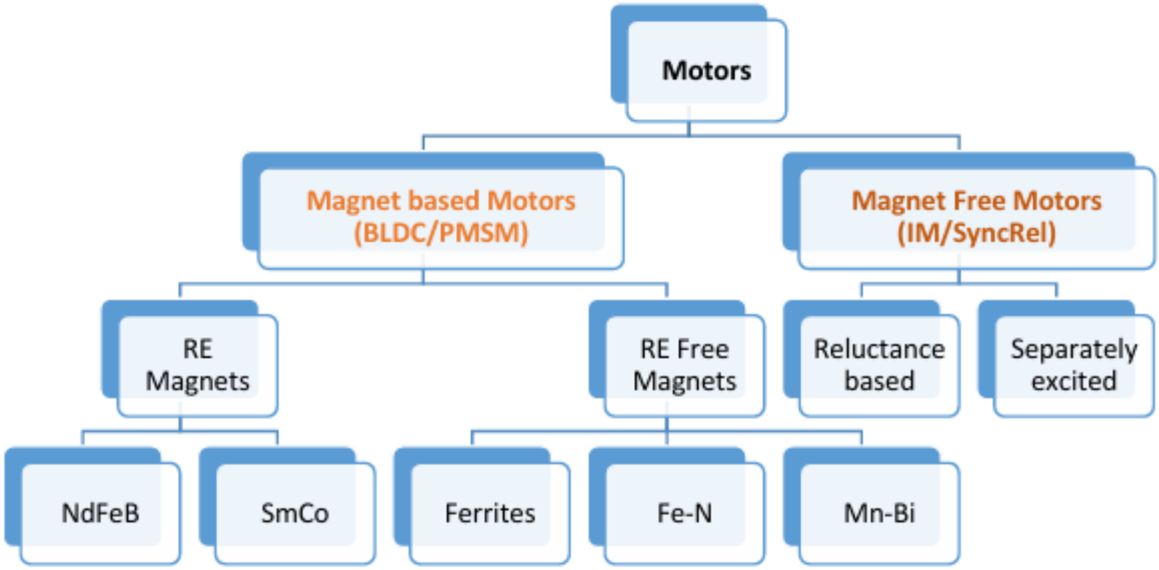
The recent rare earth crisis, sparked by China imposing stricter export controls on seven key rare earth elements and associated magnets, has received widespread media attention. However, this risk was highlighted much earlier in the *Technical Roadmap for Deployment of Zero-Emission Trucking in India*, released by the PSA's Office in March 2023. The roadmap proactively identified the potential vulnerability and recommended the evaluation of rare earth magnet-free motors for electric trucks as a priority activity.

This report, titled "**Landscape Study of e-Drives for Zero Emission Trucking (Challenges & Solution Paths)**" is the outcome of that activity. It provides a comprehensive evaluation of motor technologies that do not rely on rare earth magnets. The report also outlines the assessment criteria for traction motors meant for use in electric trucks.

India's drive to electrify its mobility sector is underpinned by four strategic imperatives: mitigating climate change, improving air quality, reducing dependence on energy imports, and establishing global leadership in next-generation mobility technologies. However, the rare earth crisis has reignited a common criticism of India's electrification efforts that it is simply shifting from dependence on oil imports to reliance on imports of other critical minerals. PSA's Office has been advocating Zero Emission Trucking as a key path to not only the nation's carbon commitments but also the bigger vision of Viksit Bharat, while highlighting the steps India must take to avoid the pitfalls on the way. Evaluation of Rare Earth Magnet-Free Motors is one of these steps.

Permanent Magnet Synchronous Motors (PMSMs) by virtue of their high efficiency, high power and torque densities, have become the de-facto technology of choice for electric vehicles in general, and for electric trucks in particular. PMSMs rely on permanent magnets made using rare earth materials such as Neodymium and Dysprosium. Rare Earth based Permanent Magnets (REPMs) such as Neodymium Iron Boron (NdFeB) and Samarium-Cobalt (SmCo) generate strong magnetic fields, retain their magnetism for long, and tolerate temperatures of 200°C. China's near-monopoly on the supply of REPMs presents significant geopolitical supply risks. Furthermore, the environmental impacts associated with rare earth mining and processing further reinforce the need to explore REPM-free motor technologies.

There are multiple alternatives to PMSMs at different levels of maturity, requiring varying level of research and developments. The classification of motors based on usage or otherwise of magnets and REPMs is shown in the Figure given below. This report covers each of these categories in varying depths depending on the current state-of-the-art and available information.



Classification of Motors based on magnet vs. magnet-free type

Mature technologies such as Induction Motors (IMs) and Synchronous Reluctance Motors (SynRMs) are completely magnet-free alternatives and are used as traction motors in electric trucks with some compromise in performance. Their evaluation against PMSM across a host of parameters is summarised in the Table below.

Quantitative Comparison of PMSM, IM & SynRM for electric trucks

Parameters	Permanent Magnet Synchronous Motor (PMSM)	Induction Motor (IM)	Synchronous Reluctance Motor (SyRM)
Principle	PMSM works in tandem with the stator's revolving magnetic field and makes use of permanent magnets on the rotor.	Rotor of an induction motor is not magnetized; instead, it induces a current through electromagnetic induction.	The SyRM does not use permanent magnets but instead relies on the reluctance torque generated by rotor design and stator excitation.
Efficiency	High efficiency, typically 90% or more, as it avoids losses associated with rotor currents.	Moderate efficiency 85-90%, lower than PMSM, due to rotor losses (eddy currents and hysteresis).	Generally higher than IM but lower than PMSM. Typically, around 85-91% efficient.
Power Density	High power density due to the use of permanent magnets, making it compact and lightweight. **3.5 kW/kg-10 kW/kg**	Lower power density compared to PMSM due to the need for larger motor volumes. **1.5 kW/kg-4.5 kW/kg**	Lower than PMSM but higher than IM due to better rotor design and less copper loss. **2 kW-6 kW/kg**

Cost	The motor is generally expensive due to the use of rare-earth magnets (like neodymium).	Generally, more cost-effective than PMSM due to the lack of rare-earth magnets.	Cost-effective as it does not require rare-earth magnets.
Maintenance	Low maintenance due to fewer moving parts but can suffer from demagnetization over time.	Relatively low maintenance due to simpler construction; no permanent magnets to demagnetize.	Similar to IM, with low maintenance requirements.
Control	Requires sophisticated control techniques like Field-Oriented Control (FOC).	Easier to control than PMSM but less efficient in operation. Typically uses scalar or vector control.	Requires vector control similar to PMSM for efficient operation.
Comparative Metrics			
Efficiency	90-96% High efficiency due to the direct magnetization of the rotor. Ideal for heavy-duty applications like trucks, where energy efficiency directly correlates with range.	85-90% Efficiency is lower due to resistive losses in the rotor and stator.	85-91% More efficient than IM, but less than PMSM due to lower rotor losses
Power Density	High As PMSMs are small and light, they can be used in applications where a high power-to-weight ratio is necessary.	Moderate Induction motors require larger volumes for the same output power due to rotor design, leading to lower power density.	Moderate to High Similar to PMSM in terms of power density but lower than PMSM.
Torque Density	Very High The interaction between the rotor magnets and the stator field produces the torque. High torque density is suitable for e-truck acceleration and hill-climbing.	Moderate Torque is generated through induced currents in the rotor, but it is lower than PMSM, requiring higher current for the same output torque.	Moderate Reluctance torque is generated, but efficiency is not as high as PMSM, and torque density is slightly lower.
Cost	High Rare-earth magnets used in PMSM significantly increase the material cost. **60-150$ (USD)/kW**	Low More cost-effective since induction motors use aluminium or copper for the rotor, eliminating the need	Moderate Lower material costs than PMSM but more expensive than IM. It doesn't require permanent magnets but uses specialized rotor designs like laminated rotor with barriers.

		for expensive permanent magnets. **20-60$ (USD)/kW**	It may require special tooling for accurate interlocking of barriers. **30-90$ (USD)/kW**
Maintenance	Low Fewer moving parts, but the magnets may degrade over time, especially if the motor operates at high temperatures for long periods.	Low to Moderate Simple construction means fewer things can go wrong, but rotor bars may wear over time and lead to faults.	Low to Moderate Similar to IM but with additional complexity in rotor design. No permanent magnets, so less risk of demagnetization. Due to non-standard shape of the rotor having barriers, on-site repair is not practical. Complete replacement is the only solution. NVH complaints due to torque ripple & low speed jerkiness are some of the practical field problems.
Reliability	Moderate to High They can suffer from demagnetization or overheating under certain conditions. **Mean Time Between Failures (MTBF) : 30k hours-60k hours**	Very High Induction motors are robust and can handle extreme operating conditions. **MTBF: 40k hours-90k hours**	High They avoid the use of permanent magnets, which can be advantageous. **MTBF: 40k hours-80k hours**
Weight and Size	Low weight and compact size due to high power density.	Larger size and weight to produce similar output power compared to PMSM.	Intermediate size and weight. It balances power density and size effectively, but it may be larger than PMSM for the same performance.
Applications for e-trucks	Best suited for: Long-range electric trucks requiring high energy efficiency, where range is a priority. Advantages: High torque and power density, best for acceleration, hill-climbing, and maintaining efficiency at highway speeds. Disadvantages: Higher initial cost since rare-earth magnets are used, and there may be problems with the	Best suited for: Budget-conscious fleet operators who prioritize cost over the highest possible efficiency or torque. Advantages: Low cost, high reliability, and robustness. The system can tolerate more challenging conditions. Disadvantages: Lower efficiency, larger size, and weight.	Best suited for: Applications that require high performance but need to avoid the high costs of PMSM while still achieving good efficiency. Advantages: Powerful and efficient without using rare-earth magnets. Disadvantages: More complex control systems are required compared to IM, and rotor design can be more challenging.

	magnets' long-term deterioration.		
Conclusion	Offers the best efficiency and power density but comes at a higher cost due to the use of rare-earth magnets.	More cost-effective and reliable, but less efficient and bulkier than PMSM.	A middle-ground solution, offering better efficiency than IM without the cost of PMSM, though it may require more advanced control systems.

This report also covers motors that use permanent magnets but do not rely on rare-earth materials. Instead, they use alternatives like ferrite magnets or ferromagnetic alloy magnets made mainly from aluminium, nickel, and cobalt (known as AlNiCo magnets). One example of such technology is the Permanent Magnet Assisted Synchronous Reluctance Motor (PMaSynRM). These technologies are already mature and require only application engineering for use in electric trucks. Other emerging rare-earth free permanent magnet technologies such as Iron Nitride (Fe-N), Manganese-Aluminium-Carbon (Mn-Al-C) and Manganese-Bismuth-Magnesium based magnets (Mn-Bi-Mg-X) hold promise but are at low Technology Readiness Levels (≤ 5).

Axial Flux Motors, Switched Reluctance Motors (SRM), separately excited magnet-free motors such as Wound Rotor Induction Motors (WRIM), and Wound Rotor Synchronous Machines (WRSM) have known challenges but cannot be ruled out with further exploration. Bar wound stator technology when applied to all these categories improves the power density as compared to the earlier technology of strand wound stators.

Since there are so many alternatives that require more detailed assessment, this report provides the methodology for such an assessment starting from basics. Practicing engineers can use the methodology and regulatory, synthetic and real-world drive cycles presented in the report to arrive at optimal motor and drivetrain design for the intended application. Specifications of electric trucks available in India and globally highlight the range in the specifications and technologies of motors used.

Electric trucks require the traction motor to respond to driver commands and provide necessary torque and operate at required speed. This requires high voltage controllers, and the report covers controllers along with other power conversion devices, their construction, requirements, technology trends such as shift towards higher voltages and wide band gap power semiconductors and challenges such as isolation, Common Mode Transient Immunity (CMTI), and thermal management.

The report concludes by describing the Noise, Vibration and Harshness (NVH) aspects of traction motors and design methodologies.

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Abbreviations

A	Amperes
AC	Alternating Current
AFIM	Axial Flux Induction Motor
AFPM	Axial Flux Permanent Magnet Motor
AIS	Automotive Indian Standard
BDU	Battery Disconnect Unit
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
BH	Energy Product
BMS	Battery Management System
B_r	Remanence
CAN	Control Area Network
C_D	Aerodynamic Drag Coefficient
CMTI	Common Mode Transient Immunity
C_{rr}	Coefficient of Rolling Resistance
DC	Direct Current
DSP	Digital Signal Processor
EV	Electric Vehicle
EM	Electric Motor
EMI	Electro Magnetic Interference
EMC	Electro Magnetic Compatibility
EMS	Energy Management System
FOC	Field-Oriented Control
FTP	Federal Test Procedure
GaN	Gallium Nitride
GPS	Global Positioning System
GVW	Gross Vehicle Weight
H_c/ H_{ci}	Coercivity
HDV	Heavy Duty Vehicles
HD-UDDS	Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles
HEV	Hybrid Electric Vehicle
HHDDT	Heavy Heavy-Duty Diesel Truck Schedule
IC	Integrated Circuit
ICE	Internal Combustion Engine
IDC	Indian Drive Cycle
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
kmph	Kilometres per hour
LCO	Lithium Cobalt Oxide
Li	Lithium
LiS	Lithium-Sulphur
LFP	Lithium Iron Phosphate
MCU	Motor Control Unit
MIDC	Modified Indian Drive Cycle
ML	Machine Learning
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NdFeB	Neodymium Iron Boron

NEDC	New European Driving Cycle
NEV	New Energy Vehicle
NMC	Nickel Manganese Cobalt
NVH	Noise, Vibration & Harshness
OBC	On-board Charger
OBD	On-board Device
PEBB	Power Electronic Building Blocks
PECU	Power Electronic Control Unit
PDU	Power Distribution Unit
PTC	Positive Temperature Coefficient
PMIC	Power Management Integrated Chip
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RE	Rare Earth
REE	Rare Earth Element
REPM	Rare Earth Permanent Magnet
RPA	Relative Positive Acceleration
SBC	System Basis Chip
SiC	Silicon Carbide
SRM	Switched Reluctance Motor
SyRM	Synchronous Reluctance Motor
TM	Transmission
UDDS	Urban Dynamometer Driving Schedule
V	Volts
W	Watts
WBS	Wide Band Gap
WHDC	Worldwide harmonized Heavy Duty Certification Procedure
WHVC	World Harmonized Vehicle Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

Glossary

Aerodynamic Drag Coefficient (C_D): It is a dimensionless number that represents the resistance an object experiences as it moves through a fluid (like air). It quantifies how easily or difficultly an object cuts through the air and depends on the object's shape, surface roughness, and flow conditions.

Coercivity (H_c / H_{ci}): Coercivity is the measure of the reverse magnetic field strength required to reduce the residual magnetism (remanence) of the magnet to zero. It tells how strongly a permanent magnet resists becoming demagnetized. High coercivity indicates magnet is hard to demagnetize (good for permanent magnets).

Coefficient of Rolling Friction (µ): It is a dimensionless constant that represents the ratio of the rolling friction force (Fr) to the normal force (N) acting on the object, expressed as $\mu = Fr/N$. It quantifies the resistance to motion of a rolling object, with a lower coefficient indicating less rolling resistance and easier rolling.

Coefficient of Rolling Resistance (C_{rr}): It is a dimensionless number that represents the ratio of the rolling resistance force to the normal load acting on a wheel or tyre. It shows how much force is needed to keep a wheel rolling compared to the weight it supports.

Energy Product (BH): It is the maximum product of magnetic flux density (B) and magnetic field strength (H) that a magnet can deliver in its second quadrant (demagnetization curve of the hysteresis loop). It represents the maximum magnetic energy stored per unit volume of the magnet, and indicates the magnet’s strength. Higher BH represents stronger magnet.

Positive Temperature Coefficient (PTC): A positive temperature coefficient means that a material’s resistance (or another property) increases as its temperature increases.

Rare Earth Element (REE): Rare earth elements are a group of 17 chemically similar metallic elements in the periodic table, consisting of the 15 lanthanides (from Lanthanum La to Lutetium Lu) plus Scandium (Sc) and Yttrium (Y). Though called “rare”, most of they are relatively abundant in the Earth’s crust, but they are rarely found in concentrated and economically exploitable forms. They are important because they are used in magnets, batteries, electronics, defence systems, and green energy technologies.

Remanence (B_r): Remanence (or remanent flux density) is the measure of the magnetic flux density that remains in the material when the external magnetizing field is reduced to zero. It represents how strongly the permanent magnet can remain magnetized on its own without any external field.

1. Introduction

Zero Emission Vehicles based on technology agnostic solutions are the Holy Grail in the electrification of transport sector. Passenger vehicles are at one end of spectrum with bulk of their duty cycle in urban circuits while on the other hand, movement of goods and services rely heavily on trucks of various payload spanning from smaller intra city commercial vehicles to heavy duty ones of 40 tons and above with 90% of duty cycle in highways with rest of the time spent in climbs and stop-go traffic. Exploration of solution paths in terms of drive train designs span a large non-linear range from as low as 2kW for e2W to 250kW and more with varying torque demands, wherein the trucks occupy the extreme end of this scale.

In the higher end of power train ratings, we find three major challenges corresponding to the three quintessential components in the propulsion system, namely motor, controller and energy device. Innovation in materials and manufacturing processes that convert the materials to devices are the key to break challenges in realizing these three devices to usher in next generation drive trains. The challenges are briefed below.

- **Motors** with high efficiency, high kW/kg and smaller size as targets moved more towards Rare Earth Permanent Magnet (REPM) based Permanent Magnet Synchronous Motor (PMSM) designs in the last two decades in all segments of vehicles. Though the quantum of REPM as a percentage of cost is typically 10% to 20% of the total drive cost, due to non-linear effect, the entire propulsion systems become a hostage in the event of disruption of just one component, namely the RE magnets and that too the higher end grades. Solution for this disruption is the first challenge. Alternatives to RE magnet-based motors is just not Plan-B anymore but has come to the forefront. Trucks and other heavy duty vehicles including mining and military vehicles, fortunately have options other than RE magnet-based motors, by the virtue of their size, payload and duty cycles which are specific to them.

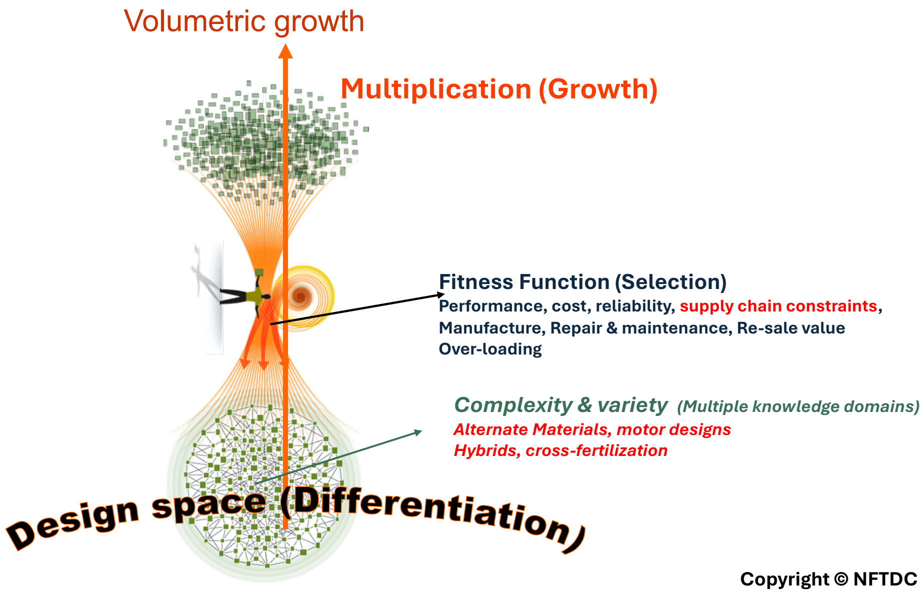
- **Controllers** are the backbone of the drive control system. Here the high voltage (>400V) and med-high frequency MOSFETs and IGBTs become non-negotiable components. Wide Band Gap semiconductors (WBS) based on **SiC and GaN** MOSFET and IGBT devices are the candidates and a disruption situation similar to RE magnets can arise. The inverter-controllers at 800V to 3000V are the norm in this segment for heavy duty vehicles and just as RE magnets, these WBS devices will rule the control part of the drive trains. Power electronics semiconductor devices are the key driver and any disruption in this segment will collapse the entire eco-system of E-mobility.

- The third challenge in drives, is the **energy device** or its combinations thereof. The progress from LCO to NMC to LFP has been well studied. However, the next generation lies in leap frogging to solid state batteries which essentially boils to development of solid electrolytes which are sulphides with and without ionic liquids and other materials as in doped garnets. Here, conventional cell manufacturing lines are disrupted while expensive cathode active materials are replaced in LiS and LFP grades while the anode is metallic lithium coated on copper foils of ever decreasing thickness.

Thus, it is evident that solution paths to these three challenges which are based on advanced materials and design &manufacturing at the core become our emphasis and solution path vectors that are to be explored should become the focus of our near future developments in R&D and innovation endeavours. Addressing all three of the challenges is an exhaustive exercise and, in this study, motors and drives are taken up as the first exercise in detail.

2. Exploration and Evolution of Solution Paths

Product development follows the evolutionary principles well known in biology. The habitant, the marketplace in our case, imposes a "fitness function" comprising of attributes which eventually does the *selection* of the solution / product. This is akin to the selected organism from a multitude of choices emanating from explorative developmental endeavour(s) (*differentiation)* in the design stable. The selected one gets *multiplied* in large scale production. The fitness function which for a long time consisted predominantly of cost, performance, utility, reliability, aesthetics, re-sale value etc. as a matrix has now added other attributes, viz. reliable supply chain of crucial components apart from specific energy consumption, range and overall efficiency.



Three important components, namely RE magnets for motors, Li cells for battery pack and power electronics semi-conductor devices could get disrupted. The materials/devices that go in to making them becoming short supply or in limited geographies and their manufacture is restricted to one or two companies or countries. The entire eco-system suffers non-linear effect due to any perturbation in this supply chain and in some cases, can even lead to system breakdown as predicted in system science studies. Thus, oil shock is substituted by "*critical materials/devices supply shock*" and they could even be weaponized in times of disputes and conflicts. The world is presently seeing the necessity of not putting all the eggs in one basket and pursuit of alternative solutions in terms of materials and design becomes paramount.

In this landscape study, the solution path for one of the three challenges, namely motors and drives are explored in terms of

(i) alternate materials
(ii) alternate motor types with and without RE magnets and
(iii) efficient design configurations

Motors are broadly classified into Magnet based motors and Magnet Free Motors. Magnet free motors are purely based on the electrical windings and does not involve any magnets. Induction motors are a traditional and extensively utilized type of motor in this category. They function based on the principle of electromagnetic induction, wherein an electric current is generated in the rotor as a result of the magnetic field created by the stator. These motors are characterized by their simplicity, reliability, and cost-effective manufacture, extensive eco-system for making them. Synchronous Reluctance Motors operate based on the principle of reluctance torque instead of magnetic induction. Unlike traditional motors such as induction motors or permanent magnet motors, synchronous reluctance motors utilize differences in reluctance (the resistance to magnetic flux) within the rotor. Air gaps in the rotor serve as the reluctance path.

Magnet-based motors can be categorized into two types: Rare Earth Permanent Magnet Motors and Rare Earth Magnet-Free Motors. A Permanent Magnet Synchronous Motor (PMSM) is a specific type of synchronous motor that features a rotor equipped with permanent magnets, eliminating the need for an external power source or windings to create the magnetic field. The PMSM motors are recognized for their high efficiency, elevated power density and superior performance characteristics. As a result, they are extensively employed in various applications that demand precise control and high efficiency. Other types of magnets that are frequently used are the ferrite-based ones and they possess significantly lower magnetic properties such as B_r (Remanence) and H_c (Coercivity).

Alternate design-based solutions are typically seen in hybrids wherein induction, synchronous motors use magnets in rotors in addition to induction or reluctance for generating the flux. An example would be ferrite magnet – assisted synchronous motors are emerging in the horizon. While all of the above developments pertain to the rotor, a major development in the last decade has been high stator fill factor (above 90%) achieved thanks to shaped bars and hair-pin winding in manufacture which allows very large stator current which in turn enhances the magnetic flux density and thereby increase kW/kg or reduce the size of the system. Axial Flux motors show highest kW/kg designs, while their manufacture is more complex. Further details are elaborated in later sections.

Design of propulsion systems even in the case of ICE drives, have always been for the maximal performance. The power and torque ratings were designed for highest performance which inevitably are not suited for all situations and are mostly in a limited 2-5% of the use of the vehicle. Design for maximal performance will always result in an over-designed system calling for very high energy demand. The oil price shock of 1970s made a rethink with emphasis on energy efficiency, and the smaller and more efficient Japanese vehicles were seen as the appropriate template for design. Performance vs cost optimization had to be revisited, and designers went back to their drawing boards.

Nearly 50 years later, the transition to electric mobility which emerged from concerns of environmental impact of carbon emissions, ushered in a bigger paradigm shift in propulsion system. It is well established scientific fact that efficiency of propulsion systems operates at high metrics only around a certain speed regime or “sweet spot” and with reduction in speed (or rpm) efficiency drastically drops. Speed profile in real world duty cycle is the key to understand the required variable performance as output of a vehicle platform. Transition to full EV propulsion forced a mind-set change amongst design teams to seriously look at real – life duty cycles for each vehicle platform, thanks to high up-front cost of energy device. While the initial designs were modest in energy demand typified in terms of limited range, extension of range necessitated large energy storage, particularly for large vehicles such as trucks.

Optimal design is the solution that will eventually be selected by the "fitness function" – a set of imposed attributes. Motor in the propulsion system that provides the required and variable power and torque without too much reduction in efficiency for all scenarios that are likely to occur in the real-world duty cycle in urban-semi urban-highway routes is the key to the optimal solution. Plethora of fluctuations akin to multiple frequencies in the duty cycle spectrum (speed vs time) occur due to stop-go events, gradients which get reflected as acceleration – deceleration – idle events in the cycle. The energy demand, therefore, is to be multiplexed in to "bits" with varying frequencies and time periods to understand the variable "load" on the prime mover and eventually the battery current from the energy device. Efficiency is no longer a single point parameter, and it is more of a map or regime over torque-speed space. Thus, the design is not for the worst case or largest load demand case, but the one that is more adaptable to the changing scenario. An adaptive prime mover that understands and adapts to the duty cycle is the ultimate goal.

As a first step in this landscape study, duty cycles are collated and analysed specifically for trucks. As discussed in the next section, it is observed that duty cycles evolved over time from simple synthetic and standard ones to fairly complex cycles that captured most of the real-world conditions. "*Different horses for different courses*" is a more apt description that captures the essence of developmental efforts for drives based on real world drive cycle analysis.

3. Drive Cycles Analysis

The driving cycle(s) and analysis is essential for extracting EV motor parameters since it offers consistent, practical information about how a vehicle will be operated in various driving scenarios. Acceleration, deceleration, cruising, idling, in flat and gradient terrains and energy recovery are just a few of the conditions that the driving cycle simulates. This aids in comprehending the motor's performance in these various driving conditions. When exposed to real driving patterns, the motor's efficiency, power output, and thermal behaviour may be more accurately assessed. The driving cycle has a direct impact on motor parameters as torque, speed, power, and efficiency. Engineers can optimize motor performance to attain desired results like range, power, and longevity by testing various design solutions of potential drives across a variety of cycles.

Thermal management systems are developed using this data to prevent overheating and promote durability. The driving cycle offers insights into energy consumption across various conditions, which is crucial for assessing the motor's energy efficiency and its compatibility with the vehicle's battery. Precise energy consumption data is vital for optimizing battery size and predicting range. Numerous driving cycles include deceleration phases, during which regenerative braking becomes significant.

The motor's capability to convert kinetic energy back into electrical energy during braking is essential for enhancing range and efficiency. Analysing driving cycle data is instrumental in evaluating and optimizing this regenerative braking performance. A single, constant speed or load fails to accurately reflect real-world driving conditions. Driving cycles incorporate various factors such as traffic patterns, road gradients, and weather conditions, all of which affect motor parameters like torque &power requirements and efficiency. Utilizing real-world driving data allows for better predictions of motor performance in everyday scenarios, which is beneficial for vehicle design and managing consumer expectations.

By employing standardized driving cycles, electric vehicle (EV) manufacturers can effectively model and simulate motor behaviour under uniform conditions. This approach facilitates improved decision-making during the design process, including considerations related to motor size, type, configurations and control strategies. Consequently, this simulation minimizes the necessity for extensive physical testing, thereby conserving time and resources. Drive cycles can be categorised as in Figure 1 below.

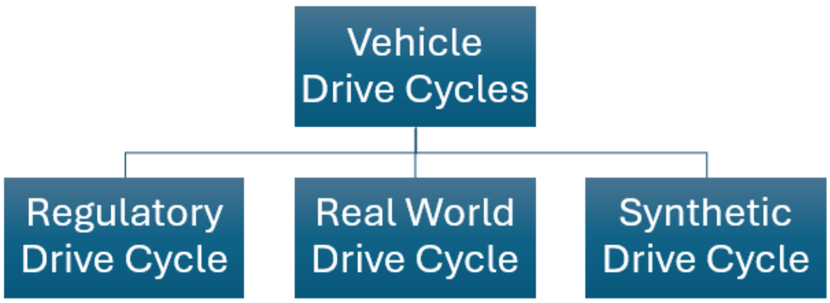


Figure 1: Categorisation of vehicle drive cycles

The electrification of heavy-duty vehicles (HDVs) is essential for achieving future carbon neutrality targets. The impact of road slope on vehicle power cannot be overlooked, as significant variations in road slope occur during long-distance travel. To effectively design the powertrain system for electrified HDVs, it is crucial to develop representative driving cycles that incorporate road slope data [10]. However, two main challenges arise in this process: the high cost of road slope measurement devices and the complexity associated with existing 3D Markov chain methods used for cycle construction. A simplified but effective methodology for incorporating slopes is utilizing a fixed gradient and time duration or distance ratio spent on the varying gradients (m/km) in the overall computation of energy consumption.

Road Load Power Requirements Calculations:

The gradient for different roads is considered as per below for the calculation of force.

- **i.** Flat road >> 0%
- **ii.** Flyovers >> 4%
- **iii.** Ghat roads >> 7%

The angle in radians is computed by the relation.

$$\theta_{\text{Radian}} = \tan^{-1}\left(\frac{\text{Gradient in }\%}{100}\right)$$

Governing equations for the calculation of force and power are as follow.

$$\text{Force @ Wheel(Fw)} = \text{mg}\sin\theta + \mu\text{mg}\cos\theta + \frac{1}{2}\rho A C_d V^2$$

$$\text{Power @ Wheel(Pw} = \text{Fw} \times \text{Vw)} = \text{mgV}\sin\theta + \mu\text{mgV}\cos\theta + \frac{1}{2}\rho A C_d V^3$$

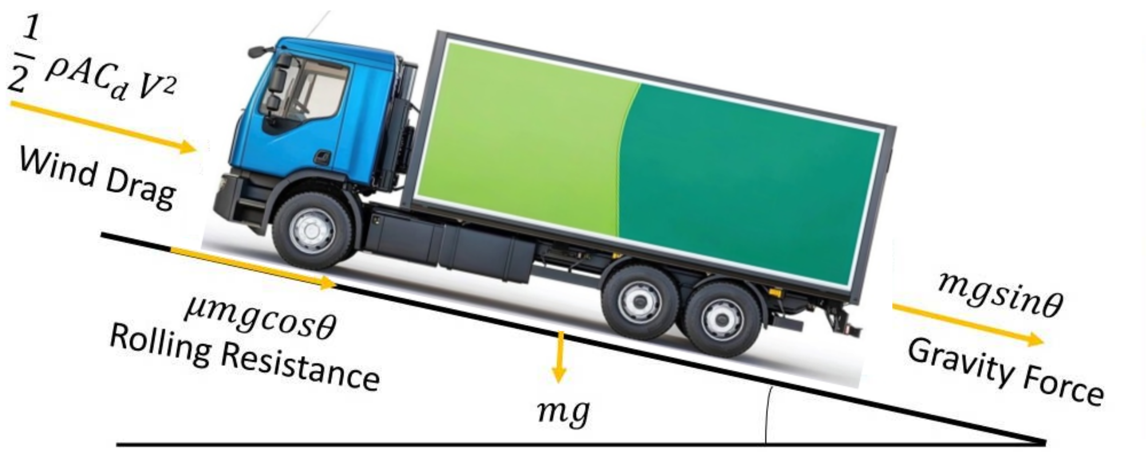


Figure 2: Representation for road load power calculation

Where,

Fw = Force at wheel	m = Mass of the vehicle (GVW)
g = Acceleration due to gravity	μ = Coefficient of Rolling Friction
Cd – Coefficient of Drag force	θ = Gradient

Velocity (Vw) vs time = Raw data that is captured

From the above governing equations, we get Force, Power and Energy consumed in time segments/snippets (Δt). Total energy divided by range (distance) gives the specific energy consumption pertaining to the vehicle and the duty cycle.

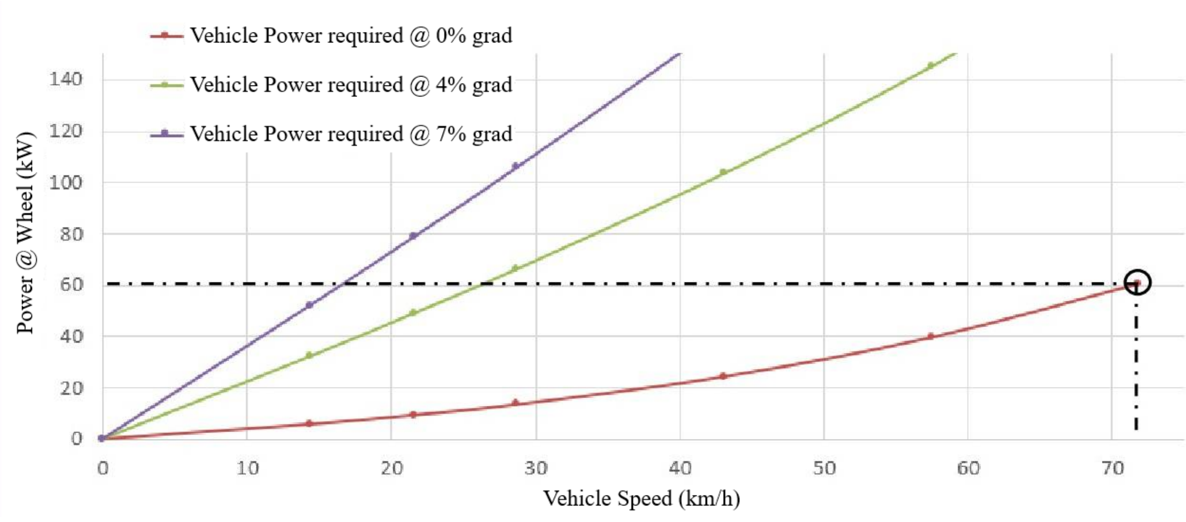
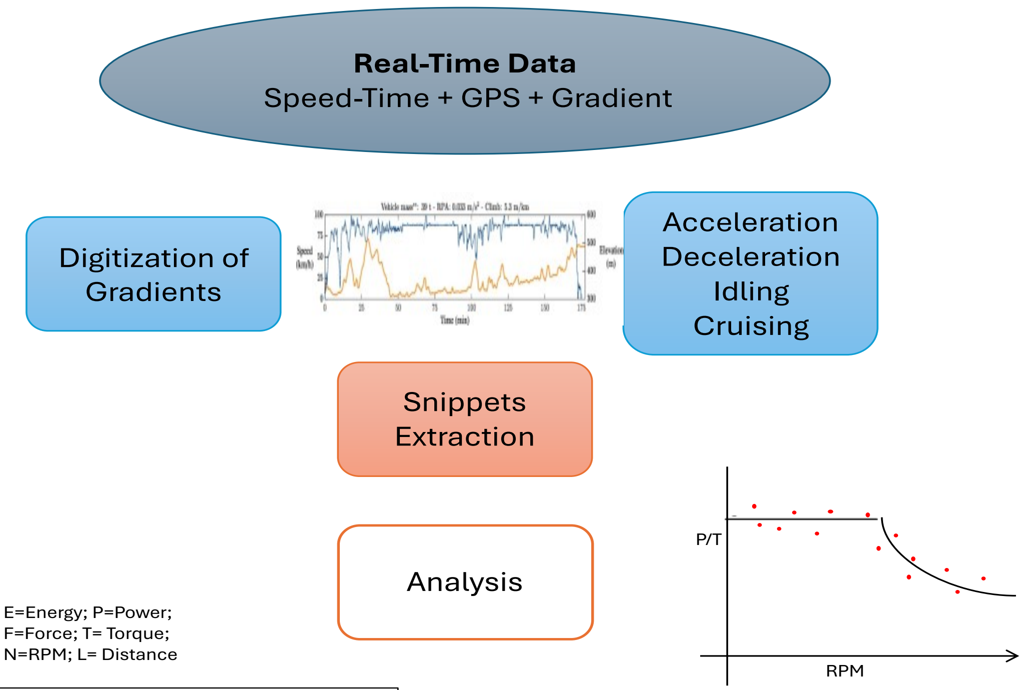


Figure 3: Speed vs. Power characteristic at different gradients

Example: 60 kW power is required at the wheel to move at 70 kmph by the vehicle in flat conditions while a 7-degree gradient on a continuous climb mode can do only at 30 kmph. A more detailed methodology uses drive cycle snippets to compute energy consumption as given below.

3.1 Realization of New Drive Cycles >> Synthetic Drive Cycle



$$E = \int F.dL = \int F.\left(\frac{dL}{dt}\right)dt \qquad P = \frac{dE}{dt} \qquad P = {}^{2\pi NT}/_{60} \qquad V = \frac{dL}{dt}$$

Figure 4: Process of constructing driving cycles with road slope

The process can be conducted in three steps as shown in Figure 4 above.

Step-1:

In this step, raw data is collected as the vehicle moves. The speed and altitude signals collected by Global Positioning System (GPS) equipment are used to observe the road slope / gradient (θ or distance travelled in meters per km in the slope). Starting with this raw data, acceleration, deceleration and idle periods are identified, and the raw data is digitized.

Step-2:

Two methods can be used to incorporate slope/gradients. In the snippet that has been extracted, slope/gradient is computed by taking an average velocity in the snippet time period, the product of which gives the equivalent horizontal distance travelled. From the altitude (GPS) data, the vertical distance is known and from these two distance parameters, slope/gradient can be computed as m/km as well as in terms of theta (o) which goes into the force equation given above.

Constructing driving cycles with road slope:

A road slope observation based on GPS signals is designed to obtain the information of road slope in the demonstration area [10]. The road slope is calculated by integrating velocity for the driving distance $s(t_m)$ and getting the slope angle α from the change of altitude and driving distance.

$$S(t_m) = v(t)\Delta t$$

$$\alpha = \sin^{-1}\frac{\Delta h}{\Delta s}$$

Where,

- Δt = sample (Snippet) time period
- $v(t)$ = sample vehicle velocity
- Δh = change of altitude during the sample time period
- Δs = change of driving distance during sample time period.

Step-3:

The effectiveness of driving cycles with road slope is verified by comparing the statistic characteristics of vehicle power between the real driving road conditions and the constructed driving cycles [10].

In this study, three distinct driving cycles representing Indian urban-city centre, suburban-city outskirts, and highway routes have been constructed considering the max speed cap in different routes shown in Figure 5. The definition of characteristics parameters is enumerated in Table 1. The characteristic parameters for the three Indian driving cycles (urban-city centre, suburban-city outskirts, and highway routes) are presented in Table 2 and compared with European drive cycle for urban, sub-urban and highway routes performed in study [10].

Table 1: Characteristics parameters definition [10]

	Parameters	Definitions
Speed Parameters	Average Speed V_m	Average Speed including idle speed
	Average Driving Speed V_{mr}	Average Speed excluding idle speed
	Maximum Speed V_{max}	Maximum Speed
Acceleration Parameters	Average Acceleration a_m	Average Acceleration
	Average Deceleration d_m	Average Deceleration
Time Ratio	Idle Ratio P_i	Proportion of idle time ($-0.01 < a < 0.01 m/s^2$, $V < 0.5 km/h$)
	Acceleration Ratio P_a	Proportion of acceleration time ($a \geq 0.01 m/s^2$)
	Deceleration Ratio P_d	Proportion of deceleration time ($a \leq -0.01 m/s^2$)
	Cruise Ratio P_r	Proportion of cruise time ($-0.01 < a < 0.01 m/s^2$, $V \geq 0.5 km/h$)

Table 2: Comparative Characteristic parameters of three different routes [10 & this study]

Parameters	Urban – City Centre Route		Suburban – City Outskirts Route		Highway Route	
	India	Europe	India	Europe	India	Europe
Overall Duration (s)	3500	1400	2100	1800	2250	1800
Average Speed V_m (kmph)	17.69	19.92	20.47	22.64	48.63	51.16
Average Driving Speed V_{mr} (km/h)	23.28	27.32	29.92	31.61	50.61	65.47
Maximum Speed V_{max} (kmph)	40	57	60	85.71	70	99.50
Average Acceleration a_m (m/s^2)	0.18	0.4947	0.22	0.3637	0.19	0.3591
Average Deceleration d_m (m/s^2)	-0.22	-0.5488	-0.26	-0.5308	-0.19	-0.3968
Idle Ratio P_i (%)	21	27.21	15	28.40	12	17.55
Acceleration Ratio P_a (%)	38	27.00	43	28.66	33	24.26
Deceleration Ratio P_d (%)	33	23.52	29	19.57	35	21.82
Cruise Ratio P_r(%)	8	22.31	13	23.34	20	36.30

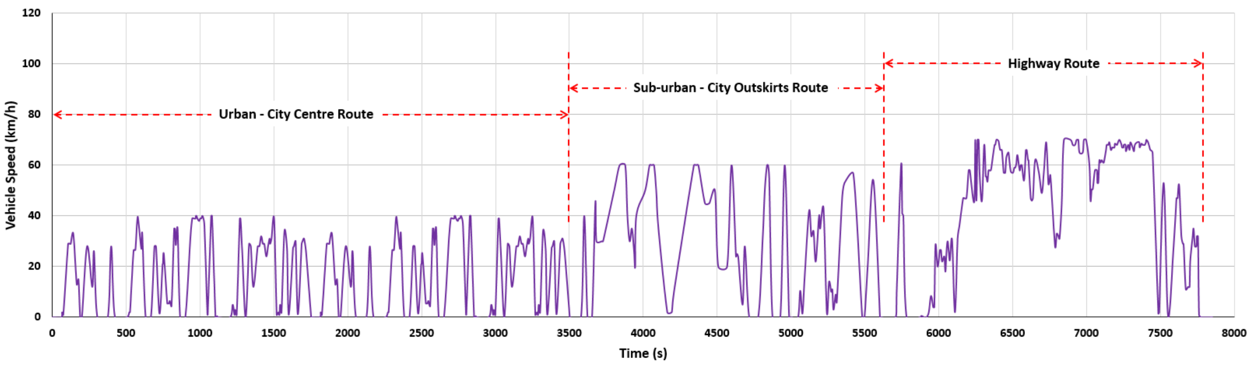


Figure 5: Representative Indian Drive Cycle (Urban - City Centre, Sub-urban - City Outskirts, Highway Route)

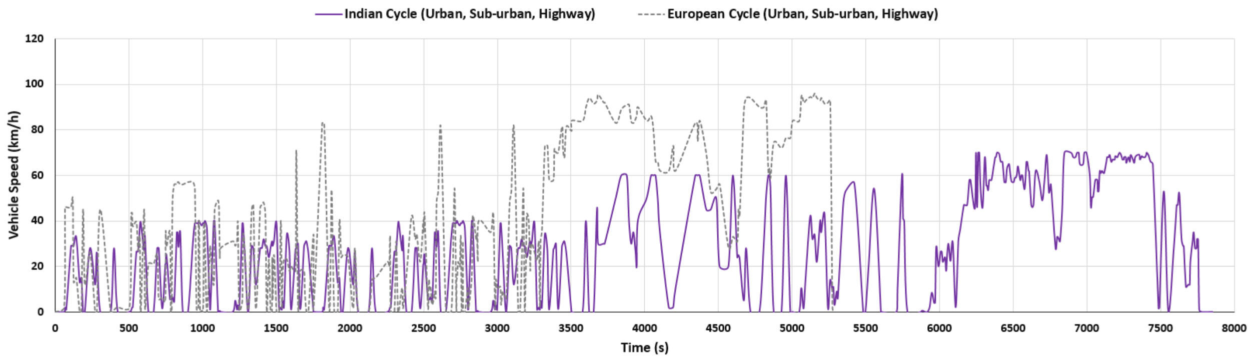


Figure 6: Comparison of Indian and European Drive Cycle (Urban - City Centre, Sub-urban - City Outskirts, Highway Route)

3.2 Regulatory Drive Cycles

To simulate the movement of urban electric or hybrid transport, several driving cycles are used. Each type of cycle has certain advantages and disadvantages. Below are the publicly available drive cycles extracted from [1] & [2] are analysed and compared.

- **i.** New European Drive Cycle (NEDC)
- **ii.** 10-15 Drive Cycle
- **iii.** Urban Dynamometer Driving Schedule (UDDS) Drive Cycle (FTP-72)
- **iv.** FTP-75 Drive Cycle
- **v.** World Harmonized Vehicle Cycle (WHVC)
- **vi.** EPA Urban Dynamometer Driving Schedule (UDDS) for Heavy-Duty Vehicles
- **vii.** Heavy Heavy-Duty Diesel Truck (HHDDT) Schedule
- **viii.** Japanese JE05 Cycle
- **ix.** Worldwide Harmonized Light Vehicles Test Procedure (WLTP)
- **x.** Worldwide harmonized Heavy Duty Certification (WHDC) Procedure

Table 3: Different regulatory drive cycles summarised

Drive Cycles	Description	
New European Drive Cycle (NEDC)	This cycle [1] is deemed relevant for urban transportation; however, the final segment suggests speeds of 100 km/h and 120 km/h, which are seldom attainable in urban environments, even for cars. Furthermore, the NEDC cycle is now regarded as outdated. Average Acceleration, a_m **0.6318 m/s², 2.27 km/(h.s)** Average Deceleration, d_m**-0.8615 m/s², -3.10 km/(h.s)**	Figure 7 & 8 Annexure-1
10-15 Drive Cycle	This cycle [1] features a reduced average speed relative to the NEDC, with a maximum speed of no more than 70 km/h in its final section. Average Acceleration, a_m **0.7946 m/s², 2.86 km/(h.s)** Average Deceleration, d_m**-0.6128 m/s², -2.20 km/(h.s)**	Figure 9 & 10 Annexure-1
UDDS Drive Cycle (FTP-72) (Federal test Procedure)	This cycle [1] consists of two phases separated by a red vertical line. During the first phase, the average speed is greater than in the second phase, indicating that the vehicle has entered a high-speed highway segment within the cycle. In contrast, the second phase exhibits speed values that align more closely with urban	Figure 11 & 12 Annexure-1

<table>
<tr><td></td><td>driving conditions. It is important to note that this cycle does not contain any repeating sections, which distinguishes it from the NEDC and 10-15 cycles. The UDDS driving cycle was designed to replicate traffic patterns in an urban setting.
Average Acceleration, a_m 0.5735 m/s^2, 2.06 km/(h.s)
Average Deceleration, d_m -0.6006 m/s^2, -2.16 km/(h.s)</td><td></td></tr>
<tr><td>FTP-75 Drive Cycle (Federal test Procedure)</td><td>An enhanced iteration of this cycle [1] is referred to as FTP 75. Unlike the UDDS, FTP 75 involves repeating the first phase after completing the second phase. This cycle specifically represents urban movement.
Average Acceleration, a_m 0.5428 m/s^2, 1.95 km/(h.s)
Average Deceleration, d_m -0.7098 m/s^2, -2.55 km/(h.s)</td><td>Figure 13 & 14 Annexure-1</td></tr>
<tr><td>World Harmonized Vehicle Cycle (WHVC)</td><td>The WHVC [2] is utilized worldwide for evaluating commercial vehicles. The test lasts for 1800 seconds and consists of three segments that simulate urban, rural, and motorway driving conditions.
Urban driving segment
i. Duration: 900 s
ii. Average speed: 21.3 kmph
iii. Maximum speed: 66.2 kmph
iv. This segment includes frequent starts, stops and idling.
Rural driving segment
i. Duration: 481 s
ii. Average speed: 43.6 kmph
iii. Maximum speed of 75.9 kmph.
Motorway driving segment
i. Duration: 419 s
ii. Average speed: 76.7 kmph
iii. Maximum speed: 87.8 kmph
iv. This segment represents highway driving.</td><td>Figure 15</td></tr>
<tr><td>EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (HD-UDDS)</td><td>The HD-UDDS cycle [2] is specifically designed for chassis dynamometer testing of heavy-duty vehicles. It is important to note that the HD-UDDS cycle is distinct from the FTP-72 cycle, which is used for light-duty vehicles and is also referred to as UDDS.
The following are basic parameters of the cycle:
i. Duration: 1060 s
ii. Distance: 5.55 miles = 8.9 km
iii. Average speed: 18.86 mi/h = 30.4 kmph
iv. Maximum speed: 58 mi/h = 93.3 kmph
<table>
<tr><th>Parameter</th><th>UDDS</th></tr>
<tr><td>Duration, s</td><td>1063</td></tr>
<tr><td>Distance, mi</td><td>5.55</td></tr>
<tr><td>Average Speed, mph</td><td>18.8</td></tr>
<tr><td>Stops/Mile</td><td>2.52</td></tr>
<tr><td>Max. Speed, mph</td><td>58</td></tr>
<tr><td>Max. Acceleration, mph/s</td><td>4.4</td></tr>
<tr><td>Max. Deceleration, mph/s</td><td>-4.6</td></tr>
<tr><td>Total KE, mph^2</td><td>373.4</td></tr>
<tr><td>Percent Idle</td><td>33.4</td></tr>
</table></td><td>Figure 16</td></tr>
</table>

<table>
<tr>
<td>Heavy Heavy-Duty Diesel Truck (HHDDT) Schedule</td>
<td>The HHDDT [2] test consists of four speed-time modes, including idle, creep, transient and cruise.
<table>
<tr><th>Parameter</th><th>HHDDT Creep</th><th>HHDDT Transient</th><th>HHDDT Cruise</th></tr>
<tr><td>Duration, s</td><td>253</td><td>668</td><td>2083</td></tr>
<tr><td>Distance, mi</td><td>0.124</td><td>2.85</td><td>23.1</td></tr>
<tr><td>Average Speed, mph</td><td>1.77</td><td>15.4</td><td>39.9</td></tr>
<tr><td>Stops/Mile</td><td>24.17</td><td>1.8</td><td>0.26</td></tr>
<tr><td>Max. Speed, mph</td><td>8.24</td><td>47.5</td><td>59.3</td></tr>
<tr><td>Max. Acceleration, mph/s</td><td>2.3</td><td>3.0</td><td>2.3</td></tr>
<tr><td>Max. Deceleration, mph/s</td><td>-2.53</td><td>-2.8</td><td>-2.5</td></tr>
<tr><td>Total KE, mph^2</td><td>3.66</td><td>207.6</td><td>1036</td></tr>
<tr><td>Percent Idle</td><td>42.29</td><td>16.3</td><td>8.0</td></tr>
</table>
</td>
<td>Figure 17, 18 & 19</td>
</tr>
<tr>
<td>Japanese JE05 Cycle</td>
<td>The JE05 emission test [2] cycle is designed for heavy vehicles with a gross vehicle weight (GVW) exceeding 3,500 kg. This transient test simulates driving conditions in Tokyo and is applicable to both diesel and gasoline vehicles.
The following are basic parameters of the cycle:
i. Duration: 1800 s
ii. Average speed: 26.94 kmph
iii. Maximum speed: 88 kmph</td>
<td>Figure 20</td>
</tr>
<tr>
<td>Worldwide Harmonized Light Vehicles Test Procedure (WLTP)</td>
<td>The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is a chassis dynamometer test cycle for the determination of emissions and fuel consumption from light-duty vehicles [2]. WLTP procedures includes several test cycles applicable to vehicle categories of different power-to-mass (PMR) ratio. PMR parameter is defined as the ratio of rated power (W) / curb mass (kg).
<table>
<tr><th>Category</th><th>PMR, W/kg</th><th>v_max, km/h</th></tr>
<tr><td>Class 3b</td><td>PMR > 34</td><td>v_max ≥ 120</td></tr>
<tr><td>Class 3a</td><td></td><td>v_max< 120</td></tr>
<tr><td>Class 2</td><td>34 ≥ PMR > 22</td><td>-</td></tr>
<tr><td>Class 1</td><td>PMR ≤ 22</td><td>-</td></tr>
</table>
<table>
<tr><th>Parameter</th><th>Class 3b</th><th>Class 3a</th><th>Class 2</th><th>Class 1</th></tr>
<tr><td>Duration, s</td><td>1800</td><td>1800</td><td>1800</td><td>1611</td></tr>
<tr><td>Stops, s</td><td>242</td><td>242</td><td>240</td><td>356</td></tr>
<tr><td>Distance, m</td><td>23266</td><td>23194</td><td>22649</td><td>11428</td></tr>
<tr><td>Max speed, kmph</td><td>131.3</td><td>131.3</td><td>123.1</td><td>64.4</td></tr>
<tr><td>Average speed, kmph</td><td>53.74</td><td>53.56</td><td>52.26</td><td>32.77</td></tr>
<tr><td>Max. Acceleration, m/s^2</td><td>1.58</td><td>1.58</td><td>0.96</td><td>0.76</td></tr>
<tr><td>Max. Deceleration, m/s^2</td><td>-1.49</td><td>-1.49</td><td>-0.94</td><td>-1.00</td></tr>
</table>
</td>
<td>Figure 21, 22 & 23</td>
</tr>
<tr>
<td>Worldwide harmonized Heavy Duty Certification (WHDC) Procedure</td>
<td>Worldwide Harmonized Heavy Duty Certification (WHDC) procedure is a globally harmonized set of regulations for testing and certifying the exhaust emissions of heavy-duty vehicles and engines [2]. WHDC procedure includes two main test cycles:
• World Harmonized Transient Cycle (WHTC): A transient test cycle simulating different driving conditions, including cold and hot starts.
• World Harmonized Steady-State Cycle (WHSC): A hot start steady-state test cycle.</td>
<td>Figure 24 & Table 4</td>
</tr>
</table>

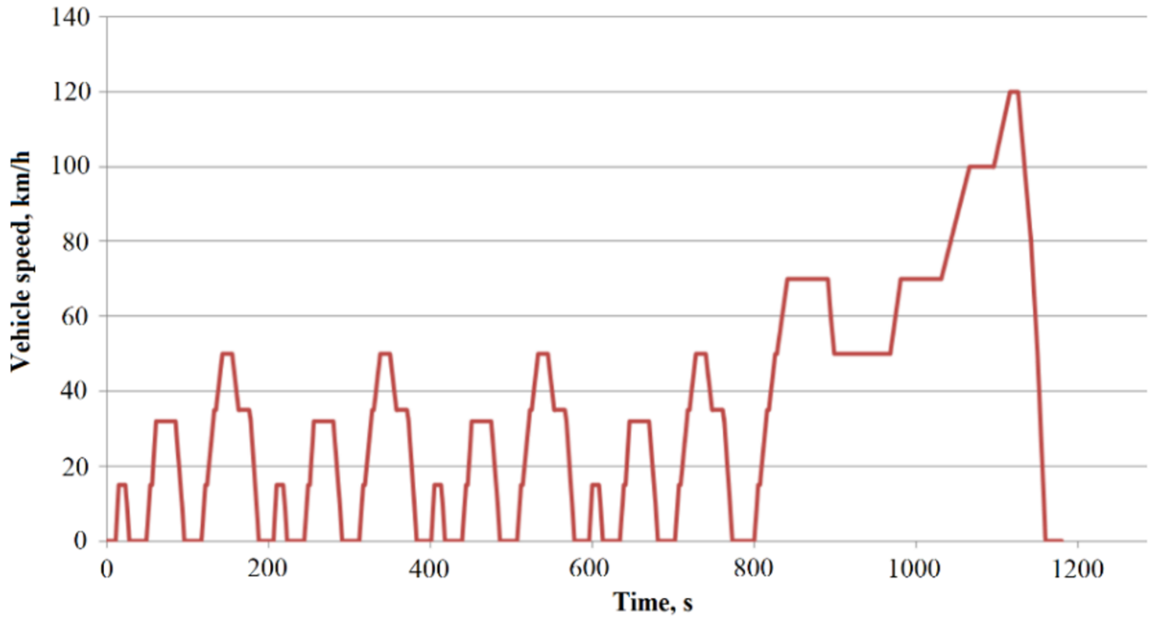


Figure 7: NEDC driving cycle graph [1]

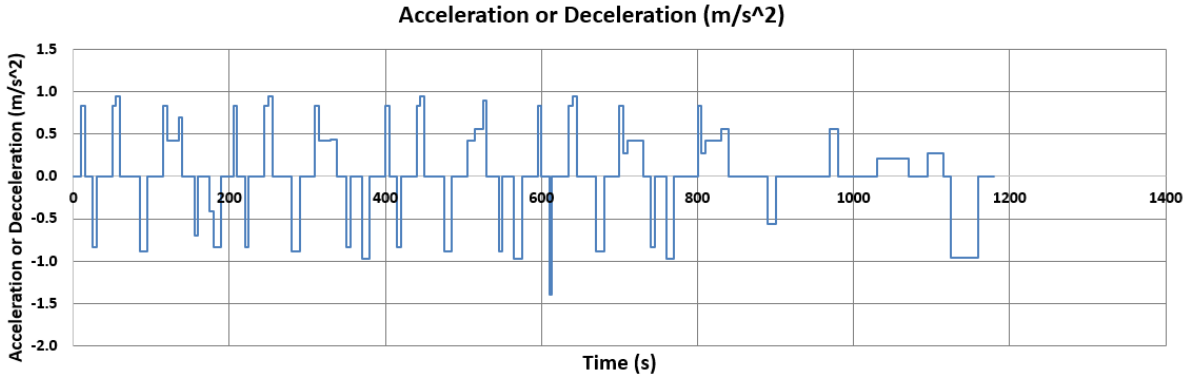


Figure 8: Acceleration & deceleration plot with reference to NEDC driving cycle

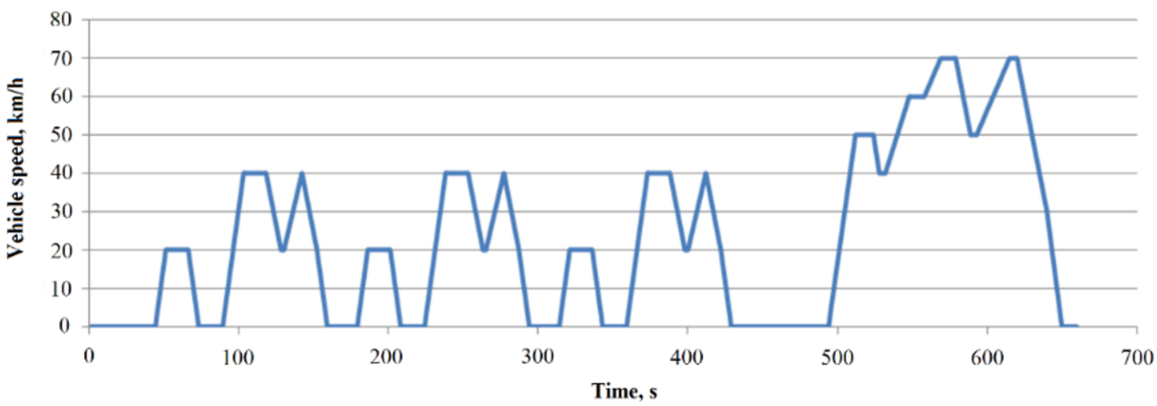


Figure 9: 10-15 driving cycle graph [1]

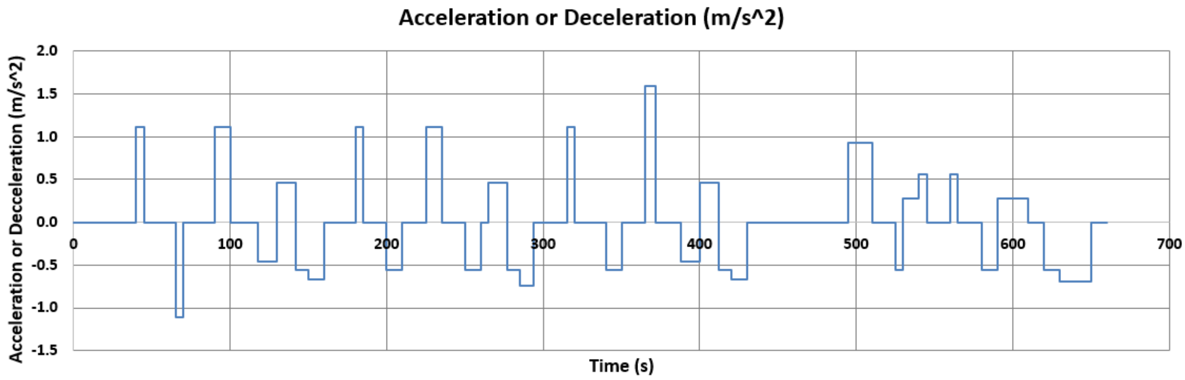


Figure 10: Acceleration & deceleration plot with reference to 10-15 driving cycle

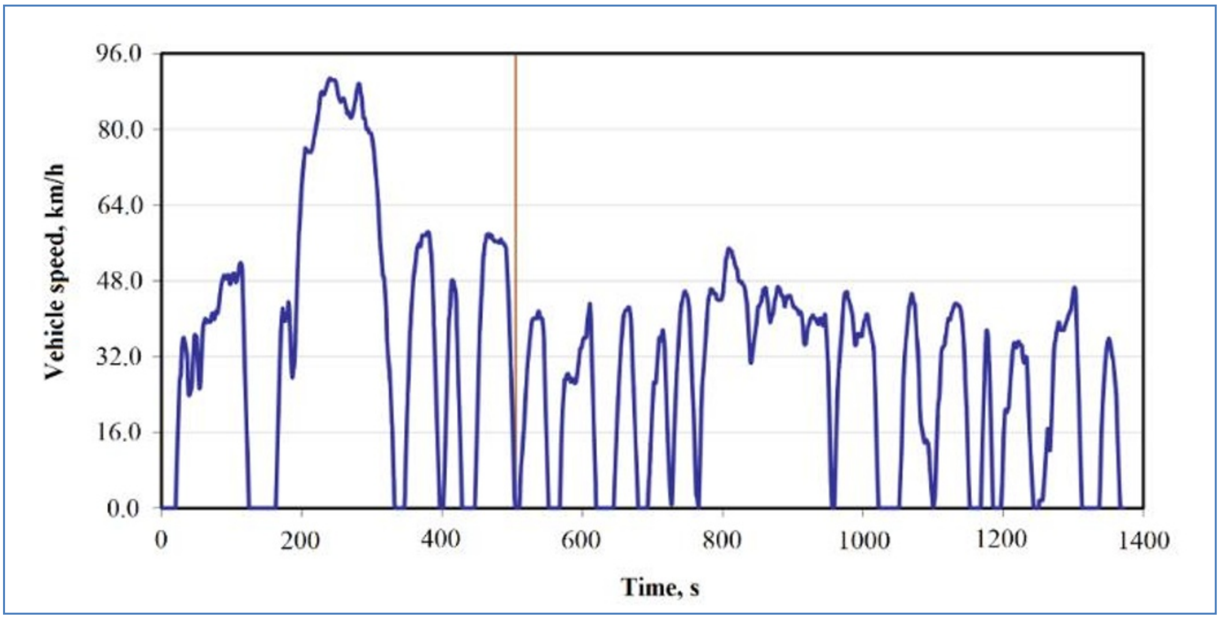


Figure 11: UDDS driving cycle graph (FTP-72) [1]

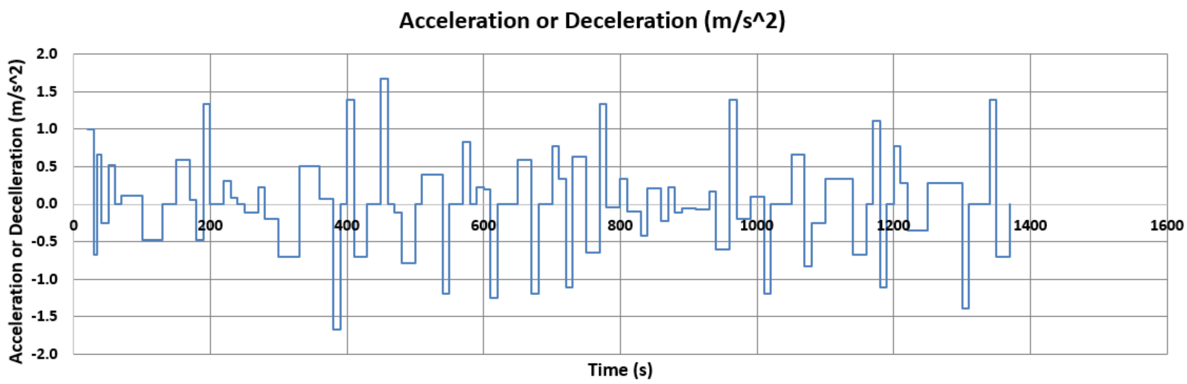


Figure 12: Acceleration & deceleration plot with reference to UDDS driving cycle (FTP-72)

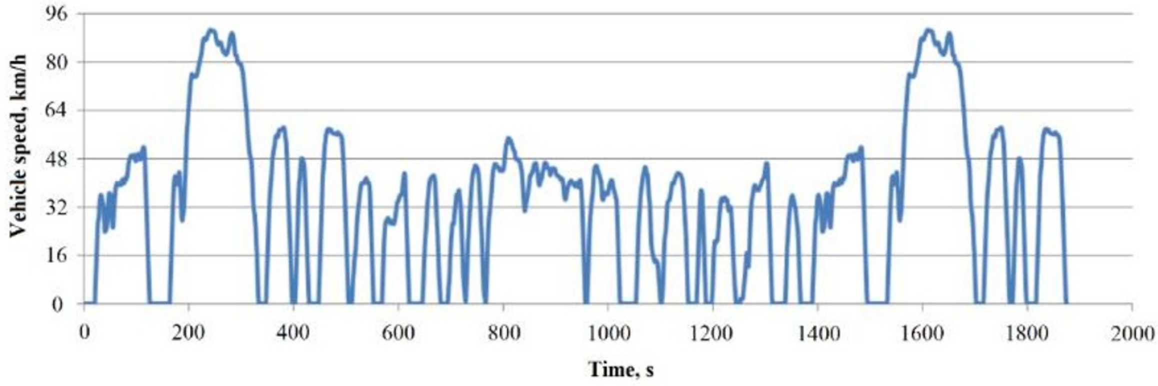


Figure 13: FTP-75 driving cycle graph [1]

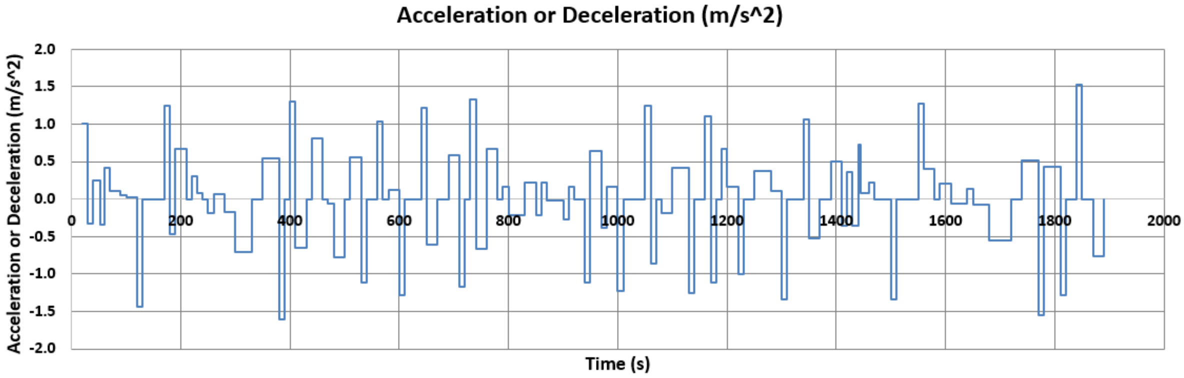


Figure 14: Acceleration & deceleration plot with reference to FTP-75 driving cycle

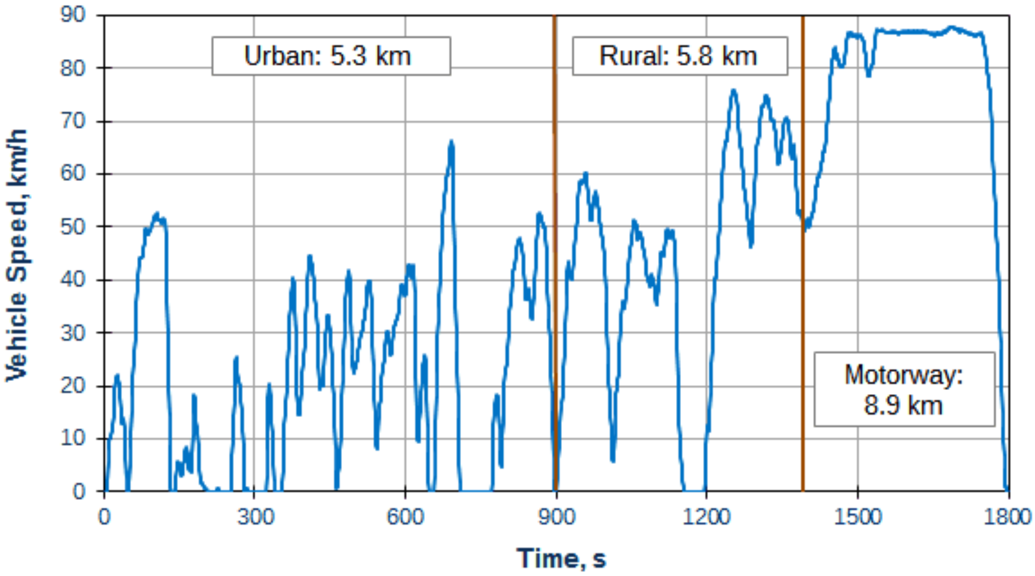


Figure 15: World Harmonized Vehicle Cycle (WHVC) [2]

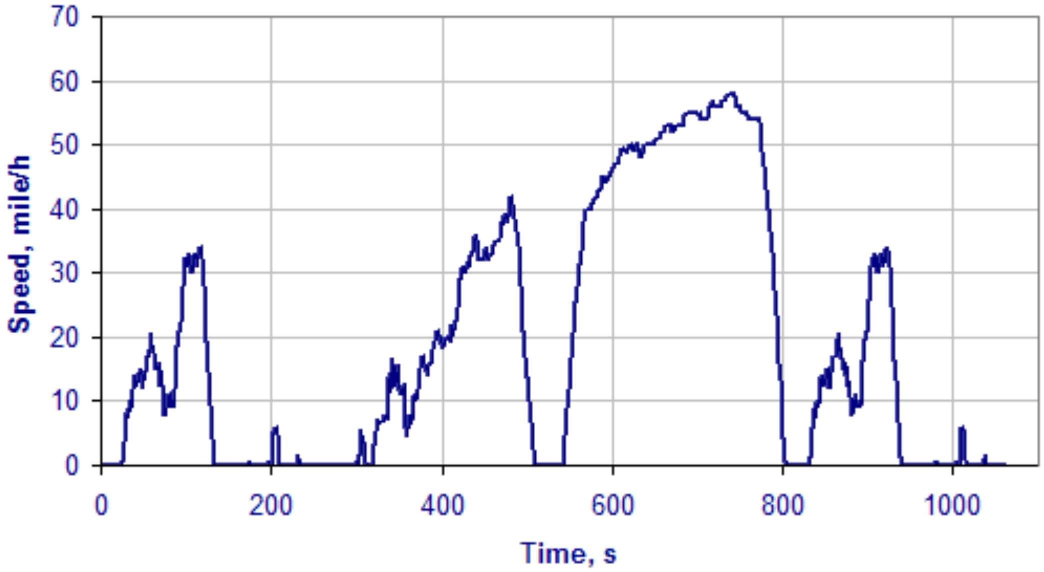


Figure 16: HD-UDDS Cycle [2]

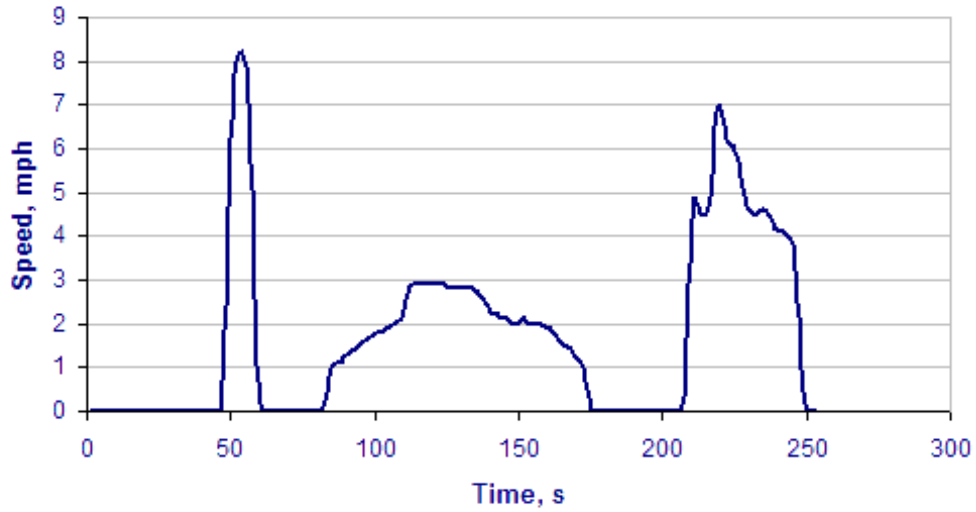


Figure 17: HHDDT Creep Mode [2]

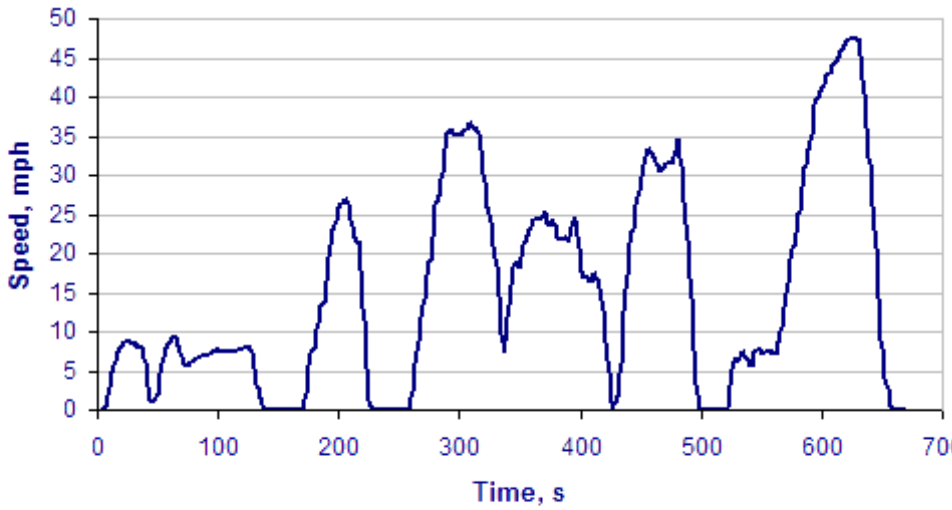


Figure 18: HHDDT Transient Mode [2]

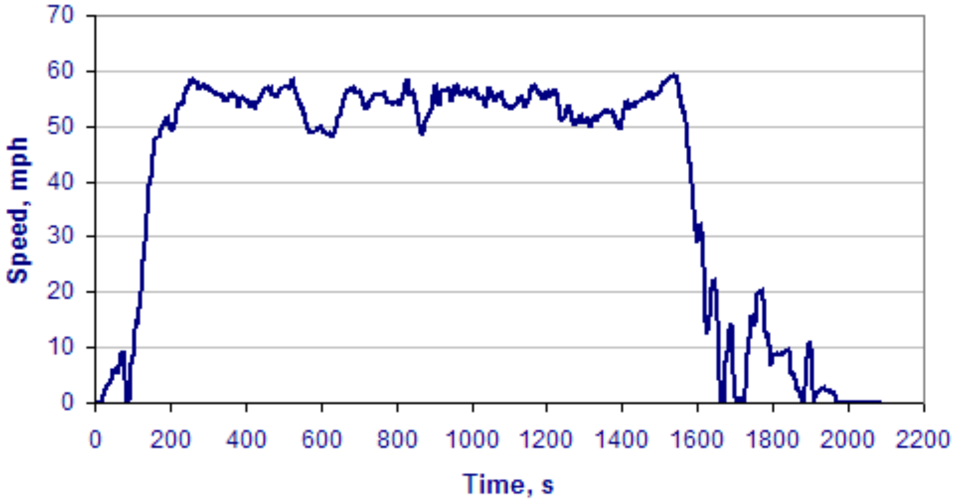


Figure 19: HHDDT Cruise Mode [2]

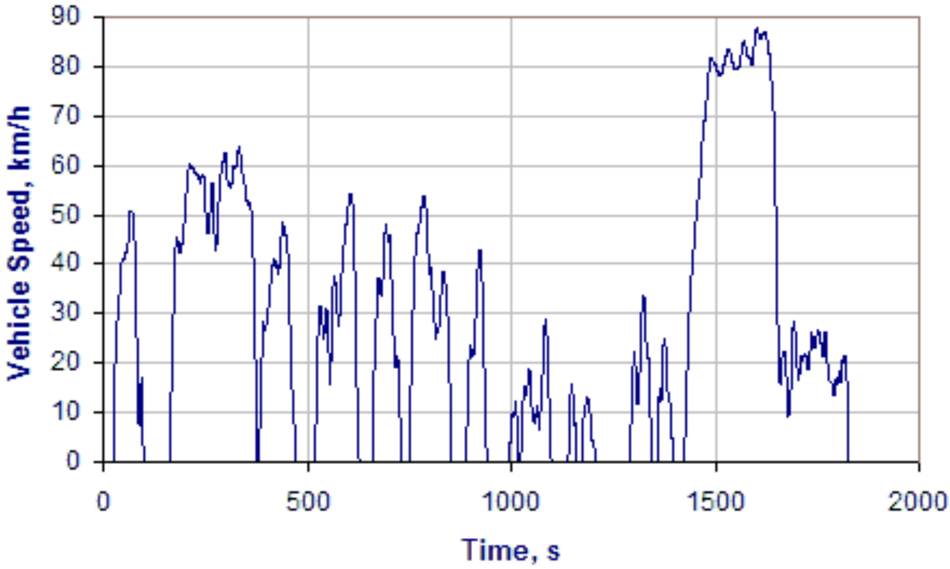


Figure 20: JE05 Test Cycle for Vehicles > 3500 kg GVW [2]

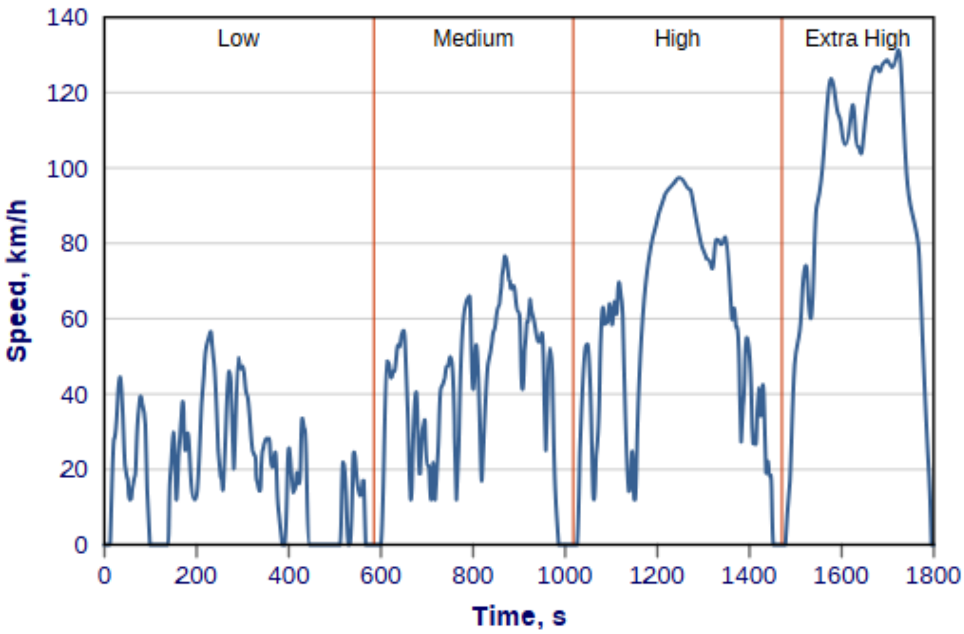


Figure 21: WLTC cycle for Class 3b vehicles [2]

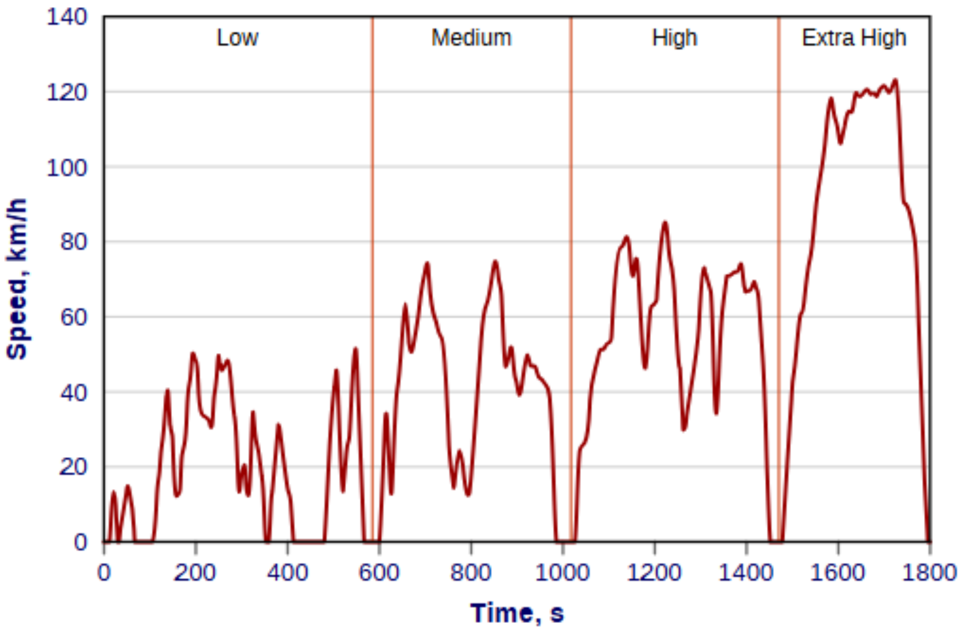


Figure 22: WLTC cycle for Class 2 vehicles [2]

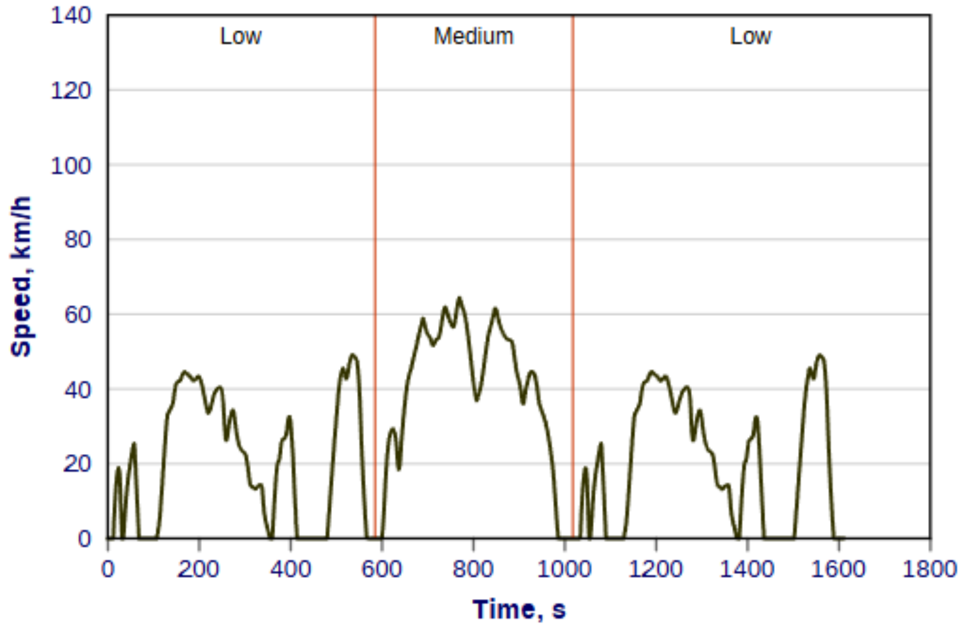


Figure 23: WLTC cycle for Class 1 vehicles [2]

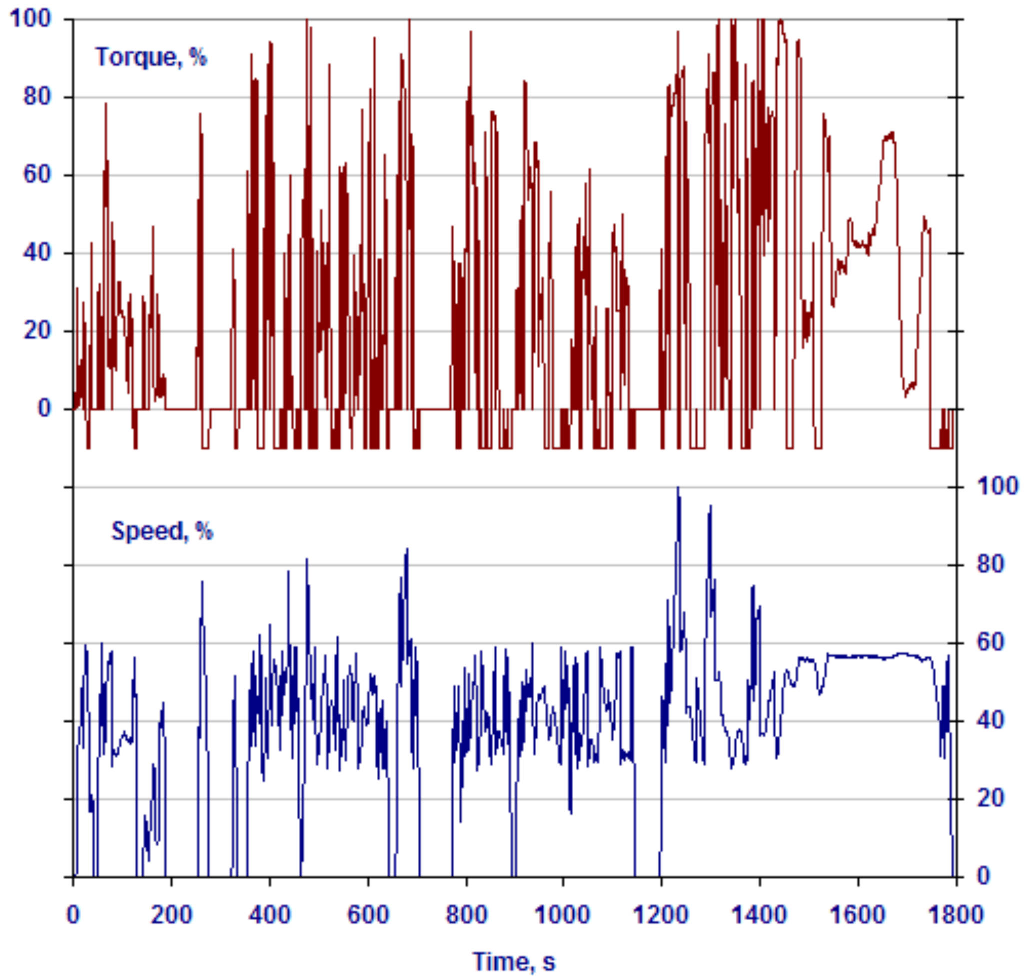


Figure 24: World Harmonized Transient Cycle (WHTC) [2]

Table 4: World Harmonized Stationary Cycle (WHSC) [2]

Mode	Normalized Speed, %	Normalized Load, %	Weighing Factor	Mode Length, s including 20s ramp
0	Motoring	-	0.24	-
1	0	0	0.17/2	210
2	55	100	0.02	50
3	55	25	0.1	250
4	55	70	0.03	75
5	35	100	0.02	50
6	25	25	0.08	200
7	45	70	0.03	75
8	45	25	0.06	150
9	55	50	0.05	125
10	75	100	0.02	50
11	35	50	0.08	200
12	35	25	0.1	250
13	0	0	0.17/2	210
Total			**1**	**1895**

3.3 Real-world Drive Cycle (Central Europe)

The study presented in [3] analyses real-world driving data collected from heavy-duty vehicles engaged in road freight transportation over a two-month period. This data was recorded from a fleet of fifteen conventional trucks operating in Central Europe. The dataset encompasses latitude, longitude, and elevation information for each vehicle, with measurements taken every second. Central Europe poses significant challenges for road freight vehicles due to its numerous hills and mountainous terrain.

A criterion was established for the systematic identification of driving cycles: a cycle concludes when the vehicle remains stationary for more than 5 minutes [3]. This approach yielded a collection of cycles that was still too extensive to analyse comprehensively. Consequently, a subset was chosen, focusing exclusively on cycles that were at least two hours long and had limited stopping durations. Ultimately, this study [3] examines 544 cycles for energy management analysis, totalling 1,750 driving hours and covering 141,000 kilometres. The study in [3] exhibits

(i) drive cycle with the lowest Relative Positive Acceleration (RPA), signifying extended and stable cruising at a constant speed of 90 kmph

(ii) drive cycle with the highest RPA, reflecting sub-urban driving conditions with heavy traffic congestion and frequent turns and

(iii) drive cycles that are distinguished by their extremes in climbing intensity - minimum and maximum - and variations in vehicle mass - minimum and maximum. The trip details in [3] are enumerated in Table 5.

Table 5: Speed, acceleration and climb data from 5 trips of different mass

	Vehicle Mass(t)	RPA (m/s^2)	Climb Gradient(m/km)	Average Speed (km/h)	
Trip-1	36	0.018	4.9	90	Lowest RPA, signifying extended and stable cruising at a constant speed
Trip-2	25	0.096	9.2	55	Highest RPA, reflecting sub-urban driving conditions with heavy traffic congestion and frequent turns
Trip-3	35	0.043	9.2	70	Maximum in climbing with maximum vehicle mass
Trip-4	14	0.086	12	85	Maximum in climbing with minimum vehicle mass
Trip-5	39	0.033	5.3	70	Minimum in climbing with maximum vehicle mass

Typical scenarios can be summarized from the above data.

- The data collected over 200 minutes and at average speed of 90 kmph would give a distance travelled of 300 km and with typical climb of 400 m. This translates to about 3-5 m/km which typifies a mass + acceleration + power (35-ton + 0.02 m/s^2 + 80 kW) duty cycle and with lowest power + lowest acceleration case. This scenario requires fairly low average energy demand. If the climb or acceleration required are both higher, for the same 35-ton truck, the distance travelled would be only for 120 minutes and correspondingly half the distance travelled.
- On the other hand, a slightly heavier truck of 40 tons travelling for 3 hours at average speed of 90 kmph would have travelled 300 km with a medium acceleration of 0.03-0.04 m/s2 and climb gradients of around 5 m/km would demand much higher energy of 160 kW.
- Very high acceleration (0.08-0.09 m/s^2) and / or higher climb/gradient of 9-12 m/km would be possible only with lower truck mass of 15 tons combined with higher power of 120 kW or heavier trucks, the ratings will go up above 250 kW.

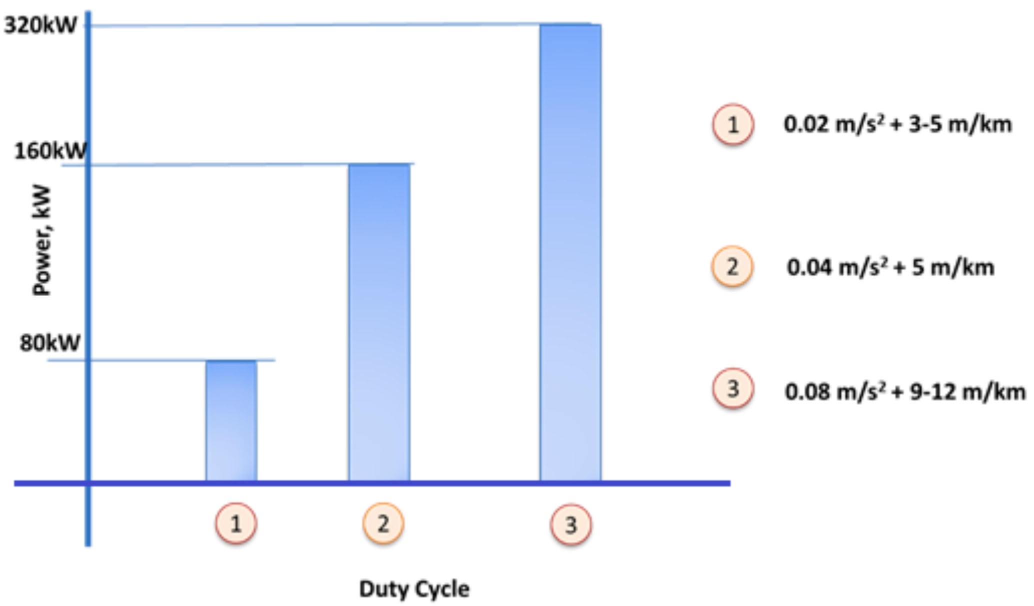


Figure 25: Power vs (Acceleration + climb/gradient) Constant Mass

Overall, this methodology comprising of mass-acceleration-speed-elevation matrix enhances our understanding of vehicle dynamics by providing a more accurate representation of truck loading conditions and their effects on energy consumption leading to optimal design solutions.

3.4 Real-World Drive Cycle >> (INDIA)

Overview of Indian Drive Cycles: The Automotive Research Association of India (ARAI) established the Indian Drive Cycle (IDC) in 1985, utilizing data gathered from major cities including Mumbai, Chennai, Bengaluru, and Pune. This original cycle lasts for 108 seconds and features an average speed of 21.9 kmph, with a maximum acceleration of 0.65 m/s^2 and a maximum deceleration of 0.63 m/s^2 [5]-[7].

Modified Indian Drive Cycle: In the year 2000, a revised version known as the Modified Indian Drive Cycle (MIDC) was introduced. The MIDC has an increased average speed of 59.3 kmph, along with a higher maximum acceleration of 0.833 m/s^2 and a maximum deceleration of 1.389 m/s^2 (as noted by the Ministry of Road Transport & Highways in 2000).

Representation of Driving Characteristics: Both the IDC and MIDC are designed to reflect various driving behaviours across different modes such as acceleration, cruising, and idling throughout diverse regions in India. However, it is important to recognize that driving characteristics can differ significantly among vehicle types and geographical areas.

Limitations of IDC and MIDC FOR Heavy Duty Vehicles: Due to these variations, neither the IDC nor the MIDC may accurately represent the driving patterns for all vehicle categories, particularly for freight vehicles. Freight vehicles generally operate on highways where they experience longer cruising periods, and reduced rates of acceleration and deceleration compared to lighter passenger vehicles. Furthermore, the urban and sub-urban parts of the duty cycle impose different conditions on the speeds which are generally lower and with many stop-go frequencies [4].

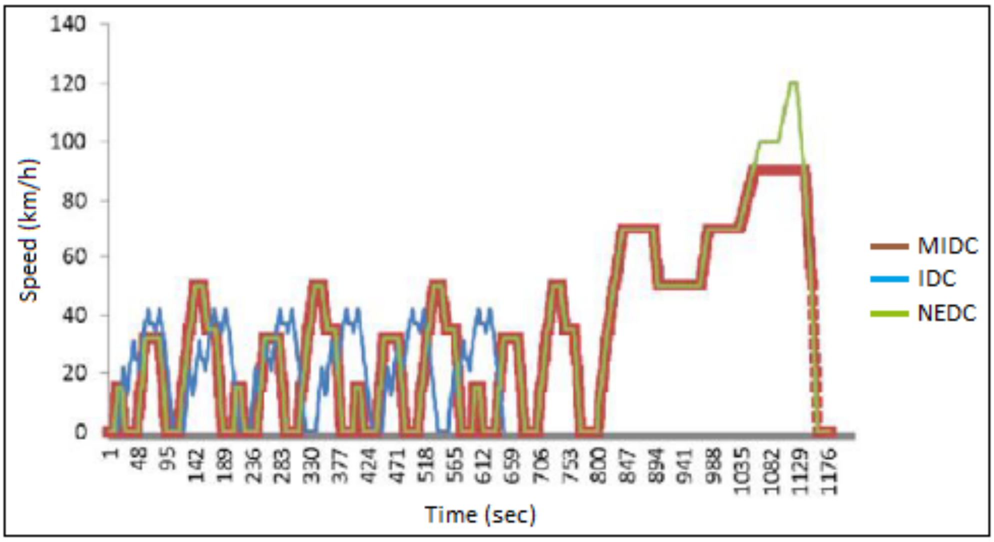


Figure 26: Speed vs time profile of IDC and MIDC compared with NEDC [7]

3.4.1 42t and 48t Truck Drive Cycle (Karnataka - INDIA)

Study Overview: The pilot data of 42t and 48t HDVs are available in [4]. The research focused on identifying key intercity freight routes within Karnataka, India, utilizing a freight volume count survey.

Data Collection Methodology: Transport operators who operate along the identified corridors were selected for data collection purposes. On-board diagnostic (OBD) devices were installed in the trucks to gather data.

Vehicle Specifications: The study specifically examined heavy-duty freight vehicles with gross vehicle weights (GVW) of 42 tons and 48 tons. The reason 42t and 48t trucks are chosen because these are commonly engaged for transporting building materials necessary for construction activities across India.

Truck Characteristics: Both trucks analysed in this study were diesel-powered models from 2020, featuring five axles and a tag-type wheelbase of 6.2 meters. The specifications of the two vehicles are as follows:

- 42t Truck: Equipped with 14 wheels.
- 48t Truck: Equipped with 16 wheels.

Both trucks had engines capable of producing a peak power output of 186 kW and were constructed with a heavy-duty ladder-type frame, adhering to Bharat Stage 6 emission standards.

Age and Mileage: At the time of the study, both trucks were approximately two years old and had accumulated a mileage of around 110,000 kilometres.

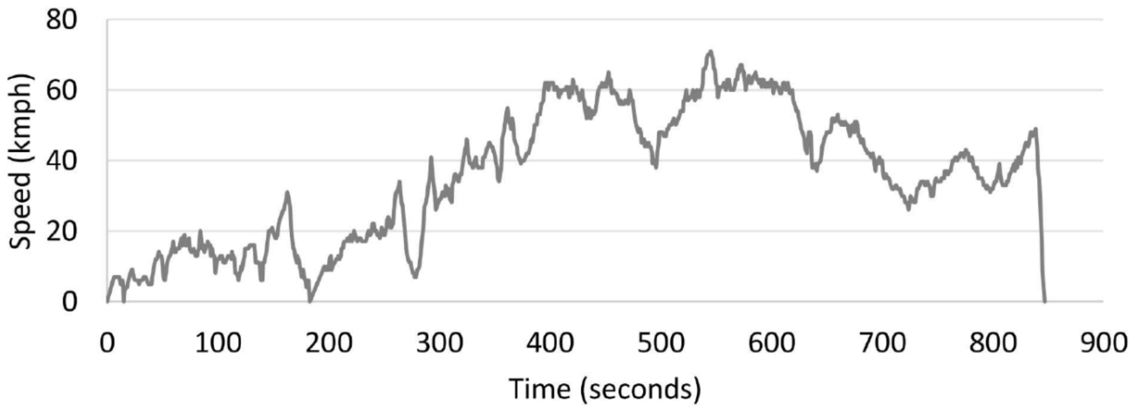


Figure 27: Drive cycle of 42t truck [4]

Table 6: Target stat and test stat of 42t truck [4]

Parameter	Unit	Test stat
Average speed	kmph	36.28
Average running speed	kmph	36.42
Percentage idle time	%	0.36
Average acceleration	m/s^2	0.464
Percentage acceleration	%	36.67
RMS acceleration	m/s^2	0.54
Average deceleration	m/s^2	0.514
Percentage deceleration	%	33.052
Positive-acceleration Kinetic energy	m/s^2	0.238
Percentage creep	%	0.724
Percentage cruise	%	28.59
Percentage acceleration to deceleration and vice-versa	%	20.65

The important characteristics are on acceleration-deceleration and creep-cruise segments in the cycles which are more India – specific. The 42t truck maintained an average speed of 35.56 kmph, with idling accounting for less than 1% of its operation time. It was primarily observed to be in accelerating (36.57%) and decelerating (32.83%), followed by cruising at 28.15% modes. Creeping constituted a negligible portion of its activity, contributing less than 1%.

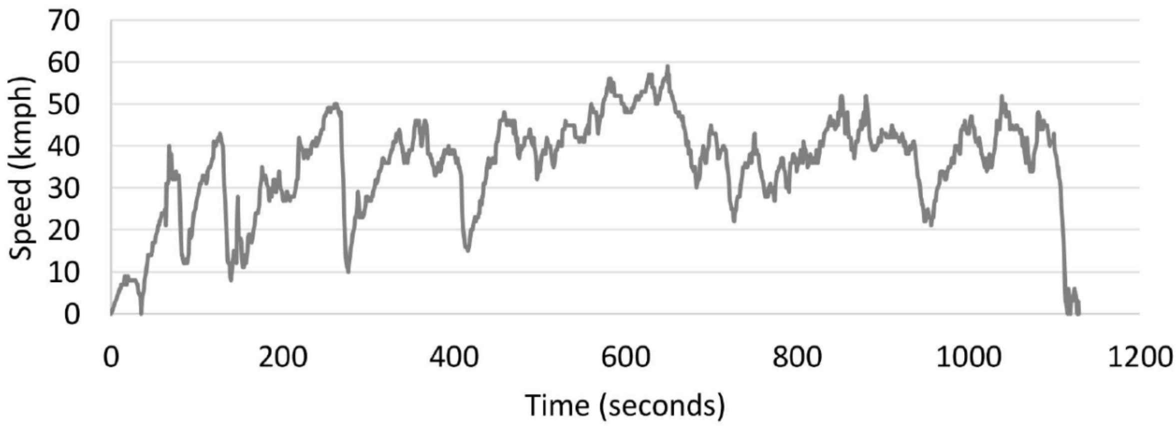


Figure 28: Drive cycle of 48t truck [4]

Table 7: Test statistics of 48t truck [4]

Parameter	Unit	Test stat
Average speed	kmph	35.76
Average running speed	kmph	35.92
Percentage idle time	%	0.45
Average acceleration	m/s^2	0.435
Percentage acceleration	%	35.72
RMS acceleration	m/s^2	0.51
Average deceleration	m/s^2	0.52
Percentage deceleration	%	31.15
Positive-acceleration Kinetic energy	m/s^2	0.076
Percentage creep	%	0.626
Percentage cruise	%	31.51
Percentage acceleration to deceleration and vice-versa	%	18.82

The average speed of the 48-ton truck was recorded as 34.27 kmph, with idling being negligible (<1%). It spent most of its time accelerating (34.08%), followed by cruising (33.88%) and decelerating (30.02%) during operation. Its average acceleration rate was measured at 0.43 m/s^2, while its deceleration rate stood at 0.49 m/s^2 - both slightly lower than those observed for the lighter, 42-ton truck, which achieved an average speed of 35.56 kmph along with an acceleration rate of 0.47 m/s^2 and a deceleration rate of 0.53 m/s^2. These differences can likely be attributed to the additional load carried by the heavier vehicle (+6 tons).

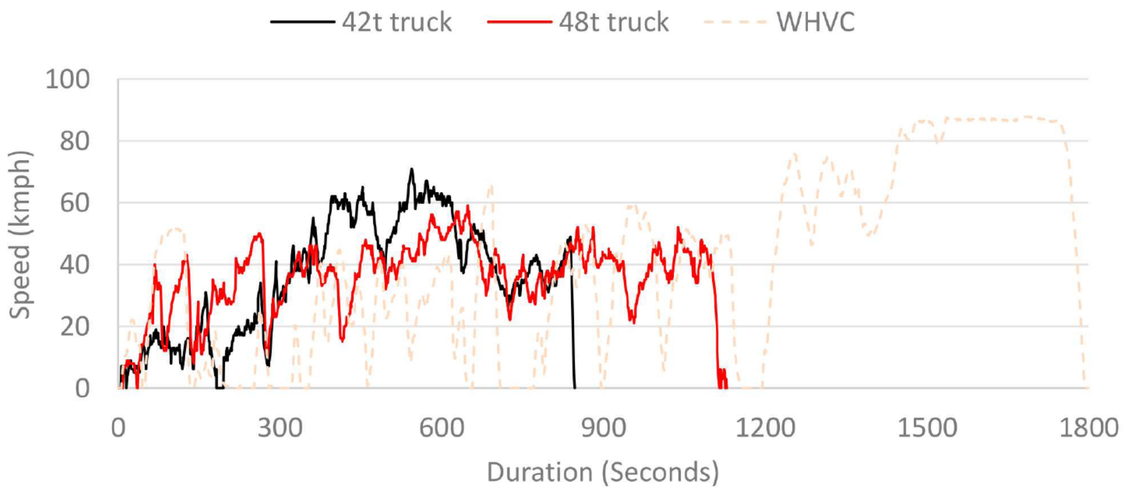


Figure 29: Comparison of the 42t and 48t drive cycles with WHVC [4]

Summary of Truck Drive Cycle Analysis:
The newly developed drive cycles for 42-ton (42t) and 48-ton (48t) trucks were found to be 953 seconds and 671 seconds shorter, respectively, compared to the World Harmonized Vehicle Cycle (WHVC) [4].

Average Speed Comparison: The average speed recorded for the WHVC was 40.13 kmph, which is notably higher than the speeds of the 42t and 48t truck drive cycles, which were 36.28 kmph and 35.76 kmph, respectively. This data suggests that heavy-duty truck speeds on Indian highways are approximately 9% to 11% lower than those observed in global commercial vehicle standards as represented by the WHVC.

Factors Influencing Speed: One potential explanation for these reduced speeds in Indian heavy-duty trucks could be attributed to the common practice of overloading, which is widespread in India. Additionally, road conditions and traffic scenarios may also contribute significantly to this phenomenon.

Additional Drive Cycles Considered: For further analysis, other drive cycles such as the "HD-UDDS drive cycle," "HHDDT drive cycle," and "JE05 Cycle with a Gross Vehicle Weight (GVW) greater than 3.5 tons" were also considered for comparison purposes. It is important to note that vehicles with a GVW exceeding 11.79 tons are classified as heavy-duty vehicles.

Table 8: Comparison with global heavy-duty drive cycles [4]

Metric	42t truck	48t truck	HD-UDDS	HHDDT	JE05
Duration (s)	847	1129	1063	2083	1829
Distance (km)	8.5	11.1	8.9	37.2	-
Average speed (kmph)	36.28	35.76	30.2	64.2	26.9
Maximum speed (kmph)	71	59	93.3	95.4	88.0

The drive cycle for the 42t truck exhibited similarities to the HD-UDDS in terms of distance, measuring 8.5 km compared to 8.9 km for the HD-UDDS. However, there were notable differences in speed and duration when compared to the three other drive cycles analysed.

Speed Analysis: The average speed of the 42t truck was significantly higher than that of both the HD-UDDS and JE05 cycles, with increases of 16.7% and 25.8%, respectively. In contrast, it was observed to be 77% lower than the average speed recorded for the HHDDT cycle.

Duration Comparison: In terms of duration, the drive cycle for the 48t truck lasted 1129 seconds, which is quite comparable to the HD-UDDS duration of 1063 seconds. Despite this similarity in duration, the average speed for the 48t truck was also higher—by 15.5% compared to HD-UDDS and by 24.7% relative to JE05—while still being significantly lower (80%) than that of HHDDT.

Acceleration and Deceleration Differences: Furthermore, both acceleration and deceleration patterns in these developed truck drive cycles showed variations when compared to those in MIDC and WHVC cycles. These differences are crucial as they contribute to varying estimates of fuel consumption and emissions across different driving conditions.
The developed drive cycles [4] have limited representativeness due to being based on a single truck for each cycle. This study [4] enhances the existing literature by creating drive cycles for two distinct vehicles, specifically 42t and 48t heavy-duty goods vehicles, which primarily operated on intercity routes.

3.4.2 Drive Cycle of 5 Reference Model Trucks categorised by GVW (India)

The study referenced in [8] adheres to the GVW-based truck classification established under the Central Motor Vehicle Rules (CMVR Rules 1989). This classification includes heavy-duty trucks with a Gross Vehicle Weight (GVW) exceeding 12 tons, as well as one medium-duty truck with a GVW ranging from 7.5 to 12 tons. The analysis identifies five distinct categories of rigid trucks based on their GVW:

- 7.5-12 tons (RV1)
- 12-16.2 tons (RV2)
- 16.2-31 tons (RV3)
- > 31 tons (RV4)
- Tractor-trailers above 40 tons (RV5)

These categories encompass a wide spectrum of the market concerning axle configuration and GVW, collectively representing 64% of India's truck sales for vehicles over 7.5 tons GVW during the fiscal year 2020-21. For the purpose of this analysis, five reference vehicles have been selected, which will be referred as: RV1, RV2, RV3, RV4, and RV5 respectively. The key parameters associated with these five Reference Vehicles are detailed in Table 9.

The data regarding real-world driving patterns was obtained in study [8]. This information was collected from the BS VI versions of five truck models using a GPS device and a data logger connected to the on-board diagnostic (OBD) port of the vehicles [8]. The recorded parameters included GPS coordinates, vehicle speed, direction, engine speed, and fuel consumption. Over a period of two months and approximately 10,000 kilometres of driving, data sets were created for each reference truck.

The study referenced in [8] introduces innovative drive cycles that represent various driving profiles of the reference trucks, ensuring that the findings closely reflect actual operational conditions. The methodology used to develop these cycles is based on research by Jin et al. (2020) [9], which focused on bus/truck routes in India. The resulting drive cycles of 5 reference vehicles in study [8] have been digitised and recreated and are illustrated in Figure 30 (a to e).

Table 9: Key parameters for Reference Vehicles [8]

Reference Vehicle	RV1	RV2	RV3	RV4	RV5
Body type	Rigid truck	Rigid truck	Rigid truck	Rigid truck	Tractor-trailer
Model name	Tata 1212	Ashok Leyland 1615 HE	Tata 2818	Ashok Leyland 4220-5.7TD HM	Ashok Leyland 5525
Axle configuration	4 × 2	4 × 2	6 × 2	10 × 2	6 × 4
Number of tyres	Steer: 2 Driver: 4	Steer: 2 Driver: 4	Steer: 2 Driver: 8	Steer: 4 Driver/Tag: 10	Steer: 2 Driver/Tag/ Trailer: 8
GVW (kg)	11990	16100	28000	42000	55000
Payload (kg)	7500	10800	20000	28000	40000
Engine displacement (cc)	3300	3839	5600	5660	5300
Emission standard	BS VI	BS VI	BS VI	BS VI	BS VI
Maximum engine power (kW)	125	111.8	140	149	186.4
Maximum engine torque (Nm)	390 @1000-2200 rpm	450 @ 1250 – 2000 rpm	850 @ 1000 – 1700 rpm	700 @ 1200 – 2000 rpm	900 @ 1200 – 1900 rpm
Tyre	8.25 R 20 – 16 PR RIB	9.00 R20 16 PR	295/90R20 16 PR	295/90R20 16 PR	295/90R20 16 PR
Transmission type	Manual				
Number of gears	5F + 1R	6F + 1R	6F + 1R	8	9F + 1R
Rear axle ratio	5.285	6.833	6.14	5.63	6.17
Coeff. of aerodynamic drag (C_D)	0.7				
Coeff. of rolling resistance (C_{rr})	0.0095				

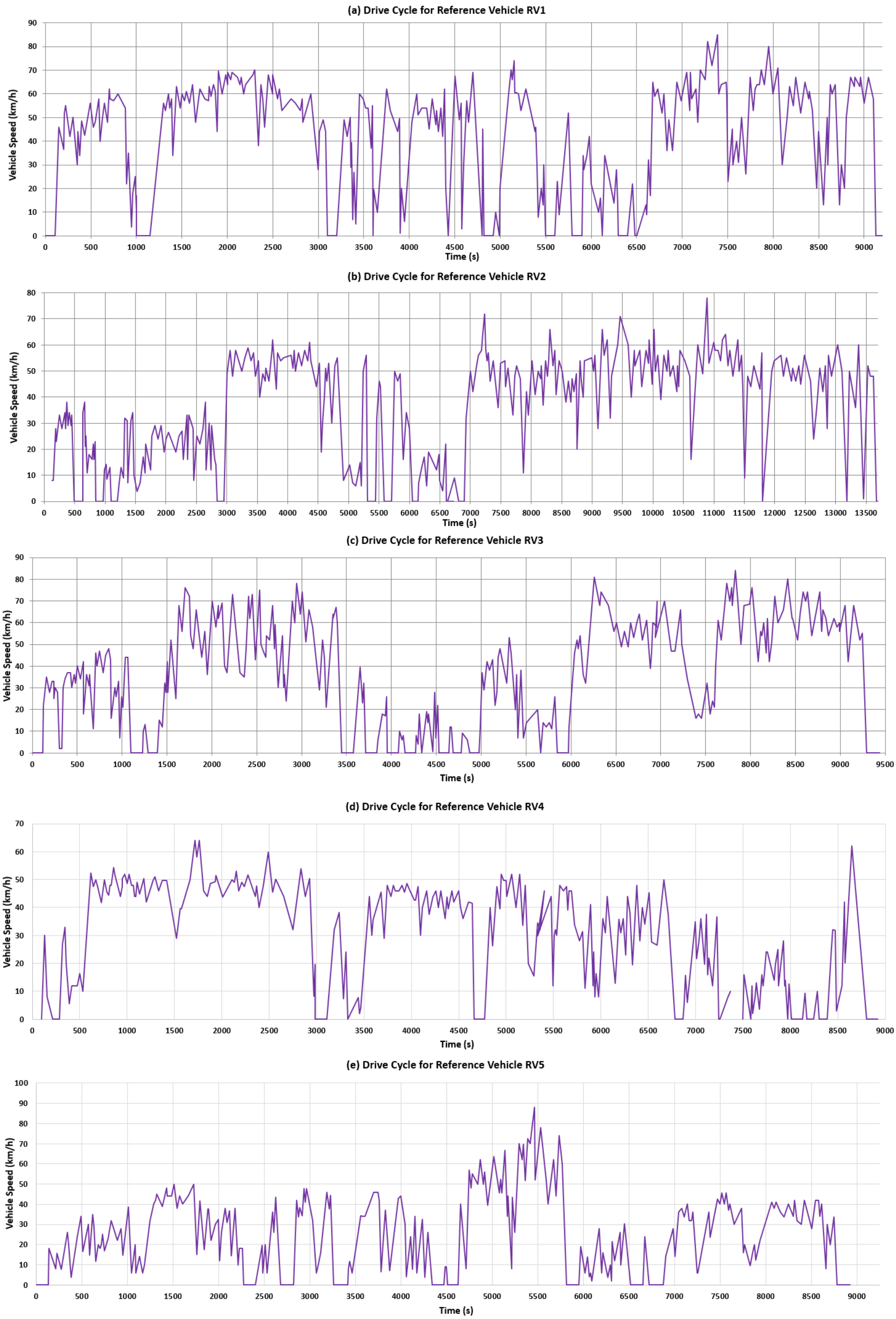


Figure 30: Drive cycle for Reference Vehicles (a) RV1 (b) RV2 (c) RV3 (d) RV4 (e) RV5

Reducing Resistive Forces in Vehicle Movement:

Technologies aimed at reducing vehicle energy consumption primarily focus on minimizing resistive forces encountered during motion. The power generated by a vehicle's drivetrain must overcome several key resistive forces: tyre deformation, aerodynamic drag (headwind), inertial forces, and the demands of auxiliary systems. This section examines potential improvements in each of these areas to enhance overall energy efficiency.

i. **Rolling resistance coefficient (C_{rr}):** The coefficient of rolling resistance (C_{rr}) is a significant contributor to overall road load power requirements and fuel use. Tyres with lower rolling resistance make trucks more fuel-efficient. As per Stage-1 implementation by Automotive Indian Standards (AIS), the C3 class tyres used for HDVs cannot exceed the rolling resistance value of 0.010 for bias tyres and 0.0085 for radial tyres. In 2022, the AIS released a notification proposing new tyre norms called Stage-2. The Stage-2 implementation specifies that new C3 class tyres used for HDVs cannot exceed the rolling resistance value of 0.0095 for bias tyres and 0.007 for radial tyres. The study in [8] assumed a baseline of 0.00925, which is the mean of the rolling resistance standard of the Stage-1 regulation for bias and radial tyres. A first step toward improvement is to phase out bias tyres by making the more fuel- efficient radial tyres mandatory which can lead to significant fuel savings.

Tire technology level	Rolling resistance coefficient
Baseline 2020	0.00925
Level 1 – Radial tires are mandatory	0.0070
Level 2 improvement	0.0062
Level 3 improvement	0.0049

Figure 31: Tyre efficiency improvements [8]

ii. **Aerodynamic drag coefficient (C_D):** Aerodynamic drag is a significant factor for long-haul Heavy-Duty Vehicle (HDV) operations due to the extensive time spent at sustained highway speeds. While its impact is currently less pronounced in regions like India due to slower average truck speeds, its significance is projected to increase with future improvements in highway networks and higher permitted speeds [8]. To mitigate aerodynamic drag, several technologies are available, including improved tractor design, integrated tractor and trailer designs, gap reduction at the tractor/trailer interface, side skirts for both tractor and trailer, rear-end aerodynamic devices (e.g., boat-tails), and trailer underbody devices [8].

Aerodynamic technology level	Cd – Coefficient of aerodynamic drag
Rigid trucks	
Baseline – 2020	0.7
Level 1 improvement	0.62
Level 2 improvement	0.55
Tractor-trailer	
Baseline – 2020	0.7
Level 1 improvement	0.65
Level 2 improvement	0.55
Level 3 improvement	0.51

Figure 32: Aerodynamic efficiency improvements [8]

iii. **Inertial Forces:** Inertial forces relate to the energy required to accelerate and decelerate the vehicle. Reducing vehicle mass is a primary strategy to minimize the energy needed to overcome inertia. Light weighting technologies, such as the increased use of high-strength steel, aluminium alloys, carbon fibre composites, and other advanced materials, are being widely adopted in vehicle manufacturing.

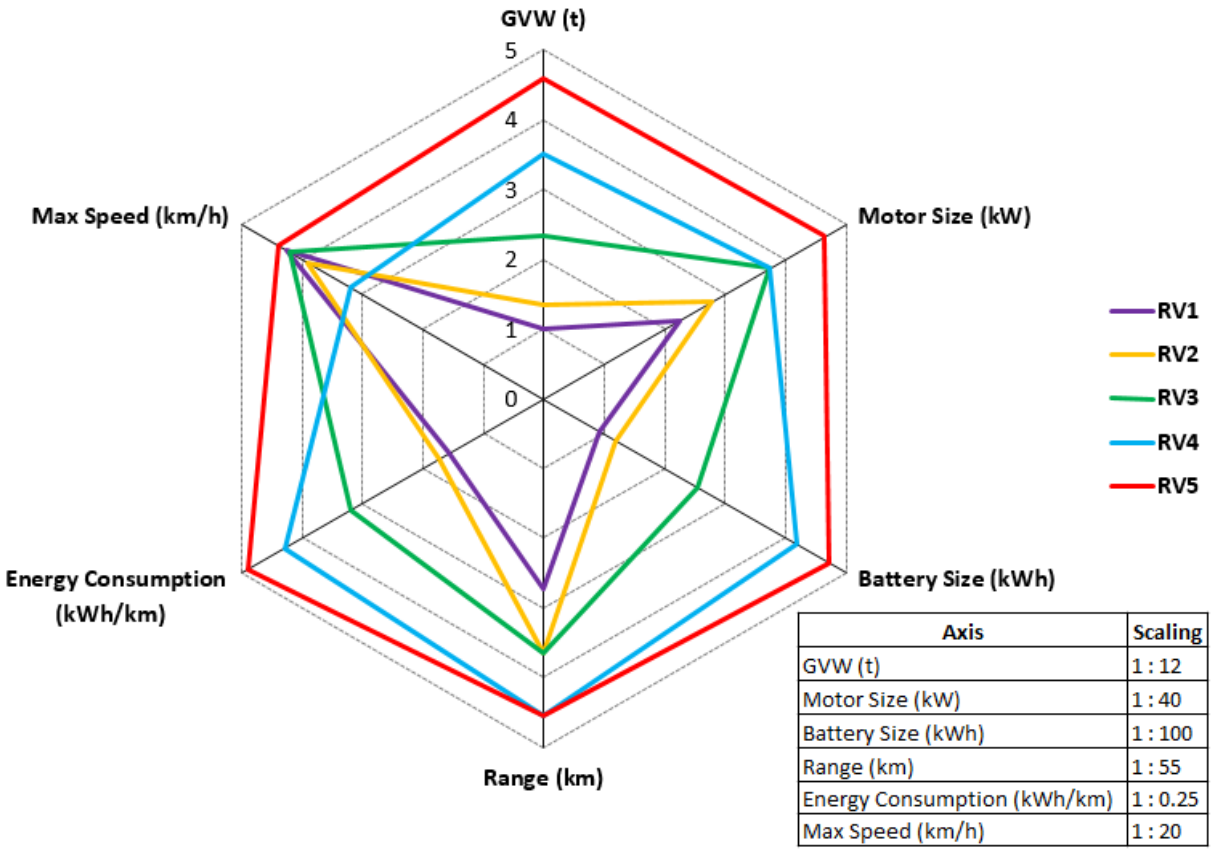
iv. **Auxiliary Systems:** Auxiliary systems, such as air conditioning, power steering, and infotainment, consume a significant amount of energy, especially in modern vehicles. Optimizing the efficiency of these systems and electrifying them where possible can lead to substantial energy savings.

Virtual models of these trucks are developed by substituting the internal combustion engine (ICE) of reference trucks with an electric motor and battery system that can deliver comparable performance in terms of speed, power, and torque. The battery utilized consists of lithium-iron-phosphate cells, which are among the most prominent chemistries currently employed in heavy-duty vehicle (HDV) electrification (Mao et al., 2021). Based on the operational data collection exercise previously mentioned, the battery size is designed to accommodate the average daily distance travelled by trucks and tractor-trailers. The specified battery sizes and ranges are lower than those reported in other studies from different regions. This conclusion is drawn from the sensitivity of Indian consumers regarding upfront truck costs and is corroborated by the ranges observed in announced future models and prototypes of battery electric trucks (BETS) within the Indian market [8].

With increase in GVW by 4.7×, the battery capacity increased by a similar factor of 5.1×. Corresponding increase is not seen in specific energy consumption (kWh/km) which is 0.4 to 1.22 and factoring in mass and range increases of 5× and 1.5× respectively, the specific energy consumption has not increased by 7.5×, (i.e. 5×1.5) but only by 3×, indicating that larger GVW with longer range is more energy efficient.

Table 10: Specifications of equivalent BET models [8] and estimated parameters [this study]

Reference Vehicle	RV1	RV2	RV3	RV4	RV5
GVW (kg)	11990	16100	28000	42000	55000
Motor Size (kW)	90	111	150	150	186
Battery Size (kWh)	92	120	255	418	471
Range (km)	150	200	200	250	250
Energy consumption (kWh/km)	0.39	0.43	0.8	1.07	1.22
Max Speed estimated from drive cycles (kmph)	85	78	84	64	88
Average Speed estimated from drive cycles (kmph)	44	37	38	31	27
Average Acceleration estimated from drive cycles (m/s^2)	0.19	0.16	0.16	0.10	0.13
Average Deceleration estimated from drive cycles (m/s^2)	-0.27	-0.13	-0.17	-0.17	-0.17



Axis	Scaling
GVW (t)	1 : 12
Motor Size (kW)	1 : 40
Battery Size (kWh)	1 : 100
Range (km)	1 : 55
Energy Consumption (kWh/km)	1 : 0.25
Max Speed (km/h)	1 : 20

Figure 33: Performance metrics for five different equivalent BETs (RV1-RV5)

4 Existing Truck Technology

Transitioning to electric vehicles represents a forward-looking investment, while also serving as an effective means of reducing CO_2 emissions. With zero tailpipe exhaust emissions and significantly lower noise levels, electric trucks can operate in areas where conventional trucks are restricted (possibilities to pick up and deliver the goods). The reduced noise allows for a broader range of transport assignments to be conducted during off-peak hours, thereby increasing operational flexibility throughout the day.

Electric trucks are notably quieter than their traditional counterparts. This results in lower noise and vibration levels both inside the cab and in the surrounding environment. Additionally, the electric motor provides smooth and seamless power delivery, making it particularly well-suited for the stop-and-go driving conditions commonly encountered in urban transportation [11].

4.1 Features of EV Trucks

Electric trucks bring a ton of benefits that make them a compelling choice for logistics.

i. **Environmental Impact:** Electric trucks generate no tailpipe emissions, greatly decreasing air pollution and greenhouse gas emissions. Embracing electric trucks in India supports our dedication to the Paris Agreement and its objective of reaching net-zero emissions by 2070.
ii. **Cost Efficiency:** While electric trucks might have a higher upfront cost, they offer substantial savings in the long run. Electricity is cheaper than diesel, and with fewer moving parts, maintenance costs are also lower.
iii. **Operational Efficiency:** Electric trucks are known for their smooth and quiet operation. This not only reduces noise pollution but also provides a better driving experience. They are perfect for urban logistics and short-haul routes, where frequent stops and starts are common.

4.2 Challenges and Barriers for EV Trucks

Despite their advantages, electric trucks face several hurdles.

i. **Infrastructure Development:** A major challenge facing the adoption of electric trucks in India is the insufficient charging infrastructure. To facilitate widespread use, it is essential to increase the number of charging stations, particularly along highways and in rural regions.
ii. **Battery Technology:** The limitations of current battery technology restrict the range and payload capacity of electric trucks. Nevertheless, ongoing research and development efforts are anticipated to yield significant advancements in this area in the near future.
iii. **High Initial Costs:** The initial purchase cost of electric trucks in India is higher compared to diesel trucks. Financial incentives and subsidies from the government can help mitigate these costs and encourage adoption.

4.3 Existing EV Trucks in India

Electric trucks are not just a trend; they are the future of logistics. As technology advances and infrastructure improves, electric trucks in India will become more prevalent, driving us towards a cleaner, greener, and more efficient future in logistics. The journey has just begun, and the road ahead is electric. The comparison of existing variants in EV Trucks [12, 13] is shown in Table 11. The specifications and brief of some of the existing EV trucks in India [12] & [13] are detailed in Annexure-2.

Table 11: Comparison of existing variants in Truck segment (India)

	OEMs - INDIA (Typical ratings)						
	Max Seed	Range (km)	Charging Time (hr)	Battery Capacity kWh	Max Power kW	Max Torque Nm	GVW (t)
Tata Ultra T7	80 kmph	100	2	62.5			7.5-8.5
Tata Prima E.28K		150-200		453	245	2950	28
Ashok Leylan Boss 1219		150		80	140	1065	12
Ashok Leylan Boss 14HB		230	1	200	120	409	14
Ashok Leyland Boss 1218		300-350	1	453	140	1065	12
Olectra Meghatron 28T	80 kmph	150	2	350	270	2400	28
Volvo FH Aero Electric		300	2.5	360-540	330-490		44
Volvo FMX Electric		300	2.5	180-540	330-490		44
Volvo FM Low Entry		200	1.5	360	330		32
Volvo FE Electric		275	2.3	280-375	225		27
Volvo FL Electric		450	2.3	280-565	130		18.6
IPLTech Rhino5536e		185	1.5	258	268	2400	55
BYD Q1R		100	2	217	180	1500	42

4.4 Global EV Truck Manufacturers

The evolution of EV truck technology has been fuelled by advances in battery efficiency, charging infrastructure, and regulatory policies aimed at reducing emissions and promoting sustainable energy sources. Key players in the industry include automotive giants, bringing unique expertise and designs to the electric truck landscape. Companies like Tesla, Rivian, and Volvo are pioneering the electric truck revolution, while traditional truck manufacturers such as Daimler, MAN, and Mercedes are transitioning their product lines to electric power. Additionally, newer entrants like Nikola and Workhorse are bringing fresh approaches to the market, particularly with hydrogen fuel-cell trucks in addition to pure electric models. The key global players in the segment of e-trucks are enumerated in **Annexure-2**. With the evolving trends in the EV industry, the data from available e-truck manufacturers has been captured and tabulated for ease of comparison. Critical data like GVW, Range, Continuous &Peak ratings of the motor was categorized. The battery pack ratings which form the critical parameter to decide on the range of the truck is also detailed in Table 12.

It is worth noting that almost all the EV trucks of global OEMs have gone in for PMSM drives, while a lone exception is seen in Nikola, who give more client flexible options including hydrogen fuelling. Furthermore, Nikola have adopted induction motor drives (REPM – free) drive and also possess the high GVW (82t) - long range (500 km) with highest kWh battery pack solution. Nikola is leading the pack in terms of adopting next – generation zero emission trucking solutions. From Table 12 and Table 26 of Annexure-2, it is observed that global players have options around 82t class of vehicles with 500 km range, pointing to the vectors of ZET. To surmise, 42t class and 150 to 300 km range vehicles in

Indian roads will over time shift to doubling of both mass and range as global OEMs start their foray in to price sensitive Indian market. This evolution also points to potential service wherein tonnage – km-based pricing for the customer become attractive for inducting vehicles with well-defined repeated routes and customer specific loads.

Table 12: Comparison of EV Truck specifications (global manufacturers)

Manufacturer	Model	Continuous Power (kW)	Peak Power (kW)	Battery (kWh)	GVW (kg)	Range (km)	Motor Type
Volvo	**FH**	330	490	540	44000	300	PMSM
Mercedes	**eActros**	400	600	621	82000	500	PMSM
BYD	**8TT**	320	400	422	83000	350	PMSM
Tesla	**Semi**	-	400	-	81000	500	-
Nikola	**Tre**	400	500	753	82000	500	AC IM
Rivian	**R1T**	-	560	-	-	600	PMSM

5 Drive Train Configuration

5.1 Drive train topologies

Drive train configurations for electric trucks can be classified into two categories: with gearbox and without gearbox. Establishing applicable configurations requires defining a solution space that includes all suitable drive train concepts known as a topology matrix. This involves identifying degrees of freedom related to component characteristics such as location and type. The solution space accommodates two-wheel, four-wheel, and six-wheel drive systems based on power demand requirements [14].

The following characteristics were defined as degrees of freedom:

i. Number of electric machines installed
ii. Electric machine type (a) central motor (b) wheel near motor and (c) wheel hub motor
iii. Alignment of the electric machine (lateral or longitudinal)
iv. Location of the electric machine (axle-near, vehicle centred, axle-distant)
v. Transmission type (direct transmission, stepped transmission)

It becomes evident at this stage that certain combinations are interdependent, leading to equivalencies among some options (e.g., placing the wheel near the motor always necessitates two machines per axle). These specific dependencies must be carefully accounted for when constructing the topology matrix. However, even after filtering out dependent combinations, the resulting solution space quickly grows vast and unwieldy, encompassing potentially hundreds of possibilities. Consequently, reducing the number of solutions emerges as a critical next step. To achieve this reduction without restricting the innovative potential of the drive train concept - ensuring no viable solutions are excluded - a different methodology will be adopted from this point onward [14].

Limiting the system to a single axle significantly reduces the solution space. However, no potential solutions are lost because the solution space for one axle can be combined with that of a second axle in a four-wheel drive configuration. This recommendation stems from the overarching concept of electric drivetrains. By leveraging the flexible arrangement options for electric motors compared to internal combustion engines (ICEs), it becomes feasible to position the motor(s) close to the wheels, thereby optimizing both efficiency and packaging of the drivetrain [14].

Electric vehicles (EVs) utilize various types of transmissions to optimize performance, efficiency, and driving experience. The three main types of transmissions are discussed.

i. **Direct Transmission:** Direct transmission is a drivetrain configuration in which the electric motor connects directly to the wheels, eliminating any intermediate gearing. This arrangement facilitates immediate power delivery from the motor to the wheels, leading to a highly efficient energy transfer. Below are the features of direct transmission.

    - **Efficiency:** Direct transmissions minimize energy loss since there are no gears or clutches involved that can absorb power.
    - **Simplicity:** The design is straightforward, which reduces the complexity of the vehicle's powertrain system.

- **Performance:** Electric motors provide maximum torque from zero RPM, making direct transmission particularly effective for acceleration and responsiveness.

ii. **Stepped Transmission:** Stepped transmission refers to a multi-speed gearbox that features distinct gear ratios. This type of transmission enables the selection of various gears based on the vehicle's speed and power needs. Below are the characteristics of stepped transmission.

- **Performance Optimization:** By having multiple gears, stepped transmissions can optimize performance across different speed ranges. For instance, lower gears can provide better acceleration while higher gears improve efficiency at cruising speeds.
- **Enhanced Driving Experience:** Stepped transmissions can offer a more engaging driving experience by allowing drivers to feel shifts similar to traditional internal combustion engine (ICE) vehicles.
- **Application in High-Performance EVs:** Some high-performance electric vehicles like the Porsche Taycan utilize stepped transmissions to enhance their dynamic capabilities and overall performance.

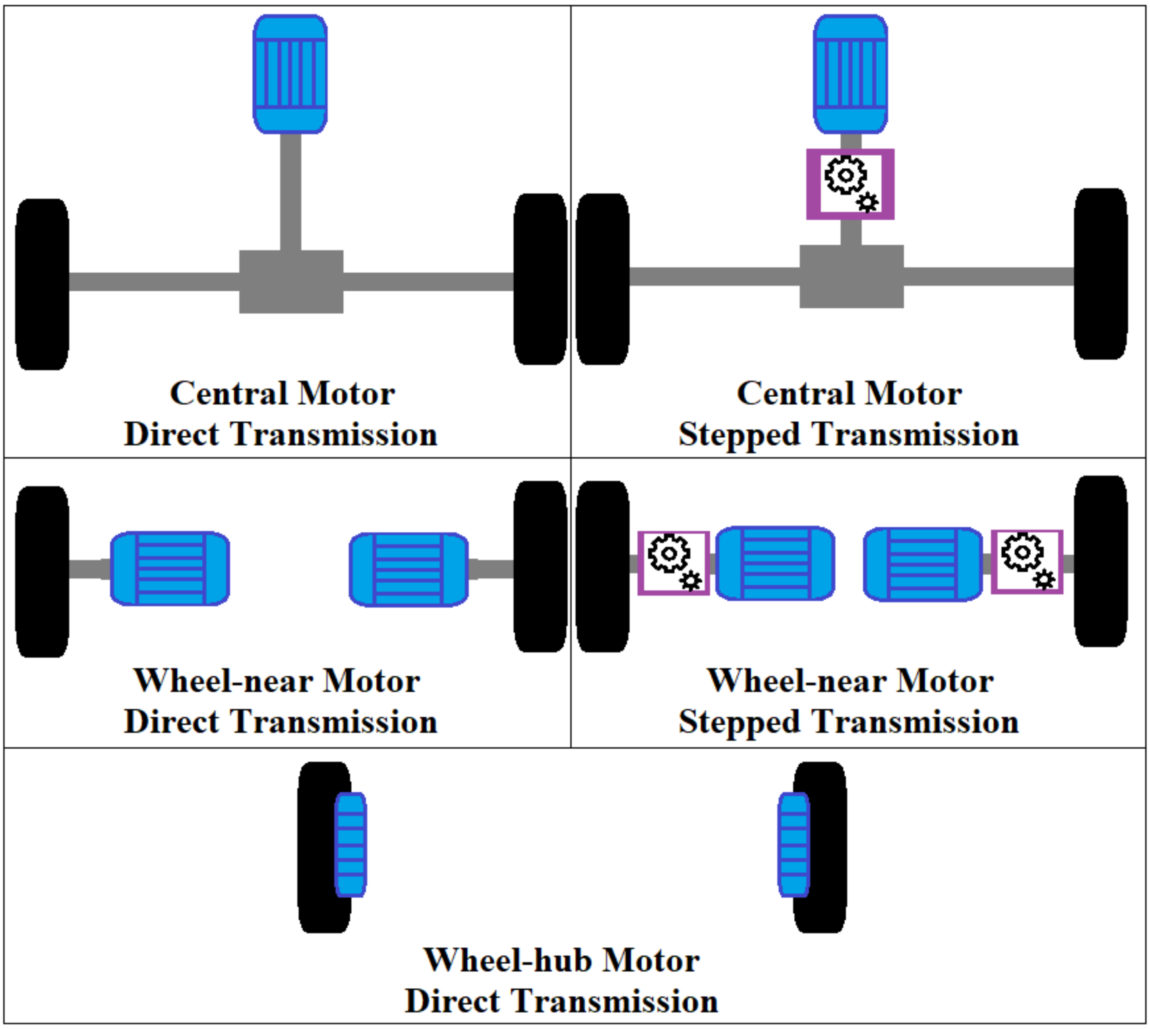


Figure 34: Topologies of various drive trains

Some more transmission schematic discussed below with reference to load sharing such as (i) single transmission (ii) split transmission.

iii. **Single Transmission Schematic:** Two electric motors are linked to a single shaft at the input of the transmission junction within a single transmission system. This setup can be configured for either a single speed or multiple higher speeds based on requirements.

iv. **Split Transmission and Torque Share:** In split transmission systems, two electric motors are independently connected to the transmission, allowing the total torque demand to be distributed across different drivetrains. These motors can operate at the same speed or at different speeds from one another.

5.2 Dual E-motors and their benefits

The primary reasons for opting for dual e-motors instead of a single e-motor can be summarized as follows:

Cost Efficiency: Utilizing off-the-shelf products allows for lower overall costs. This approach leverages existing technology, which can reduce development and manufacturing expenses. Dual E-motors can be cost-efficient when truck volumes are low due to their operational efficiency, potential for cost savings through reduced energy consumption and longer maintenance intervals, and the ability to optimize performance under varying load conditions.

Power Consumption Management: By having two e-motors, it is possible to turn off one motor during operation when full power is not required. This capability enhances energy efficiency and reduces overall power consumption, contributing to better vehicle range.

Torque Fill Feature in Split Transmission: The use of split transmission systems enables effective torque filling during gear changes. This feature helps maintain performance and smoothness in acceleration by optimizing the torque delivery from the motors.

Simulation Insights of transmission speed from double and single e-motor:
According to the simulation work referenced in [15], when total e-motor torque demands are below 200 Nm, operating one e-motor while deactivating the other results in lower total energy consumption. Although this energy advantage fluctuates depending on the driving cycle, it remains a critical consideration for maximizing vehicle range. The simulation findings comparing double and single e-motor configurations with a 3-speed transmission are detailed in Table 13.

Table 13: Simulation results using double and single e-motor for 3-speed transmission [15]

Route Single	320kW e-motor	Dual 160kW × 2 e-motor	Energy Saving Benefit
-	**kWh**	**kWh**	**%**
Vecto RD	33.63	33.62	0.05
Vecto UD	124.78	124.45	0.26
Vecto MU	13.58	13.49	0.66

The results [15] indicate that extending the duration of cycle-based low load demand enhances the energy obtained from deactivating one of the e-motors in a dual motor application.

In summary, the choice of dual e-motors over a single unit is driven by cost savings, improved energy efficiency through selective motor operation, and enhanced performance via advanced transmission features. If, we consider the hybrid urban-semi-urban-highway drive cycle described in earlier sections, dual e-drives are envisaged to perform better in these conditions.

5.3 Prime – movers & Energy Device configurations

If one were to consider, two energy devices, one as battery (High Energy Source) and the other as super capacitor (High Power source) along with at least two prime movers connected by bi-directional inverter-converter power electronic devices, we can construct many configurations as per need and the exigencies of the duty cycle. Recently, NFTDC and E-mobility Lab in IIT Guwahati under Prof Praveen Kumar did a detailed analysis of multiple configurations of motors that can address various duty cycle demands with increased re-generation capacity and storage using super capacitors along with batteries. Some of potential configurations are presented hereunder.

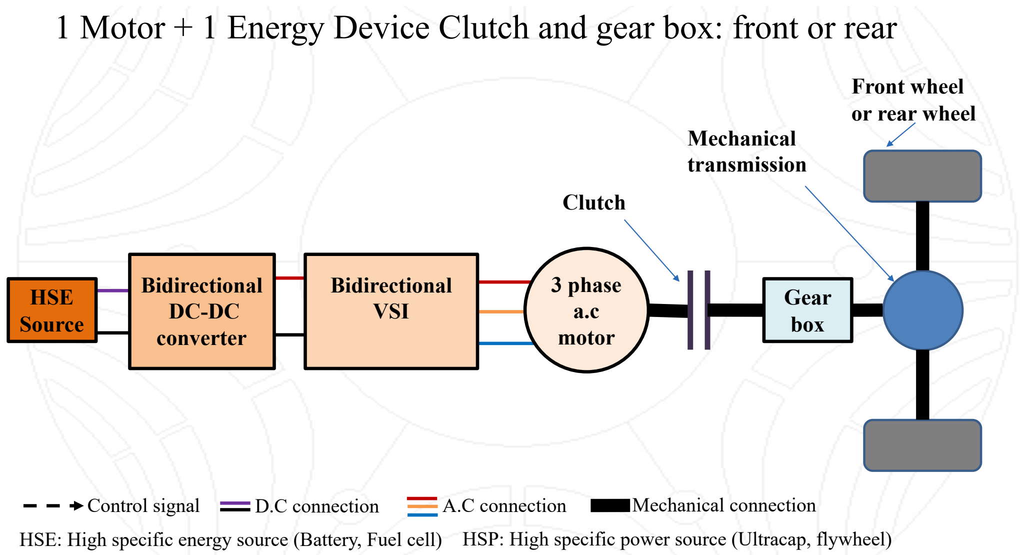


Figure 35: 1-Motor & 1-Energy Device configuration

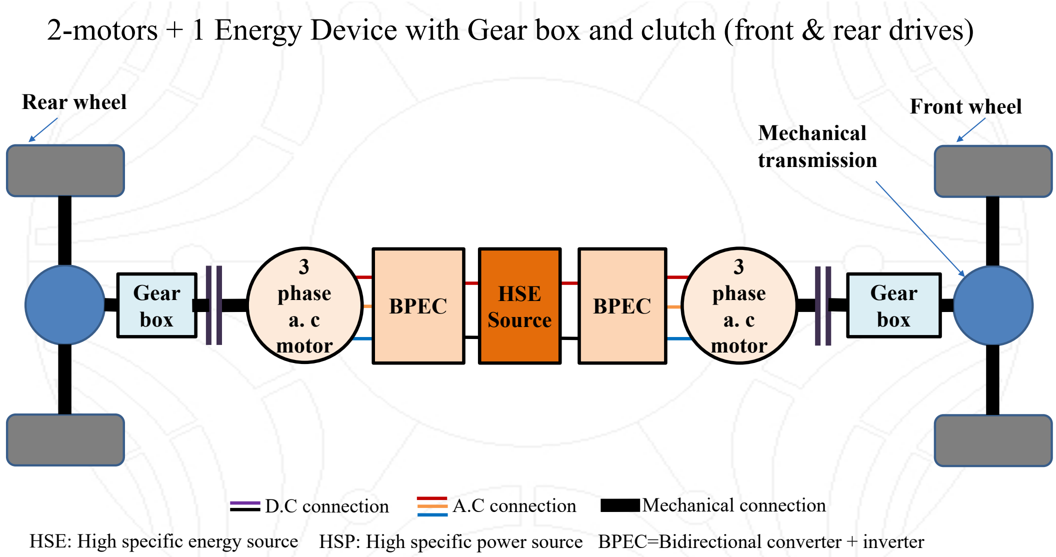


Figure 36: 2-Motor & 1-Energy Device configuration

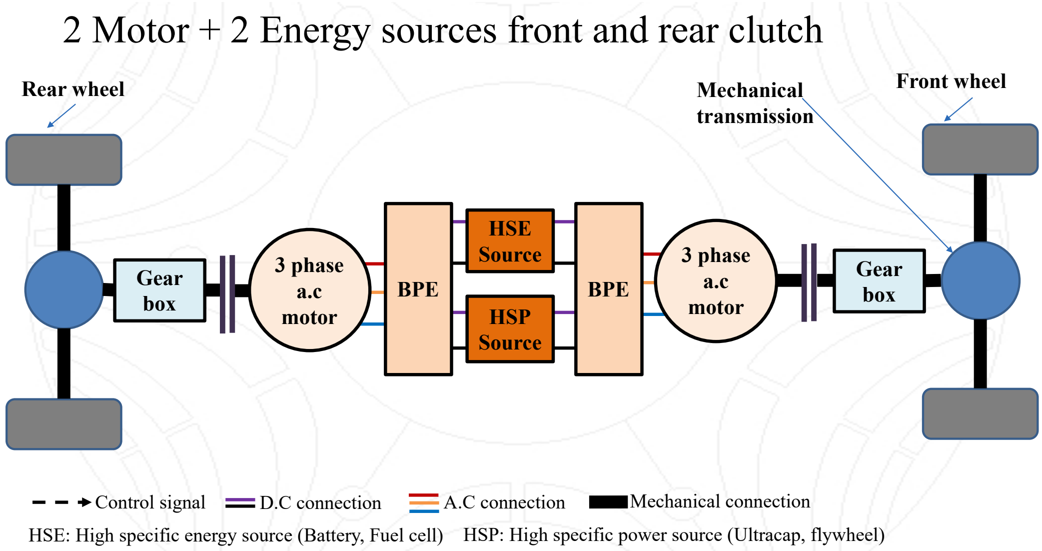


Figure 37: 2-Motor & 2-Energy Device configuration

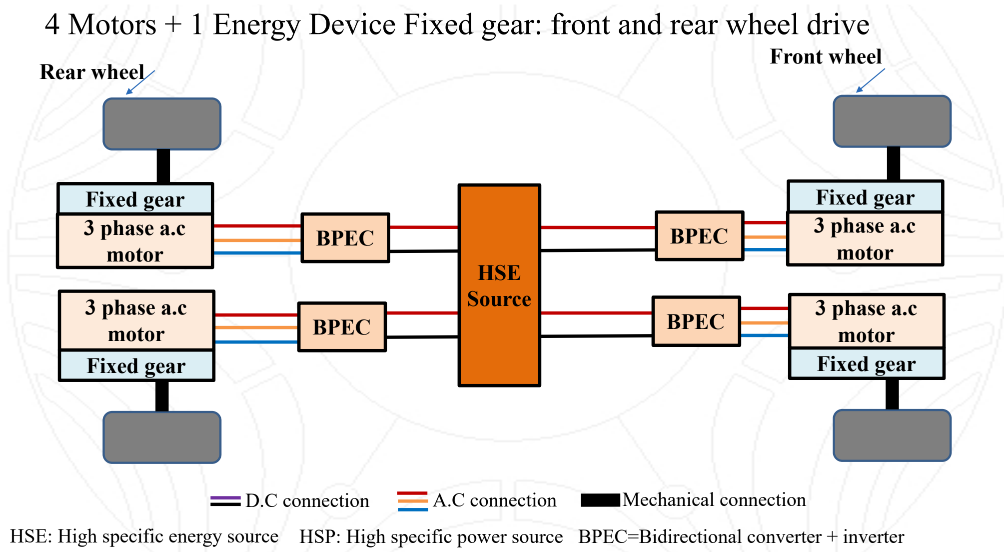


Figure 38: 4-Motor & 1-Energy Device configuration

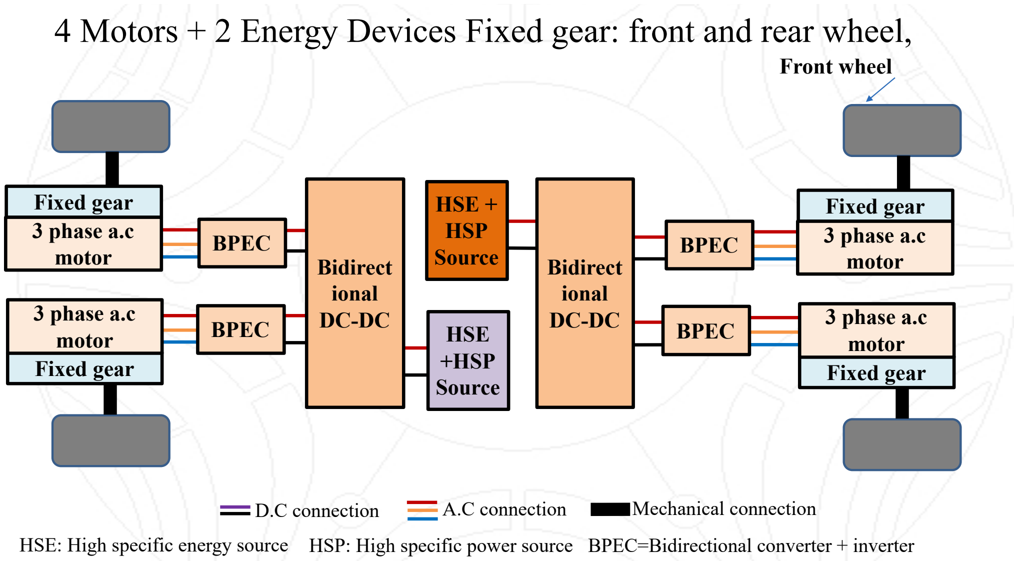


Figure 39: 4-Motor & 2-Energy Device configuration

5.4 Quantitative Evaluation & description of process tools

Identifying suitable drive train concepts for a specific vehicle design requires the establishment of evaluation process tools. These tools will help clarify the drive train concepts through defined evaluation criteria. Each criterion is unique and must be tailored to the specific application at hand. To obtain quantitative insights regarding these criteria, it is essential to develop underlying evaluation functions. Since the significance of results may vary based on the vehicle concept, it is important to assign different weights to these criteria according to relevant scenarios associated with the vehicle design [14].

The identification of evaluation criteria along with their corresponding evaluation functions enables the comparison of solutions. When integrated with scenario-based weighting, this approach facilitates the assessment of solutions and helps identify the most suitable drive train concept(s) [14]. The criteria established for the evaluation process include the following:

- **i.** Costs
- **ii.** Installation Space Requirements
- **iii.** Modularity and Scalability
- **iv.** Driving Dynamic Performance
- **v.** Safety
- **vi.** Efficiency
- **vii.** Mass
- **viii.** Reliability
- **ix.** Durability
- **x.** Repairability

The identified criteria for the evaluation process are costs, installation space requirements, modularity and scalability, driving dynamic performance, safety, and efficiency. Determining costs is challenging due to the limited availability of BEVs and component studies. Installation space requirements should be specified through empirical estimations and literature references.

The concepts of modularity and scalability are relevant when considering four-wheel drives and their potential applications in other vehicle designs. Modularity generally refers to the ability to interchange various components within the same system. For instance, one example of modularity is the replacement of an electric motor in a drivetrain without necessitating modifications to other components. Another example could involve switching the axle from front to rear as a demonstration of modularity. Furthermore, this criterion also encompasses scalability in terms of power for a drivetrain concept, allowing for component exchanges such as varying motor diameters to achieve higher torque [14]. Driving dynamic performance refers to the ability of a specific drivetrain to integrate functions such as torque vectoring. This requires the use of two electric machines, with one assigned to each wheel. Additionally, these machines must meet specific dynamic performance criteria [14].

Safety is a critical consideration that should be addressed from the outset. When evaluating a drivetrain configuration, it is essential to focus on safety aspects related to electrical components, particularly the electric motor and converter. These components need to be evaluated for potential functional failures, such as electrical short circuits within them [14].

Efficiency is a critical criterion that holds significant importance. It serves as an indicator for various subareas and reflects the overall quality of the drive train. Each component within the drive train can be assessed based on its individual efficiency. The electric machine is the component that has the greatest impact on overall efficiency; thus, it will be examined in greater detail in the following sections. After defining and quantifying the evaluation criteria, it is essential to scale them to achieve a uniform point allocation [14].

To facilitate the quantification process, a comprehensive database must be available to support the calculation and simulation methods. Each evaluation criterion must be quantified with high detail and depth. The necessary torque and power will be calculated at the wheel to meet both static and dynamic driving requirements of the vehicle. Subsequently, the sizing of the required components for the drivetrain can be executed, and their characteristics can be quantified according to the established criteria [14].

The calculations can be performed using a longitudinal dynamics tool developed in MATLAB/Simulink. Initially, the calculated driving power requirements and the torque-speed characteristic curve at the wheels are independent of the drivetrain concept. However, it is essential to consider the location of the driven axle - whether it is front-driven, rear-driven, or all-wheel drive - due to the traction forces available between the wheels and the road surface. The rotational mass inertia is estimated using empirical values at this stage [14]. Once the calculations are complete, the results can be utilized to quantify all power-based evaluation criteria equations. For instance, one criterion that can be evaluated is the electric motor, which significantly impacts overall efficiency [14].

5.5 Classification of Motors (Magnet vs Magnet Free)

Based on the analysis, the motors are broadly classified into Magnet based motor and Magnet Free Motors. Magnet free motors are purely based on the electrical windings and do not involve any magnets. Induction motors are a traditional and extensively utilized type of motor. They function based on the principle of electromagnetic induction, wherein an electric current is generated in the rotor as a result of the magnetic field created by the stator. These motors are characterized by their simplicity, reliability, and cost-effectiveness, making them among the most commonly employed motor types. Synchronous Reluctance Motors operate based on the principle of reluctance torque instead of magnetic induction. Unlike traditional motors such as induction motors or permanent magnet motors, synchronous reluctance motors utilize differences in reluctance (the resistance to magnetic flux) within the rotor. Magnet-based motors can be categorized into two types: Rare Earth Permanent Magnet Motors and Rare Earth Magnet-Free Motors. A Permanent Magnet Synchronous Motor (PMSM) is a specific type of synchronous motor that features a rotor equipped with permanent magnets, eliminating the need for an external power source or windings to create the magnetic field. The PMSM motors are recognized for their high efficiency, elevated power density, and superior performance characteristics. As a result, they are extensively employed in various applications that demand precise control and high efficiency.

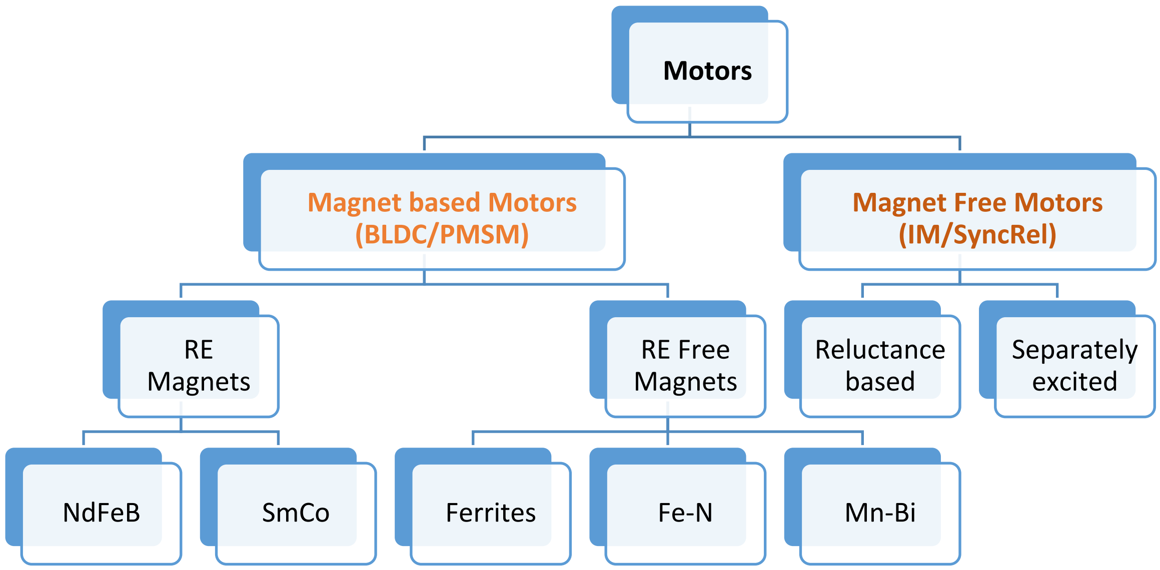
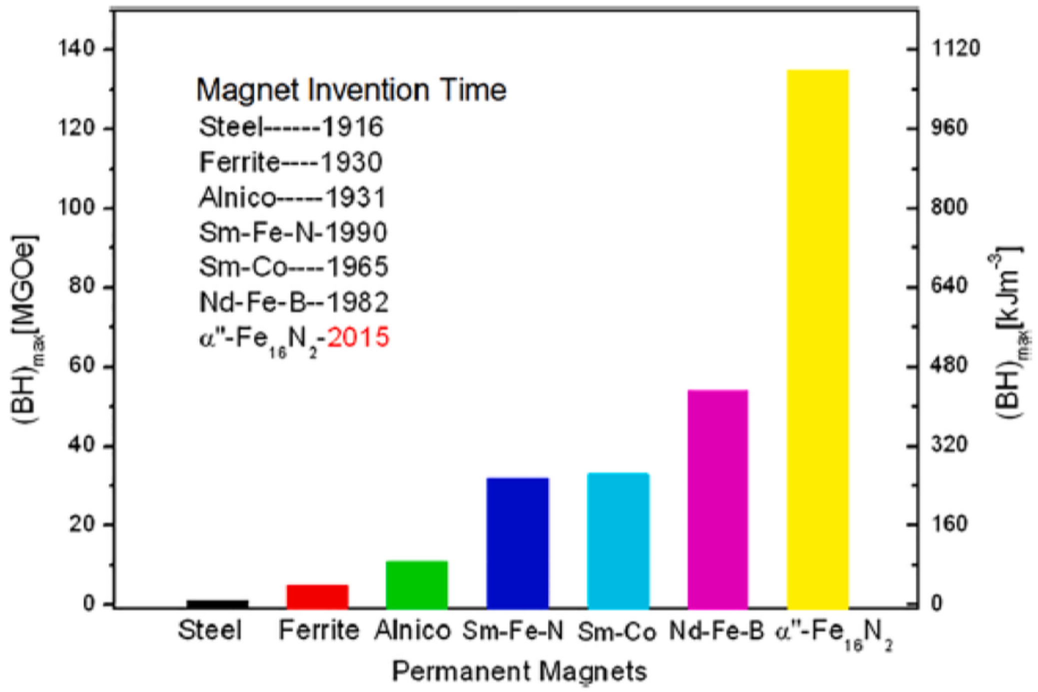


Figure 40: Classification of Motors based on magnet vs magnet–free type

5.6 Requirements of Rare Earth Magnet Free Electric Motors for e-trucks

Remanence (Br), Coercivity (Hci) and Energy Product (BH) or in other words, the second quadrant characteristic in B-H trace is used for electromagnetic design of RE permanent motors. The magnetic flux density value for design that the magnet to be eventually used for is given by Remanence (Br), for NdFeB magnets it is typically stand at 1.1-1.3 Tesla. The other property is coercivity (Hc), which determines the ability of the permanent magnet to resist demagnetization in an opposing field condition. This scenario comes in to play when the stator poles change polarity due to rotating magnetic field while the polarity of the permanent magnet inserted into the rotor should not flip easily. If the flipping happens easily (as in the case of soft iron), the shaft will not rotate and develop torque. Coercivity is also sensitive to increase in temperature and that is why additions such as dysprosium and terbium are done to retain most of the coercivity while remanence drops to around 1 Tesla. A high value of coercivity of 10-20 kilo Oersted (kOe) achieved in NdFeB magnet is responsible for high resistance to demagnetization. The energy product of remanence and coercivity on every point in the curve continuously changes and its maximum is (BH)max is a figure of merit used to rank potential permanent magnets. A quick back of the envelope computation is done as follows: B_r at 1 Tesla or 10^4 Gauss x Hc of 10kOe implies = $(100x10^6)/0.5$ = 50 MGOe (Mega Gauss Oersted). Another rough calculation would be to use an (BH)max = $(M_s)^2/4$ where Ms is saturation magnetization. Take Ms as 1 Tesla, we get 25 MGOe as energy product. (Note Br is residual magnetization in the magnetic material when applied field is zero while Ms is max saturation obtained when maximum field is applied). Ms will always be higher than Br. In the figure (with reference) below, the energy product (BH)max is depicted for hard magnetic materials that have evolved over last few decades starting with ferrites in 1930s. The ubiquitous steel is a soft magnetic material is given for comparison. It is worth noting that increase in (BH)max with increases only in Br (or Ms saturation magnetization) is not useful as adequate coercivity is simultaneously required for application in PM motors. Coercivity of 4kOe and

(BH)max of at least 20MGOe with minimal or no reductions with increase in temperature up to 120°C is necessary and sufficient for design of most motors.



Ref: Wang et al: J Magnetism and Magnetic Materials 497 (2020)

Figure 41: (BH)max comparison of various magnets

Potential Alternatives to NdFeB Magnets:

Alternative to RE based magnets of NdFeB and SmCo are known in Ferrites and AlNiCo systems. The Br and Hc values of are much smaller value in ferrites and AlNiCo which are also utilized in practice in larger volumes for multitude of applications. Typical values of Br, Hc and (BH)max are

Table 14: Br, Hc and (BH) max of various magnets

	Br (k Gauss)	Hc (kOe)	BH_{max} (MGOe) (Br x Hc)* 0.25 (approx.)	Remarks
Ferrites	4	3	3.8	
Sm-Co (2-17)	12	15	30	High Curie T = 1000K
FeNdB	13	12-20	42 -52	60 MGOe with high Dy and Tb additions Reduction of Nd by 40% and Dy by 50% as bulk alloy compositions achieved with small penalty in Hc. 10-12KOe Hc is acceptable with 40% reduction in Nd+Dy.
Potential New candidates BHmax around 10-20 MGOe				
AlNiCo -9	10.5	2	10	Improvements up to BH_{max} 20MGOe possible with refinement of microstructure.
$Fe_{16}N_2$	10-15	2-4	10-20	20 MGOe achieved in lab scale; Theoretical (45 MGOe) Ordered bct structure is ferromagnetic $Fe_{16}N_2$ decomposes @473K >> high T sintering difficult. First gen motors already prototyped. Innovative Processing solutions needed.
Mn-Al - C	7-8	2.5 - 5	7-8	Metastable ordered L10 tau phase; Thin films exhibited 10kOe Coercivity. Coercivity increases with decrease in particle size (nm)
Mn-Bi-Mg-X	8-9	5.5	12	Coercivity of 11KOe achieved with Indium additions. Melt spinning process + Annealing in magnetic field
High Co, Co_3Mn_2Ge And Co-Hf alloys				Expensive elements. Co supply chain is restricted and highly volatile. Renewed interest in high cobalt alloys

Design of PM motors with BHmax around 10-20 MGOe is the sweet spot between very low ferrites and very high end FeNdB alloys. Recently, Iron–Nitrogen system-based compositions have been known to exhibit giant saturation magnetization (Ms) of 1.5 T while the best remanence Hc values are around 4KOe. Giant saturation magnetization allows one to design the motors in terms of maximum flux while the 4KOe coercivity is just about sufficient to oppose the demagnetizing field. A positive effect of this FeN system is that the coercivity does not drop with increase in temperature.

The second category of materials worth pursuing Mn – Al – C and Mn-Bi-X alloys which show promise as they possess decent coercivity. However, the challenges remain in their synthesis methods and processing into magnets.

Challenges and potential solution paths:

i. The critical challenge in synthesis of FeN materials is the low decomposition temperature of the nitride and so high T sintering that is normally adopted does not work here. Nitriding of ribbons, wires, foils and powders under pressure has been the only alternative and the metastable magnetic phase fraction has to be increased via innovative processing. This is the main reason for scatter of properties and reproducibility.

ii. Similar challenges lie for Mn based systems. Here again reproducibility has been an issue. Thermal processing under magnetic field unlike compaction under field followed by high T sintering of FeNdB magnets is to be adopted which will require development of process equipment.

iii. Therefore, emphasis for future R&D on these two system categories lie in:
   - Concentrate on two systems namely FeN and Mn-Bi-X based.
   - Robust process methods for synthesis of metastable magnetic phase in FeN System with high phase fraction.
   - Till date only research on gram scale is done for Mn-Bi based materials. Larger scale materials synthesis has to be pursued and robust methods to be developed.
   - Development of process equipment that are more customized to making these materials.
   - Design of PM motors with higher Br (or Ms) that is available in these materials with lower coercivity compared to FeNdB magnets. First generation motors with FeN materials are recently achieved (NIRON – Louisiana USA)
   - Nano composite magnets containing two phases with appropriate microstructure to achieve an optimal combination of properties.

The development of **rare earth magnet-free electric motors** for electric trucks (e-trucks) is a highly relevant topic. The creation of electric motors for e-trucks that do not rely on rare earth magnets is increasingly significant due to rising concerns over the availability, expense, and environmental consequences tied to rare earth elements (REEs). Rare earth magnets, typically used in high-performance electric motors, are made from elements such as **neodymium** and **dysprosium**, which are essential in generating strong magnetic fields in motors. However, the reliance on these materials presents challenges, including geopolitical supply risks and significant environmental impacts from mining and processing.

As a result, many automakers and researchers are looking into alternatives for **rare earth magnet-free electric motors**. These motors would ideally offer similar or even better performance without relying on these scarce resources.

5.6.1 Key Requirements for Magnet-free & REM-free Electric Motors for e-trucks

1) High Efficiency

- The main objective of electric motors in e-trucks is to achieve high efficiency, which enhances energy conversion, minimizes energy consumption, and increases the vehicle's range. A motor that does not use rare earth magnets must deliver efficiency levels similar to those of conventional permanent magnet motors.
- **Challenges:** Without rare earth magnets, achieving similar torque density and efficiency can be difficult because rare earth magnets provide stronger magnetic fields, especially in high-performance applications like e-trucks.

- **Solution:** One common approach is to use **synchronous reluctance motors (SynRM)** or **induction motors**, both of which do not require permanent magnets. For example, **high-efficiency induction motors** can be optimized using sophisticated control strategies to improve efficiency.

2) High Power Density

- **Power density** is a measure of a motor's capacity to generate significant power in relation to its size and weight. In electric trucks, achieving high power density is essential for enabling the vehicle to transport heavy loads over extended distances while maintaining optimal performance.
- **Challenges:** Rare earth magnets are crucial in providing a high-power density, and achieving the same performance without them requires advanced design and material innovation.
- **Solution:** To compensate for the lack of rare earth magnets, **interior permanent magnet-free motors**, such as **induction motors**, **synchronous reluctance motors (SynRM)**, and **axial flux motors**, can be optimized for higher power density using advanced motor design, cooling techniques, and enhanced control systems.

3) High Torque Output

- Torque output is a crucial parameter in heavy-duty vehicles like e-trucks, which need to perform under high-load conditions, such as during acceleration and climbing hills.
- **Challenges:** Motors without rare earth magnets may have lower torque output, making it harder to achieve the necessary performance, particularly under high-load conditions.
- **Solution:** Advanced techniques, such as **wound rotor induction motors (WRIM)** and **synchronous reluctance motors**, can be used to improve torque output. **Magnetic field modulation** and **field-weakening techniques** can also be employed to enhance the torque performance at different speeds and load conditions.

4) Cost-Effectiveness

- A key motivation for investigating motors that do not use rare earth magnets is to **lower the costs** linked to rare earth minerals, which tend to be both volatile and costly.
- **Challenges:** While **rare earth magnet-free electric motors** have the potential to lower material costs, they often require more advanced and expensive motor designs, better thermal management, and specialized control electronics to achieve equivalent performance.
- **Solution:** The use of induction motors and **synchronous reluctance motors (SynRM)** can reduce costs by eliminating the need for expensive rare earth magnets. Additionally, **novel manufacturing techniques**, like additive manufacturing (3D printing), could be explored to reduce motor manufacturing costs.

5) Durability and Reliability

- e-trucks require motors that can withstand demanding operating conditions over long periods. Rare earth magnet-free motors should maintain **reliable performance** over the lifespan of the vehicle, especially in harsh environments.
- **Challenges:** Motors without rare earth magnets might face higher wear or stress in certain conditions. For example, **induction motors** are typically more susceptible to overheating

compared to permanent magnet motors due to their reliance on current-induced magnetic fields.

- **Solution:** Advanced thermal management systems, such as **liquid cooling**, and the use of durable materials and motor coatings can enhance the reliability and longevity of rare earth magnet-free motors. Additionally, incorporating **robust motor designs** with high thermal tolerance and vibration damping features can improve their durability.

6) Improved Thermal Management

- Electric motors produce heat while functioning, making efficient thermal management crucial for maintaining peak performance and avoiding overheating.
- **Challenges:** Without rare earth magnets, the efficiency of motor designs like induction motors may be more sensitive to temperature, and thermal management becomes critical to maintain performance.
- **Solution:** Efficient heat management in rare earth magnet-free motors necessitates employing **liquid cooling systems, integrating heat sinks, and utilizing advanced insulation** methods. High thermal conductivity materials, such as **copper and aluminium alloys**, play a crucial role in effectively dissipating the generated heat.

7) Compatibility with Existing Power Electronics and Control Systems

- The motor control system and power electronics should be compatible with rare earth magnet-free motors to ensure seamless integration into the overall e-truck architecture.
- **Challenges:** Some alternative motor technologies, like induction motors, require sophisticated control strategies (e.g., vector control or direct torque control) to optimize performance, which can add complexity to the system.
- **Solution:** With **digital control systems**, the performance of rare earth magnet-free motors can be enhanced. Additionally, the **development of advanced inverters** and **power electronics** that can work efficiently with these motors will be essential for optimal power delivery and performance.

8) Sustainability

- A crucial requirement for motors that do not use rare earth magnets is to enhance **sustainability** by minimizing the environmental effects linked to the mining and processing of rare earth elements.
- **Challenges:** The extraction and production of rare earth metals raise significant environmental issues, such as high energy usage and the generation of toxic by-products. Consequently, creating alternatives that do not depend on these materials can contribute to lowering the environmental impact of electric trucks.
- **Solution:** Induction motors, synchronous reluctance motors (SynRM), and other rare earth magnet-free solutions contribute to sustainability by avoiding rare earth materials and reducing dependence on mining activities. Additionally, using more **sustainable materials** for windings, housing, and cooling systems can further enhance the sustainability of these motors.

5.6.2 Key Technologies for Magnet-Free e-Motors

1) Induction Motors (IM):

- Well-established and widely used in many electric vehicles.
- Can be designed for high efficiency and torque output with proper control systems.
- No rare earth materials needed.
- Requires sophisticated control systems to enhance efficiency and torque density.

2) Synchronous Reluctance Motors (SynRM):

- Highly efficient and does not require rare earth magnets.
- Requires advanced design techniques for high torque density.
- Can be optimized with control strategies like **vector control** or **direct torque control (DTC)** to achieve high performance.

3) Axial Flux Motors:

Axial flux motors can be either induction motors or permanent magnet motors, depending on the design and application. Axial Flux Induction Motors (AFIM) are less common than Axial Flux Permanent Magnet Motors (AFPM). AFPM motors use permanent magnets on the rotor and are known for their high torque density and efficiency. They are commonly used in electric vehicles, aerospace, and other applications where high power density is required. The key technologies to rare earth magnet-free AFPM motors are:

- Provide a superior power-to-weight ratio in comparison to conventional radial flux motors.
- Can be designed without rare earth magnets and are seen as a promising alternative for heavy-duty applications like e-trucks.
- More compact and can provide better torque density.

4) Permanent Magnet assisted Synchronous Reluctance Motors (PMa-SynRM):

- PMa-SynRMs are a type of electric motor that combines permanent magnets and reluctance features, offering high efficiency, smooth torque, and high dynamic performance. They are particularly well-suited for electric vehicle applications.
- The choice of permanent magnet materials (such as Rare-earth magnets and Ferrite magnets which is not a rare-earth material) significantly impacts the motor's performance and cost.
- Rare-earth magnets offer excellent efficiency and high-power density but are expensive and subject to supply chain volatility. Ferrite magnets have lower magnetic properties and are more cost-effective.
- While the Rare-earth magnet assisted SynRMs offer superior performance and demagnetization resistance, the Ferrite-magnet assisted SynRMs provide a more cost-effective solution. Hybrid approaches offer a promising way to balance these competing factors.

To develop effective **rare earth magnet-free e-motors** for e-trucks, manufacturers must focus on achieving a balance between efficiency, power density, cost-effectiveness, durability, and sustainability. Technologies like **induction motors**, **synchronous reluctance motors**, and **axial flux motors** are promising alternatives that can reduce reliance on rare earth materials while still delivering the performance required for heavy-duty applications. Advanced design improved thermal management, and sophisticated motor control strategies will be key to ensuring that these motors meet the demanding needs of electric trucks.

5.7 Guidelines for Motor Technology for Zero Emission Trucking

Creating guidelines for motor technology for zero-emission trucking is essential in supporting the transition to more sustainable transportation systems. These guidelines focus on various aspects of motor technology that help ensure zero-emission trucks are efficient, reliable, and effective in reducing environmental impact. Below are the key guidelines for motor technology in zero-emission trucking:

1) **Energy Source Selection**
   - **Battery-Electric Motors:** For short to medium-range applications, battery-electric trucks (BETs) are a viable solution. The motors used in BETs should be optimized for efficiency, power delivery, and thermal management.
   - **Hydrogen Fuel Cells:** Hydrogen fuel cell technology presents a viable zero-emission option for long-haul trucks. These fuel cell powered motors are expected to provide high power output and extended range, along with quick refuelling times and low maintenance needs.
   - **Hybrid Systems:** Hybrid systems that integrate electric motors with alternative fuels, such as natural gas or hydrogen, can serve as a transitional solution. These systems should be engineered for efficient energy management between electric and fuel modes.

2) **Motor Efficiency and Performance**
   - **High Efficiency:** Motors must exhibit high efficiency to reduce energy consumption and enhance overall range. This can be achieved by utilizing advanced technologies such as permanent magnet synchronous motors (PMSMs) or induction motors, which provide superior torque and power density.
   - **Regenerative Braking:** Incorporating regenerative braking systems is essential for capturing kinetic energy during braking. This energy is then converted back into electrical energy to recharge the batteries, thereby improving energy efficiency and extending the vehicle's range.
   - **Thermal Management:** Zero-emission truck motors should have advanced cooling and heating systems to maintain optimal operating temperatures, especially under high loads or in extreme weather conditions.
   - **Power-to-Weight Ratio:** The power-to-weight ratio of the motor needs to be optimized to ensure sufficient torque and speed. Prioritize a high power-to-weight ratio by using lightweight materials like aluminium alloys to reduce the weight of motor components. This helps improve efficiency and payload capacity.
   - **Compact Motor Design:** Design motors to be as compact as possible while maintaining high performance. The motor should be small enough to fit into the space available in the truck’s powertrain layout without sacrificing power or torque.

3) **Durability and Longevity**

- **Long Lifespan:** Motors should be designed for long-term durability with minimal degradation over time, particularly for heavy-duty use. Regular performance degradation should be slow, ensuring long life cycles and lower total cost of ownership.
- **Maintenance Considerations:** Zero-emission truck motors should require minimal maintenance. Simplified designs, such as fewer moving parts (e.g., no gearboxes or transmissions), can reduce wear and tear and improve reliability.

4) **Regulatory Compliance**

- **Noise Reduction:** Motors for zero-emission trucks should operate quietly to reduce noise pollution, particularly in urban environments. This includes optimizing the motor's operation to minimize sound production and vibration.
- **Safety Standards:** Motors must adhere to global safety standards, such as ISO 26262 for functional safety in automotive systems, ensuring the safety of electrical systems, particularly high-voltage battery connections and fuel cell systems.

5) **Scalability and Adaptability**

- **Modular Motor Design:** Create modular motor systems that can be scaled to accommodate various truck sizes and applications, such as light-duty, medium-duty, and heavy-duty vehicles. This modular approach provides flexibility and facilitates easier adaptation to changing market demands.
- **Flexible Power train Integration:** Ensure that the motor technology is adaptable to different vehicle architectures and powertrains, including configurations for all-wheel drive (AWD) and rear-wheel drive (RWD).

6) **Cost-Effectiveness**

- **Affordability:** As zero-emission trucks will have higher initial costs than conventional trucks, motors must be designed to be cost-effective, balancing performance with cost efficiency to support widespread adoption.
- **Efficiency over Lifetime:** To reduce the total cost of ownership, motors should be designed for maximum efficiency, thereby lowering operating costs throughout the vehicle's lifecycle, which encompasses energy use, maintenance, and repair expenses.

7) **Research and Innovation**

- **Continuous Improvement:** The motor technology used in zero-emission trucks must be continuously improved through research and innovation. This includes advancing materials (e.g., rare-earth magnets), improving motor control systems, and exploring alternative energy sources like solid-state batteries or ammonia-based fuels.
- **Collaborative Development:** Manufacturers should collaborate with research institutions, government bodies, and industry leaders to ensure the ongoing evolution of motor technology, addressing challenges such as energy density, motor weight, and charging speed.

8) Smart Integration with IoT and AI

- **Connected Systems:** Combine motors with Internet of Things (IoT) sensors to enable real-time tracking of performance, health, and efficiency. This information can assist in optimizing motor operations and enhancing predictive maintenance.
- **AI for Optimization:** Utilize Artificial Intelligence (AI) to optimize motor performance based on route, load, and driving conditions, further improving energy efficiency and reducing wear and tear on the motor.

9) Environmental Considerations

- **Sustainable Materials:** Incorporate sustainable and recyclable materials in the production of motor components to minimize the environmental effects associated with manufacturing, operation, and disposal. Additionally, motors should be engineered for straightforward disassembly at the conclusion of their lifecycle.
- **Reduction of Environmental Footprint:** Consider the entire life cycle of the motor, from material sourcing to manufacturing to operation, ensuring that the overall environmental footprint is minimal.

10) Safety and Compliance

- **Regulatory Compliance:** Confirm that the motor system complies with all applicable safety and emissions regulations, including ISO 26262 for functional safety and UNECE R100 for electric vehicle safety. In addition, the motor must comply with local and regional zero-emission standards, including those set by the EPA or EU’s Euro 6 for electric vehicles.
- **Crash Safety:** The motor and battery/fuel cell components must be designed with crash safety in mind, including impact resistance and fire prevention measures (e.g., fire-resistant casings for batteries or hydrogen systems).
- **Electromagnetic Compatibility (EMC):** Ensure that the motor and its components are electromagnetically compatible, avoiding interference with other systems (such as communication devices or navigation systems).

11) Noise and Vibration

- **Low Noise Emissions:** Motors should operate quietly to reduce environmental noise, especially in urban environments. The design should minimize vibration and aerodynamic noise while operating.
- **Vibration Isolation:** Use advanced vibration-damping materials or systems to reduce unwanted vibrations that could affect driver comfort or motor performance.

6 Machines for Electric Vehicle Drive Trains

Approaches using a variety of machine types, including the direct current motor (DC), the induction motor (IM), the permanent magnet excited synchronous motor (PMSM), and the switched reluctance motor (SRM), can be found in light of the advancements and prototype presentations of electrical and hybrid electrical vehicles over the past ten years. All of these machine applications imply that they each have unique benefits and drawbacks that make them intriguing for various electric and hybrid vehicles.

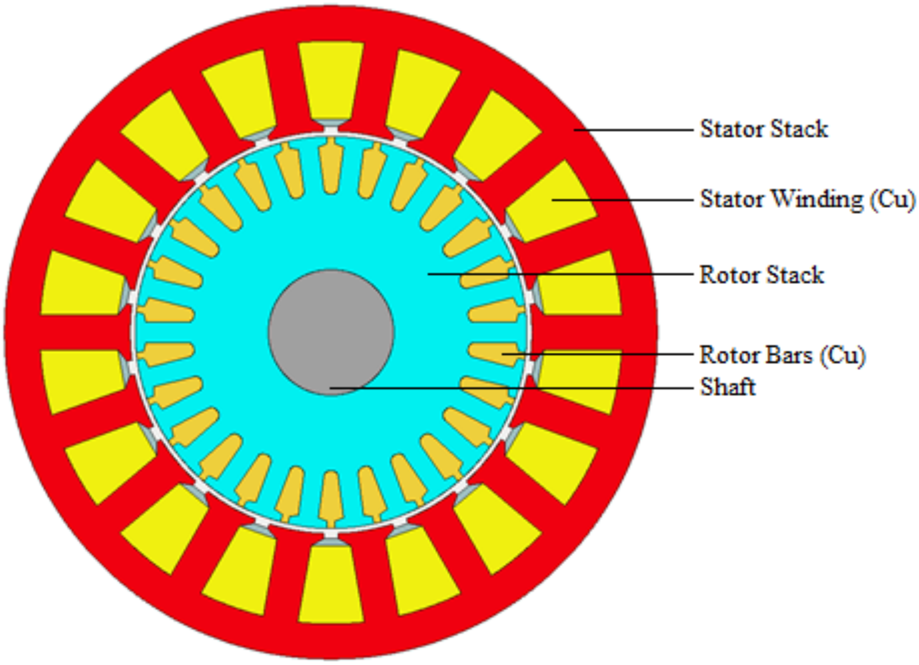


Figure 42: Induction Motor (IM)

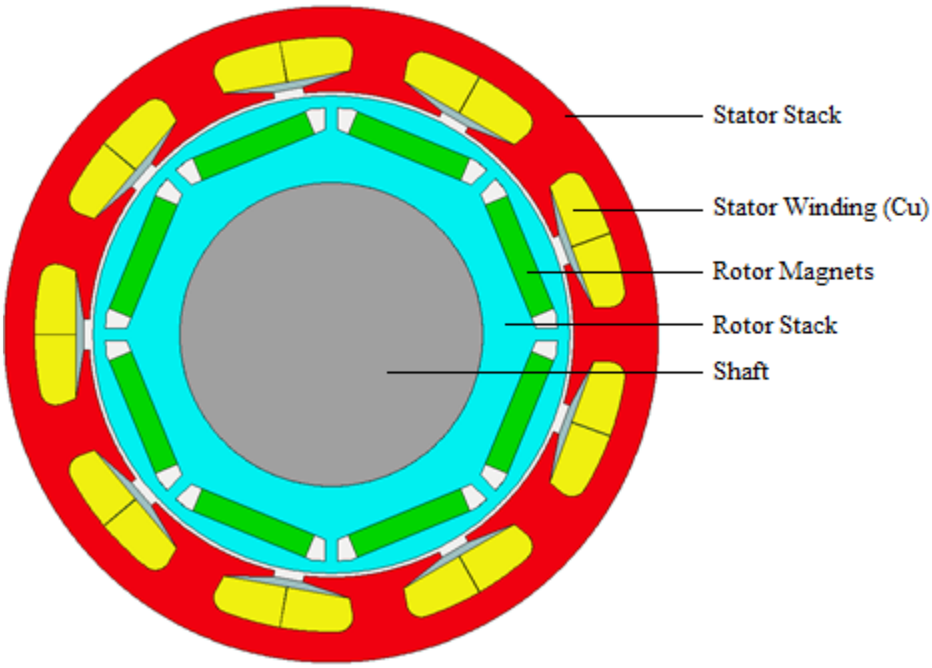


Figure 43: Permanent Magnet Synchronous Motor (PMSM)

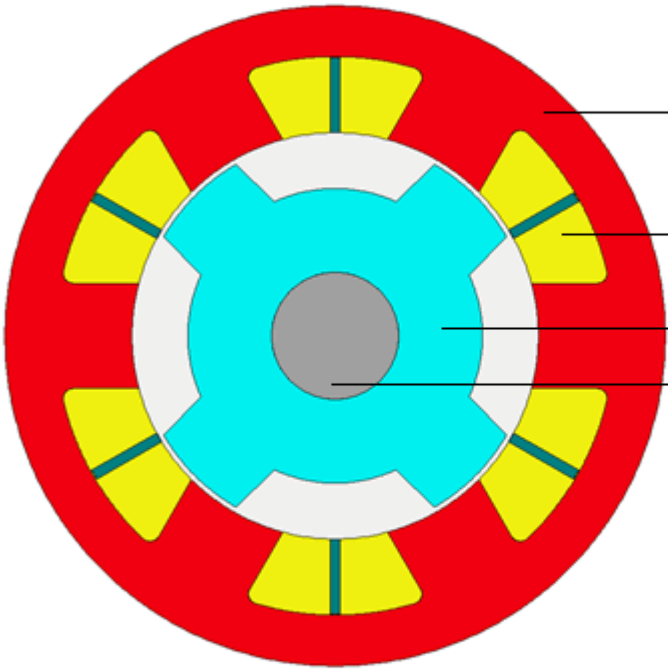


Figure 44: Switched Reluctance Motor (SRM)

6.1 Induction Motor (IM)

Similar to DC machines, induction machines with squirrel-cage rotors are among the most technically advanced machines; nevertheless, they are more efficient and have a higher power density. Copper losses are the most common losses in IM & it offers a broad speed range together with a relatively high efficiency at high speeds because of the decreased copper losses caused by the lower magnetization current in the field weakening range. In comparison to PMSMs, the rotor's copper losses and the necessary magnetization potential reduce efficiency within the nominal speed range. One drawback is that the losses cause the rotor to heat up, limiting overload capacity and necessitating cooling. Additionally, to reduce the magnetization current, the smallest possible air gap is required; however, this necessitates tighter tolerances during fabrication, which raises production costs. [14].

6.2 Permanent Magnet Synchronous Motor (PMSM)

Permanent magnets in the rotor give the PMSM the required excitation. Because the permanent magnet excitation takes up minimal space, this machine benefits from the high energy density of the magnets. In the range of nominal speed, the PMSM offers a high overall efficiency because no excitation current is needed. Iron losses are the PMSM's main losses, and since they largely happen in the stator, a case cooling system can readily dissipate them. Therefore, in terms of efficiency and power density, the PMSM outperforms the IM. The pricey nature of rare-earth magnets like NdFeB is its main drawback. Another drawback is that field weakening necessitates an extra current component, which raises stator losses and reduces efficiency at high speeds. Additionally, the magnet characteristics limit the overload capacity. Reliable temperature detection is crucial to avoiding high magnet temperatures combined with high stator currents, which can cause irreversible demagnetization [14].

6.3 Switched Reluctance Motor (SRM)

Although the SRM idea has long been understood, it was not useful until power electronics advanced. The efficiency and power density of the SRM are on par with those of the IM. However, it has a simple construction without rotor winding and with concentrated stator windings, and therefore a better thermal characteristic. In addition, it is cost-effective in production and low-maintenance. To reach a high-power density, a high air-gap induction is recommended - this however increases acoustic noise radiation. Measures for noise reduction decrease the power density and diminish the appeal of the SRM compared to the IM. The significant torque ripple at low speeds is another drawback. Furthermore, the substantial non-linearity of the current-switching angle determination makes the control of the SRM more complex than that of a three-phase drive. Consequently, up to now, the SRM has only been utilized in a small number of HEV prototypes. [14].

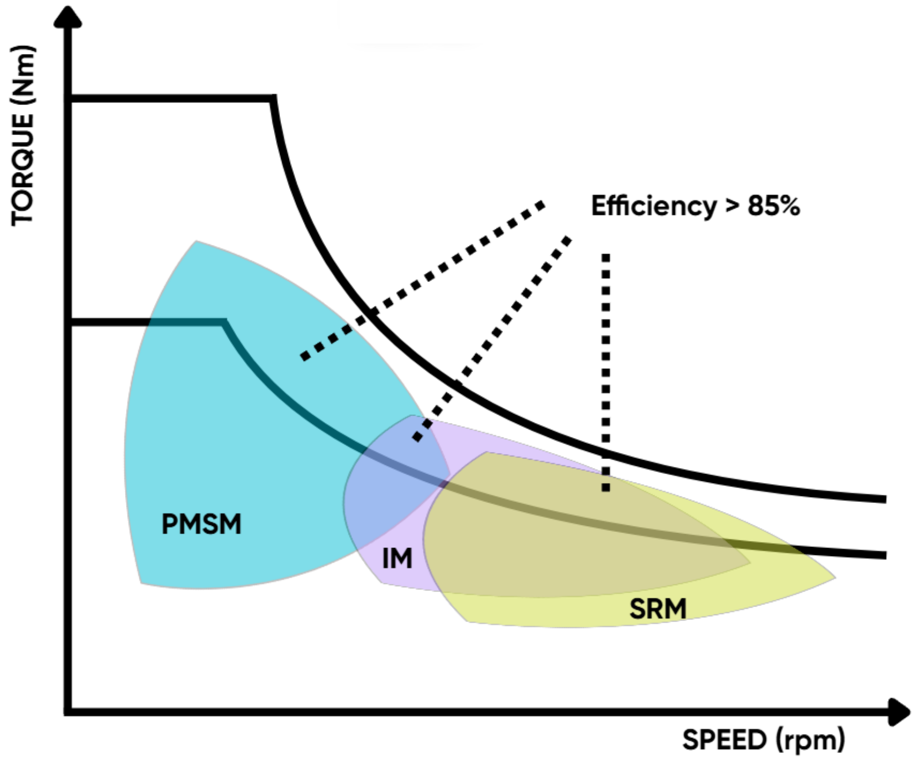


Figure 45: Exemplary efficiency maps for different machine types

The detailed comparative study of Permanent Magnet Synchronous Motor (PMSM), Induction (IM) & Synchronous Reluctance Motor (SyRM) for e-trucks is listed in Table 15 [16].

Table 15: Quantitative comparison of PMSM, IM & SyRM Motors for e-trucks

Parameters	Permanent Magnet Synchronous Motor (PMSM)	Induction Motor (IM)	Synchronous Reluctance Motor (SyRM)
Principle	PMSM works in tandem with the stator's revolving magnetic field and makes use of permanent magnets on the rotor.	Rotor of an induction motor is not magnetized; instead, it induces a current through electromagnetic induction.	The SyRM does not use permanent magnets but instead relies on the reluctance torque generated by rotor design and stator excitation.
Efficiency	High efficiency, typically 90% or more, as it avoids losses associated with rotor currents.	Moderate efficiency (85-90%), lower than PMSM, due to rotor losses (eddy currents and hysteresis).	Generally higher than IM but lower than PMSM. Typically, around 85-90% efficient.
Power Density	High power density due to the use of permanent magnets, making it compact and lightweight. **3.5 kW/kg-10 kW/kg**	Lower power density compared to PMSM due to the need for larger motor volumes. **1.5 kW/kg-4.5 kW/kg**	Lower than PMSM but higher than IM due to better rotor design and less copper loss. **2 kW-6 kW/kg**
Cost	The motor is generally expensive due to the use of rare-earth magnets (like neodymium).	Generally, more cost-effective than PMSM due to the lack of rare-earth magnets.	Cost-effective as it does not require rare-earth magnets.
Maintenance	Low maintenance due to fewer moving parts but can suffer from demagnetization over time.	Relatively low maintenance due to simpler construction; no permanent magnets to demagnetize.	Similar to IM, with low maintenance requirements.
Control	Requires sophisticated control techniques like Field-Oriented Control (FOC).	Easier to control than PMSM but less efficient in operation. Typically uses scalar or vector control.	Requires vector control similar to PMSM for efficient operation.
Comparative Metrics			
Efficiency	90-96% High efficiency due to the direct magnetization of the rotor. Ideal for heavy-duty applications like trucks, where energy efficiency directly correlates with range.	85-90% Efficiency is lower due to resistive losses in the rotor and stator.	85-91% More efficient than IM, but less than PMSM due to lower rotor losses

Power Density	High As PMSMs are small and light, they can be used in applications where a high power-to-weight ratio is necessary.	Moderate Induction motors require larger volumes for the same output power due to rotor design, leading to lower power density.	Moderate to High Similar to PMSM in terms of power density but lower than PMSM.
Torque Density	Very High The interaction between the rotor magnets and the stator field produces the torque. High torque density is suitable for e-truck acceleration and hill-climbing.	Moderate Torque is generated through induced currents in the rotor, but it is lower than PMSM, requiring higher current for the same output torque.	Moderate Reluctance torque is generated, but efficiency is not as high as PMSM, and torque density is slightly lower.
Cost	High Rare-earth magnets used in PMSM significantly increase the material cost. **60-150$ (USD)/kW**	Low More cost-effective since induction motors use aluminium or copper for the rotor, eliminating the need for expensive permanent magnets. **20-60$ (USD)/kW**	Moderate Lower material costs than PMSM but more expensive than IM. It doesn't require permanent magnets but uses specialized rotor designs like laminated rotor with barriers. It may require special tooling for accurate interlocking of barriers. **30-90$ (USD)/kW**
Maintenance	Low Fewer moving parts, but the magnets may degrade over time, especially if the motor operates at high temperatures for long periods.	Low to Moderate Simple construction means fewer things can go wrong, but rotor bars may wear over time and lead to faults.	Low to Moderate Similar to IM but with additional complexity in rotor design. No permanent magnets, so less risk of demagnetization. Due to non-standard shape of the rotor having barriers, on-site repair is not practical. Complete replacement is the only solution. NVH complaints due to torque ripple & low speed jerkiness are some of the practical field problems.
Reliability	Moderate to High They can suffer from demagnetization or overheating under certain conditions. **MTBF: 30k hours-60k hours**	Very High Induction motors are robust and can handle extreme operating conditions. **MTBF: 40k hours-90k hours**	High They avoid the use of permanent magnets, which can be advantageous. **MTBF: 40k hours-80k hours**

Weight and Size	Low weight and compact size due to high power density.	Larger size and weight to produce similar output power compared to PMSM.	Intermediate size and weight. It balances power density and size effectively, but it may be larger than PMSM for the same performance.
Applications for e-trucks	Best suited for: Long-range electric trucks requiring high energy efficiency, where range is a priority. Advantages: High torque and power density, best for acceleration, hill-climbing, and maintaining efficiency at highway speeds. Disadvantages: Higher initial cost since rare-earth magnets are used, and there may be problems with the magnets' long-term deterioration.	Best suited for: Budget-conscious fleet operators who prioritize cost over the highest possible efficiency or torque. Advantages: Low cost, high reliability, and robustness. The system can tolerate more challenging conditions. Disadvantages: Lower efficiency, larger size, and weight.	Best suited for: Applications that require high performance but need to avoid the high costs of PMSM while still achieving good efficiency. Advantages: Powerful and efficient without using rare-earth magnets. Disadvantages: More complex control systems are required compared to IM, and rotor design can be more challenging.
Conclusion	Offers the best efficiency and power density but comes at a higher cost due to the use of rare-earth magnets.	More cost-effective and reliable, but less efficient and bulkier than PMSM.	A middle-ground solution, offering better efficiency than IM without the cost of PMSM, though it may require more advanced control systems.

7 Construction of Motor Winding

This chapter discuss the construction of motor winding which is either a bar wound or stranded wound. When comparing bar wound stators and stranded wound stators, it is essential to understand the fundamental differences in their construction, performance characteristics, and applications.

7.1 Construction Differences

i. **Bar Wound Stator:** In a bar wound stator, solid copper or aluminium bars are used instead of traditional wire windings. These bars are typically inserted into the slots of the stator core and can be configured to optimize electrical conductivity and thermal management. The design allows for a larger cross-sectional area for current flow, which can lead to improved efficiency.

ii. **Stranded Wound Stator:** A stranded wound stator consists of multiple strands of wire that are wound around the stator core. This traditional method involves wrapping insulated copper or aluminium wires in a specific pattern to create coils that generate magnetic fields when energized. The winding process can be complex and time-consuming, but it allows for flexibility in design and configuration.

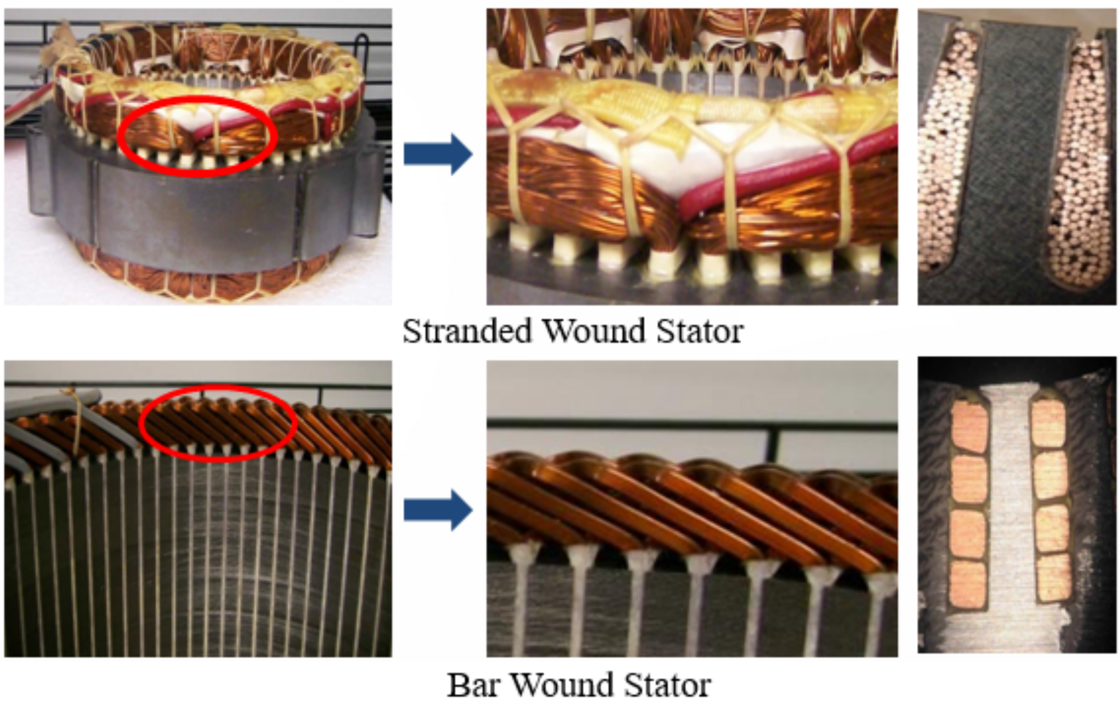


Figure 46: Bar Wound Stator vs. Stranded Wound Stator construction [17]

Figures from [17] collaged. For more details go to Ref [17]

7.2 Performance Characteristics

i. **Cooling Efficiency:** Bar wound stators generally exhibit better cooling performance than stranded wound counterparts due to their larger surface area and lower resistance. Studies have shown that motors with bar windings can dissipate heat more effectively, leading to higher operational efficiency during use, particularly in electric vehicles (EVs). The exposed end area of winding (see Table 16) enables further cooling which is useful when stator currents are increased to obtain higher ratings for same stack length and stator diameter.

ii. **Current Handling:** Bar wound designs can handle higher currents more effectively than stranded windings because they minimize resistive losses associated with longer wire lengths and connections found in traditional windings. This characteristic makes them suitable for high-power applications.

iii. **Manufacturing Ease:** Bar wound stators are often easier to manufacture since they require fewer components compared to stranded windings. The assembly process is simplified as solid bars can be inserted directly into the stator slots without the need for intricate winding techniques.

Table 16: Motor Details Comparison [17]

Attribute	Stranded Wound Design	Bar Wound Design
Motor OD (mm)	261	261
Motor Length (mm)	94	94
Peak Torque (Nm)	400	400
Air Gap Diameter	212	212
Number of Poles	12	12
Number of Turns / Phase	24	24
% Copper Fill	70%	85-90%
DC Phase Resistance (23°C)	14.08 mΩ	10.7 mΩ
Exposed End turn Area Used for Cooling	117,804 mm^2	175,226 mm^2

Bar wound stators are increasingly being adopted in high-performance electric motors, particularly in electric vehicles where efficiency and cooling are critical factors. Stranded wound stators remain prevalent in many industrial applications due to their established manufacturing processes and versatility.

ZF (Zahnrodfabrik Friedrichshafen) have pioneered separately excited magnet free motors that possess higher power/torque to weight ratios. They operate at high voltages of 400-800 V, thus minimizing the stator currents at low moderate power ratings and with advanced cooling techniques, very currents at high voltages have also been achieved. These designs are the pointers for the most efficient magnet free motors.

8 Development Trends of High-Voltage Controller for Electric Vehicles

Electrification is reshaping the automotive industry. Electric vehicles (EVs) call for the extensive use of not just batteries to supply energy but hardware in the form of Electronics to charge the energy device, make the efficient use of the power and harvest energy from braking, and other opportunities to extend battery life. The migration from internal combustion engine (ICE) to electric traction does not just demand more extensive power electronics but devices able to operate at voltages far higher than those used in the past [18]. This chapter briefs about the High-Voltage (HV) controller architecture, isolation which is a key challenge in HV controllers and its present technological trend.

8.1 Upgrade of HV Controller Architecture

The electrical systems in electric vehicles encompass every area of the car, including the charging and distribution network as shown in Figure 47 supplying power for charging the battery when the vehicle is connected to the main supply [18]. The charging and distribution system provides energy to the electric drive system, motors, and other subsystems like thermal management while in operation. Previous EV models utilized 400 V power rails, but the current shift towards 800 V platforms aims to leverage advancements in fast-charging technologies and enhanced drive train efficiency at high torque or speeds [18].

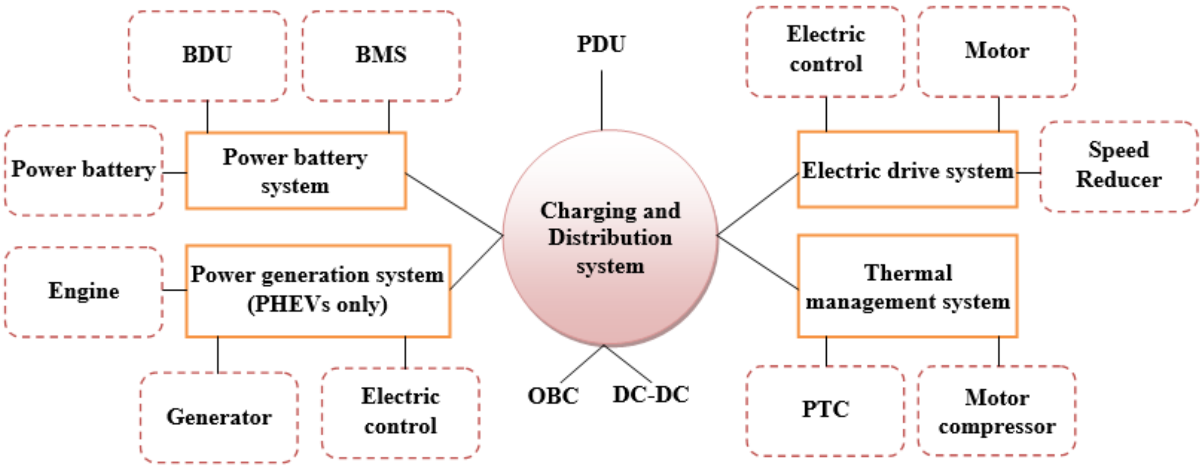


Figure 47: High-Voltage (HV) architecture

Two key advantages lie behind the migration to 800 V. One is that at 800 V, the batteries can be charged more quickly, which eases anxiety over the range of the vehicle and the time it takes to be recharged. A further advantage, which adds to the effective range, is that 800V platforms have lower energy consumption at high power output levels [18]. There are a variety of upgrade solutions for 800 V platforms. The trend is toward using high voltage for the whole system to guarantee that voltage for the entire system is stable and uniform. In addition, to be compatible with existing 400 V platform DC charging piles, a booster unit is added, with the most common booster units at present integrated into the electric drive system and using the same power device as the motor controller, thus helping to reduce costs [18].

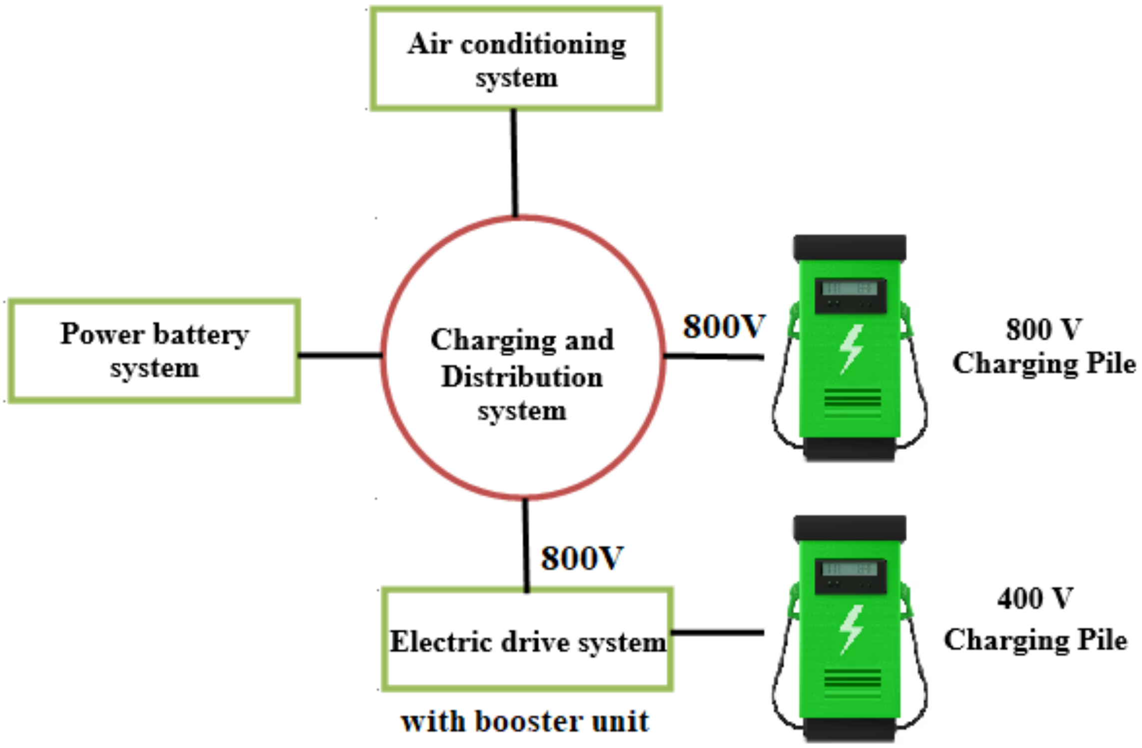


Figure 48: Booster unit enables compatibility with existing 400V platforms

8.2 Current Situation and Technological Trends of HV Controller

The electrical subsystems must be manufactured at low cost while delivering high performance, small size, and low weight. These demands led to the trend toward higher levels of integration in motors, controllers, speed reducers, and other components. As parts are integrated, savings can be made on enclosures and fitting, as well as high-voltage cabling. The integration also tends to improve electromagnetic compatibility (EMC), with less need for shielding overall [18]. There are several levels of integration. Integrated electric drive systems represent a two-in-one integration of motors and controllers or motors. This gradually developed into a three-in-one design with integrated motor, controller, and speed reducer architecture, ultimately fitting all of them within one enclosure [18].

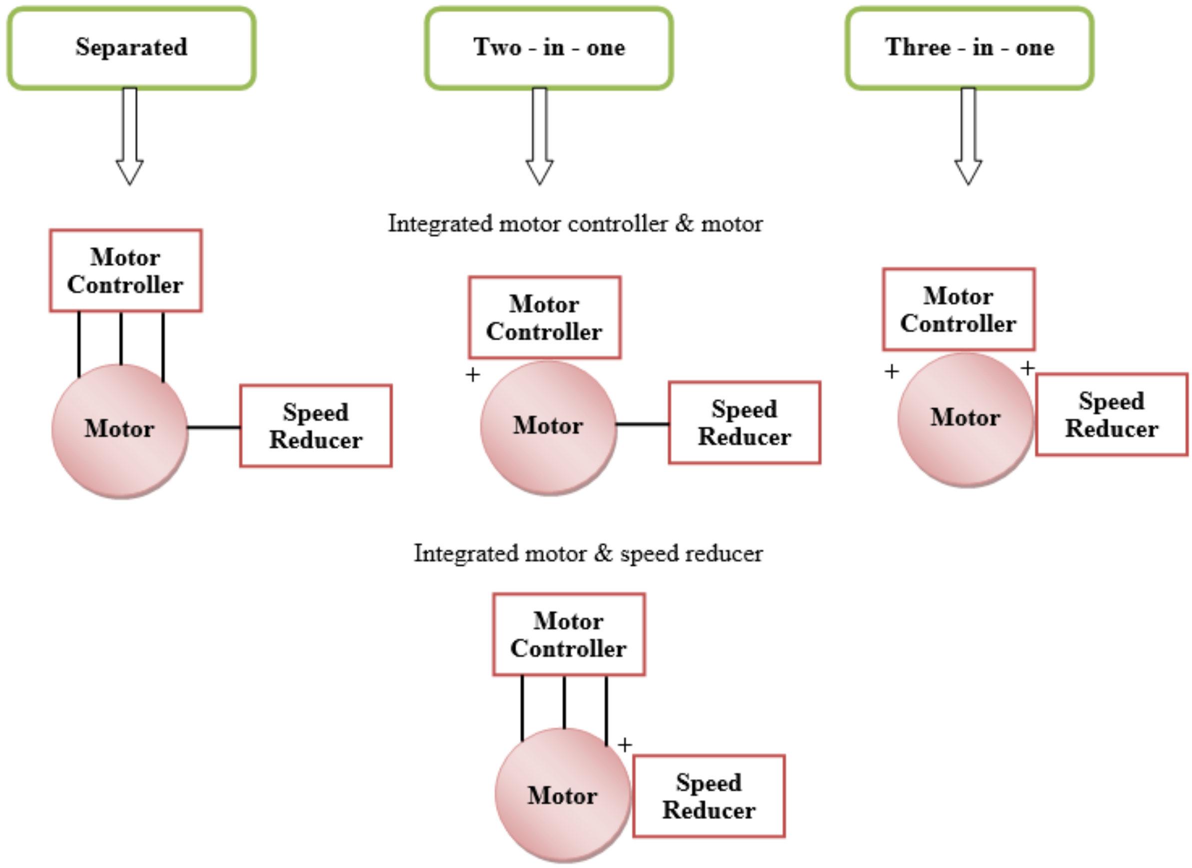


Figure 49: Integrated motor, controller, and speed reducer structure

The traction inverter consists of a low-voltage control unit, which includes an MCU, CAN transceiver, SBC/PMIC, gate drive, signal detection circuits, and power supply components, as well as a high-voltage power stage made up of power devices, all interconnected with isolated chips for enhanced safety between the two stages [18].

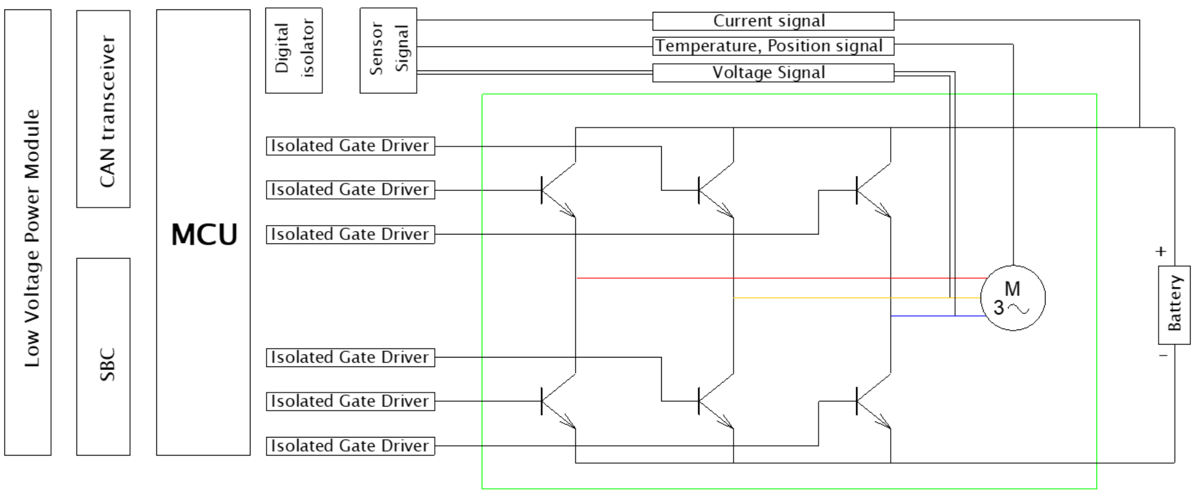


Figure 50: Isolation of gate-driver circuitry in an MCU-based environment

8.3 Integrated isolation solution for HV Controllers

The chapter highlights isolation technologies (traditional optocoupler, capacitive isolation, digital isolators and integrated isolation solution) and their applications in High-Voltage EV Controllers, emphasizing the need for not only reliable, efficient, and safe motor design but also robust power electronics, isolation, and control systems capable of handling high voltage (800V+), high current, and EMI-sensitive environments in ZETs.

The optocoupler is widely used in the industrial market due to its low cost; however, it is relatively uncommon in automotive applications because of its light decay problem. To overcome this, capacitive isolation leverages the coupling effects of electric fields to transmit signals across an insulator, utilizing semiconductor process technology and thereby eliminating the light decay issue. Building on this, digital isolators not only reduce system size through multi-channel integration but also provide higher CMTI and longer operating life, making them highly suitable for automotive applications. The digital nature of capacitive isolation further enables the use of noise-suppression techniques to prevent voltage spikes from disrupting sensor inputs to high-frequency control processors [18].

Because capacitive elements can be easily integrated into single ICs, this technology delivers high-isolation protection for multiple channels within the same package and at high communication rates. This supports the high channel counts required in automotive designs, while also allowing integration of other functions such as gate drivers used to control power transistors [18].

Isolated gate drivers are key components in traction inverter and on-board charger (OBC) systems. In traction inverter applications, functional safety requirements demand higher CMTI to handle complex operating environments. In 800V platforms, where dv/dt levels are higher and can negatively impact EMI performance, well-designed gate drivers can help reduce dv/dt and optimize EMI [18].

Equally important, current and voltage sampling is essential to ensure the stable operation of the system. This can be achieved using isolated amplifiers and Hall current sensors. Isolated amplifiers, which are operational amplifiers (op amps) with galvanic isolation, are widely used for current sensing in traction inverter and OBC applications. They provide high CMTI to ensure accurate and reliable measurements even when operating alongside high-power switches. Hall current sensors, which detect the magnetic field generated by carriers using the Hall Effect, deliver high accuracy with maximum output errors of 2% and non-linearity as low as 0.2%. The interface circuitry required for CAN connectivity presents yet another opportunity for integrated isolation, further enhancing system safety and robustness.

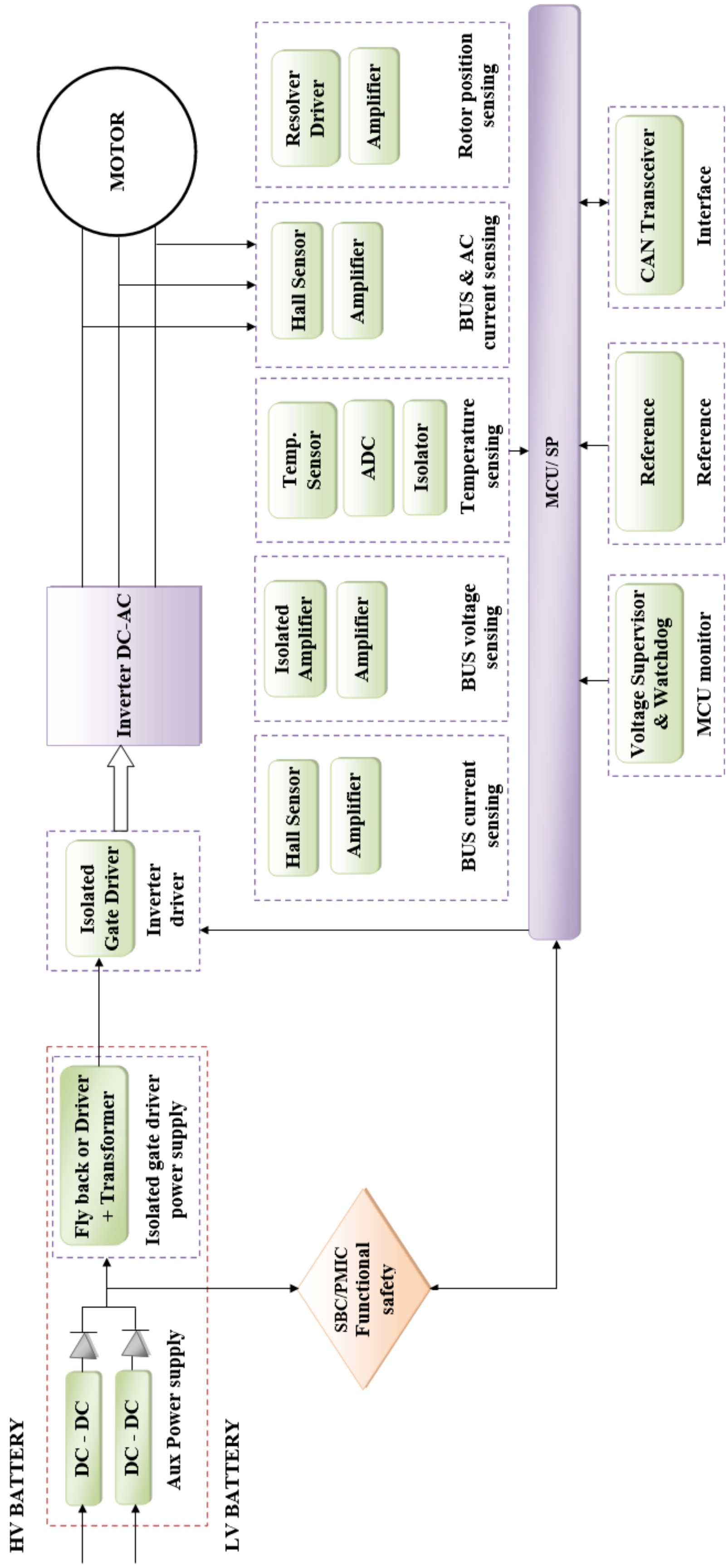


Figure 51: Block diagram of a drive and controller unit fed by two voltage rails

9 Power Electronics

Power inverters and DC/DC converters utilize semiconductors as switching elements to reduce voltage conversion losses, enabling the control of DC and AC outputs, while managing thermal losses through cooling surfaces that need to be larger with increased current and ambient temperature, all while differing in their on-state power and switching losses based on the circuit design [19]. High-speed machines also benefit from increased switching frequencies since motor losses and noise emissions can be reduced. The currently available semiconductors such as IGBTs and MOSFETs or SiC diodes have been developed and optimised for stationary and on-grid applications. All global power transmission systems can use IGBTs with blocking voltages between 600 and 1200 V, which makes them suitable for 200V and above applications. Transmission systems typically fall into either the single-phase 220V-240V or the three-phase 380V-440V voltage classes. IGBT blocking voltages may result from the voltage amplitudes caused by these voltage classes as indicated in Table 17 & 18 [19].

Table 17: Voltage levels in passenger vehicles [19]

Voltage levels passenger vehicles								
Components	Mild Hybrid			Full Hybrid Plug – in		EV (Battery/RE/FC)		
	12V	48V	HV	mid	Power	Small car	Medium car	Sports car
Drive and Charging components								
Electric motor (rated voltage)	12	36	120	300	250	300	300	300/600
Inverter DC/AC	15	60	200	400	420	400	400	420/800
Voltage converter DC/DC	-	60-12	200-12	400-12	450 -12	400-12	400-12	800/420-12
Charger AC/DC	-	-	-	-	230/420	230/400	230/400	230/450/800
Battery	15	60	200	400	400	400	400	420/800
Sub-component power								
Compressor	12	36	120	300	250	300	300	300/600
Heater	36	36	36/120	36/300	36/250	36/300	36/300	36/300
Electric pumps	12	36	12	12	12	12	12	12
Steering	12	36	12	12	12	12	12	12
Energy transfer components								
(Trad. on-board system)	12	12	12	12	12	12	12	12
Power distributor	12	60	200	400	420	400	400	420/800
Cable	12	60	200	400	420	400	400	420/800
Connector	12	60	200	400	420	400	400	420/800
Isolating elements	12	60	200	400	420	400	400	420/800
Relays/contactors	12	60	200	400	420	400	400	420/800
Integrated components								
Power semiconductor	75	75	250	650	650	650	650	650/1.200
Capacitors	16.5	66	220	440	462	440	440	460/880
Resistors	16.5	66	220	440	462	440	440	460/880
Inductors/motor coils	16.5	66	220	440	462	440	440	460/880
Relays/Contactors	16.5	66	220	440	462	440	440	460/880
Fuses	16.5	66	220	440	462	440	440	460/880
Current sensors	12	12	12	12	12	12	12	12
Position sensors	12	12	12	12	12	12	12	12
Temperature sensors	12	12	12	12	12	12	12	12

Table 18: Voltage levels in commercial vehicles [19]

E-mobility voltage level overview for commercial vehicles. Buses								
Components	Mild Hybrid (up to approx. 40% internal combustion engine power)				Plug – in Hybrid	EV/RE/FC		
	< 7.5t	7.5 – 12t	> 12t	Bus (18t)	7.5 – 12t	< 7.5t	7.5 – 12t	Bus (18t)
Drive and Charging components								
Electric motor (rated voltage)	280	300	300/600	300/600	300	300	400	600
Inverter (DC/AC – Wandler)	420	420	420/800	420/800	420	420	420	800
Voltage converter DC/DC	400 -120	400 -24	420/800-24	420/800-24	400 -24	400 -12	800-24	800-24
Charger AC/DC	-	-	-	-	3x400/420	3x400/420	400/420	3x400/800
Battery	420	420	420/800	420/800	420	420	420	400/800
Sub-component power								
Compressor	420	420	420/800	420/800	420	420	420	800
Heater	12/48	24	24	800-24	24	12	24	800-24
Electric pumps	2/48	24	420/800-24	24	24	12	24	24
Steering (electro – hydraulic)	Hydraulic	Hydraulic	Hydraulic	Hydraulic	Hydraulic	(420-12)	(420-12)	(800-24)
Energy transfer components								
(Trad. on-board system)	12	24	24	24	24	12	24	24
Power distributor	420	420	420/800	420/800	420	420	420	800
Cable	420	420	420/800	420/800	420	420	420	800
Connector	420	420	420/800	420/800	420	420	420	800
Isolating elements	420	420	420/800	420/800	420	420	420	800
Relays/contactors	420	420	420/800	420/800	420	420	420	800
Integrated components								
Power semiconductor	650	650	650/1200	650/1200	650	650	650	650
Capacitors	450	450	450/880	450/880	450	450	450	450
Resistors	450	450	450/880	450/880	450	450	450	450
Inductors/motor coils	450	450	450/880	450/880	450	450	450	450
Relays/Contactors	450	450	450/880	450/880	450	450	450	450
Fuses	450	450	450/880	450/880	450	450	450	450
Current sensors	12	24	24	24	24	24	12	24
Position sensors	12	24	24	24	24	24	12	24
Temperature sensors	12	24	24	24	24	24	12	24

The Maximum power transfer at peak voltage is made possible by choosing a DC voltage that lowers the current flow needed for the same power output. Proportionately lowering the DC voltage raises the expenses per kW and decreases the transmittable power. Capacitors are used in power electronic components to buffer reactive power. They may be optimized and purchased even in small quantities because they are made as electrolytic or film capacitors and come in accurately graduated increments for various DC voltages. The internal circuitry of an inverter's power components and printed circuit boards are similarly affected. Higher voltages reduce costs because the necessary currents can be reduced. Special attention must be paid to the maximum currents occurring in printed circuit board, especially in the semiconductors themselves, because their fine structures reach the maximum permissible temperatures after only a short time (0.1-10 s). Unlike motors, connectors and cables, power semiconductors must be designed for permanent load at the required maximum currents to achieve substantial cost savings by reducing maximum current. To minimise total losses and EMC interferences, inverters and DC/DC converters must be designed with intelligent circuitry concepts [19].

10 PECU Architecture vs Building Blocks for High-Voltage Inverters

In the realm of power electronics, understanding the distinction between control unit architecture and building blocks is crucial for designing efficient systems. Both concepts play significant roles in the functionality and performance of power electronic systems, but they serve different purposes and are structured differently.

10.1 Definition and Purpose

The Power Electronics Control Unit (PECU) Architecture refers to the systematic arrangement of components that manage and regulate the operation of power electronic devices. This architecture encompasses various elements such as microcontrollers, digital signal processors (DSPs), sensors, and communication interfaces that work together to control the behaviour of power converters, inverters, and other devices. The primary purpose of this architecture is to ensure precise control over voltage, current, frequency, and other operational parameters to achieve desired performance levels.

On the other hand, Power Electronics Building Blocks (PEBB) represent a modular approach to integrating power devices along with their associated components into standardized units or modules. Each PEBB is designed with specific functionalities that can be utilized across multiple applications. The aim here is to simplify design processes while reducing costs, size, weight, and engineering efforts associated with power electronics systems.

10.2 Structural Difference

The structural differences between these two concepts are notable:

i. **Control Unit Architecture:** This architecture is typically hierarchical and may include layers such as:
   - Sensor Layer: Collects data on system performance.
   - Control Layer: Processes data from sensors using algorithms to make decisions.
   - Actuation Layer: Implements control commands by adjusting the operation of power devices.
   - Each layer has distinct responsibilities that contribute to the overall functionality of the system.

ii. **Building Blocks (PEBB):** Power Electronic Building Blocks (PEBB) are designed as self-contained units that integrate various components such as:
   - Power devices (e.g., transistors or thyristors)
   - Gate drives
   - Thermal management systems
   - Protection circuits
   - These blocks can be combined or scaled according to application needs without requiring extensive redesigns.

10.3 Introduction to Power Electronics Control Unit Architecture

The architecture of a power electronics control unit is crucial for the efficient operation of power electronic systems, particularly in applications involving high voltage inverters. The control unit typically consists of several key components that work together to manage the conversion and flow of electrical energy. These components include:

i. **Control Algorithms:** Advanced algorithms are implemented to regulate voltage and current, ensuring optimal performance under varying load conditions. Common techniques include sensor-less field-oriented control (FOC) and space vector modulation (SVM), which enhance efficiency and reduce harmonic distortion.

ii. **Microcontroller or Digital Signal Processor (DSP):** This component executes the control algorithms and processes feedback from sensors or estimators. It plays a critical role in real-time decision-making, enabling rapid adjustments to maintain system stability.

iii. **Communication Interfaces:** These interfaces allow the control unit to communicate with other system components, such as sensors, actuators, and external networks. They ensure coordinated operation and facilitate monitoring and diagnostics.

iv. **Protection Mechanisms:** Safety features are integrated into the control architecture to prevent damage from overcurrent, overvoltage, overheating, or other fault conditions. These mechanisms can include hardware fuses, software limits, and emergency shutdown protocols.

v. **User Interface:** A user interface may be included for monitoring system performance and making adjustments as necessary. This can range from simple LED indicators to complex graphical displays.

Application Focus for Control Unit Architecture: Primarily concerned with real-time operation management and optimization of existing systems. It emphasizes software development for control algorithms and hardware integration for effective communication among components.

Benefits of Control Unit Architecture:

- Enhanced precision in controlling power electronic devices.
- Improved adaptability through sophisticated algorithms.
- Real-time monitoring capabilities leading to better system reliability.

10.4 Building Blocks for HV Inverters

High voltage inverters are essential in converting DC power into AC power at high voltages for various applications such as renewable energy systems, electric vehicles, and industrial drives. The building blocks of these inverters typically consist of:

i. **Inverter Modules:** Each module contains power semiconductor devices (such as IGBTs or MOSFETs) that switch on and off to convert DC into AC power. The design must ensure minimal switching losses while handling high voltages.

ii. **DC Link Capacitor:** This component acts as an energy buffer between the inverter modules, smoothing out voltage fluctuations and providing stable DC voltage levels necessary for efficient inverter operation.

iii. **Inductors/Filters:** Inductors are used on both the input and output sides of the inverter to filter out harmonics generated during the switching process. Proper sizing of these inductors is critical to minimize losses while ensuring compliance with grid standards.

iv. **Cooling Systems:** Given the high-power levels involved, effective thermal management is vital for maintaining reliability and performance. Cooling systems may include heat sinks, fans, or liquid cooling solutions depending on the application requirements.

v. **Control Circuitry:** Similar to the control unit architecture discussed earlier, this circuitry manages the operation of each inverter module based on feedback from current sensors and voltage measurements.

vi. **Protection Circuits:** High voltage inverters require robust protection circuits that can detect faults quickly and isolate affected components without disrupting overall system functionality.

Application Focus for Building Blocks (PEBB): Focuses on creating versatile modules that can be easily adapted for different applications like Power Quality/Custom Power solutions, FACTS (Flexible AC Transmission Systems), HVDC (High Voltage Direct Current), distributed generation systems, and energy storage solutions. The emphasis here is on standardization and modularity which allows for broader applicability across various sectors.

Benefits of Building Blocks (PEBB):

- Reduced complexity in design processes due to modularity.
- Cost savings through shared components across applications.
- Simplified maintenance due to standardized interfaces.

While both Power Electronics Control Unit Architecture and Power Electronics Building Blocks are integral parts of modern power electronics systems, they serve different functions - one focusing on control strategies while the other emphasizes modular design for efficiency in construction and application versatility.

In summary, while both power electronics control unit architecture and building blocks for high voltage inverters share some common elements such as control algorithms and protection mechanisms, they differ significantly in their specific functions within a system designed for managing electrical energy efficiently at high voltages.

11 Key Features of High-Voltage Motor Controllers

i. **Voltage Range:** High-voltage motor controllers for electric trucks typically operate within a voltage range of 600V to above 1000V. This allows for higher efficiency and better performance, particularly in heavy-duty applications where power demands are significant.

ii. **Cooling Systems:** There are two primary types of cooling systems used in high-voltage motor controllers: air-cooled and liquid-cooled systems. Liquid cooling is often preferred for electric trucks due to its ability to handle higher thermal loads, ensuring that the controller operates within safe temperature limits during extended use.

iii. **Integration with Advanced Technologies:** Many modern high-voltage motor controllers incorporate advanced technologies such as artificial intelligence (AI) and machine learning (ML) algorithms. These technologies enhance control efficiency, optimize energy usage, and improve overall vehicle performance.

iv. **Compact Design:** As manufacturers strive to create lighter and more efficient vehicles, there is a trend towards compact designs in high-voltage motor controllers. This is particularly important for electric trucks that require substantial power without adding excessive weight.

v. **Durability and Reliability:** Given the demanding environments in which electric trucks operate, high-voltage motor controllers are designed to be robust and reliable. They must withstand vibrations, temperature fluctuations, and exposure to various environmental conditions.

12 Market Trends Influencing High-Voltage Motor Controllers for Electric Trucks

i. **Rising Demand for Electric Trucks:** The global push towards reducing carbon emissions has led to an increase in demand for electric trucks across various sectors including logistics, construction, and public transportation.

ii. **Government Regulations and Incentives:** Many governments are implementing stringent emission regulations while also providing incentives for adopting electric vehicles (EVs). This regulatory environment encourages fleet operators to transition from traditional diesel-powered trucks to electric alternatives.

iii. **Technological Advancements in Power Electronics:** Innovations in semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) have improved the efficiency and performance of high-voltage motor controllers significantly. These materials allow for higher power density and reduced energy losses.

iv. **Collaboration between Manufacturers:** There is an increasing trend of collaboration between truck manufacturers and technology providers to develop customized solutions tailored specifically for heavy-duty applications.

v. **Focus on Energy Efficiency:** With rising fuel costs and environmental concerns, there is a strong emphasis on energy-efficient solutions within the trucking industry. High-voltage motor controllers play a crucial role in optimizing energy consumption by effectively managing power delivery to motors.

The market for high-voltage motor controllers tailored for electric trucks is characterized by rapid growth driven by technological advancements, regulatory support, and increasing demand for sustainable transportation solutions. As manufacturers continue to innovate in this space, we can expect further enhancements in efficiency, reliability, and integration with smart technologies.

13 High-Voltage EV Controllers Topologies

Electric vehicles (EVs) utilize various high voltage controller topologies to efficiently manage power conversion and distribution within the vehicle's electrical system. The choice of topology is crucial as it directly affects the performance, efficiency, cost, and complexity of the traction inverter, which is responsible for converting direct current (DC) from the battery into alternating current (AC) for the electric motor [20].

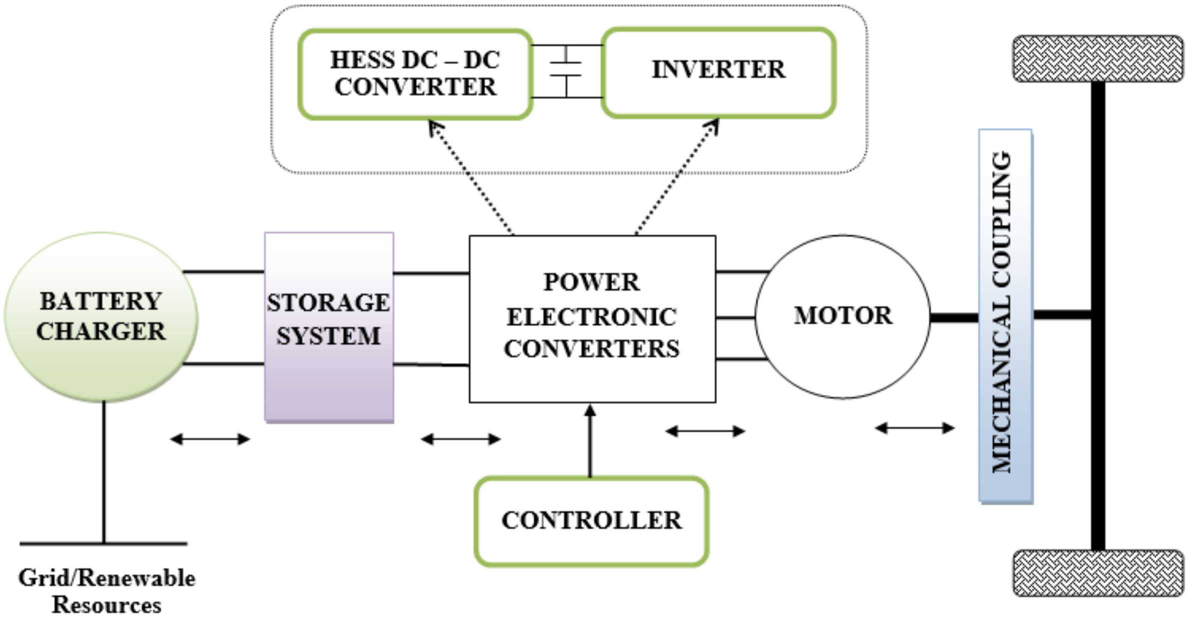


Figure 52: Block diagram of BEV propulsion system

13.1 Overview of Traction Inverter Topologies

There are four primary topologies commonly used in EV traction inverters:

i. **2-Level Topology featuring 650V IGBT Switch:** This configuration uses Insulated Gate Bipolar Transistors (IGBTs) that are well-suited for medium voltage applications. It provides a good balance between performance and cost, making it popular in many EV applications.

ii. **2-Level Topology featuring 650V SiC MOSFET Switch:** Silicon Carbide (SiC) MOSFETs offer higher efficiency and thermal performance compared to traditional silicon devices. This topology is advantageous for applications requiring high switching frequencies and reduced losses.

iii. **2-Level Topology featuring 1200V SiC MOSFET Switch:** This topology allows for operation at higher voltages, which can be beneficial for larger EV systems or those requiring more power. The use of SiC technology enhances efficiency and reduces thermal management challenges.

iv. **3-Level Topology featuring 650V GaN Switch:** Gallium Nitride (GaN) switches enable even higher switching frequencies and lower losses than SiC devices. This topology is particularly useful in applications where size and weight reduction are critical.

These topologies can be categorized into two subsets based on their operating voltage levels: 400V Powertrains and 800V Powertrains. The 2-level configurations are more prevalent due to their simplicity and cost-effectiveness, while multi-level topologies are typically reserved for specialized applications like electric trains or ships due to their increased complexity and expense.

13.2 Importance of SiC devices

Silicon carbide (SiC) devices are increasingly important in various industries due to their superior performance characteristics, especially in high-power, high-temperature, and high-frequency applications. Here are some key reasons why SiC devices are so important,

i. Silicon carbide can operate at much higher temperatures compared to traditional silicon-based devices. SiC material itself can withstand much higher temperatures above 600°C, the practical limitations of packaging, processing, and other factors currently restrict the maximum junction temperature of Power Electronic devices to around 175°C. However, research is ongoing to explore and improve SiC MOSFETs for higher temperature applications.

ii. The high temperature capability of SiC devices compared to traditional Si based devices makes them ideal for use in harsh environments, such as in automotive, industrial, and aerospace applications.

iii. SiC devices have lower power losses than their silicon counterparts, especially at higher voltages and frequencies. They enable more efficient power conversion and energy savings, which is critical in applications like electric vehicles (EVs), renewable energy (solar and wind), and industrial motor drives.

iv. SiC has a wide band gap that allows devices made from this material to withstand high voltage. This capability makes SiC devices ideal for high-voltage power systems, such as electric power grids, inverters, and motor drives in EVs and renewable energy systems.

v. SiC devices can switch faster than traditional silicon-based components. Faster switching improves the efficiency of power converters and reduces the size and cost of passive components like capacitors and inductors in circuits, leading to lighter, more compact designs.

vi. Because SiC devices are more efficient, they allow for smaller and lighter power electronics designs. This is particularly beneficial for applications in electric vehicles and renewable energy systems, where space and weight are crucial considerations.

vii. While SiC devices may have higher initial costs than silicon devices, their efficiency and durability lead to long-term cost savings in many applications. Lower energy consumption and reduced need for heat dissipation can result in substantial operational savings.

Table 19: Characteristics of Si devices & SiC devices

Characteristic	Si Devices	SiC Devices
Voltage Rating	Up to 250V	> 600 V
Switching Speed	Lower Speed (up to 200kHz)	Faster Switching Speeds (1kHz to 650kHz)
Thermal Performance	Low (125-150˚C)	High (175-200˚C)
Efficiency	Lower Efficiency due to high ON state resistance (200-500mΩ)	Higher Efficiency due to low ON state resistance (30-100mΩ)
Size & Weight	Larger, heavier components	Smaller, Lighter Components
Cost	Lower Cost	Higher Cost (Usually 4-5 times the Si Devices)

13.3 Importance of Capacitors in HV Controllers

Capacitors play a vital role in the operation of high voltage EV controllers by ensuring stability, filtering noise, suppressing voltage spikes, and enhancing overall reliability. Key types of capacitors used include:

i. **Snubber Capacitors:** These protect circuits from large voltage spikes by connecting to high-current switching nodes.

ii. **X & Y Safety Capacitors:** Designed to mitigate transient voltages and electromagnetic interference (EMI), these capacitors are essential in high-voltage applications.

iii. **Bypass Capacitors:** They filter out high-frequency noise to ensure clean power delivery.

iv. **Decoupling Capacitors:** Positioned near sensitive components, they suppress fluctuations on power supply lines.

v. **DC-Link Capacitors:** This help offset inductance effects in inverters while protecting subsystems from surges.

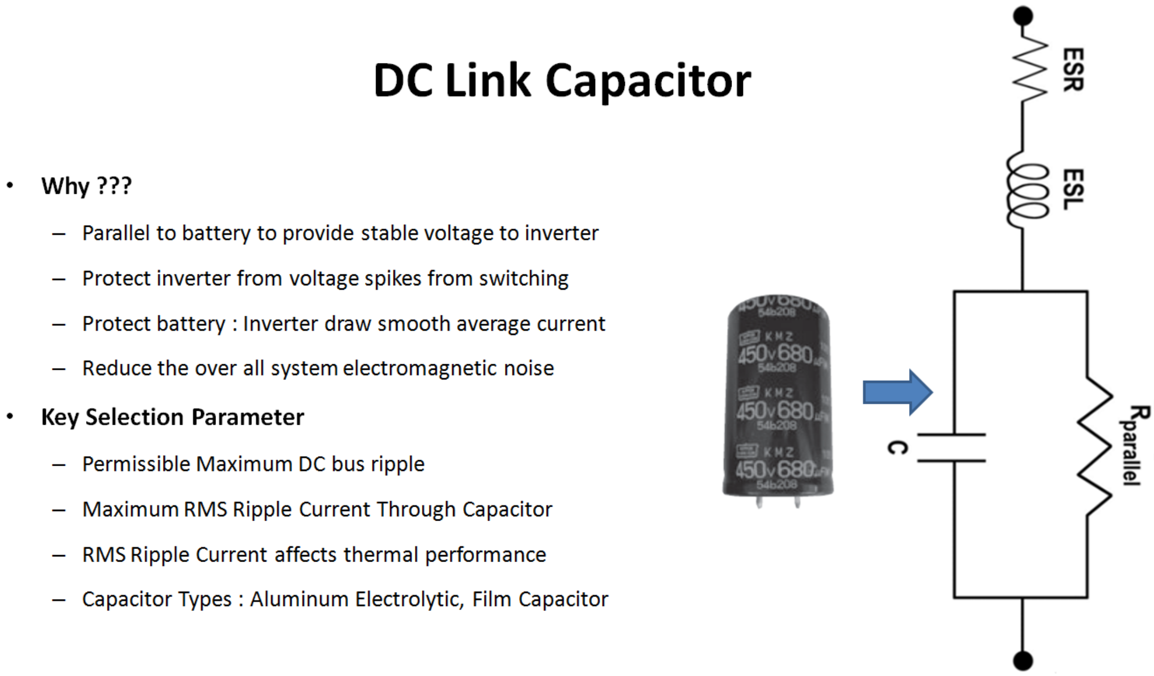


Figure 53: DC link capacitor selection

vi. **Flying Capacitors:** Lightweight components that balance voltage across systems, extending component longevity.

The design specifications of these capacitors vary depending on the chosen traction inverter topology, emphasizing the need for careful selection based on application requirements.

In summary, selecting an appropriate high voltage controller topology involves understanding both the technical specifications of different switch technologies as well as the critical roles played by various capacitors within those systems. This ensures optimal performance and reliability in electric vehicle applications.

14 Noise, Vibration & Harshness (NVH) in EV

14.1 Introduction

The general shift towards electrification in the electric vehicle (EV) market and beyond has created a need for higher fidelity simulation of electric power trains. One aspect of this trend that has been getting attention is the desire for detailed analysis of an electric motor's noise, vibration, and harshness (NVH) characteristics early in the design stage [21].

The electric motor has a very desirable torque speed curve because it can not only produce max torque at 0 speed, but across a wide range of speeds. While this ability creates new opportunities with the electric motor, it also creates some new challenges in comparison to internal combustion engines. One of these challenges is torque ripple, which has several implications including control, power output, noise, vibration, and durability. Torque ripple can be described as the variance of output torque as the motor rotates [21].

Electrical excitation of the machine contributes to the torque ripple because the torque of the machine will follow the current. The most extreme example of this is the single-phase machine where there will be cyclical torque at two-times the fundamental frequency, and a zero-torque element [21]. As noted by Krishnan (2010), three-phase machines are widely used in industrial applications due to their simplicity and reliability, but they still require careful design to minimize torque ripple. Techniques such as optimizing the winding configuration, increasing number of poles and using advanced control strategies can help mitigate torque ripple in three-phase machines.

Since the torque is created by the sinusoidal excitation, the torque ripple from excitation will be at the same frequency as the electrical signal, which means as speed increases, so will the torque ripple frequency. In addition, other elements of torque ripple will be present, because excitation is not a perfect sine wave. Inverters which operate at a high frequency are often employed, and the machine winding will affect the distribution of current. As a result, these issues will create additional torque ripple [21].

Construction is another example of a contributing factor which can impact torque ripple. In all machines torque ripple is driven by the machine winding function, and each machine type has a contribution of torque ripple form the rotor magnetic interacting with the stator iron. In induction machines, the torque ripple is smaller in amplitude and could be managed with the skew of the rotor bars. With an increase in the utilization of permanent magnet machines, you need to account for the effects of the magnets on the rotor, in addition to the winding function and skew. The magnets on the rotor will attract to the iron on the stator, and as the machine spins, the magnets will attract to each stator tooth. Since there are a fixed number of rotor magnets and stator slots, this element of torque ripple will also be proportional to speed. The high amplitude, and potentially high frequencies due to the speed of the machine make torque ripple from permanent magnets a difficult problem to characterize and reduce [21].

The sources of the characteristic high-pitch whine of electric motors are the interaction between different air gap field harmonics inside the machine, as well as the switching voltage inputs from the inverter. These elements generate force waves in the air gap, which can excite the structure of the motor and cause vibrations, particularly at specific resonant frequencies. Imperfect torque and stator load profiles cause further vibration of attached machinery components and the gearbox housing (e-axle). Unlike internal combustion engines, where the engine sound is often a prominent feature that we want to accentuate, with electric drive units, any sound that is produced is usually undesirable, so the goal is to minimize it [21].

To estimate the noise radiated by an electric motor numerically, methods performing a weak coupling between electromagnetic, dynamic and acoustic models are frequently applied to diverse motor technologies. These methods offer good accuracy when compared with measurements, and they enable for the estimation of the level of noise radiated by any design. Some minimization algorithms can be used in order to modify the electric motors design so as to minimize the radiated noise estimated using the multi physical workflow, while ensuring, by means of optimization constraints, that overall electromechanical performance criteria, such as mean torque, torque ripple or efficiency, are not deteriorated. Using this method, significant noise level reductions can be achieved, owing to the high sensitivity of the electromagnetic excitations harmonic and spatial content to slight design modifications [22].

Such optimization algorithms are used to reduce the noise of electric motors. To overcome the generally high number of cost function evaluations required by optimization algorithms, the authors of these articles use fast modelling workflows, i.e. respectively a fully analytical modelling workflow and a surrogate model. In the context of computing power increase, the use of a more accurate finite element electromagnetic model makes it possible to take full advantage of the noise reduction possibilities offered by slight geometric variations. However, the sensitivity can be so high that slight geometric deviations of the magnetic active parts within the manufacturing tolerances can lead to very high variations of the electromagnetic excitations spectral content and thus to the loss of the radiated noise reductions achieved by optimization [22].

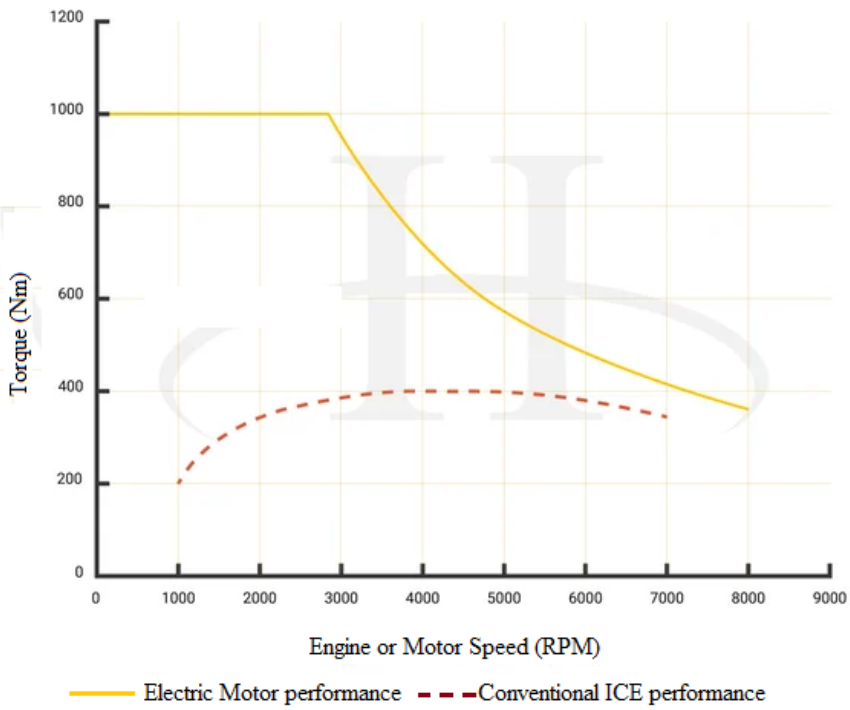


Figure 54: EV Powertrain Design vs. ICE Powertrain [23]

For such cases where deterministic optimization is not suited, a robust optimization method is presented. The probabilistic robust optimization methodology has been used for various applications in dynamics, but it is applied for the first time to the vibro-acoustic optimization of electric motors. It ensures, when considering random deviation of the uncertain parameters, to converge towards a design with a low average noise level, and a low variability. After describing the simulation methodology, the deterministic and robust optimization methods are described and applied to minimize the noise radiated by automotive traction motors. It can be divided into four steps:

i. The supply of the motor by Pulse Width Modulation (PWM) of the supply voltage leads to the appearance of high order harmonics in the currents.

ii. These current harmonics, combined with the stator and rotor geometry and with the windings distributions, result in harmonic contributions in the air gap flux density, and as a consequence to dynamic contributions in the radial and tangential Maxwell pressures, which constitute the prevailing electromagnetic excitation in electric motors.

iii. The electromagnetic excitations apply to the stator and the rotor and cause vibrations, with an amplitude depending on the modal basis and damping of the power train structure, and on the amplitude, frequency and spatial distribution of the electromagnetic excitations.

iv. Depending on the operating deflection shapes and the vibration frequencies, the structure will prove to be more or less prone to radiating noise.

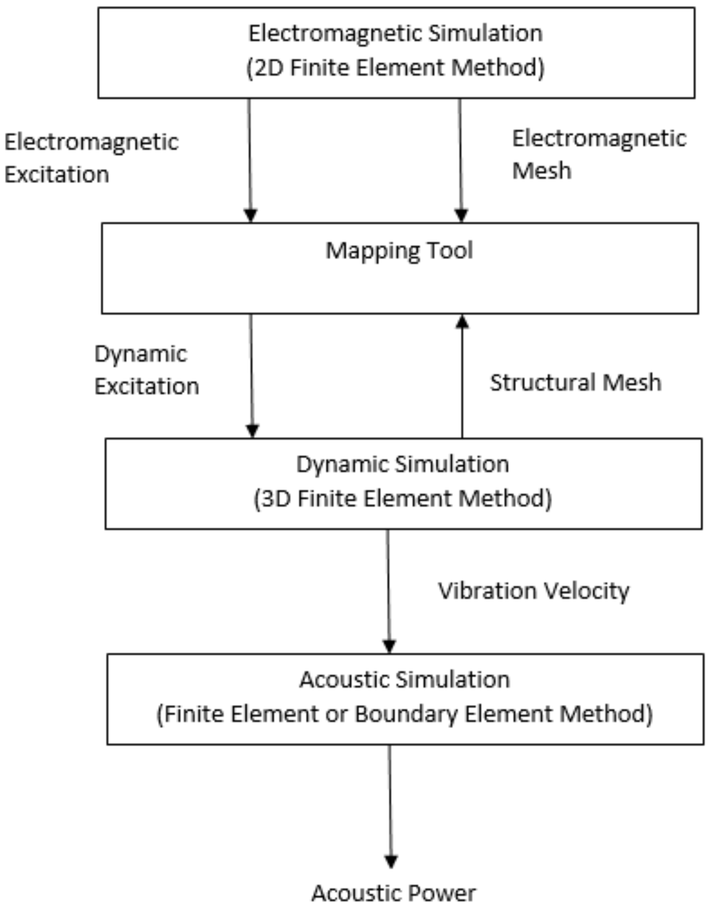


Figure 55: Basic principle of the multi-physical simulation methodology [22]

The common consumer wants a car that will get them from point A to point B without any added hassle or distraction. Electric vehicles improve driver experience by reducing NVH (noise, vibration, and harshness). Traditional internal combustion engine vehicles suffer from NVH a lot more than electric vehicles do, which impacts driver quality-of-life. The classic feature of an electric motor is almost zero NVH. The most sound you will get is minimal gear whine.

NVH in electric motors is a negligible factor because:

- **i.** Rotation is limited to a central axis, limiting motor and power train vibration
- **ii.** Electric motors are typically more compact
- **iii.** EVs require less energy to move because electric motors generate instantaneous max torque so you eliminate the need to rev the engine.
- **iv.** Manufacturers of automotive electrical components have been using steel laminations for a long time, but that method is restrictive in a few ways.

14.2 NVH between Various Technologies of Drives

A comparative study on Noise, Vibration, and Harshness (NVH) for electric trucks (e-trucks) is crucial in understanding how different drive technologies affect the overall driving experience, comfort, and operational efficiency. As e-trucks use electric drivetrains instead of traditional internal combustion engines, they present distinct NVH characteristics that vary depending on the underlying drive technology. In this context, it's valuable to compare various drive technologies used in e-trucks, such as **Battery Electric Vehicles (BEV)**, **Fuel Cell Electric Vehicles (FCEV)**, and **Plug-in Hybrid Electric Vehicles (PHEV)**, while considering how each affects noise, vibration, and harshness.

14.2.1 NVH in Battery Electric Vehicles (BEV)

Technology Overview: BEVs are powered solely by electric motors and batteries. These vehicles operate without an internal combustion engine, which eliminates many of the noise sources typically found in conventional vehicles, such as engine noise and exhaust noise.

NVH Characteristics:

- **Noise:** BEVs typically have lower overall noise levels, especially at low speeds, because they lack an internal combustion engine. However, noise from the electric motor, inverter, and tyres becomes more prominent at higher speeds. The absence of engine noise makes tyre and wind noise more noticeable.

- **Vibration:** The vibration levels in BEVs are generally low compared to traditional vehicles due to the smooth operation of electric motors. However, vibrations from the motor and power electronics can be transmitted through the chassis and impact cabin comfort. Depending on the type of motor used (e.g., permanent magnet, induction), the vibration frequencies can vary.

- **Harshness:** BEVs exhibit low levels of harshness compared to traditional ICE vehicles. The lack of engine noise and harsh gear shifts leads to a smoother driving experience. However, the NVH performance can degrade if the vehicle is poorly insulated or if the drive train is not optimized for low vibrations.

Key Technologies for NVH Reduction:

- **Motor & Inverter Design:** Advanced designs and optimization of the motor and inverter can reduce vibration and high-frequency noise. For instance, using low-vibration permanent magnet motors instead of high-frequency induction motors can improve NVH.

- **Active Noise Cancellation:** BEVs can implement active noise cancellation (ANC) technology to reduce unwanted cabin noise.

- **Soundproofing Materials:** Improved soundproofing materials in the cabin and the use of low-rolling-resistance tyres can help mitigate tyre and road noise.

14.2.2 NVH in Fuel Cell Electric Vehicles (FCEV)

Technology Overview: FCEVs are powered by hydrogen fuel cells, which generate electricity to drive electric motors. Like BEVs, FCEVs have no internal combustion engine but instead use a chemical process to produce electricity on-demand.

NVH Characteristics:

- **Noise:** FCEVs tend to produce slightly more noise than BEVs at higher speeds due to the operation of the fuel cell system and air compressors. The fuel cell stack, cooling system, and hydrogen pumps generate higher-frequency noise compared to the electric motor in BEVs. The overall noise level can still be lower than conventional diesel-powered trucks, but it may be more noticeable at higher speeds.

- **Vibration:** The fuel cell system produces vibrations that can be transmitted through the chassis. These vibrations, while generally low compared to traditional diesel engines, can still be a concern in certain FCEV designs. The hydrogen pumps, fuel cell stack, and compressors are key contributors to vibrations.

- **Harshness:** The vibration and noise produced by the fuel cell system can lead to slightly higher harshness levels compared to BEVs. However, the absence of an internal combustion engine means that the overall driving experience is much quieter than traditional vehicles.

Key Technologies for NVH Reduction:

- **Fuel Cell Stack Isolation:** Using advanced isolation techniques to decouple the fuel cell stack and other components from the vehicle body helps reduce transmitted vibrations.

- **Active Noise Control:** Like BEVs, FCEVs can benefit from active noise cancellation to reduce unwanted sounds from the fuel cell system.

- **Optimized Pump & Compressor Design:** Minimizing the noise and vibration generated by the hydrogen pumps and compressors through advanced design and damping solutions.

14.2.3 NVH in Plug-in Hybrid Electric Vehicles (PHEV)

Technology Overview: PHEVs use a combination of an internal combustion engine and an electric motor. They can operate on electric power alone for short distances and switch to the internal combustion engine for longer trips.

NVH Characteristics:

- **Noise:** PHEVs can have more variable noise characteristics due to the presence of both an internal combustion engine and an electric motor. When the engine kicks in, it generates noise and vibration, which can affect the overall NVH. At low speeds, when the electric motor is in use, the vehicle behaves similarly to a BEV in terms of noise.
- **Vibration:** The combustion engine and the transition between the electric motor and engine cause additional vibration. At low speeds or when running on electric power, the vibration is minimal. However, when the engine is engaged, the vibration increases.
- **Harshness:** The dual powertrain leads to a more complex driving experience in terms of harshness, as the transition between the electric motor and internal combustion engine can create noticeable shifts in the driving experience. In addition, the combustion engine itself may contribute to harshness.

Key Technologies for NVH Reduction:

- **Seamless Engine Transition:** Advanced control systems to ensure a smooth transition between the electric motor and the combustion engine can reduce the harshness associated with engine engagement.
- **Dual Motor & Engine Isolation:** Effective isolation of the internal combustion engine and the electric motor can minimize vibration transmission.
- **Hybrid-Specific Sound Insulation:** Additional sound insulation can help minimize noise from the internal combustion engine when it is running.

Table 20: Comparative summary of NVH between various technologies of drives

Technology	Noise	Vibration	Harshness
Battery Electric Vehicles (BEV)	Low noise, especially at low speeds, but tyre and wind noise become prominent at higher speeds.	Low vibration due to smooth motor operation but can increase with low-quality drive trains.	Low harshness due to absence of combustion engine and smooth electric motor operation.
Fuel Cell Electric Vehicles (FCEV)	Slightly higher noise than BEVs due to the fuel cell stack, hydrogen pumps, and compressors.	Slightly higher vibrations than BEVs due to fuel cell stack and associated components.	Higher harshness than BEVs, mainly due to fuel cell vibrations and mechanical systems.
Plug-in Hybrid Electric Vehicles (PHEV)	Variable noise depending on whether the engine or electric motor is in use.	Increased vibration when the internal combustion engine is in use.	Higher harshness due to the transition between electric and combustion powertrains.

14.3 Technological Innovations for Improved NVH in e-trucks

- **Advanced Soundproofing Materials:** The use of new sound-absorbing materials like acoustic foams and composites can significantly improve NVH in all electric drive technologies.
- **Noise and Vibration Sensors:** Real-time monitoring and analysis of NVH characteristics using sensors can help detect and correct issues early in the development cycle.
- **Simulation and Modelling:** Advanced NVH simulation tools, including virtual prototyping and real-time simulation of driving conditions, help design quieter and smoother vehicles.

The NVH characteristics of electric trucks vary depending on the drive technology used. BEVs typically offer the best NVH performance due to the absence of an internal combustion engine, but tyre and wind noise remain significant at higher speeds. FCEVs are relatively quiet but may have higher-frequency noise from the fuel cell system. PHEVs provide a more complex NVH profile, with noise, vibration, and harshness levels changing depending on whether the vehicle is running on electric power or the combustion engine. By incorporating advanced NVH reduction techniques like active noise control, vibration isolation, and soundproofing, manufacturers can improve the comfort and driving experience of e-trucks, irrespective of the drive technology.

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Annexure-1

1) NEDC driving cycle:

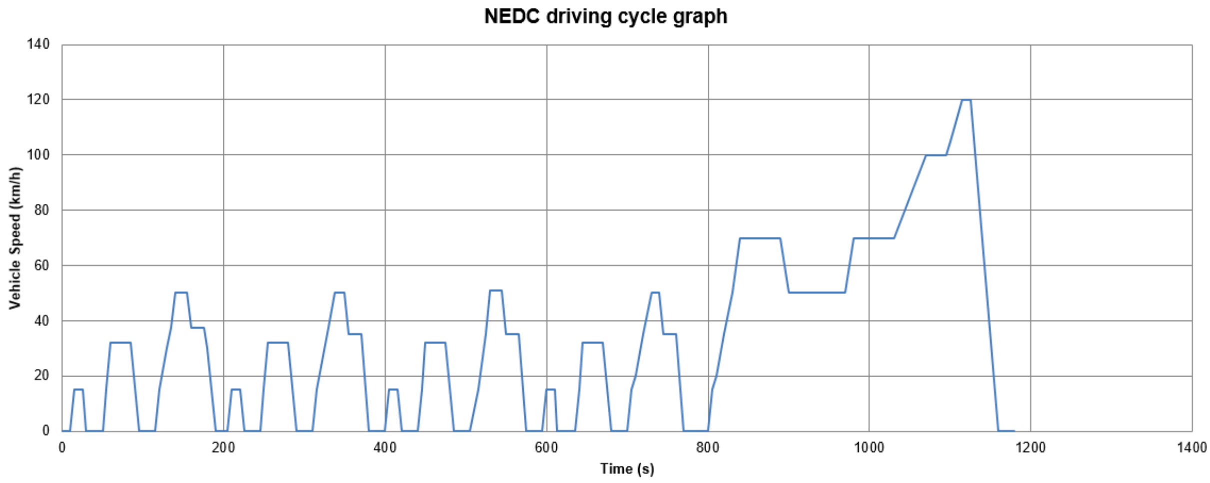

Figure 56: NEDC driving cycle graph (digitised)

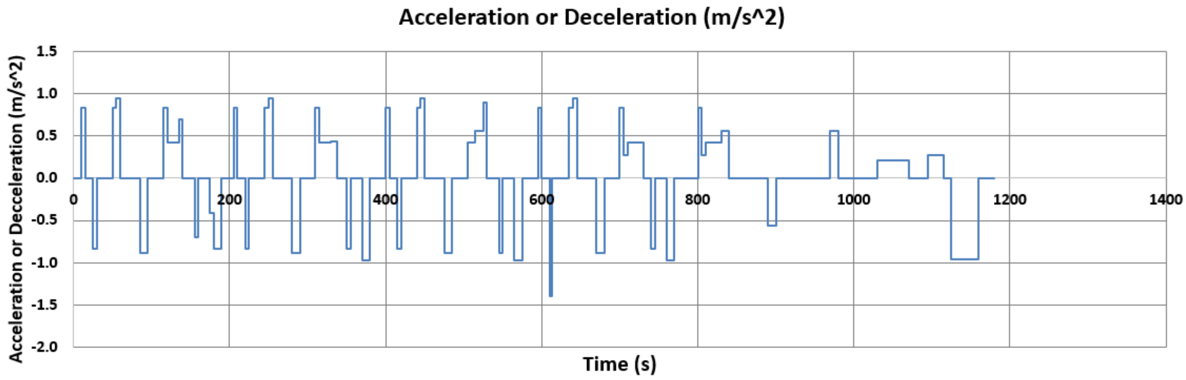

Figure 57: Acceleration & deceleration plot with reference to NEDC driving cycle

Average Acceleration, a_m	**0.6318 m/s²**	**2.27 km/(h.s)**
Average Deceleration, d_m	**-0.8615 m/s²**	**-3.10 km/(h.s)**

Table 21: Tabular data of NEDC driving cycle and acceleration plot

Time (s)	Vehicle Speed (kmph)
0	0
10	0
15	15
25	15
30	0
50	0
55	15
60	32
85	32
95	0

T1	V1	T2	V2	Acceleration or Deceleration (m/s²)
0	0	10	0	0.0000
10	0	15	15	0.8333
15	15	25	15	0.0000
25	15	30	0	-0.8333
30	0	50	0	0.0000
50	0	55	15	0.8333
55	15	60	32	0.9444
60	32	85	32	0.0000
85	32	95	0	-0.8889
95	0	115	0	0.0000

115	0
120	15
130	30
135	37.5
140	50
155	50
160	37.5
175	37.5
180	30
190	0
205	0
210	15
220	15
225	0
245	0
250	15
255	32
280	32
290	0
310	0
315	15
330	37.5
338	50
350	50
355	35
370	35
380	0
400	0
405	15
415	15
420	0
440	0
445	15
450	32
475	32
485	0
505	0
515	15
525	35
530	51
545	51
550	35
565	35
575	0
595	0

115	0	120	15	0.8333
120	15	130	30	0.4167
130	30	135	37.5	0.4167
135	37.5	140	50	0.6944
140	50	155	50	0.0000
155	50	160	37.5	-0.6944
160	37.5	175	37.5	0.0000
175	37.5	180	30	-0.4167
180	30	190	0	-0.8333
190	0	205	0	0.0000
205	0	210	15	0.8333
210	15	220	15	0.0000
220	15	225	0	-0.8333
225	0	245	0	0.0000
245	0	250	15	0.8333
250	15	255	32	0.9444
255	32	280	32	0.0000
280	32	290	0	-0.8889
290	0	310	0	0.0000
310	0	315	15	0.8333
315	15	330	37.5	0.4167
330	37.5	338	50	0.4340
338	50	350	50	0.0000
350	50	355	35	-0.8333
355	35	370	35	0.0000
370	35	380	0	-0.9722
380	0	400	0	0.0000
400	0	405	15	0.8333
405	15	415	15	0.0000
415	15	420	0	-0.8333
420	0	440	0	0.0000
440	0	445	15	0.8333
445	15	450	32	0.9444
450	32	475	32	0.0000
475	32	485	0	-0.8889
485	0	505	0	0.0000
505	0	515	15	0.4167
515	15	525	35	0.5556
525	35	530	51	0.8889
530	51	545	51	0.0000
545	51	550	35	-0.8889
550	35	565	35	0.0000
565	35	575	0	-0.9722
575	0	595	0	0.0000
595	0	600	15	0.8333

600	15
610	15
613	0
635	0
640	15
645	32
670	32
680	0
700	0
705	15
710	20
720	35
730	50
740	50
745	35
760	35
770	0
800	0
805	15
810	20
820	35
830	50
840	70
890	70
900	50
970	50
980	70
1030	70
1070	100
1095	100
1100	105
1115	120
1125	120
1160	0
1180	0

600	15	610	15	0.0000
610	15	613	0	-1.3889
613	0	635	0	0.0000
635	0	640	15	0.8333
640	15	645	32	0.9444
645	32	670	32	0.0000
670	32	680	0	-0.8889
680	0	700	0	0.0000
700	0	705	15	0.8333
705	15	710	20	0.2778
710	20	720	35	0.4167
720	35	730	50	0.4167
730	50	740	50	0.0000
740	50	745	35	-0.8333
745	35	760	35	0.0000
760	35	770	0	-0.9722
770	0	800	0	0.0000
800	0	805	15	0.8333
805	15	810	20	0.2778
810	20	820	35	0.4167
820	35	830	50	0.4167
830	50	840	70	0.5556
840	70	890	70	0.0000
890	70	900	50	-0.5556
900	50	970	50	0.0000
970	50	980	70	0.5556
980	70	1030	70	0.0000
1030	70	1070	100	0.2083
1070	100	1095	100	0.0000
1095	100	1100	105	0.2778
1100	105	1115	120	0.2778
1115	120	1125	120	0.0000
1125	120	1160	0	-0.9524
1160	0	1180	0	0.0000
1180	0	1180	0	0.0000

2) 10-15 driving cycle:

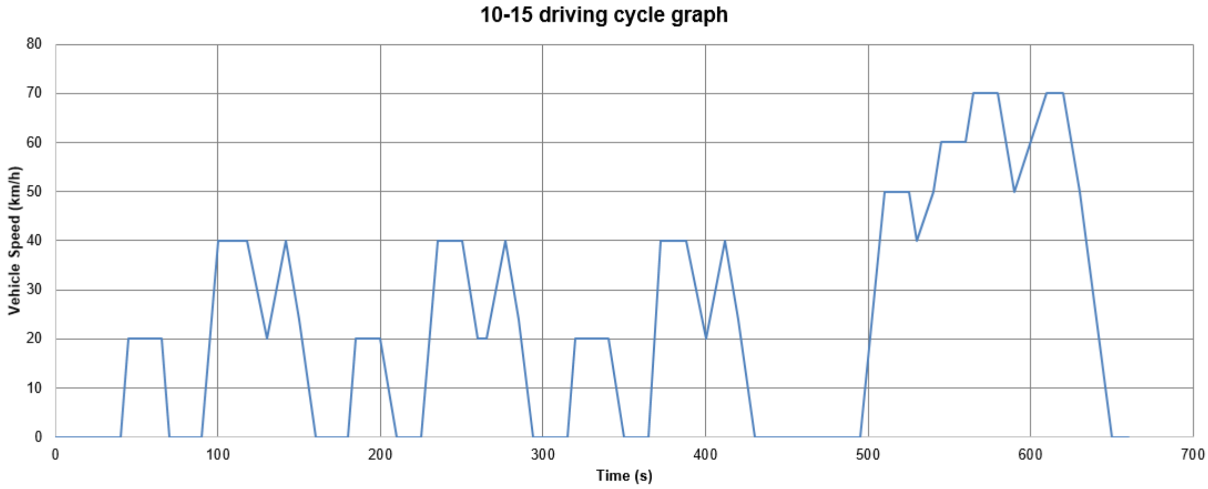

Figure 58: 10-15 driving cycle graph (digitised)

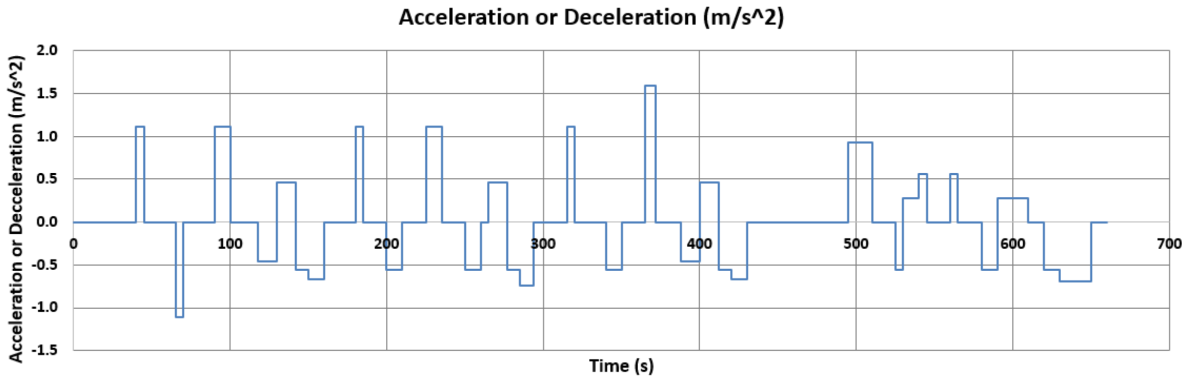

Figure 59: Acceleration & deceleration plot with reference to 10-15 driving cycle

Average Acceleration, a_m	**0.7946 m/s^2**	**2.86 km/(h.s)**
Average Deceleration, d_m	**-0.6128 m/s^2**	**-2.20 km/(h.s)**

Table 22: Tabular data of 10-15 driving cycle and acceleration plot

Time (s)	Vehicle Speed (kmph)
0	0
40	0
45	20
60	20
65	20
70	0
90	0
100	40
118	40
130	20
142	40

T1	V1	T2	V2	Acceleration or Deceleration (m/s^2)
0	0	40	0	0.0000
40	0	45	20	1.1111
45	20	60	20	0.0000
60	20	65	20	0.0000
65	20	70	0	-1.1111
70	0	90	0	0.0000
90	0	100	40	1.1111
100	40	118	40	0.0000
118	40	130	20	-0.4630
130	20	142	40	0.4630
142	40	150	24	-0.5556

150	24
160	0
180	0
185	20
200	20
210	0
225	0
235	40
250	40
260	20
265	20
277	40
285	24
294	0
315	0
320	20
340	20
350	0
365	0
372	40
388	40
400	20
412	40
420	24
430	0
495	0
510	50
525	50
530	40
540	50
545	60
560	60
565	70
580	70
590	50
610	70
620	70
630	50
650	0
660	0

150	24	160	0	-0.6667
160	0	180	0	0.0000
180	0	185	20	1.1111
185	20	200	20	0.0000
200	20	210	0	-0.5556
210	0	225	0	0.0000
225	0	235	40	1.1111
235	40	250	40	0.0000
250	40	260	20	-0.5556
260	20	265	20	0.0000
265	20	277	40	0.4630
277	40	285	24	-0.5556
285	24	294	0	-0.7407
294	0	315	0	0.0000
315	0	320	20	1.1111
320	20	340	20	0.0000
340	20	350	0	-0.5556
350	0	365	0	0.0000
365	0	372	40	1.5873
372	40	388	40	0.0000
388	40	400	20	-0.4630
400	20	412	40	0.4630
412	40	420	24	-0.5556
420	24	430	0	-0.6667
430	0	495	0	0.0000
495	0	510	50	0.9259
510	50	525	50	0.0000
525	50	530	40	-0.5556
530	40	540	50	0.2778
540	50	545	60	0.5556
545	60	560	60	0.0000
560	60	565	70	0.5556
565	70	580	70	0.0000
580	70	590	50	-0.5556
590	50	610	70	0.2778
610	70	620	70	0.0000
620	70	630	50	-0.5556
630	50	650	0	-0.6944
650	0	660	0	0.0000
660	0	660	0	0.0000

3) UDDS driving cycle graph (FTP-72):

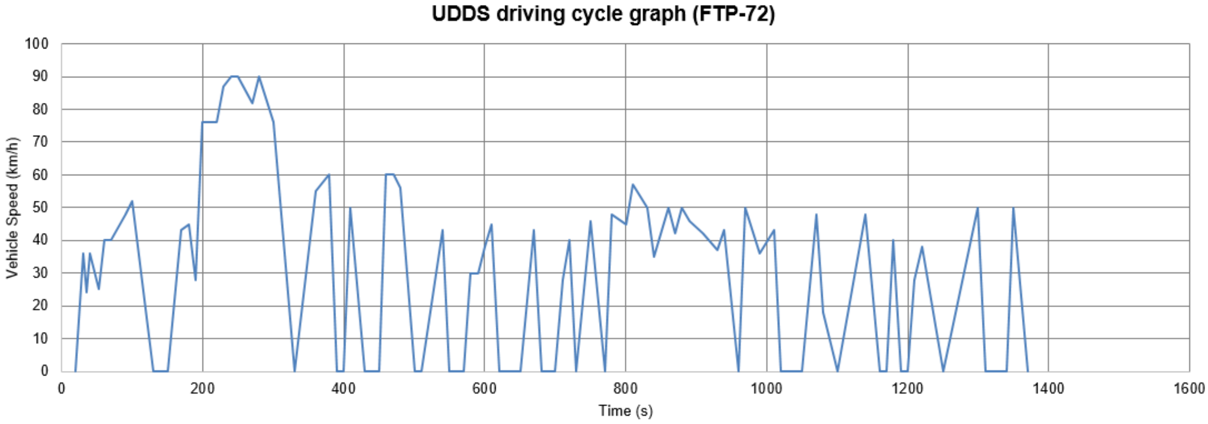

Figure 60: UDDS driving cycle graph (FTP-72) (digitised)

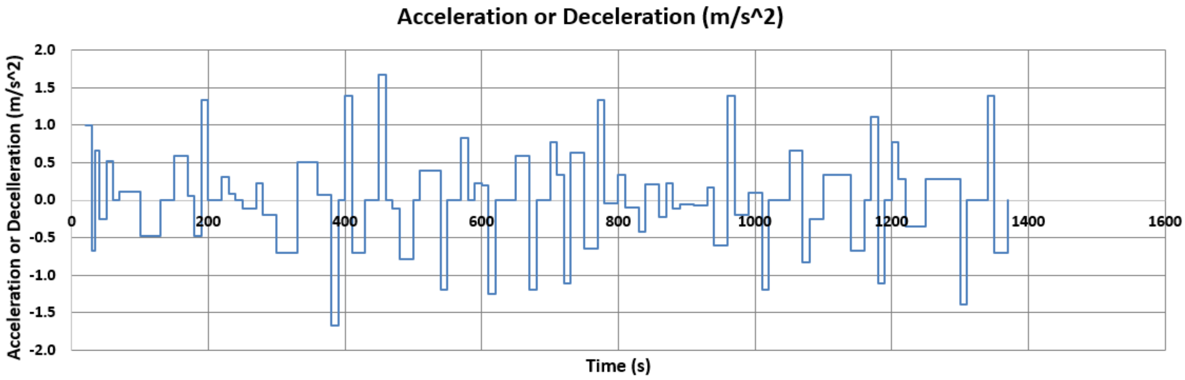

Figure 61: Acceleration & deceleration plot with reference to UDDS driving cycle (FTP-72)

Average Acceleration, a_m	**0.5735 m/s²**	**2.06 km/(h.s)**
Average Deceleration, d_m	**-0.6006 m/s²**	**-2.16 km/(h.s)**

Table 23: Tabular data of UDDS driving cycle (FTP-72) and acceleration plot

Time (s)	Vehicle Speed (kmph)
20	0
30	36
35	24
40	36
52	25
60	40
70	40
90	48
100	52
130	0
150	0
170	43
180	45

T1	V1	T2	V2	Acceleration or Deceleration (m/s²)
20	0	30	36	1.0000
30	36	35	24	-0.6667
35	24	40	36	0.6667
40	36	52	25	-0.2546
52	25	60	40	0.5208
60	40	70	40	0.0000
70	40	90	48	0.1111
90	48	100	52	0.1111
100	52	130	0	-0.4815
130	0	150	0	0.0000
150	0	170	43	0.5972
170	43	180	45	0.0556
180	45	190	28	-0.4722

190	28
200	76
210	76
220	76
230	87
240	90
250	90
270	82
280	90
300	76
330	0
360	55
380	60
390	0
400	0
410	50
430	0
450	0
460	60
470	60
480	56
500	0
510	0
540	43
550	0
570	0
580	30
590	30
600	38
610	45
620	0
650	0
670	43
680	0
700	0
710	28
720	40
730	0
750	46
770	0
780	48
800	45
810	57
830	50
840	35

190	28	200	76	1.3333
200	76	210	76	0.0000
210	76	220	76	0.0000
220	76	230	87	0.3056
230	87	240	90	0.0833
240	90	250	90	0.0000
250	90	270	82	-0.1111
270	82	280	90	0.2222
280	90	300	76	-0.1944
300	76	330	0	-0.7037
330	0	360	55	0.5093
360	55	380	60	0.0694
380	60	390	0	-1.6667
390	0	400	0	0.0000
400	0	410	50	1.3889
410	50	430	0	-0.6944
430	0	450	0	0.0000
450	0	460	60	1.6667
460	60	470	60	0.0000
470	60	480	56	-0.1111
480	56	500	0	-0.7778
500	0	510	0	0.0000
510	0	540	43	0.3981
540	43	550	0	-1.1944
550	0	570	0	0.0000
570	0	580	30	0.8333
580	30	590	30	0.0000
590	30	600	38	0.2222
600	38	610	45	0.1944
610	45	620	0	-1.2500
620	0	650	0	0.0000
650	0	670	43	0.5972
670	43	680	0	-1.1944
680	0	700	0	0.0000
700	0	710	28	0.7778
710	28	720	40	0.3333
720	40	730	0	-1.1111
730	0	750	46	0.6389
750	46	770	0	-0.6389
770	0	780	48	1.3333
780	48	800	45	-0.0417
800	45	810	57	0.3333
810	57	830	50	-0.0972
830	50	840	35	-0.4167
840	35	860	50	0.2083

860	50
870	42
880	50
890	46
910	42
930	37
940	43
960	0
970	50
990	36
1010	43
1020	0
1050	0
1070	48
1080	18
1100	0
1140	48
1160	0
1170	0
1180	40
1190	0
1200	0
1210	28
1220	38
1250	0
1300	50
1310	0
1340	0
1350	50
1370	0

860	50	870	42	-0.2222
870	42	880	50	0.2222
880	50	890	46	-0.1111
890	46	910	42	-0.0556
910	42	930	37	-0.0694
930	37	940	43	0.1667
940	43	960	0	-0.5972
960	0	970	50	1.3889
970	50	990	36	-0.1944
990	36	1010	43	0.0972
1010	43	1020	0	-1.1944
1020	0	1050	0	0.0000
1050	0	1070	48	0.6667
1070	48	1080	18	-0.8333
1080	18	1100	0	-0.2500
1100	0	1140	48	0.3333
1140	48	1160	0	-0.6667
1160	0	1170	0	0.0000
1170	0	1180	40	1.1111
1180	40	1190	0	-1.1111
1190	0	1200	0	0.0000
1200	0	1210	28	0.7778
1210	28	1220	38	0.2778
1220	38	1250	0	-0.3519
1250	0	1300	50	0.2778
1300	50	1310	0	-1.3889
1310	0	1340	0	0.0000
1340	0	1350	50	1.3889
1350	50	1370	0	-0.6944
1370	0	1370	0	0.0000

4) FTP-75 driving cycle:

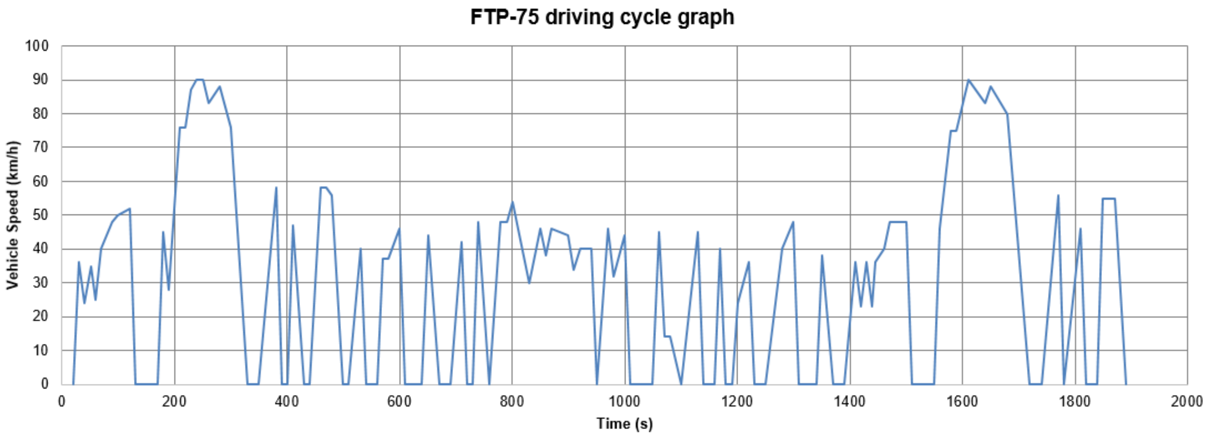

Figure 62: FTP-75 driving cycle graph (digitised)

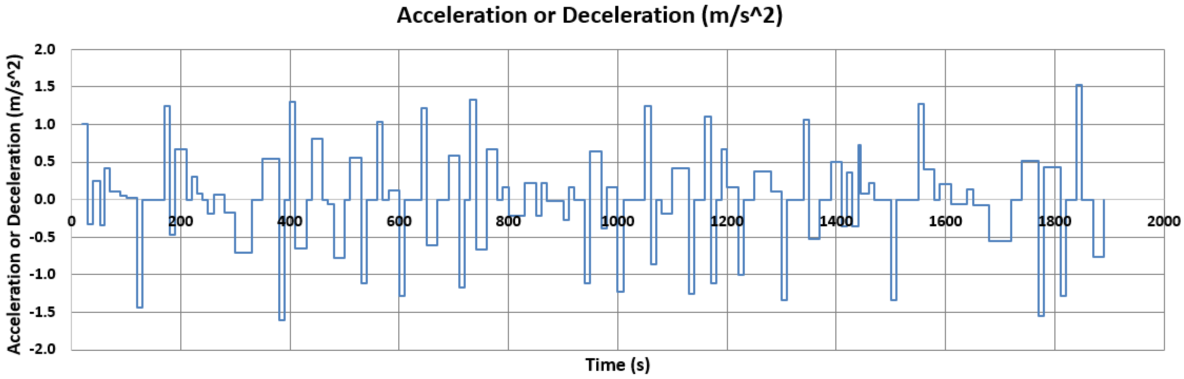

Figure 63: Acceleration & deceleration plot with reference to FTP-75 driving cycle

Average Acceleration, a_m	**0.5428 m/s²**	**1.95 km/(h.s)**
Average Deceleration, d_m	**-0.7098 m/s²**	**-2.55 km/(h.s)**

Table 24: Tabular data of FTP-75 driving cycle and acceleration plot

Time (s)	Vehicle Speed (kmph)
20	0
30	36
40	24
52	35
60	25
70	40
90	48
100	50
120	52
130	0
150	0
170	0

T1	V1	T2	V2	Acceleration or Deceleration (m/s²)
20	0	30	36	1.0000
30	36	40	24	-0.3333
40	24	52	35	0.2546
52	35	60	25	-0.3472
60	25	70	40	0.4167
70	40	90	48	0.1111
90	48	100	50	0.0556
100	50	120	52	0.0278
120	52	130	0	-1.4444
130	0	150	0	0.0000
150	0	170	0	0.0000
170	0	180	45	1.2500

180	45
190	28
210	76
220	76
230	87
240	90
250	90
260	83
280	88
300	76
330	0
350	0
380	58
390	0
400	0
410	47
430	0
440	0
460	58
470	58
480	56
500	0
510	0
530	40
540	0
560	0
570	37
580	37
600	46
610	0
620	0
640	0
650	44
670	0
690	0
710	42
720	0
730	0
740	48
760	0
780	48
790	48
800	54
830	30
850	46

180	45	190	28	-0.4722
190	28	210	76	0.6667
210	76	220	76	0.0000
220	76	230	87	0.3056
230	87	240	90	0.0833
240	90	250	90	0.0000
250	90	260	83	-0.1944
260	83	280	88	0.0694
280	88	300	76	-0.1667
300	76	330	0	-0.7037
330	0	350	0	0.0000
350	0	380	58	0.5370
380	58	390	0	-1.6111
390	0	400	0	0.0000
400	0	410	47	1.3056
410	47	430	0	-0.6528
430	0	440	0	0.0000
440	0	460	58	0.8056
460	58	470	58	0.0000
470	58	480	56	-0.0556
480	56	500	0	-0.7778
500	0	510	0	0.0000
510	0	530	40	0.5556
530	40	540	0	-1.1111
540	0	560	0	0.0000
560	0	570	37	1.0278
570	37	580	37	0.0000
580	37	600	46	0.1250
600	46	610	0	-1.2778
610	0	620	0	0.0000
620	0	640	0	0.0000
640	0	650	44	1.2222
650	44	670	0	-0.6111
670	0	690	0	0.0000
690	0	710	42	0.5833
710	42	720	0	-1.1667
720	0	730	0	0.0000
730	0	740	48	1.3333
740	48	760	0	-0.6667
760	0	780	48	0.6667
780	48	790	48	0.0000
790	48	800	54	0.1667
800	54	830	30	-0.2222
830	30	850	46	0.2222
850	46	860	38	-0.2222

860	38
870	46
900	44
910	34
920	40
940	40
950	0
970	46
980	32
1000	44
1010	0
1050	0
1060	45
1070	14
1080	14
1100	0
1130	45
1140	0
1160	0
1170	40
1180	0
1190	0
1200	24
1220	36
1230	0
1250	0
1280	40
1300	48
1310	0
1340	0
1350	38
1370	0
1390	0
1410	36
1420	23
1430	36
1440	23
1445	36
1460	40
1470	48
1500	48
1510	0
1550	0
1560	46
1580	75

860	38	870	46	0.2222
870	46	900	44	-0.0185
900	44	910	34	-0.2778
910	34	920	40	0.1667
920	40	940	40	0.0000
940	40	950	0	-1.1111
950	0	970	46	0.6389
970	46	980	32	-0.3889
980	32	1000	44	0.1667
1000	44	1010	0	-1.2222
1010	0	1050	0	0.0000
1050	0	1060	45	1.2500
1060	45	1070	14	-0.8611
1070	14	1080	14	0.0000
1080	14	1100	0	-0.1944
1100	0	1130	45	0.4167
1130	45	1140	0	-1.2500
1140	0	1160	0	0.0000
1160	0	1170	40	1.1111
1170	40	1180	0	-1.1111
1180	0	1190	0	0.0000
1190	0	1200	24	0.6667
1200	24	1220	36	0.1667
1220	36	1230	0	-1.0000
1230	0	1250	0	0.0000
1250	0	1280	40	0.3704
1280	40	1300	48	0.1111
1300	48	1310	0	-1.3333
1310	0	1340	0	0.0000
1340	0	1350	38	1.0556
1350	38	1370	0	-0.5278
1370	0	1390	0	0.0000
1390	0	1410	36	0.5000
1410	36	1420	23	-0.3611
1420	23	1430	36	0.3611
1430	36	1440	23	-0.3611
1440	23	1445	36	0.7222
1445	36	1460	40	0.0741
1460	40	1470	48	0.2222
1470	48	1500	48	0.0000
1500	48	1510	0	-1.3333
1510	0	1550	0	0.0000
1550	0	1560	46	1.2778
1560	46	1580	75	0.4028
1580	75	1590	75	0.0000

1590	75
1610	90
1640	83
1650	88
1680	80
1720	0
1740	0
1770	56
1780	0
1810	46
1820	0
1840	0
1850	55
1870	55
1890	0

1590	75	1610	90	0.2083
1610	90	1640	83	-0.0648
1640	83	1650	88	0.1389
1650	88	1680	80	-0.0741
1680	80	1720	0	-0.5556
1720	0	1740	0	0.0000
1740	0	1770	56	0.5185
1770	56	1780	0	-1.5556
1780	0	1810	46	0.4259
1810	46	1820	0	-1.2778
1820	0	1840	0	0.0000
1840	0	1850	55	1.5278
1850	55	1870	55	0.0000
1870	55	1890	0	-0.7639
1890	0	1890	0	0.0000

Annexure-2

Table 25: Existing EV Trucks in India

Manufacturer	Model	Specification / Description	
TATA	**ULTRA T7 Electric** [12]	Engine Norm	Zero Tailpipe
		Motor Capacity	295 HP
		Max Torque	2800 Nm
		Max Speed	80 kmph
		No. of Tyres	6
		GVW	7490-8750 kg
		Payload Capacity	3692-4935 kg
		Load Body Size	HDLB, CLB & CABIN CHASSIS
		Kerb Weight	3798-3815 kg
		Range	100 Km/charge
		Charging Time	~2 hours
		Battery Capacity	62.5 kWh
		Charger Type	Off Board DC Fast Charging
TATA	**Prima E.28K** [12] 	Engine Norm	Zero Tailpipe
		Motor Capacity	325 HP
		Max Torque	2950 Nm
		Max Speed	80 kmph
		GVW	28,000 kg
		Payload Capacity	20,000 kg
		Range	150 - 200 Km/charge
		Charging Time	80% in ~2 hours
		Battery Capacity	453 kWh
		No. of Tyres	10
		Transmission	2 Speed AT
Ashok Leyland	**Boss 1219 EV** [12] 	Engine Norm	Zero Tailpipe
		Motor Capacity	187 HP
		Max Torque	1065 Nm
		Max Speed	80 kmph
		No. of Tyres	6
		GVW	11,990 kg
		Payload Capacity	6,000 kg
		Range	150 Km/charge
		Charging Time	80% in ~2 hours
		Battery Capacity	80 kWh
		Transmission	2 Speed AT

Ashok Leyland

Boss 14 HB EV [12]

Engine Norm	Zero Tailpipe
Motor Capacity	160 HP
Max Torque	409 Nm
GVW	14,050 kg
Payload Capacity	5,000 kg
Range	230 Km/charge
Charging Time	80% in ~1 hour
Battery Capacity	201.5 kWh
Axle	6 x 4 Axle Configuration

Ashok Leyland

Boss 1218 HB EV [12]

Engine Norm	Zero Tailpipe
Motor Capacity	187 HP
Max Torque	1065 Nm
Max Speed	80 kmph
GVW	11,990 kg
Payload Capacity	5,000 kg
Range	300-350 Km/charge
Charging Time	80% in ~1 hour
Battery Capacity	453 kWh
Wheel	10 Wheel Configuration
Transmission	2 Speed AT

Olectra

Meghaetron 28T [12]

Engine Norm	Zero Tailpipe
Motor Capacity	362 HP
Max Torque	2400 Nm
Max Speed	80 kmph
No. of Tyres	10
GVW	28,000 kg
Payload Capacity	19 cubic meters of payload
Range	150 Km/charge
Charging Time	80% in ~2 hours
Battery Capacity	350 kWh
Axle configuration	6 x 4 Axle

Volvo	**FH Aero Electric** [13]		
		Axle Configuration (Air suspended)	Tractor: 4x2, 6x2, 6x4 Rigid: 4x2, 6x2, 6x4, 8×2, 8x4
		Cab	Low sleeper cab, sleeper cab, Globetrotter cab, Globetrotter XL cab
		GCW	Up to 44 tons
		Battery capacity	360-540 kWh, 4-6 batteries
		Range	Up to 300 km (4x2 tractor trailer)
		Charging time (100%)	9.5h with AC (43 kW) 2.5h with DC (250 kW)
		Powertrain	2-3 electric motors, I-Shift gearbox
		Performance	330-490 kW
		Applications	3 PTOs (electrical, mechanical and transmission)
Volvo	**FMX Electric** [13]		
		Axle Configuration (Air suspended)	Tractor: 4×2, 6×2, 6x4. Rigid: 4x2, 6x2, 6x4, 8x2, 8x4
		Cab	Low day cab, day cab, low sleeper cab, sleeper cab, Globetrotter cab
		GCW	Up to 44 tons
		Battery capacity	180-540 kWh, 2-6 batteries
		Range	Up to 300 km
		Charging time (100%)	9.5h with AC (43 kW) 2.5h with DC (250 kW)
		Powertrain	2-3 electric motors, I-Shift gearbox
		Performance	330-490 kW (450-666 hp)
		Applications	3 PTOs (electrical, mechanical and transmission)

Volvo	**FM Low Entry** [13]	Axle Configuration	Rigid: 4x2, 6x2, 6x4, 8x2, 8x4
		Cab	Short crew
		GCW	Up to 32 tons
		Battery capacity	360 kWh, 4 batteries
		Range	Up to 200 km
		Charging time (100%)	8.5h with AC (43 kW) 1.5h with DC (250kW)
		Powertrain	2 electric motors, I-Shift gearbox
		Performance	330 kW
		Applications	3 PTOs (electrical, mechanical and transmission)
Volvo	**FE Electric** [13]	Axle Configuration (Air suspended)	Rigid: 4x2, 6x2
		Cab	Day cab, short sleeper cab, sleeper cab, low entry cab
		GCW	Up to 27 tons
		Battery capacity	280-375 kWh, 3 to 4 batteries
		Range	Up to 275 km
		Charging time (100%, 4 battery packs)	8 h with AC (43 kW) 2.3 h with DC (150 kW)
		Powertrain	2 electric motors, 2-speed gearbox
		Performance	225 kW (300 hp)
		Applications	Electric PTO
Volvo	**FL Electric** [13]	Axle Configuration	Rigid: 4x2
		Cab	Day cab, short sleeper cab
		GCW	Up to 18.6 tons
		Battery capacity	280-565 kWh, 3 to 6 batteries
		Range	Up to 450 km
		Charging time (100%, 4 battery packs)	8 h with AC (43 kW) 2.3 h with DC (150 kW)
		Powertrain	Single electric motor, 2-speed gearbox
		Performance	130 kW (175 hp)
		Applications	Electric PTO

<table>
<tr>
<td>IPL Tech</td>
<td>Rhino 5536e [12]

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<td>
<table>
<tr><td>Engine Norm</td><td>Zero Tailpipe</td></tr>
<tr><td>Motor Capacity</td><td>360 BHP</td></tr>
<tr><td>Max Torque</td><td>2400 Nm</td></tr>
<tr><td>GCW</td><td>55,000 kg</td></tr>
<tr><td>Range</td><td>185 Km/charge</td></tr>
<tr><td>Charging Time</td><td>~90 Minutes (100%)</td></tr>
<tr><td>Battery Capacity</td><td>258 kWh</td></tr>
<tr><td>Transmission</td><td>12 Speed AMT</td></tr>
</table>
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<tr>
<td>BYD</td>
<td>Q1R Electric Truck [12]
</td>
<td>
<table>
<tr><td>Engine Norm</td><td>Zero Tailpipe</td></tr>
<tr><td>Motor Capacity</td><td>180 KW</td></tr>
<tr><td>Max Torque</td><td>1500 Nm</td></tr>
<tr><td>GVW</td><td>42,000 kg</td></tr>
<tr><td>Range</td><td>100 Km/charge</td></tr>
<tr><td>Charging Time</td><td>100% in ~2 hours</td></tr>
<tr><td>Battery Capacity</td><td>217 kWh</td></tr>
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Table 26: Global EV Truck Manufacturers

Sl. No.	Manufacturer	Description
1	**Volvo**	• Well-known brand in the automotive and transportation sector. • Emphasizing sustainability and electrification, especially within the electric truck market. • Leader in producing heavy-duty trucks, construction machinery, and other large vehicles. • In line with its sustainability goals, Volvo is dedicated to lowering carbon emissions and enhancing fuel efficiency by shifting from conventional diesel-powered trucks to electric trucks (e-trucks).
2	**Tesla**	• Renowned for its electric vehicles, has also entered the electric truck market with the aim of transforming heavy-duty transportation. • As a leader in electric vehicle technology, Tesla has been instrumental in driving substantial changes within both the automotive and energy sectors. • Tesla has already made significant strides in the consumer electric car market. • It is now focused on revolutionizing the commercial trucking industry with its electric trucks.
3	**Mercedes**	• A leading global automotive manufacturer, actively engaged in the development and promotion of electric trucks as part of its commitment to sustainability and the electrification of transportation. • Known for its luxury vehicles, Mercedes-Benz also has a robust commercial vehicle division. • The company has made significant advancements in electric mobility, especially within the heavy-duty truck sector, aligning with its broader sustainability strategy. • By focusing on electrifying its commercial vehicle line-up, including trucks, Mercedes-Benz aims to minimize the environmental impact of the transportation industry and comply with increasingly stringent global emissions regulations. • The company has introduced a variety of electric trucks designed to meet the demands of regional, urban, and local distribution.
4	**Nikola Corporation**	• A leader in technological innovation and integration, focused on creating advanced energy and transportation solutions. • They are establishing a business model that allows corporate clients to adopt next-generation truck technology, hydrogen fuelling infrastructure, and maintenance services. • By building this ecosystem, Nikola, along with its strategic partners and suppliers, aims to become a global leader in zero-emission transportation and contribute positively to the world.

5	**BYD Co Ltd**	• BYD is a technology-driven company dedicated to utilizing innovative technologies to enhance quality of life. • Over the past three decades, BYD has significantly impacted sectors such as electronics, automotive, renewable energy, and rail transportation. • With an emphasis on energy generation, storage, and utilization, BYD provides a wide range of comprehensive zero-emission new energy solutions.
6	**Rivian**	• Rivian Automotive, Inc. is an American manufacturer of electric vehicles and automotive technology, established in 2009. • The company specializes in producing an electric sport utility vehicle (SUV) and a pickup truck built on a versatile "skateboard" platform that can accommodate future vehicle designs or be utilized by other manufacturers. • Additionally, Rivian has developed the electric delivery van known as the Rivian EDV. Deliveries of the R1T pickup truck commenced in late 2021. • In 2022, Rivian introduced a dedicated charging network across the United States, which was later made accessible to other vehicles in 2024.
7	**Volta Trucks**	• Volta is developing a fully electric truck intended for use in urban environments. • This vehicle will produce zero tailpipe emissions and operate quietly, eliminating engine noise. • By removing the bulky diesel engine, we can completely redesign the cabin with a focus on driver safety, as well as the safety of pedestrians and cyclists. • The driver's seat is positioned centrally, and the cab has been lowered to enhance visibility while allowing easy access from both sides through sliding doors. • In summary, we are fundamentally reimagining the design of urban trucks from the ground up.
8	**Daimler**	• Daimler Truck ranks among the largest manufacturers of commercial vehicles globally. • The company provides a range of products, including light, medium, and heavy-duty trucks, as well as city and intercity buses, coaches, and bus chassis. • Additionally, tailored financial services are included in their offerings.
9	**MAN Truck & Bus**	• MAN Truck & Bus stands as a prominent manufacturer of commercial vehicles and transport solutions in Europe. • Its extensive product range encompasses vans, trucks, buses, diesel and gas engines, along with various services for both passenger and freight transportation. • With over a century of experience in advancing commercial vehicle technology, MAN Truck & Bus SE has established itself as a global leader in the provision of trucks, vans, and buses, as well as innovative and sustainable transport solutions.

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8.	Sh. Sathish S, Senior Project Associate, Nonferrous Materials Technology Development Centre (NFTDC), Hyderabad
9.	Sh. Sai Spandana L, Project Associate, Nonferrous Materials Technology Development Centre (NFTDC), Hyderabad
10.	Sh. Shankar Ram C S, Principal Investigator, CoEZET, Department of Engineering Design, IIT Madras, Chennai
11.	Sh. Sundaresan S A, Professor of Practice, Department of Engineering Design, IIT Madras, Chennai
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15.	Sh. Saravanan B, Lead-Technical Projects, CoEZET, IIT Madras, Chennai
16.	Sh. Prakash M, Senior Project Officer, CoEZET, IIT Madras, Chennai

सत्यमेव जयते

Office of the Principal Scientific Adviser to the Government of India

Kartavya Bhavan-3, Janpath, New Delhi – 110001

Phone: 011 23022038 | Fax: +91 11 2302 2113

/prinsciadvoff/ @prinsciadvoff /PrinSciAdvOff /prinsciadvoff