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Technical Report
"Electric 2-wheeler drive cycle based drivetrain sizing: A comprehensive analysis"

26 March 2022

- Driving data collection
- Drive cycle generation
- Analysis of drive cycles
- Motor performance analysis
- Battery Sizing
- Drivetrain system integration
- Comprehensive comparison & analysis
- Conclusion

Title: "Electric 2-wheeler drive cycle based drivetrain sizing: A comprehensive analysis"

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Contents

1 Introduction

1.1 Drive cycle

Drive Cycle is a dataset of the vehicle speed collected at every instant of time, which can be used to determine the vehicle parameters, torque ratings, power ratings, emissions and fuel consumption.

1.2 Advantages of drive cycle

The advantages are based on the utilisations, a few of which are listed below:

- Measuring the performance potential of the new vehicle technology.
- Simulate laboratory tests (chassis dynamometer).
- Design the power train of the vehicle and help in making decisions effectively.
- Design of transient thermal management of Engine/Motors/Batteries
- Design products focussed on meeting specific application requirements.
- Measure effectiveness of powertrain in reducing the impact of pollutants.
- Estimation of fuel consumption.
- Determine battery capacity and mileage.

1.3 Types of drive cycle

There are two types of drive cycles:

1. **Transient drive cycle:** It represents the real drive cycle pattern. It contains acceleration, deceleration and constant speed. American FTP-75 is an example of a transient drive cycle.
2. **Modal drive cycle:** This model driving cycle comprises of constant speed over a long duration. It does not represent a real drive cycle pattern. It is mainly used for the measurement of emission tests. NEDC, JC10-15 MODE, JC 08 are examples of the modal drive cycle.

1.4 Drive cycle history

Many of us are aware of “The Great London Smog”. It was the result of air pollution. The incident questioned the preparedness to counter the increase in air pollution. The incident later leads to the development of standard test procedures to determine vehicle emissions. In the early 60s, vehicles were tested for compliance with the emission standards using standardised tests; these have been known as test cycles or driving/drive cycles. Today, there are many standard drive cycles. A few of them are listed below:

- **Federal test procedure (FTP-75):** It is the transient drive cycle. The US Environmental Protection Agency (EPA) developed it to measure tailpipe emission and fuel economy of passenger cars. The characteristics of the drive cycle are:
  - Distance travelled: 17.77 km
  - Duration: 1874 seconds
  - Average speed: 34.1 km/h
  - Maximum Speed: 91.25 km/h
- **JC 10-15 mode:** It is based on a model drive cycle developed by the Japanese Industrial Safety and Health Association, JISHA 899, 1983. It is the Japan official fuel economy and emission certification test. The test is carried out on chassis dynamometers. The characteristics of the drive cycle are:
  - Distance travelled: 6.34 km
  - Duration: 660 seconds
  - Average speed: 25.6 km/h
  - Maximum speed:70 km/h

    Since JC 10-15 mode is a soft dive cycle test. Hence, to make it a more natural drive cycle, modification and a new drive have been developed JC 08.

    The JC08 test is significantly longer and more rigorous than the 10–15 mode test. The running pattern with JC08 stretches out to 1204 seconds and top speed 81.6 km/h, and average speed is 24.6 km/h and having both cold and warm start measurements. Its economy is less than the former, but it is more realistic than the JC10-15 mode.
- **NEDC:** The New European Driving Cycle (NEDC) is the model-based drive cycle. It was last updated in 1997 now it is obsolete. It was developed to measure the emission and fuel economy of passenger cars. The characteristics of the drive cycle are:

  For urban drive cycle
  - Distance travelled: 0.95 km
  - Duration: 195 seconds
  - Average speed: 18.35 km/h
  - Maximum speed:50 km/h

    This cycle is repeated four times to measure fuel economy and pollution. NEDC is replaced with WLTC

- **World harmonised Light-duty vehicles Test Cycle (WLTC):**

  It aims to replace the previous NEDC and develop a more realistic world-class drive cycle. Its final version came in 2015. It is a widely adopted drive cycle all over the world. It is stricter than NEDC. It has three class drive cycles according to power to kerb ratio (PWR):

  Class 1 Lower Power Vehicle (PWR<=22)

  - Distance travelled: 8.1 km
  - Duration: 1022 seconds
  - Average speed: 28.5 km/h

  Class 2 Medium Power Vehicle (22<PWR<=34)

  - Distance travelled: 14.664 km
  - Duration: 1477 seconds
  - Average speed: 35.7 km/h

  Class 3 High Power Vehicle (PWR>34)

  - Distance travelled: 23.26 km
  - Duration: 1800seconds
  - Average speed: 46.5 km/h

1.5 Need for India specific drive cycle

Drive cycle patterns are different for different countries. It depends on traffic intensity, road profile, driving skill and geographical location. The primary purpose of standard drive cycle is to measure fuel consumption and emissions. Its acceleration and deceleration profile are very soft. It does not match with the actual drive cycle pattern. We need actual drive cycle data for the design of the power train, heat exchanger, and research purpose. Further, it is necessary for the efficient and economical design.

1.6 Aim of the report

With the evolution of transportation systems towards electrification, there is a rapid growth in demand for electric vehicles, especially in the two-wheelers segment in India. But there is no standard procedure or formal strategy to develop the power train of an EV. This report provides a comprehensive procedure for estimating battery size, design and optimization of motor specifications, fuel consumption and emission analysis from the raw drive cycle data. Since this raw drive cycle data is collected from different parts of India and comprises of both urban and rural drive data, this report is anticipated to represent the Indian driving scenario.

2 Acknowledgement

We take the privilege to thank the institute - **Indian Institute of Technology, Guwahati** for providing us with the services that helped in completing the planned methodology for the report and its disbursal.

We would further extend our appreciation to the people who provided inputs to the variety of concepts being debated in various social media platforms. The report is an output of contributions made by individuals of varied backgrounds. **We want to thank every individual who was voluntarily involved in various phases of the report.**

3 The authors and the contributors

The **E-Mobility team from the Department of Electrical and Electronics Engineering** prepared this report on behalf of the Indian Institute of Technology Guwahati which focuses on **2-wheeler (2-W) electric drivetrain technology**. Further, the report is **an exhaustive analysis right from drive cycle raw data to the entire powertrain and battery sizing for an Electric Vehicle design**. The E-Mobility team, led by Dr.-Ing. Praveen Kumar, who is a professor in the Department of Electronics and Electrical Engineering at Indian Institute of Technology Guwahati, has been working for more than a decade to ensure swift transition to the zero-emission transportation in India. The team have gained expertise in designing, analysis, prototyping, innovation, and research on various system and subsystems of the EV ecosystem. The works in the lab is majorly funded by industry partners, a few by government agencies, and others are self funded.

The area of expertise of the electric mobility lab although not limited to are: (i) design, prototyping and development of industrial and traction motors, (ii) Loss evaluation in motors and design optimization for its reduction (iii) Design automation for electromagnetic design, (iv) electromagnetic actuators for application in vehicles, (v) intelligent EV charging infrastructure and controllers for, (vi) causes of EV battery degradation, (vii) fast charging techniques to reduce the rate of battery degradation, (viii) power electronics converters for powertrain and charging of EVs, (ix) control strategy for traction motor, (x) optimization of the powertrain to improvise efficiency, (xi) techno-commercial analysis of EV systems, (xii) electric mobility as a service, (xiii) Applications of AI/ML in electrical machine design and parameter estimation.

The lead authors of the report Sai Krsihna Mulpuri, Om Jee Singh, are PhD candidates working with Prof. Praveen Kumar in the Electric Mobility Lab and Dr. Bikash Sah, Scientific Staff in the Department of Power Electronics and Electrical Drives at the Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (IEE). The other contributors are students of the M.Tech course, batch 2020-2022 and MS (R) course in Electric Mobility, batch 2020-2022 and 2021-2023. The courses of MS (R) in Electric Mobility were developed in close collaborations and inputs from industry by Prof. Praveen Kumar.

The enthusiastic team of electric mobility lab is open to collaborative projects related to various domains of electric vehicle ecosystem from organisations worldwide.

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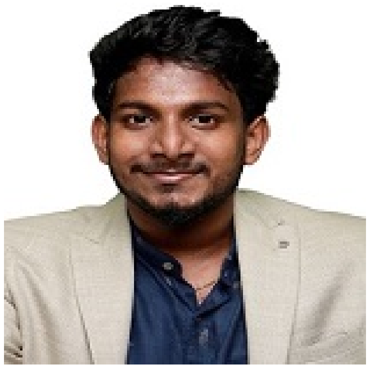

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4 Executive Summary

It's becoming apparent that we are moving towards a future where electric vehicles are becoming mainstay of transportation. The effects of IC engine vehicles on the mother earth are alarming. Also the prices of fuels used in the present time are way higher than that for EVs. The advantages of EV such as ease of recharging, reduction in noise pollution, etc. are very tempting. We need to analyze ways to bring down the cost but still make a viable product. In pursuit of this goal, from the perspective of drivetrain analysis, we at IIT Guwahati have tried to make a thorough report.

Students of the E-Mobility lab drove their internal combustion engine-powered two-wheelers in different cities for about two weeks each at other times of the day. They collected the data from each trip and analyzed the data collected by each of them to create drive cycles of their respective cities. Further detailed analysis of the respective drive cycles has been performed.

To study the performance needs of the electric two-wheelers of the future, the team did the performance analysis of the vehicles used, assuming EV powertrain in place of their internal combustion engines. We analyzed the different types of motors, ways of mounting motors, battery ratings, etc., that our electric vehicles would demand to achieve parity with our original vehicles on their respective drive cycles. Also, parameters such as presence and absence of pillion, motor optimization for acceleration figures or for normal everyday driving, etc., were kept in mind. Battery ratings thus obtained were also extrapolated to decent range targets.

Furthermore, the electric drivetrain analysis achieved similar acceleration figures, like 0-60 kmph times, as their original ICE counterparts. Also, the reduction in battery and motor ratings can be delivered if the acceleration target is kept a little lower.

Later, ways to reduce the energy requirement were studied, such as using regenerative braking, replacing the constant gear ratio to a different number, or using an intelligently controlled CVT in place. A significant part of this was done by taking efficiency maps of motors with operating points plotted on them. In addition, we also pointed out the reduction in emissions that could be achieved.

For Instance, the table below depicts the result of incorporating regenerative braking in Honda Activa for different Indian drive cycles. The table below shows the Fuel Consumption and Battery ratings with and without Regenerative braking for a Honda Activa for the case where the payload is 150 kg.

Table 4.1: Fuel consumption and battery ratings with and without regenerative braking

		Without regenerative braking		**With regenerative braking**		
Sl.	Drive cycle	Fuel consumption [kWh/km]	Battery rating [kWh/100 km]	Fuel consumption [kWh/km]	Battery rating [kWh/100 km]	Percentage reduction [%]
1	Hydearabad	0.062	6.2	0.049	4.9	21.6
2	Renukoot	0.044	4.4	0.036	3.6	18.4
3	Guwahati	0.053	5.3	0.047	4.7	10.5

The observations from these analyses look promising. The possibilities of reducing cost and increasing efficiency are available. Hopefully, these possibilities are taken and made into realties to make the future of masses electric.

5 Driving data collection

This report is based on the 2-wheeler driving pattern that the team members here at EML, Guwahati, measured in September and October. Collectively, the team drove over 1500 kms in different geographic locations of the country, including Tier 2 and Tier 3 cities, out of which over 1500 kms were driven in urban centers and over 1000 kms in rural area. Based on these driving data, varieties of real-world drive cycles were extracted. The driving data covers Karnataka, Madhya Pradesh, Punjab, Uttar Pradesh, New Delhi, Telangana, West Bengal, Bihar and Haryana.

Eventually, using these drive cycles, we estimated the motor rating (rated and peak power and torque values, base and maximum speeds), converter rating, and appropriate energy and voltage rating of the battery pack. The report also gives an insight into types of motors that can be used (hub versus frame), motor topologies (induction, permanent magnet, synchronous reluctance, permanent magnet assisted synchronous reluctance motors, etc.), and suitable converter topologies. The report also has detailed pros and con analyses of different motor and converter topologies.

5.1 Key points in driving data collection

5.1.1 Geographic locations

Geographic locations for the extractions of the drive cycles consist of rural and urban places. The list of areas used by extraction of drive cycles are listed below:

Table 5.1: Fuel consumption and battery ratings with and without regenerative braking

Geographic locations		
Urban locations		
S.no	**Place**	**State**
1	Kundapura	Karnataka
2	Zirakpur	Punjab
3	Renukoot(Dt. Sonebhadra)	Uttar Pradesh
4	Kapasaher	New Delhi
5	Hyderabad	Telangana
6	Kaithlal	Haryana
7	Guwahati	Assam
Rural locations		
S.no	**Place**	**State**
8	Khedli	Madhya pradesh
9	Izzatnagar (Dist. Bareilly)	Uttar Pradesh
10	Panskura	West Bengal
11	Kalyanpur(Dist Gopalganj)	Bihar

Figure 5.1: Geographical locations on India map

5.1.2 Geographic locations of the Drive Path

In this section the locations and path in which the vehicles were driven along with the path are given.

1. Izzatnagar: It is in district Bareilly, Uttar Pradesh. The area is a rural region. A total of 132.9 kms of distance was travelled on this track.

Figure 5.2: Geographical location - Izzatnagar

2. Kundapura: It is an urban region in Karnataka. A total of 174 kms of distance was travelled on this track.

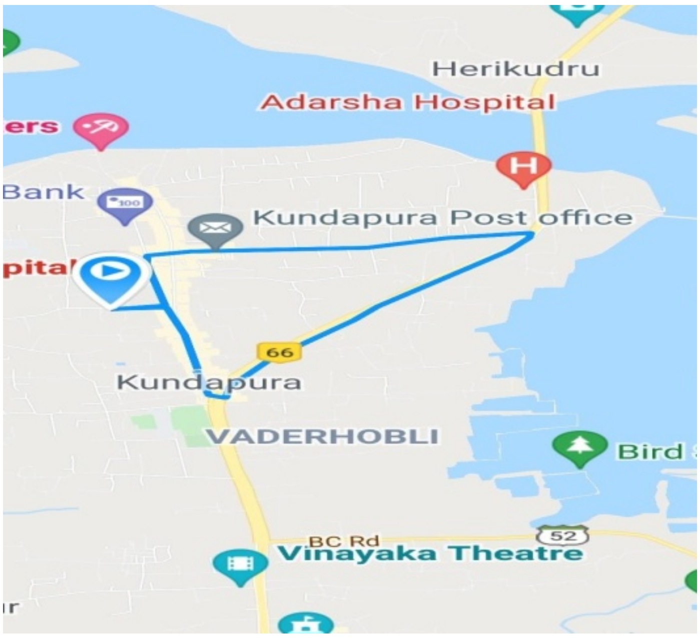


Figure 5.3: Geographical location - Kundapura

3. Panskura: The location is an urban region in West Bengal. A total of 160 km of distance was travelled on this track.

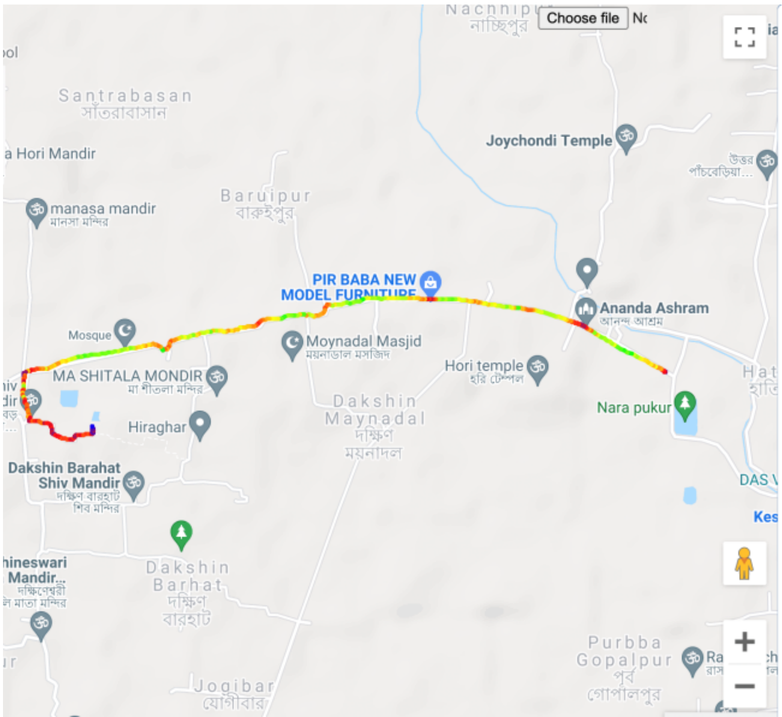


Figure 5.4: Geographical location - Panskura

4. Khedli: The location is a rural region of Madhya Pradesh. A total of 161 km of distance was travelled on this track.

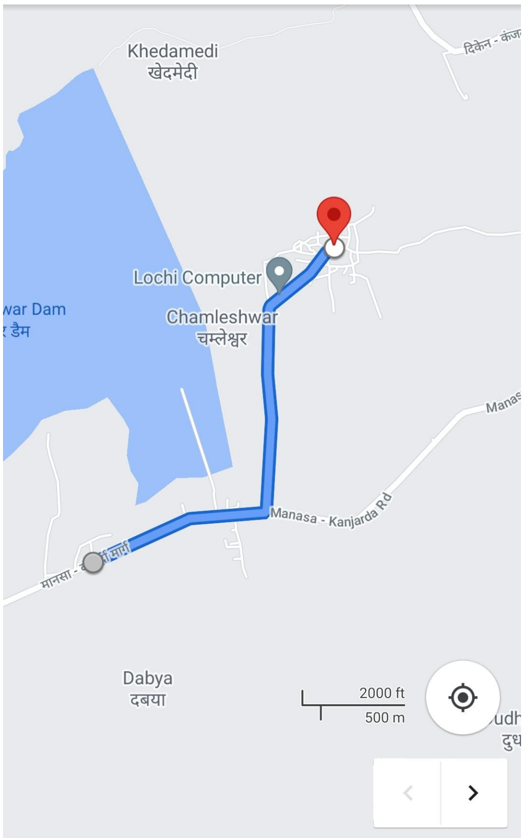


Figure 5.5: Geographical location - Khedli

5. Telangana: It is an urban region of Hyderabad. A total of 154 km of distance was travelled on this track.

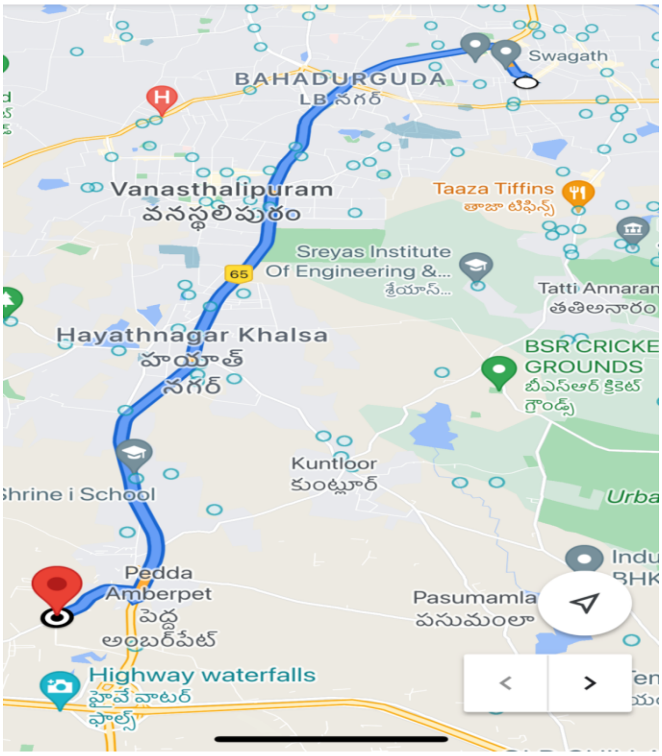


Figure 5.6: Geographical location - Telangana

6. Kapasahera: This place is an urban region located in New Delh. A total of 210 km of distance was travelled on this track.

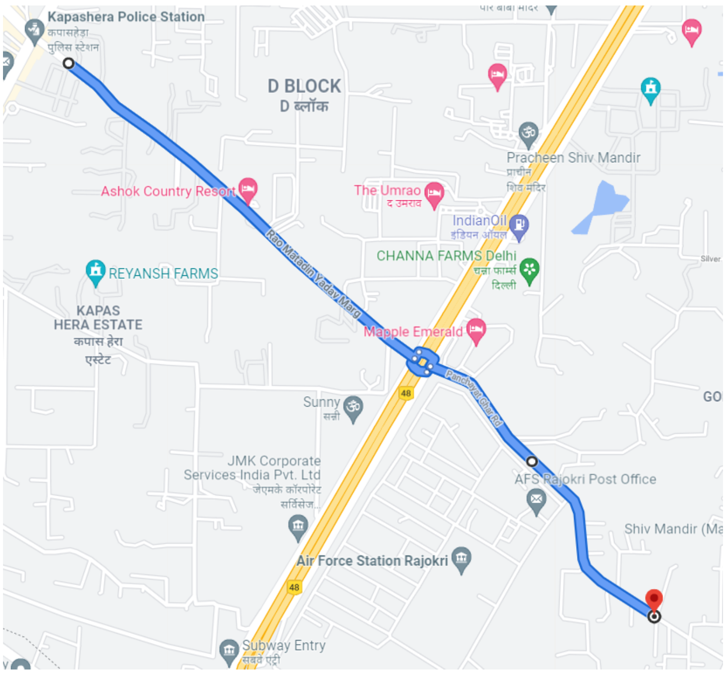


Figure 5.7: Geographical location - Kapasahera

7. Kalyanpur: It is a rural region in Gopalganj district of Bihar. A total of 93 km distance was travelled on this track.

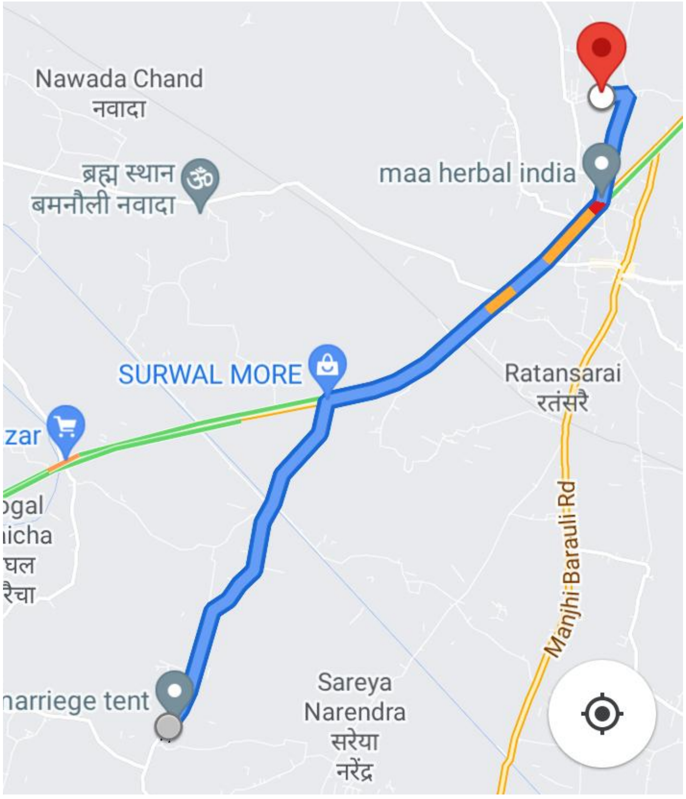


Figure 5.8: Geographical location - Kalyanpur

8. Zirakpur: This is an urban region in the Punjab. A total of 229 km distance was travelled on this track.

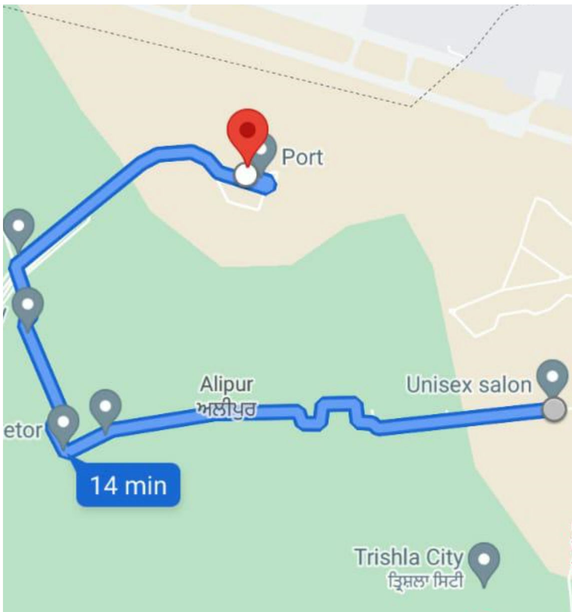


Figure 5.9: Geographical location - Zirakpur

9. Renukoot: The location is a rural region in Sonebhadra district of Uttar Pradesh. A total of 105 kms was travelled in this region.

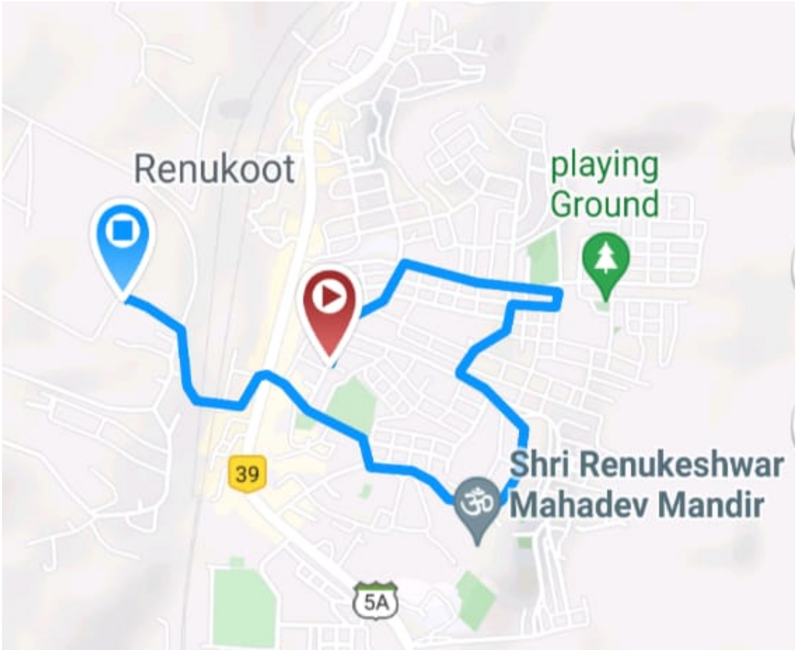


Figure 5.10: Geographical location - Renukoot

5.1.3 Vehicle details

Table 5.2: Vehicle details

Vehicle name	**Kerb weight (m) [kg]**	**Total wheel radius(r) [m]**	**Aerodynamic drag coefficient (Cd)**	**Frontal area of vehicle (Af) [m^2]**
RE Classic 350	195	0.2413	0.78	0.68
Hero Honda(Splender plus)	110	0.2	0.78	0.68
TVS star city	116	0.2	0.78	0.68
Honda Activa	110	0.175	0.78	0.68
Hero Honda CD Deluxe	112	0.2	0.78	0.68
Hero Passion Pro	118	0.2	0.78	0.68
Honda Activa	110	0.175	0.78	0.68
Honda CB Shine 125cc	114	0.2	0.78	0.68
TVS Radeon	118	0.2	0.78	0.68
Bajaj discover	120	0.2	0.78	0.68

5.1.4 Driver profiles

Table 5.3: Driver profiles

Vehicle name	Driver age	Driver gender
RE Classic 350	33	Male
Hero Honda (Splender plus)	22	Male
TVS star city	50	Male
Honda Activa	52	Male
Hero Honda CD Deluxe	23	Male
Hero Passion Pro	25	Male
Honda Activa	52	Male
Honda CB Shine 125cc	25	Male
TVS Radeon	27	Male
Bajaj discover	23	Male

5.2 Analysis of raw data

5.2.1 General description

Table 5.4: General description

Name of the city/ village	Rural/ Urban	Vehicle Name	Total Kms driven	Average speed (kmph)	Maximum speed (kmph)	Total stop durations (s)	Total trip duration (s)	Duration of the day
Kundapura (Karnatka)	Urban	RE CLASSIC 350	174	32.9	64.2	106	12398	8-11AM, 12-3PM, 6-9PM
Khedli (Madhya Pradesh)	Village	Hero Honda (splender plus)	161	23.5	51.6	1213	21808	9-11AM, 4-6PM
Zirakpur (Punjab)	Urban	TVS star city Honda	229.4	27.5	59.1	1319	30781	9-10 AM, 5-6PM
Izzatnagar (Bareilly) (Uttar Pradesh)	Village	Hero Honda CD Deluxe	132.9	15	66.5	1832	24946	6:30AM-7:15AM, 7PM-8PM
Kapasahera (New Delhi)	Urban	Hero Passion Pro	210	23.5	55.4	531	31650	3-4PM, 8PM-9PM
Hyderabad (Telangana)	Urban	Honda Activa	152	20	76.9	240	14600	8AM - 9AM
Panskura (West Bengal)	Village	Honda CB Shine 125cc	160	23.7	70	2977	24270	12-1PM, 2PM-3PM
Kalyanpur (Gopalganj Bihar)	Village	TVS Radeon	93	34.7	76	888	9631	12-1PM, 2PM-3PM

5.2.2 Total distance covered

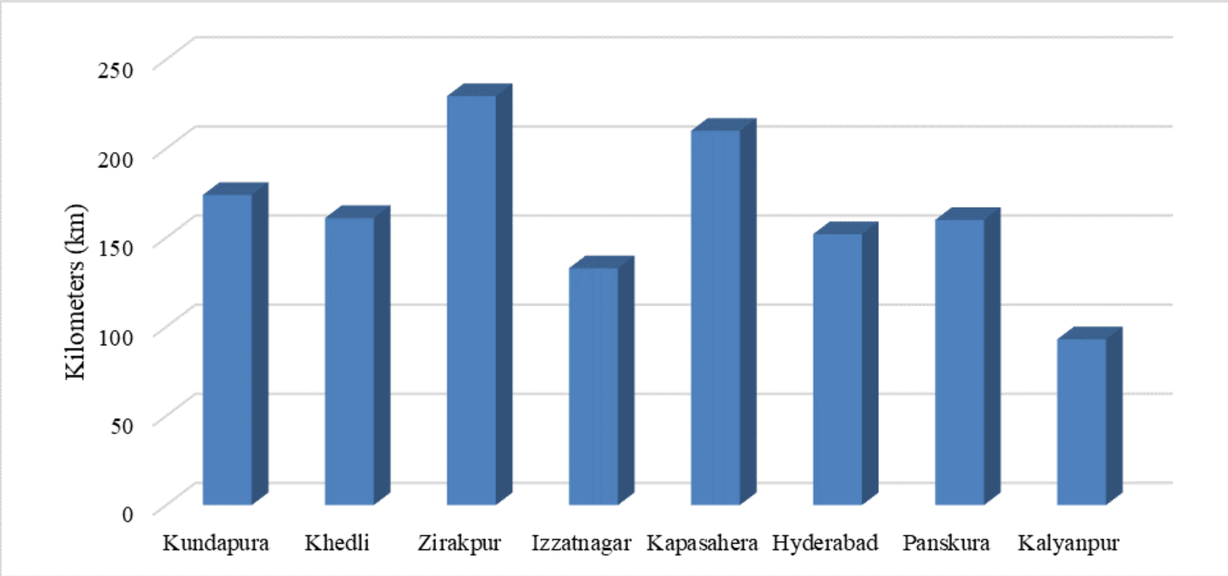


Figure 5.11: Total distance covered in various locations

5.2.3 Average speed in different locations

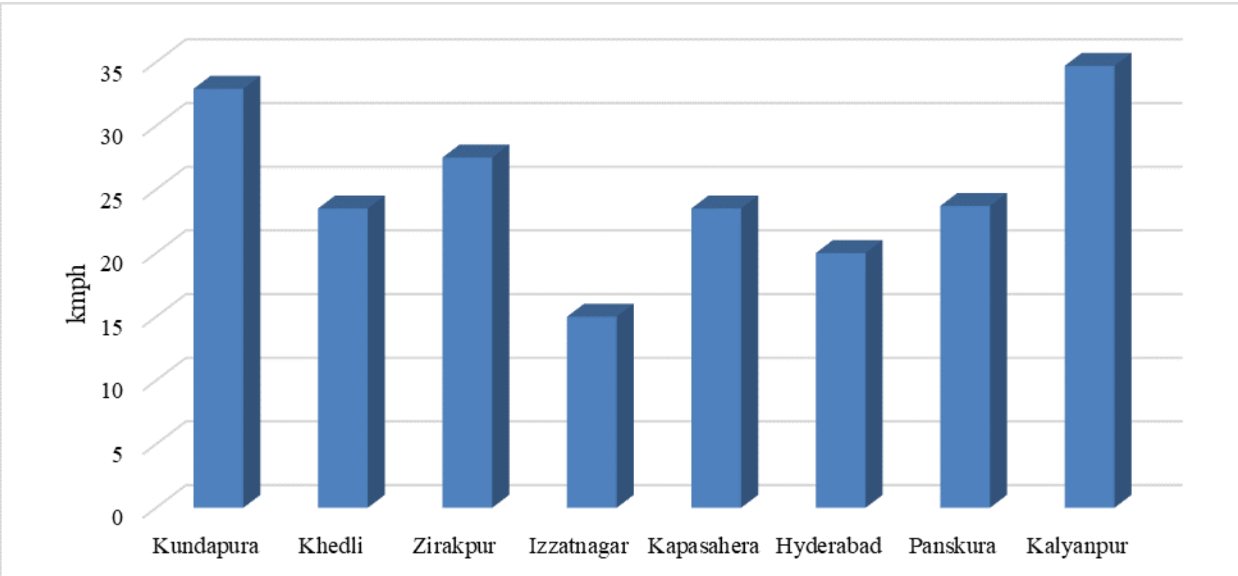


Figure 5.12: Average speed in various locations

5.2.4 Maximum speed in different locations

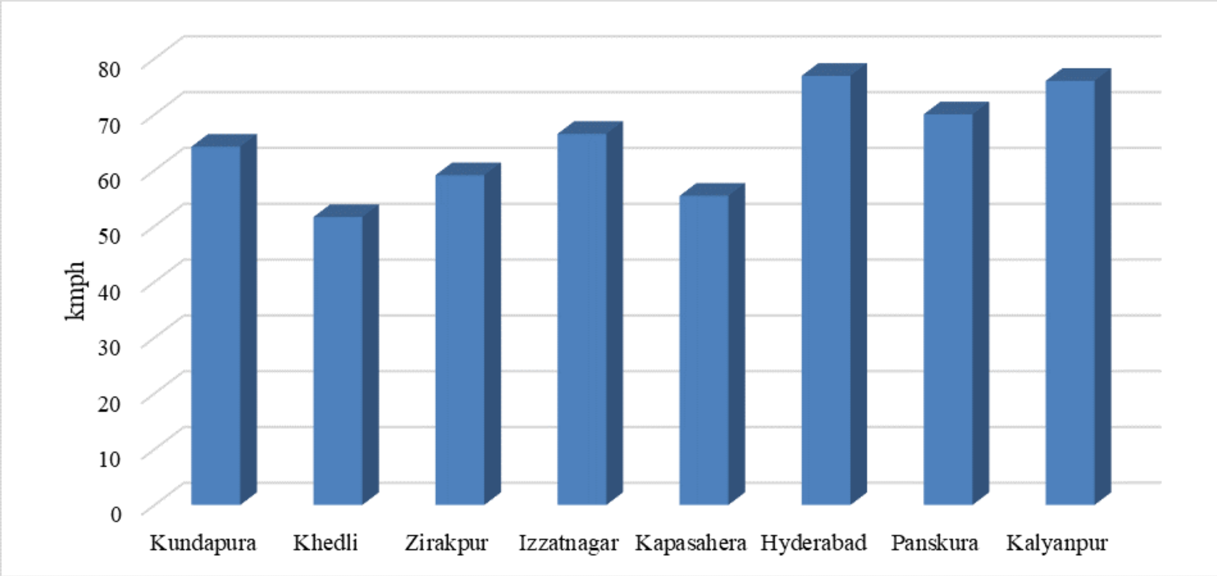


Figure 5.13: Maximum speed in various locations

5.2.5 Stop time in different locations

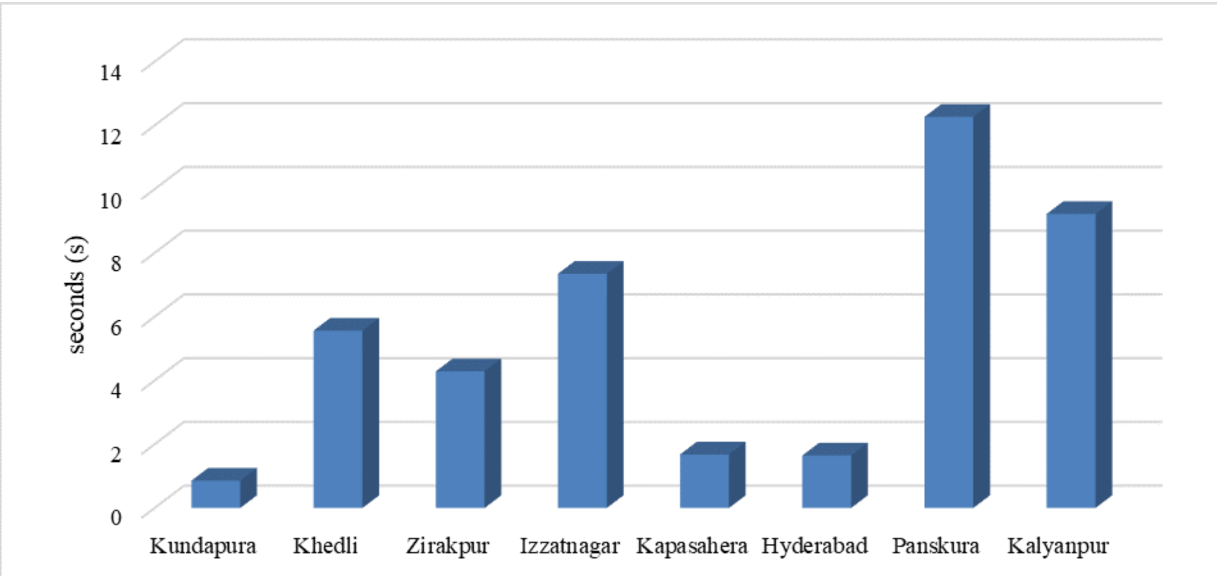


Figure 5.14: Percentage stop time for various locations

6 Drive cycle generation

6.1 General description

The formation of a drive cycle, in general, involves the following steps:

1. Gathering real-world driving data,
2. Segmenting the data/ data filtering,
3. Creating cycles,
4. Analyzing and choosing the final cycle.

Based on the type of driving activity, various drive cycle construction methodologies can be divided into four categories: micro-trip cycle construction, trip segment-based cycle construction, cycle construction based on pattern classification, and modal cycle construction.

In this study, the modal cycle construction approach is adopted, following which, the per-second speed data for the target vehicle (two-wheeler) are collected. The data collection is done in different types of roadways under different congestion levels in two/three/four differentially urbanized areas. Detailed stepwise description of the overall process is as mentioned below.

6.2 Data filtering

After the collection of data, there is a need to filter the raw data. The need is substantiated because of the following reasons:

1. Unwanted spikes in speed and acceleration data.
2. Data repetition.
3. High-frequency oscillations over measured speed.

The process of filtering is performed in MATLAB/Simulink. A filter is designed which takes the raw data and provides the processed filtered data for use in next steps.

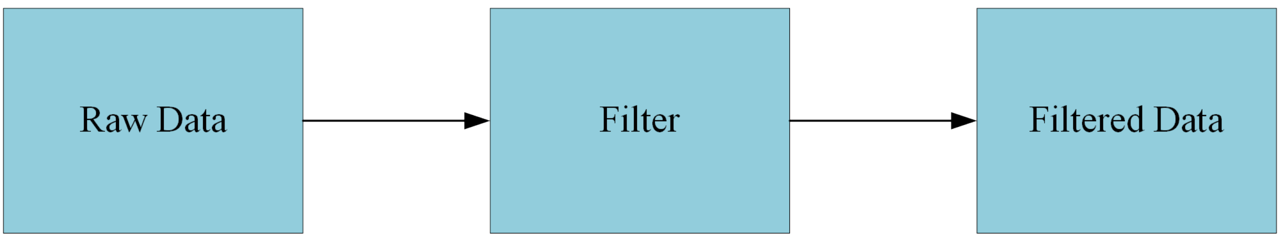


Figure 6.1: Block diagram of simulink model

The filter used is a second order Butterworth filter with a cut off frequency of 0.5Hz. The transfer function of the filter is given below:

$$H\left(s\right)=\frac{B\left(s\right)}{A\left(s\right)}=\frac{b\left(1\right)s^{n}+b\left(2\right)s^{n-1}+...+b\left(n+1\right)}{a\left(1\right)s^{n}+a\left(2\right)s^{n-1}+...+a\left(n+1\right)} \tag{6.1}$$

Steps followed:

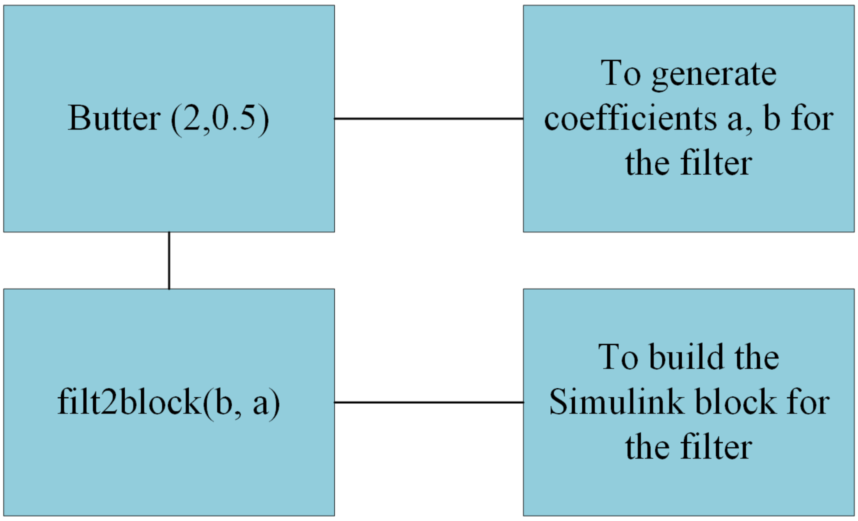


Figure 6.2: Flow chart to build the filter

Following the filtering of the raw speed time data, the formation of the drive cycle is implemented in the following steps:

1. Snippet segmentation,
2. Transition matrix estimation,
3. Cycle synthesis.

6.3 Snippet segmentation

The data was first partitioned into modal events, or "snippets," such as acceleration, deceleration, cruise, and idle modes. In the formation of a cycle, these snippets serve as an elementary cells. Each mode of the driving patterns is defined with a set of four parameters viz. a1, a2, n, and, Δ. Here, any instant or continuous observation of accelerations of more than a1 mph/s, lasting n seconds or longer, and that accumulate a speed increment of more than Δ kmph constitutes an acceleration event. Similarly, any instantaneous or continuous observation of deceleration greater than or equal to a1mph/s, lasting for n seconds or more, and with a decrease in speed greater than Δ, is defined as a deceleration event.

The snippets are further categorized into four clusters based on average speed, and we define each cluster as a class of driving patterns. This characterization of the snippets for each class is given in Table 6.1.

Table 6.1: Characterization of snippets

Mode	Time (s)	Total snippets	Average speed	Std deviation in speed	Average acceleration	Std deviation in acceleration
Class-1						
acceleration						
deceleration						
Cruise						
Class-2						
acceleration						
deceleration						
Cruise						
Class-3						
acceleration						
deceleration						
Cruise						
Class-4						
acceleration						
deceleration						
Cruise						

Hence, each particular type of roadway is partitioned into classes and states based on speed and acceleration data. The states are associated with acceleration and speed profiles, while the classes pertain solely to velocity profiles.

6.4 Generation of transition probability matrix

Classification of the snippets into driving states is described in the previous subsection. After this classification, a probability matrix including transitions between acceleration states is generated for each speed class-i by counting the number of transitions from this class-i to another classes. This state transition probability matrix, in fact, shows the probability of a state changing in a single unit of time. More elaborately, the entry P(i,j) represents the probability of being in state sj at time t(n+1), given that one is in state si at time tn.

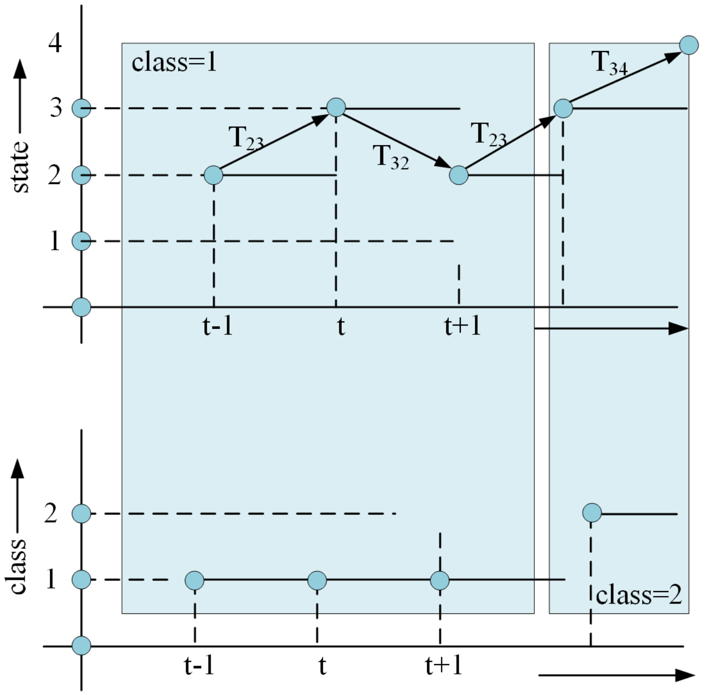


Figure 6.3: State transition probability matrix

The entries of the transition probabilities represent the Markov chain and are used to generate driving cycles. The Markov chain is a stochastic process whose future state is determined only by the current state and is unaffected by the past form. It has been frequently used to eliminate the randomness of driving cycles. A Markov chain is a discrete-time series of random variables X_k with the Markov property, which can be represented as follows:

where X_k denotes the sequence of the state. As mentioned earlier, in the formation of the drive cycle with the Markov chain, the variables selected to represent a state are velocity and, acceleration. So once the current time instant state is known, the state for the next instant is determined using the cumulative transition probabilities, which are expressed as follows:

$$\begin{aligned} P\left\{\left(X_{k+1} \in x_j\right) | X_0, X_0, ..., X_k\right\} \\ = P\left\{\left(X_{k+1} \in x_j\right) | X_k\right\} \end{aligned} \tag{6.2}$$

where, X_k denotes the sequence of the state. As mentioned earlier, in the formation of the drive cycle with the Markov chain, the variables selected to represent a state are velocity and, acceleration. So once the current time instant state is known, the state for the next instant is determined using the cumulative transition probabilities, which are expressed as follows:

$$P_{ij} = P\left\{X_{k+1} = x_j \,|X_k = x_i\right\} \tag{6.3}$$

where P_{ij} is the probability of transition from the state X_k to X_{k+1} and, it is evaluated with the following expressions:

$$P_{ij} = \frac{Q_{ij}}{\sum_j Q_{ij}} \tag{6.4}$$

where Q_{ij} is the number of transitions from state X_k to X_{k+1} in the recorded filtered data.

Since the probabilities values are time-independent, and the sum of all probabilities belonging to a specific state must adhere to the below-mentioned condition:

$$\sum_j P_{ij} = \sum_j P\left\{X_{k+1} = x_j \,|X_k = x_i\right\} = 1 \tag{6.5}$$

6.5 Synthesis of the driving cycle

A driving cycle is constructed using the Monte Carlo method when each kinematic segment dataset's TPM is transformed into a vector for each row. Equation (4) must be satisfied for each row vector. Afterward, the collective summation for each row is calculated, and each element of this modified TPM is characterized by a new row vector whose values start from zero and end with unity.

The Monte Carlo method is used to generate random numbers in the interval of [0, 1] repeatedly. The nth state bin is calculated for the transition of the next state, and the velocity is picked randomly from the associated state bin to synthesize a velocity profile when the random number (μ) falls in an interval that meets equation (6.6).

$$\sum_{j=1}^{n-1} P_{ij} < \mu \leq \sum_{j=1}^{n} P_{ij} \tag{6.6}$$

where n is the number of state bins that each kinematic segment dataset determines. Figure 6.4 shows the procedural steps of the cycle synthesis.

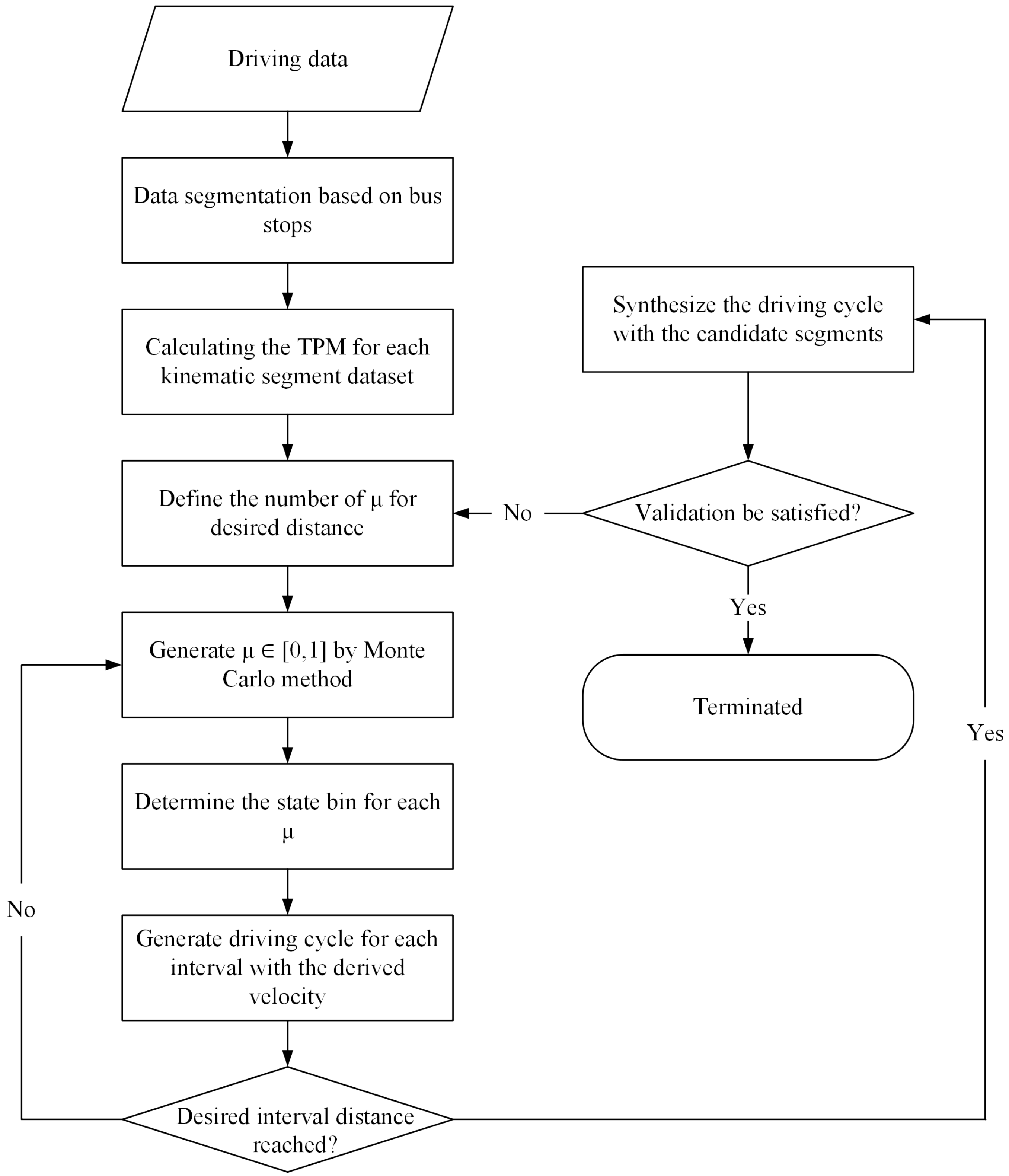


Figure 6.4: Steps involved in drive cycle synthesis

6.6 Drive cycles generated

Using mode based cycle construction method, we generated 11 drive cycles, as shown in the table below. Since our data is taken from different types of vehicles and also from diverse parts of the country in Urban and Rural areas, these drive cycles are expected to illustrate the Indian driving scenario.

Table 6.2: Drive cycles generated

Drive cycles generated		
Urban locations		
S.No.	**Place**	**State**
1	Kundapura	Karnataka
2	Zirakpur	Punjab
3	Renukoot(Dt. Sonebhadra)	Uttar Pradesh
4	Kapasaher	New Delhi
5	Hyderabad	Telangana
6	Kaithlal	Haryana
7	Guwahati	Assam
Rural locations		
S.No.	**Place**	**State**
8	Khedli	Madhya Pradesh
9	Izzatnagar (Dist. Bareilly)	Uttar Pradesh
10	Panskura	West Bengal
11	Kalyanpur(Dist Gopalganj)	Bihar

7 Analysis of drive cycles

Drive Cycles describe the workloads imposed on the vehicles. Therefore, they have been used to assess the environmental impact of traffic and optimize new vehicles' powertrain configurations and engine control strategies to reduce fuel consumption[4]. A drive cycle [1] provides a concise, repeatable sequence of vehicle input operations over some time. A typical drive cycle consists of second-by-second values of speed and elevation, though time-based information on the process of other systems is sometimes included.

7.1 Drive cycle metrics

Drive cycles are most valuable when they are representative of how a vehicle will operate in a target application. The energy equation will form the basis for discussing the drive cycle. The tractive power required to move a vehicle over a roadway surface is the summation of the power needed to overcome aerodynamic drag, rolling resistance, vehicle inertia, and gravitational potential energy [1]. In order to evaluate the drive cycle, the following metrics are to be discussed.

Positive Kinetic Energy (PKE) is defined as the sum of the differences between the squares of the final and initial speeds in successive acceleration, divided by total trip distance D, where the speed v is expressed in meters per second.

7.1.1 Kinetic intensity

The kinetic intensity metric reflects the nature of energy consumption along a given drive cycle. A sizeable kinetic intensity value corresponds to drive cycles where the energy consumed is more strongly influenced by vehicle acceleration than driving speed. Similarly, a small kinetic intensity value corresponds to drive cycles where vehicle speed dominates acceleration concerning energy consumption. Lower average speeds and higher kinetic intensity and stops per mile indicate a duty cycle with more aggressive transient conditions typical of a heavy traffic urban environment and typically gets lower fuel economy than duty cycles with higher average speeds and lower kinetic intensity and stops per mile [2].

7.1.2 Average running time

It is defined as the average drive cycle time considered over several sample drive cycles.

7.1.3 Average acceleration

Average acceleration refers to the rate at which the velocity changes. We divide the change in velocity by an elapsed time to determine the average acceleration. In a similar speed range, acceleration distance and acceleration time of vehicles with lower acceleration capability is higher than other vehicle types with higher acceleration capability [5].

7.1.4 Average deceleration

Deceleration is the opposite of acceleration. It is the rate at which an object slows down. Deceleration is the final velocity minus the initial velocity, which is negative because the velocity is dropping.

7.1.5 Average speed

Average speed is the average speed over the entire time a vehicle engine is on. It is commonly used to describe transit routes, while average running speed does not consider zero speed time and is more indicative of the intensity of a duty cycle [2]. Average speed and average running speed imply the overall road condition and length of time for a journey, which should be similar or identical if any given expressway [3] is free of congestion.

7.1.6 Average stop duration

It is the ratio of the total period of the drive cycle duration in which the vehicle was at zero speed to the entire duration of the drive cycle. Higher stop duration implies higher traffic density, usually in urban drive cycles.

7.2 Kinetic intensity analysis

This section discusses the energy consumption and nature of driving by the four different categories of bikes considered, i.e., retro bike, sports bike, mid-range bike, and commute scooter, by analyzing the drive cycle data developed. A total of ten different two-wheelers were driven in rural and urban areas. Royal Enfield Classic 350 is categorized as Retro bike; Honda CB shine, TVS Radeon and Bajaj Discover classified under Sports bike category; Splendor plus, CD Delux and Passion pro models by Hero Honda and TVS Star City were categorized as mid-range bikes and two Honda Activa as commute scooter category. For all ten bikes, graphs of kinetic intensity, average speed, stop time per kilometer, and average acceleration was plotted in figures 7.1 to 7.4 to analyze the energy consumption and nature of the drive cycle. These plots are colored as brown for retro bikes, green for sportbikes, blue for mid-range bikes, and yellow for scooters for our easy understanding.

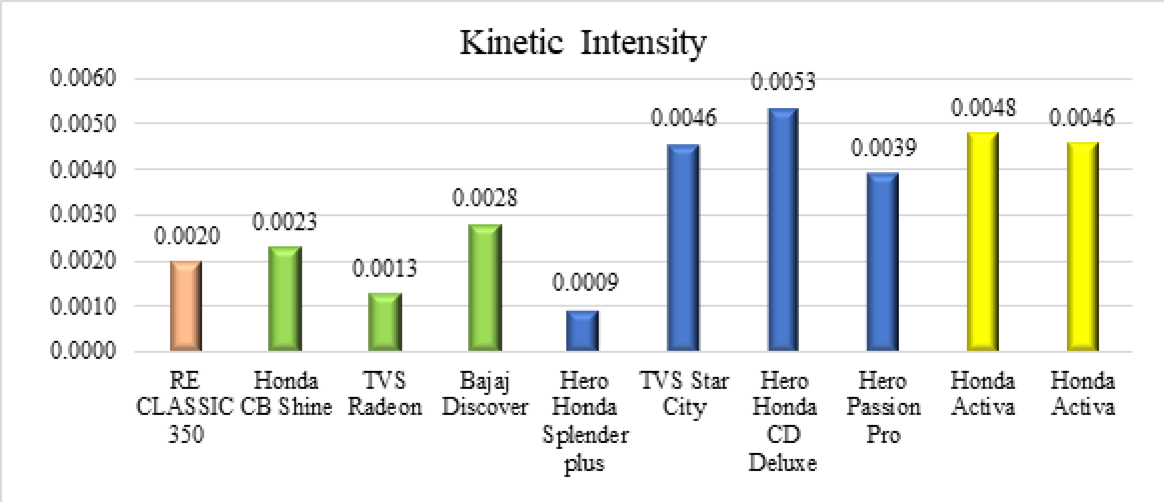


Figure 7.1: Kinetic intensity in per meter

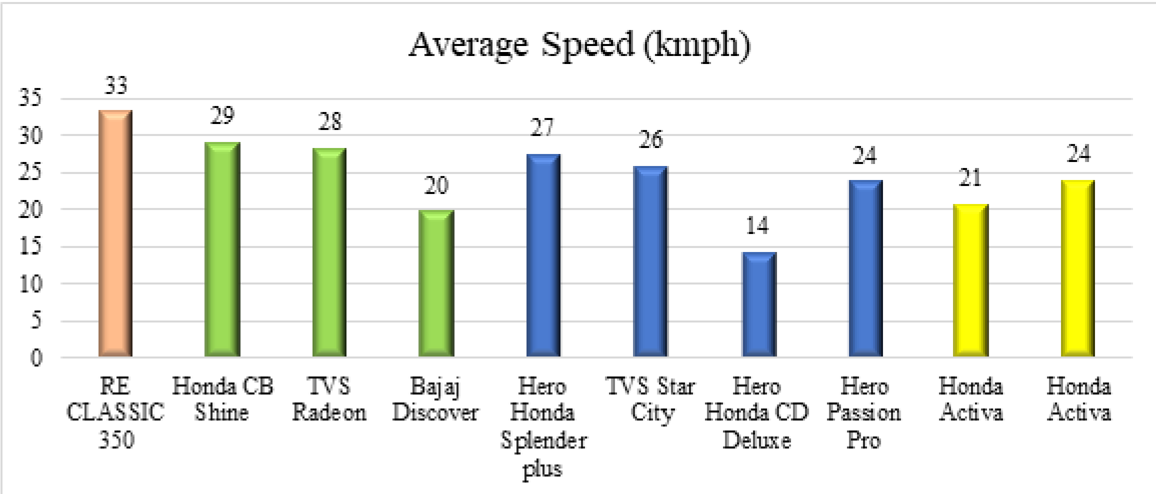


Figure 7.2: Average speed in kmph

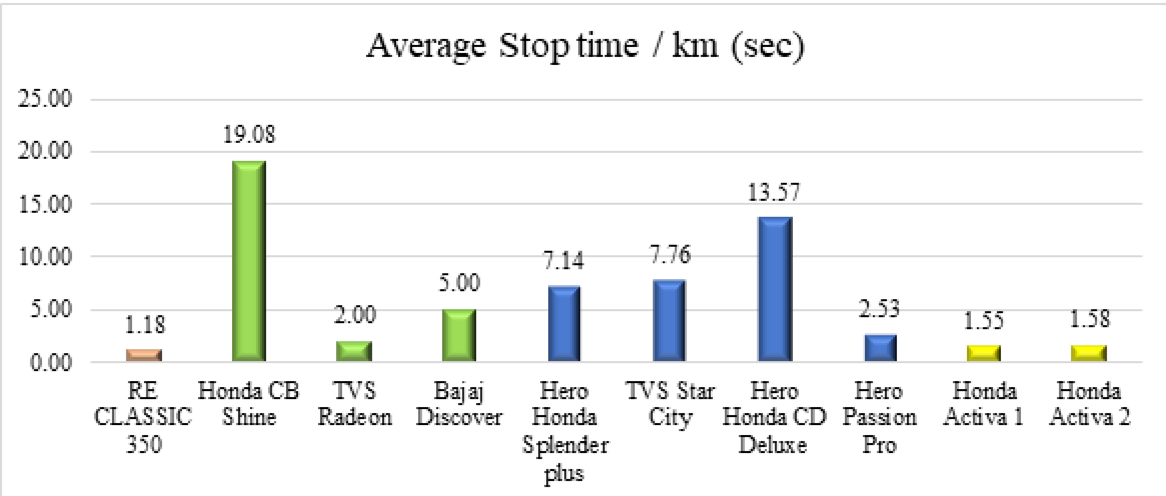


Figure 7.3: Average stop time per kilometer in seconds

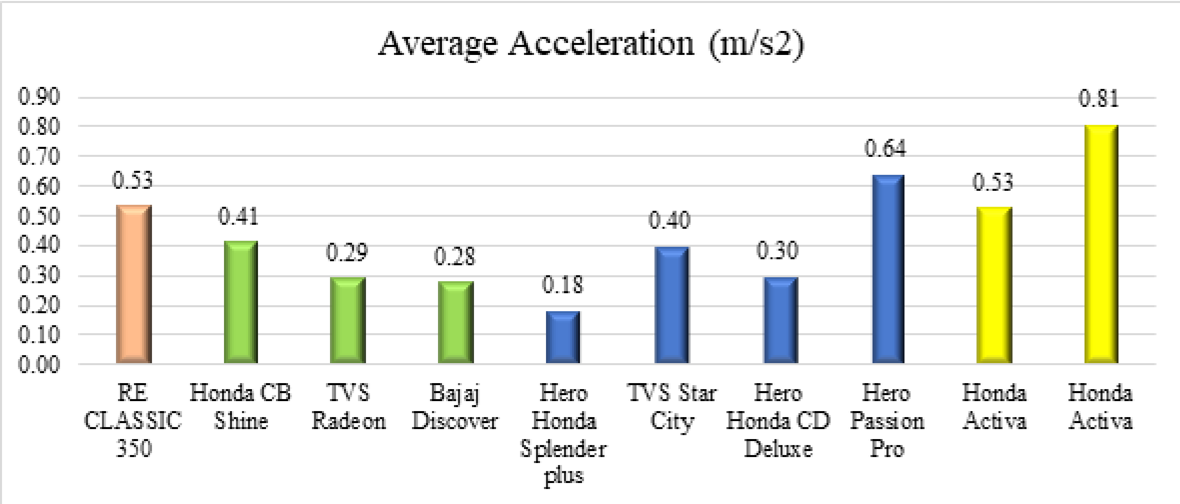


Figure 7.4: Average acceleration in meter per square seconds

7.2.1 Retro bikes

Royal Enfield classic 350, which has a fairly higher average speed than other bike categories and lower kinetic intensity and stop time per kilometer, is considered in this category. This infers that the fuel efficiency of the bike is higher. Also, though the motorcycle was driven in an urban environment, the drive cycle depicts lower traffic density.

7.2.2 Sport bikes

In this category, we have three bikes where Hero Honda CB Shine and TVS Radeon were driven in a rural environment and Bajaj Discover in an urban setting.

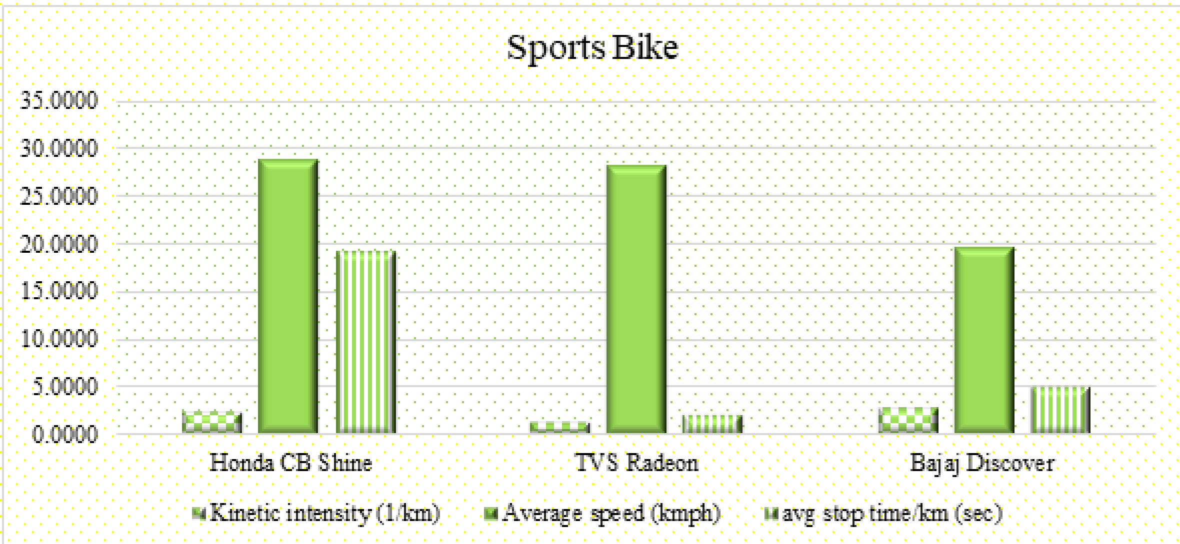


Figure 7.5: Comparison of kinetic intensity, average speed and average stop time per kilometer among sport bikes

From the above graph in figure 7.5, it is observed that, though both Honda CB Shine and TVS Radeon have similar average speed, Honda CB Shine showed a higher kinetic intensity and average stop time, which infers that traffic condition was higher or road condition was poor compared to TVS Radeon drive cycle. So, the fuel efficiency of Honda CB shine is lower than TVS Radeon. But when both bikes' drive cycles are compared to Bajaj Discover's drive cycle, which was driven in an urban environment the higher value of kinetic intensity with reduced average speed and increased average stop time per kilometer depicts the aggressive urban traffic results in reduced fuel efficiency.

7.2.3 Mid-range bikes

The mid-range bike category considered four bikes, with two each in the rural and urban environment. Splender Plus and CD Delux of Hero Honda have drive cycles under rural settings, and TVS Star City and Hero Passion Pro have drive cycles under urban environments. Their Kinetic Intensity, Average Speed, and Average Stop time per kilometer are plotted in a graph given below in figure 7.6.

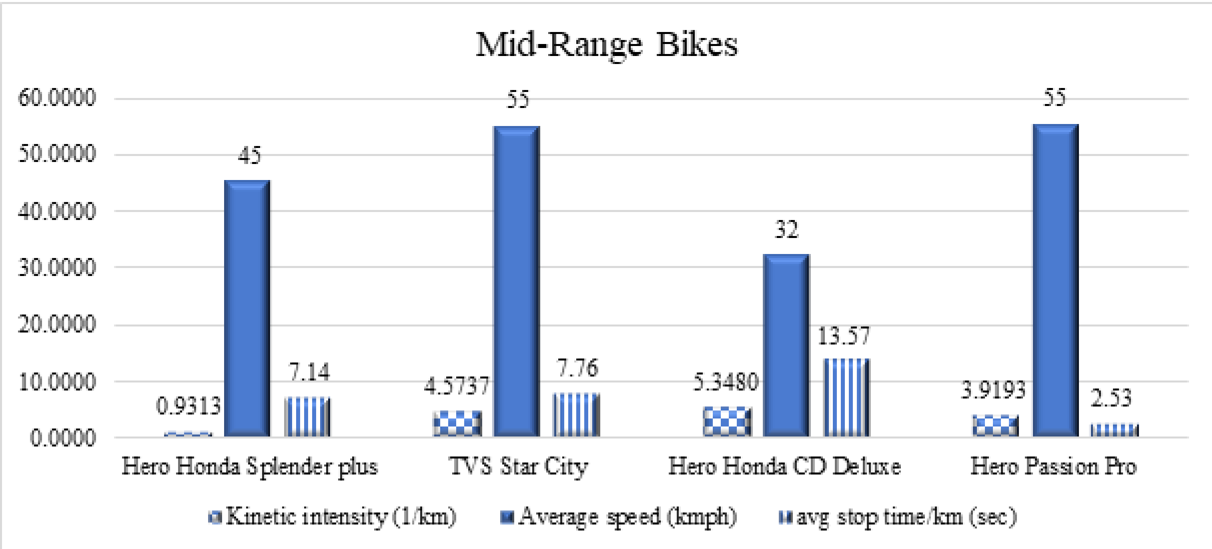


Figure 7.6: Comparison of kinetic intensity, average speed and average stop time per kilometer among mid-range bikes

Among the urban drive cycles, both Star City and Passion have similar average speed and kinetic intensity, more or less in a similar range, but the higher average stop time value of Star city depicts the aggressive urban traffic, which infers that the fuel efficiency of Passion pro is better. Comparing the rural drive cycles of Splender plus and CD Delux, Splender plus has better fuel efficiency.

7.2.4 Commute scooters

Under the Commute scooters category, we have considered two scooters, where both of them are Honda Activa gearless and were driven in the urban environment. Their kinetic intensity, average speed, and average stop time per kilometer are plotted in a graph given below in figure 7.7.

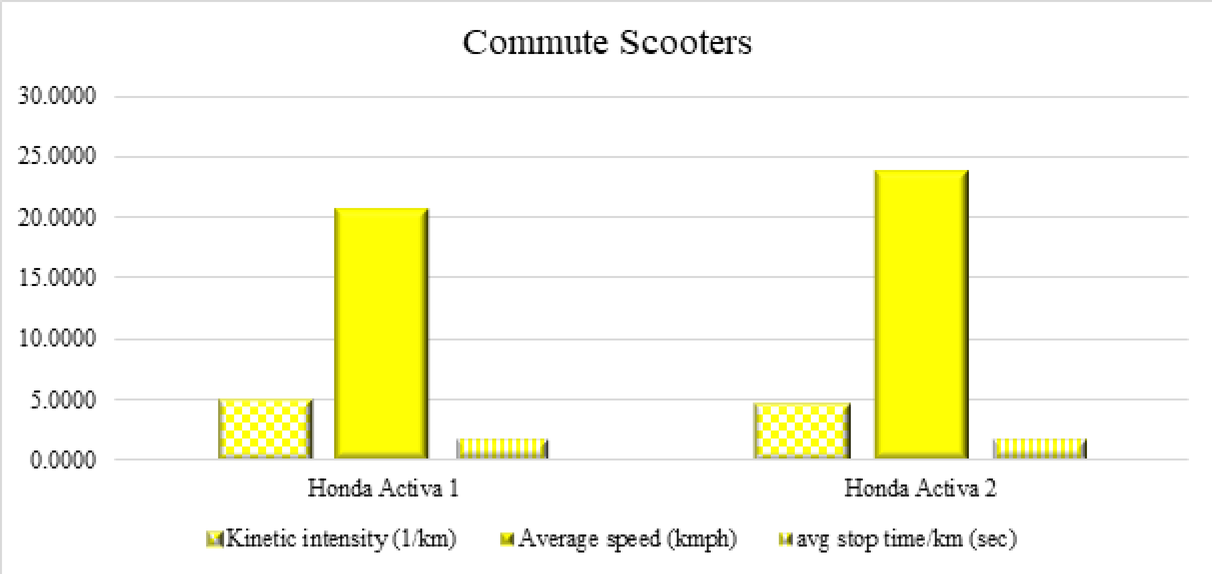


Figure 7.7: Comparison of kinetic intensity, average speed and average stop time per kilometer among commute scooters

Observing their drive cycle characteristics, having similar average speed range for both scooters with higher value of kinetic intensity and comparatively lower average speed, it can be said that the drive cycle is of the urban environment, and it is expected to have a low fuel economy. But contradictorily, it will have a better fuel economy than other bike categories with a low stop time per kilometer.

7.3 Speed and acceleration analysis

7.3.1 Maximum speed

It is the largest possible rate at which the vehicle was driven. In a drive cycle, the driver need not have attained the maximum possible speed of the vehicle. Instead, it is the maximum speed attained by a driver in the given road condition and environment. Achieving top speed varies with the vehicle type and drive [5].

7.3.2 Maximum acceleration

Maximum acceleration is the most significant possible change in velocity over the shortest period. The maximum acceleration depends on the traffic condition, vehicle type, top speed, and road type in a drive cycle.

7.3.3 Percentage of time spent in acceleration, deceleration, and idle mode

It is the total amount of time where a vehicle had a positive rate of velocity change called acceleration, a negative rate of velocity change called deceleration, and zero rates of velocity change called idle mode over the total duration of the drive cycle.

A plot of percentage time of acceleration, deceleration, and idle mode is shown below in figure 7.8. Higher acceleration and lower deceleration show that the nature of the drive cycle is of less traffic density. Higher time on idle mode infers that the traffic density is more. Maximum acceleration is also dependent on the top speed of the vehicle. Also, the deceleration time varies with vehicle type, driver, and speed at which driver starts decelerating [5]. Here the average speed curve along with percentage time on different modes of operation has been plotted.

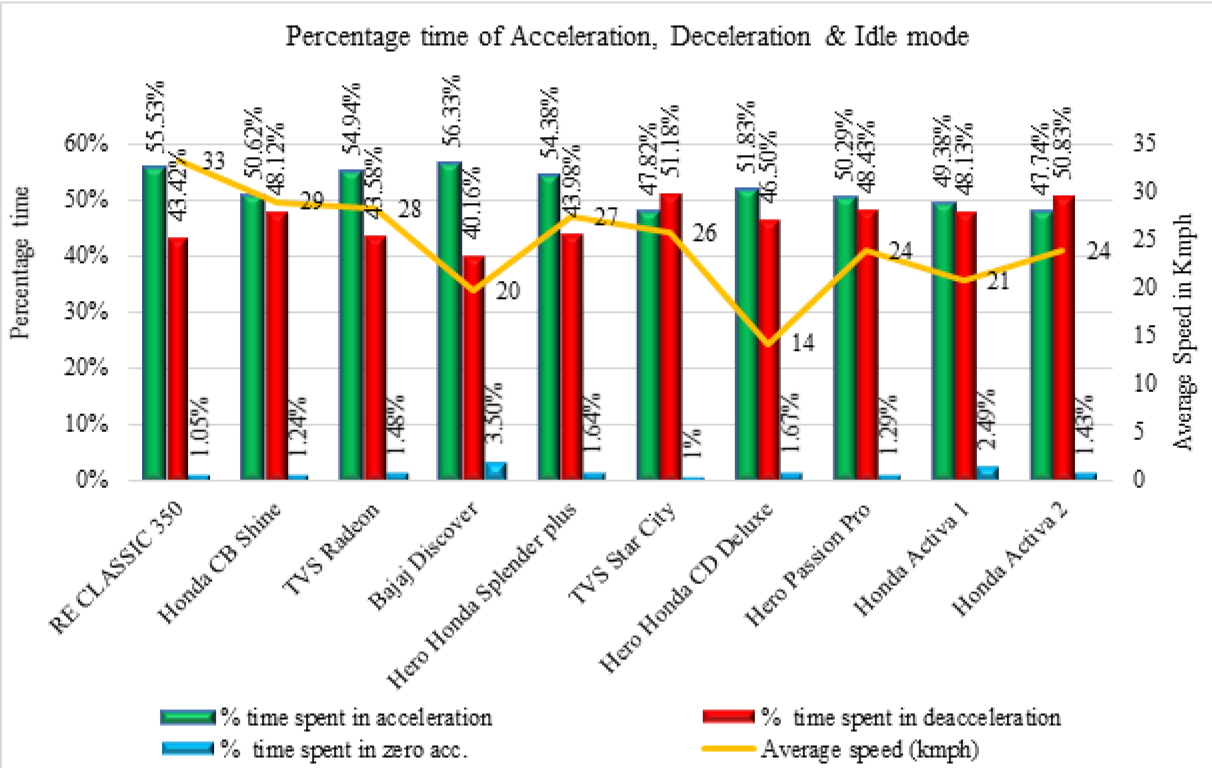


Figure 7.8: Plot of the percentage of acceleration-deceleration and idle mode.

It can be observed from the above graph that, Retro bike RE Classic 350 has a higher average speed and higher acceleration, and lower deceleration compared to other bikes. Though it was driven in urban limits, a lower percentage of time in idle mode depicts low traffic density. In the sports bike category, it is evident that Honda shine and TVS Radeon have similar acceleration and deceleration patterns with approximately the same idle mode time and average speed driven in a rural environment. Whereas Bajaj Discover, another sports bike, has a lower average rate and higher idle mode time, it is driven in the urban environment.

In contradiction, Hero Honda CD Delux has a lower average speed under the mid-range segment, even if driven in rural. It is found that TVS Star City, which is driven in the city, has a lower acceleration and higher deceleration which infers that traffic intensity is very high. Both bikes go cycles depict the city or urban environment driving conditions coming to commute segment bikes. However, with the above inferences, we can say that acceleration and deceleration patterns depend not on the traffic environment but also on the type of road and driving styles.

8 Motor performance analysis

8.1 Motor's rated and peak torque vs. speed characteristics

This section elucidates a scenario when the frame and hub motors replace conventional internal combustion engines in two-wheelers. Motors with higher power ratings enable higher speed, whereas higher torque ensures higher acceleration. The rate at which peak torque is achievable is also essential. Since acceleration is determined by torque, a motor that achieves peak torque at higher speed demands propelled at a higher speed to attain higher acceleration. An ideal drive cycle should possess a good combination of sufficient speed, power, and torque.

The speed-torque characteristics and motors' power rating requirements for various categories of two-wheelers, i.e., sports bikes, retro bikes, commute scooters, and mid-range bikes, will be discussed below.

8.1.1 Sports bikes:

The torque-speed characteristics and motor characteristics derived from the drive cycle analysis of two sports bikes, Honda CB Shine and Bajaj Discover, are discussed in the following sections.

8.1.1.1 Honda CB Shine:

Figure 8.1 and figure 8.3 represent the torque-speed characteristics of a frame and hub motor derived from the drive cycle of a Honda CB Shine. It is observed that the torque of a hub motor (108 Nm) is significantly higher than that of a frame motor (27 Nm). From Figure 8.2, Figure 8.4, and Figure 8.6, it is seen that the rated and peak power of the hub motor are 3.62 kW and 6.51 kW, respectively, whereas that of the frame motor is 4.07 kW and 7.33 kW.

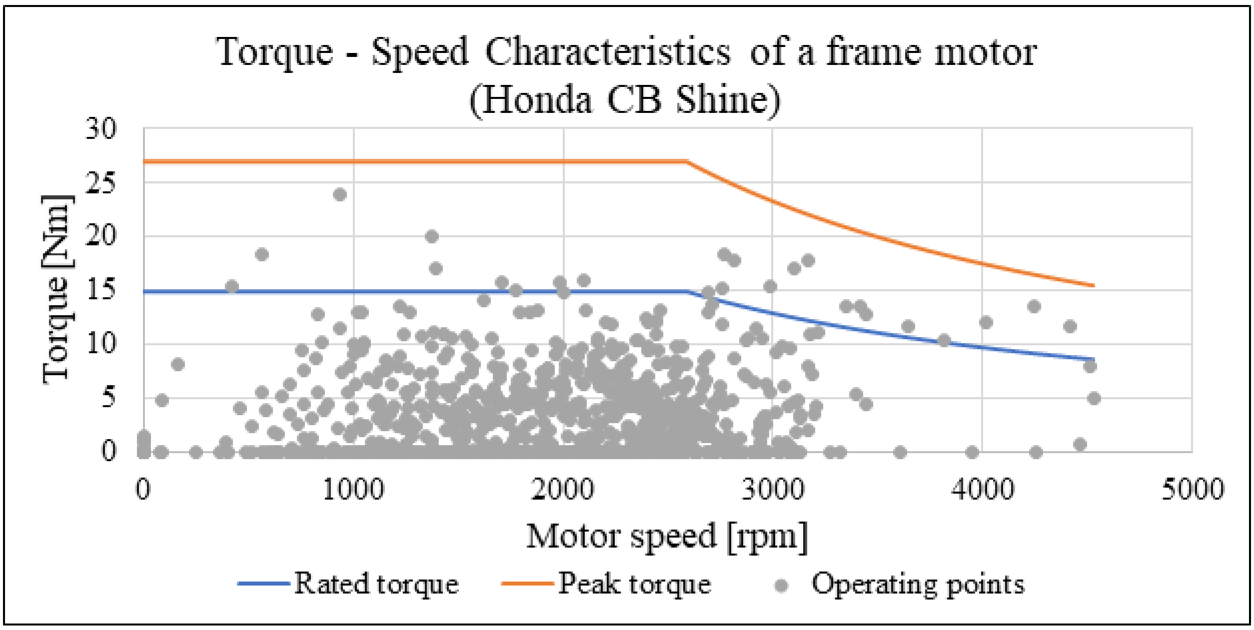


Figure 8.1: Torque - speed characteristics of a frame motor derived from the drive cycle analysis of Honda CB Shine drive cycle

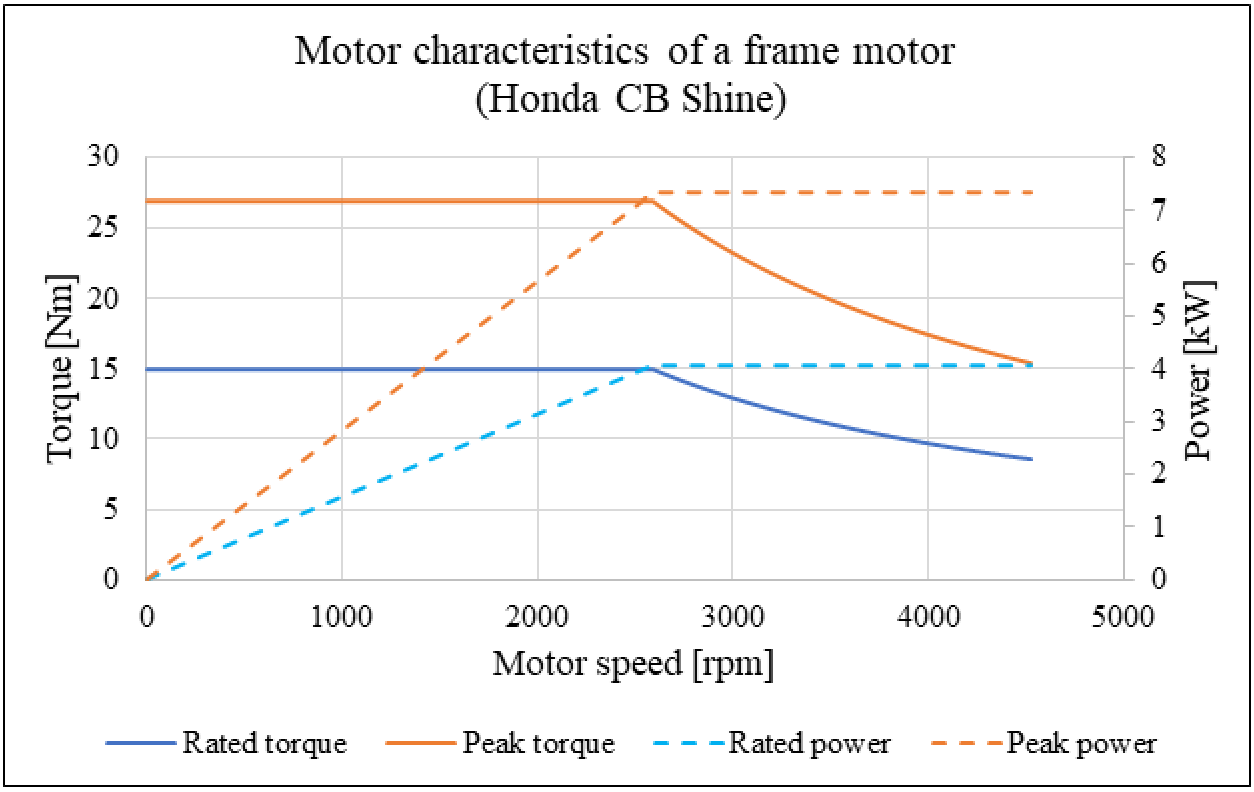


Figure 8.2: Motor characteristics of a frame motor derived from the drive cycle analysis of Honda CB Shine drive cycle

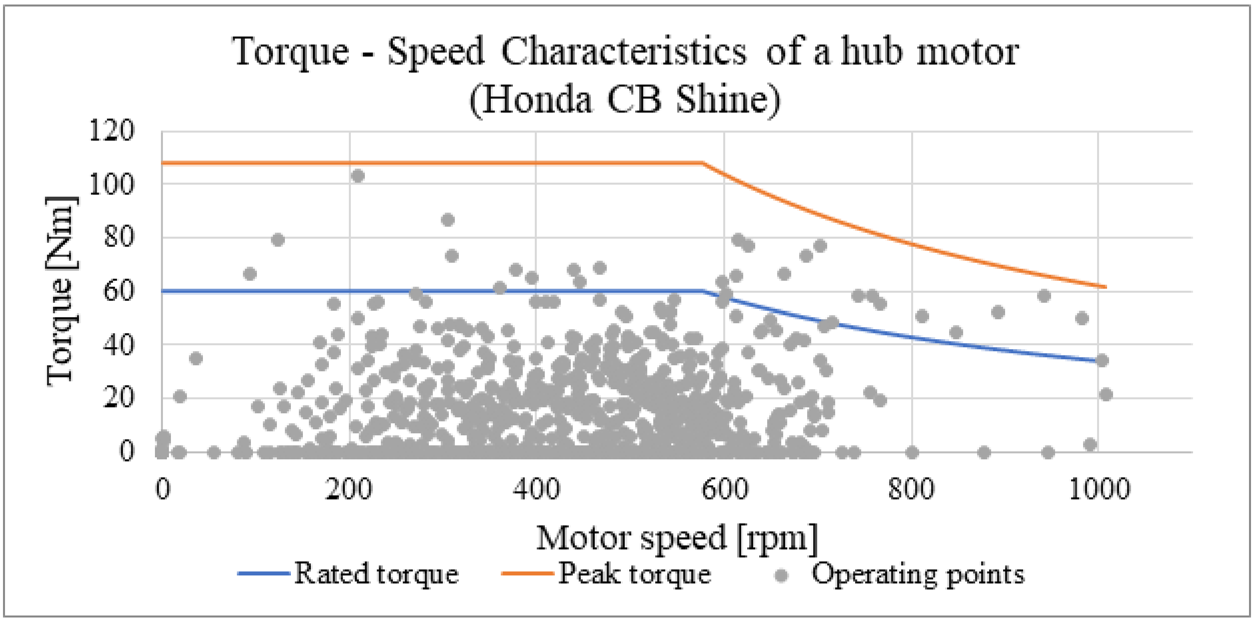


Figure 8.3: Torque - speed characteristics of a hub motor derived from the drive cycle analysis of Honda CB Shine

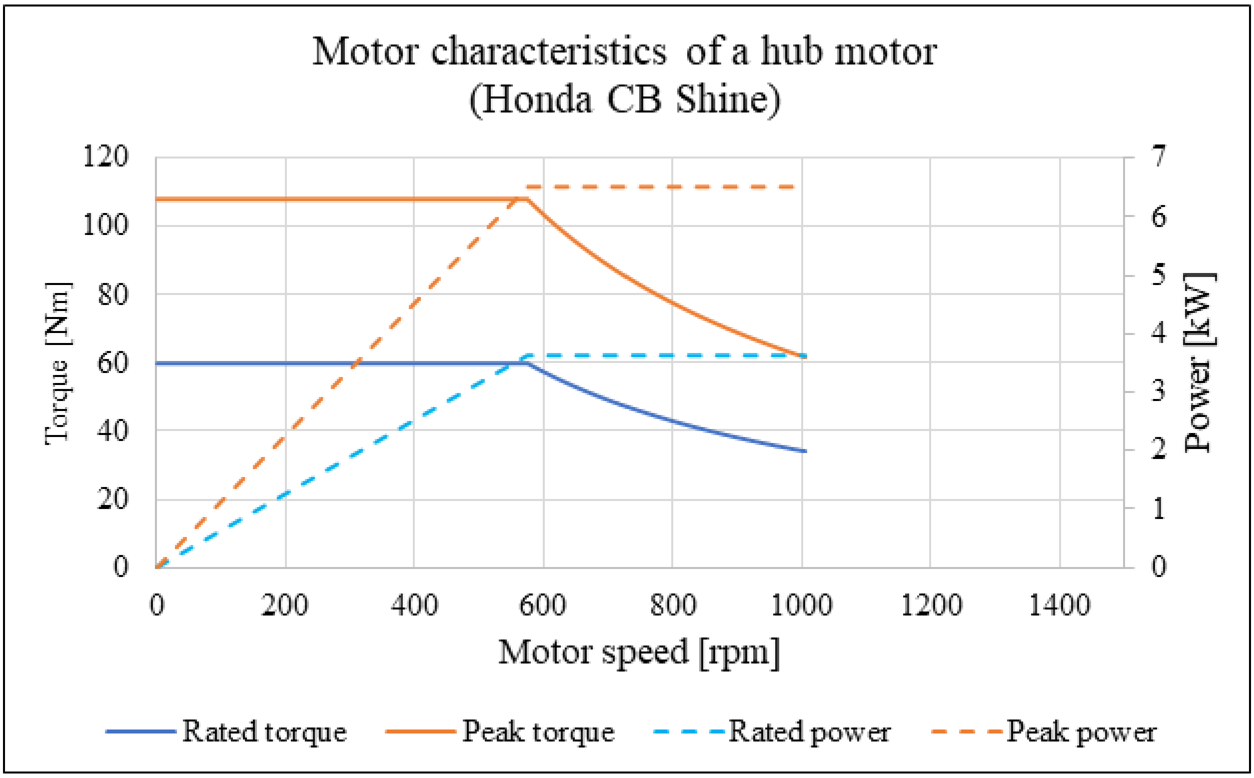


Figure 8.4: Motor characteristics of a hub motor derived from the drive cycle analysis of Honda CB Shine

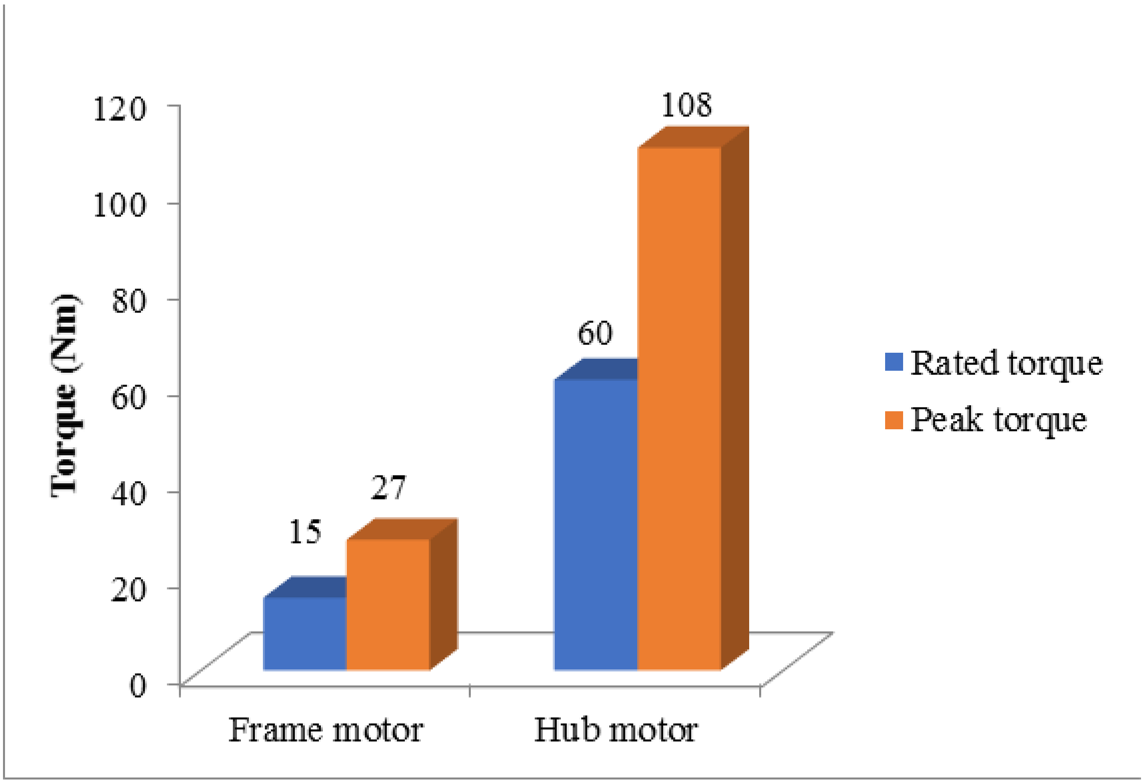


Figure 8.5: Torque ratings of frame and hub motors derived from the drive cycle analysis of a Honda CB Shine

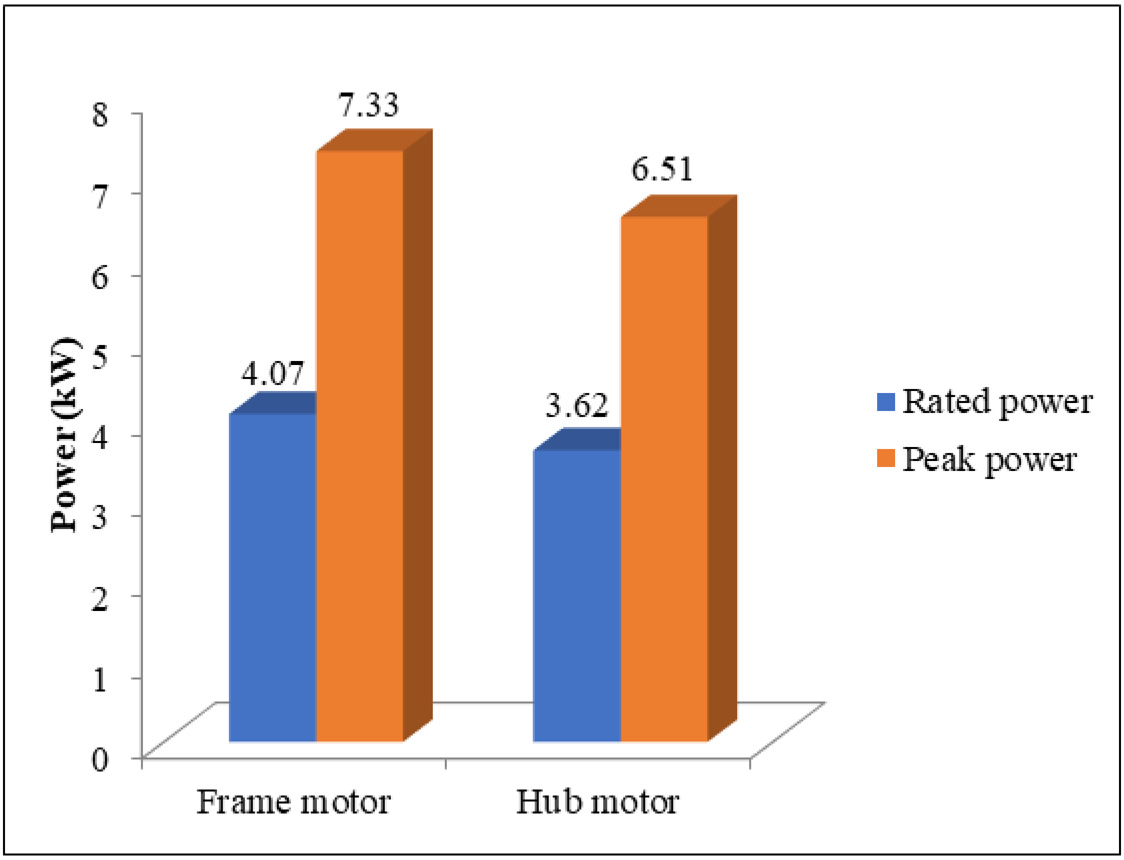


Figure 8.6: Power ratings of frame and hub motors derived from the drive cycle analysis of for a Honda CB Shine

8.1.1.2 Bajaj Discover:

The low speed, high torque, and low power characteristics of hub motors are observed in the torque-speed, and motor characteristics are derived from the drive cycle analysis of Bajaj discover. The peak torque and peak power ratings of the hub motor are 100.8 Nm and 3.67 kW, respectively, whereas frame motors are 23.4 Nm and 3.84 kW, as seen in Figure 8.11 and Figure 8.12.

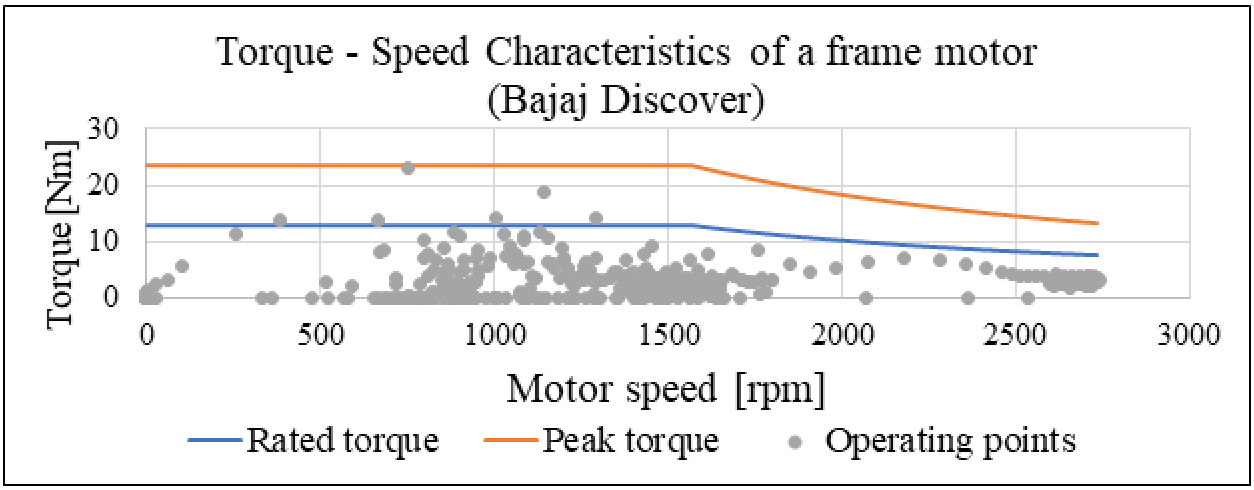


Figure 8.7: Torque speed characteristics of a frame motor derived from the drive cycle analysis of a Bajaj Discover

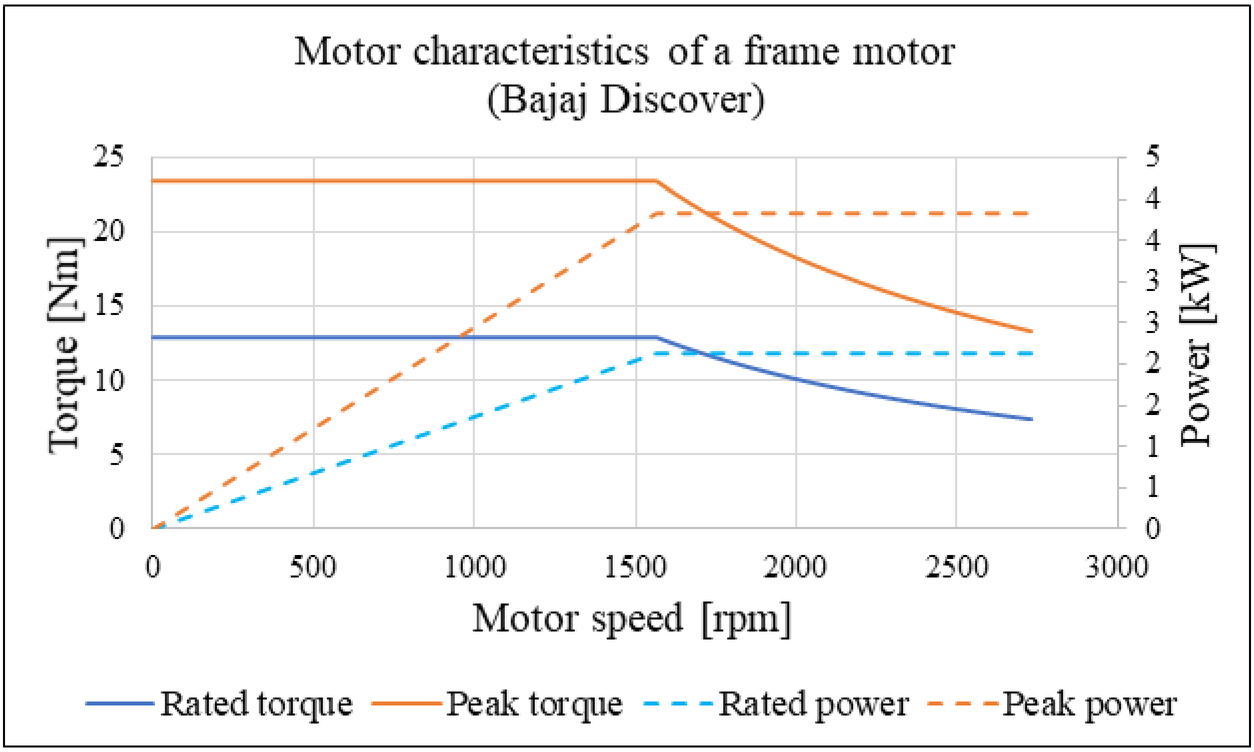


Figure 8.8: Motor characteristics of a frame motor derived from the drive cycle analysis of a Bajaj Discover

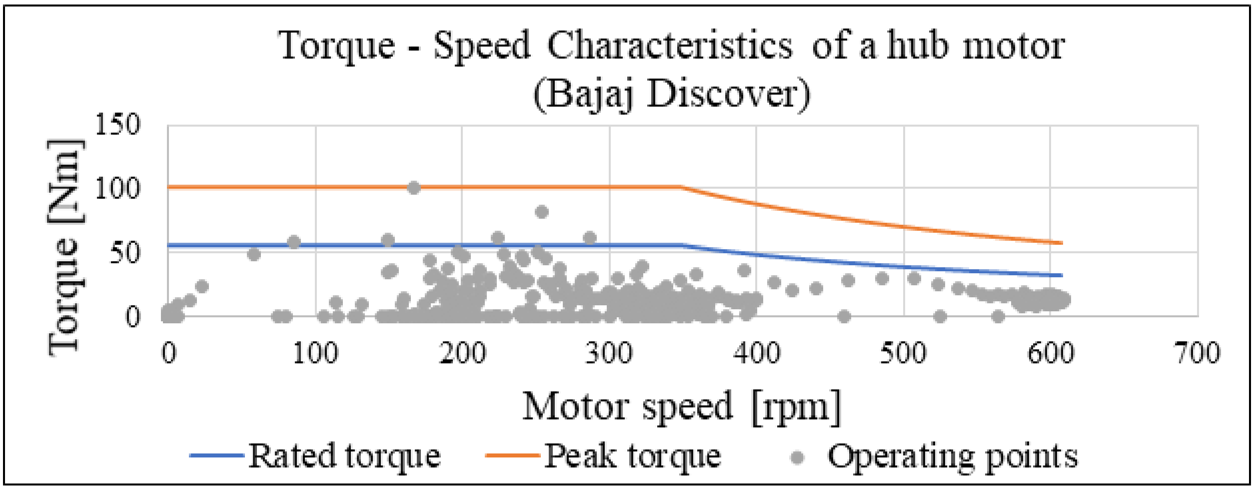


Figure 8.9: Torque speed characteristics of a hub motor derived from the drive cycle analysis of a Bajaj Discover

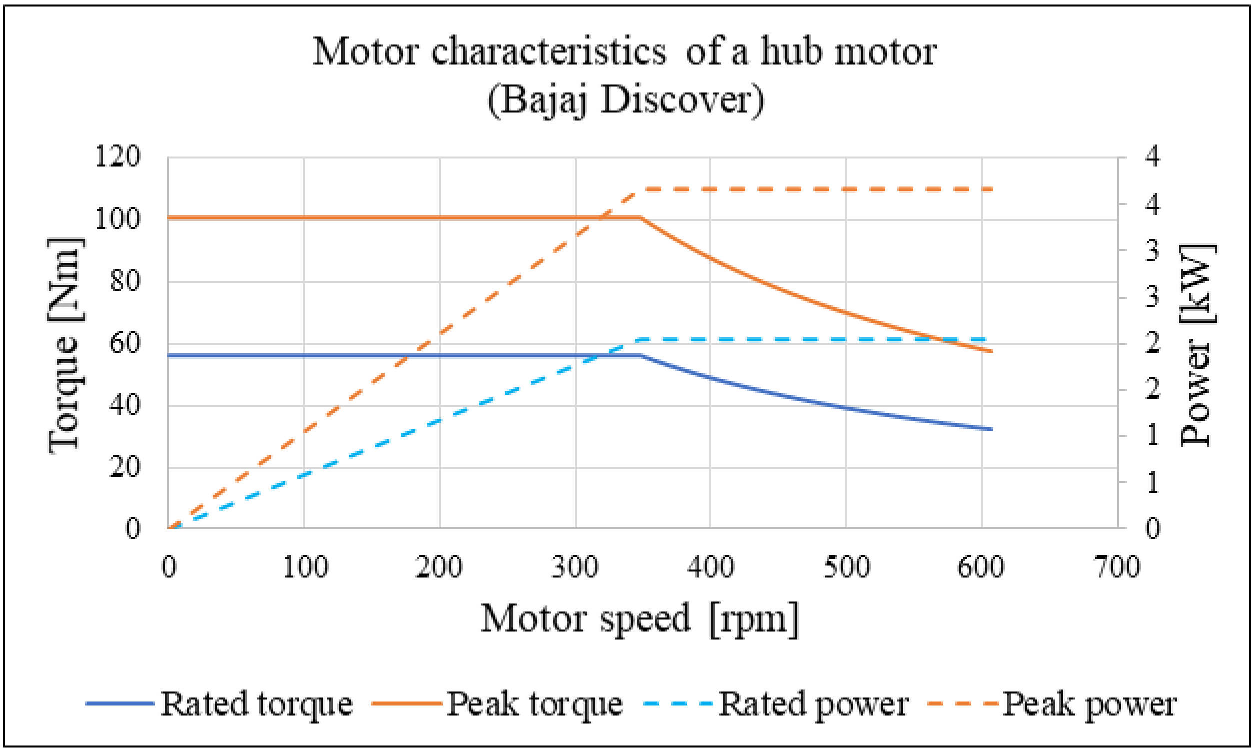


Figure 8.10: Motor characteristics of a hub motor derived from the drive cycle analysis of a Bajaj Discover

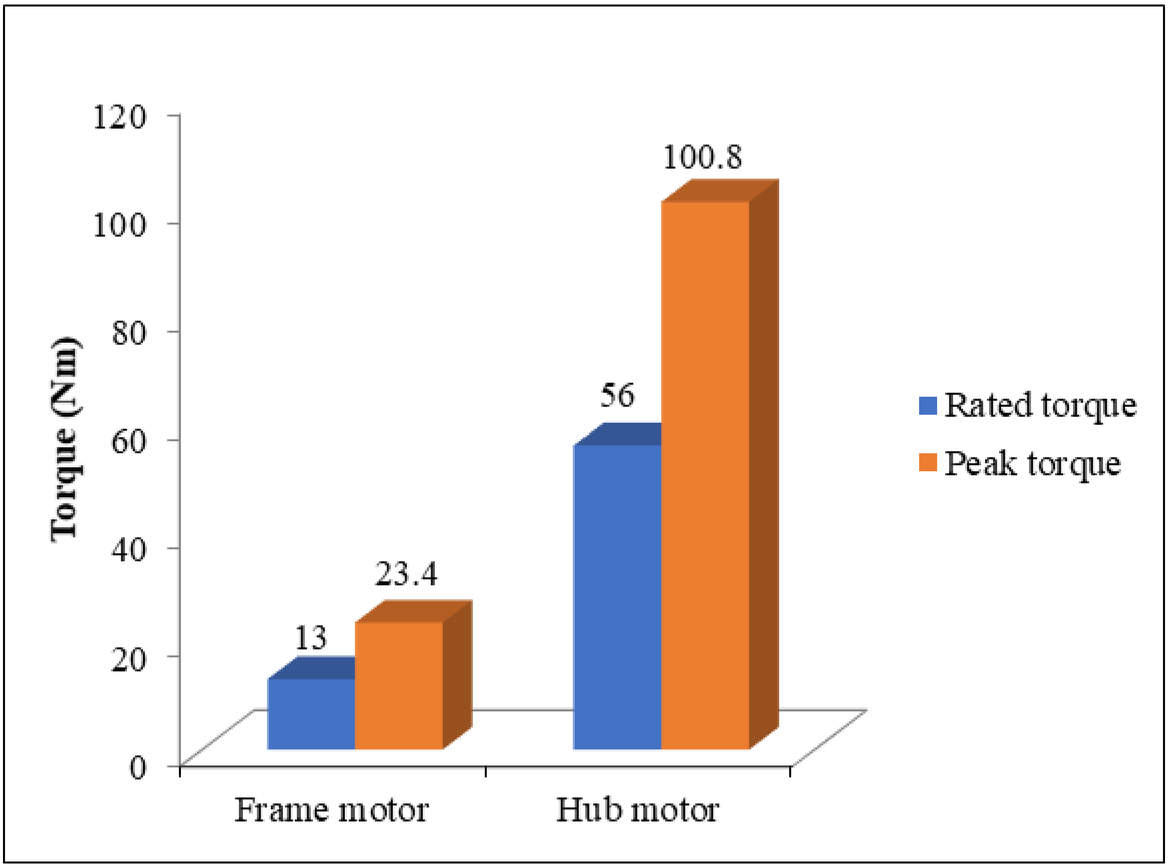


Figure 8.11: Torque ratings of frame and hub motors derived from the drive cycle of a Bajaj Discover

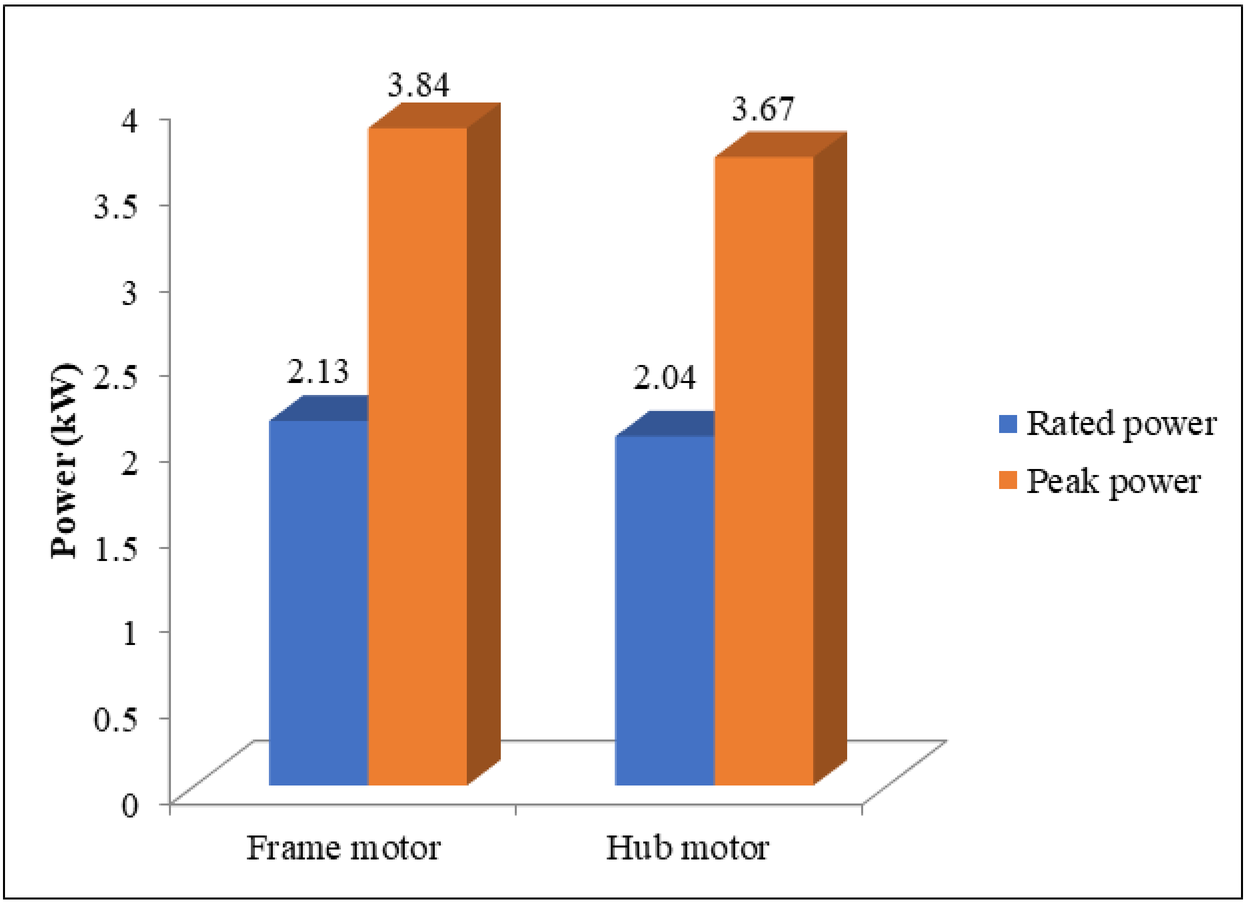


Figure 8.12: Power ratings of frame and hub motors derived from the drive cycle of a Bajaj Discover

From Figure 8.6 and Figure 8.12, Bajaj Discover requires a smaller motor (2.13 kW and 2.04 kW for frame and hub motor, respectively) compared to Honda CB Shine (4.07 kW and 3.62 kW for the frame and hub motor, respectively).

8.1.2 Retro bike:

8.1.2.1 RE Classic 350:

From Figure 8.18, it is observed that the power rating requirements of the motors of a RE Classic 350 are higher than that of all other motors considered in this study. Interestingly, the difference in power requirements of the two motors is minimal (5.15 kW for frame motors and 5.1 kW for hub motors) for the drive cycle of RE Classic 350. However, from Figure 8.13 and Figure 8.15, it is observed that there is a significant difference in torque and speed that can be attained with frame and hub motors. The frame and the hub motor's rated torques are 33 Nm and 100 Nm, respectively, as shown in Figure 8.17. It can be inferred that hub motors produce significantly higher torque for the same input power than frame motors.

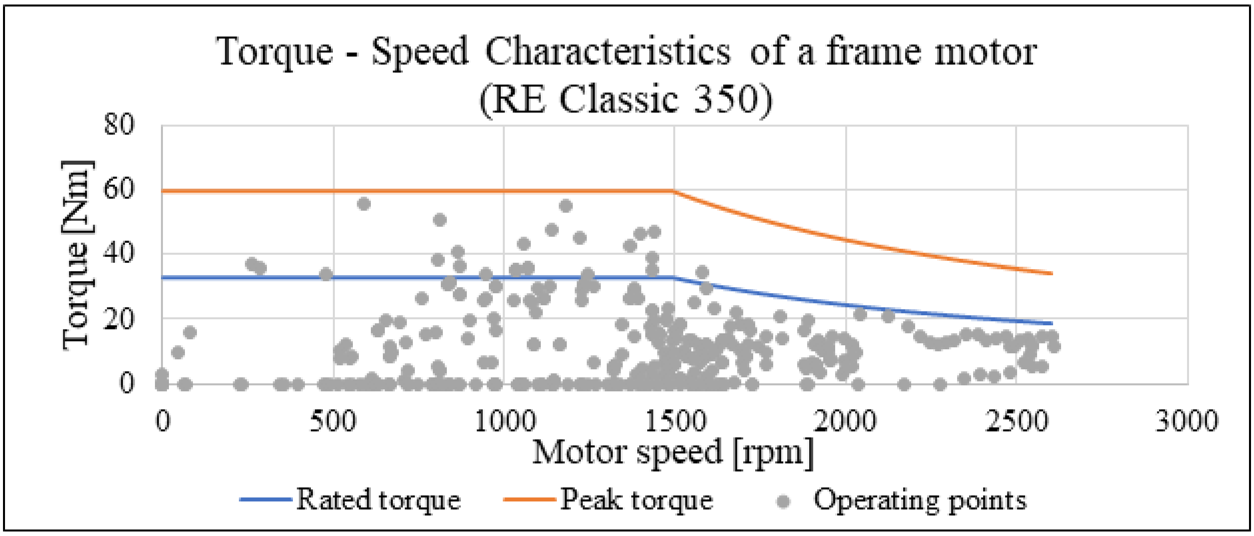


Figure 8.13: Torque speed characteristics of a frame motor derived from the drive cycle analysis of a RE Classic 350

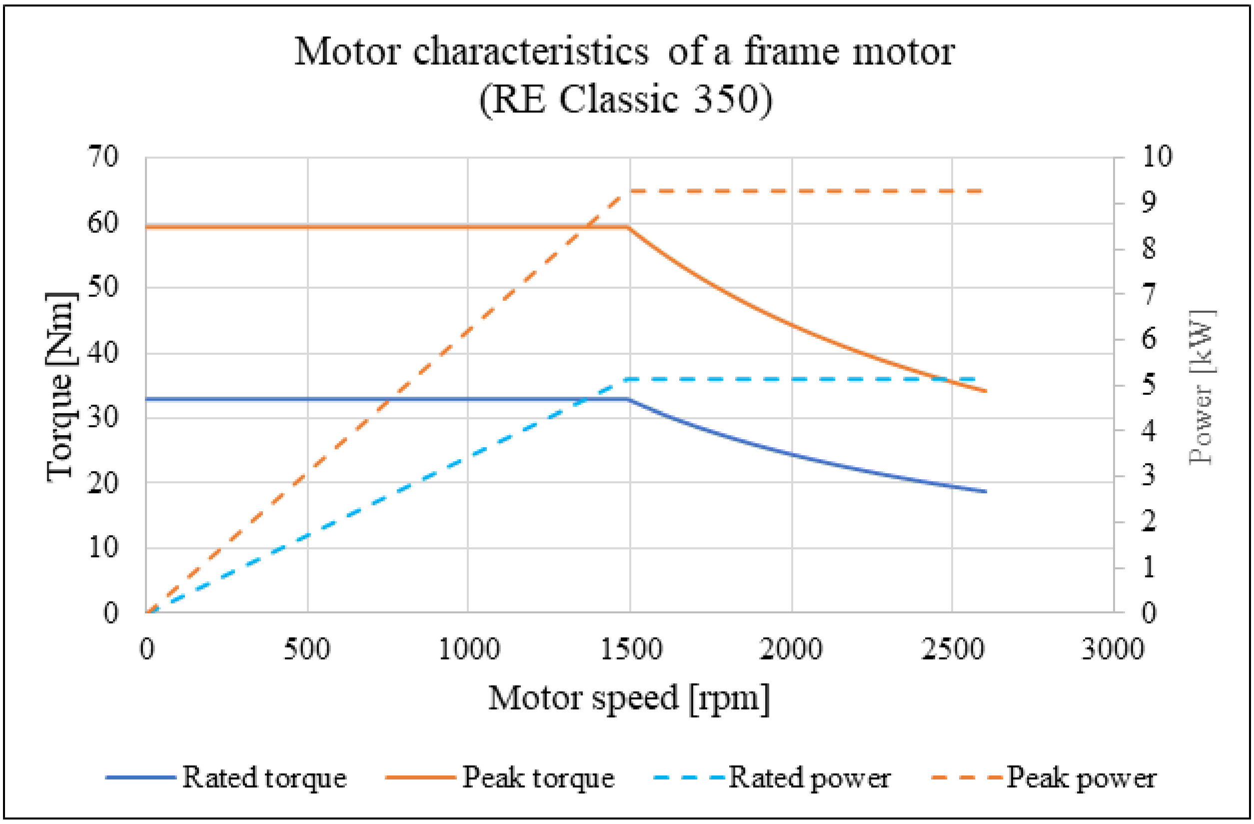


Figure 8.14: Motor characteristics of a frame motor derived from the drive cycle analysis of a RE Classic 350

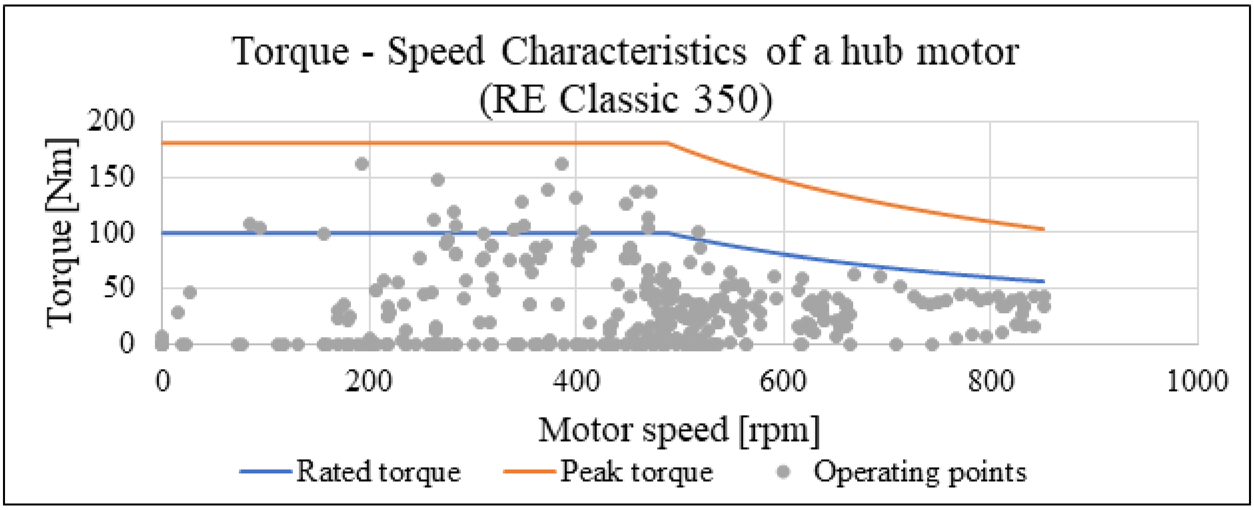


Figure 8.15: Torque speed characteristics of a hub motor derived from the drive cycle analysis of a RE Classic 350

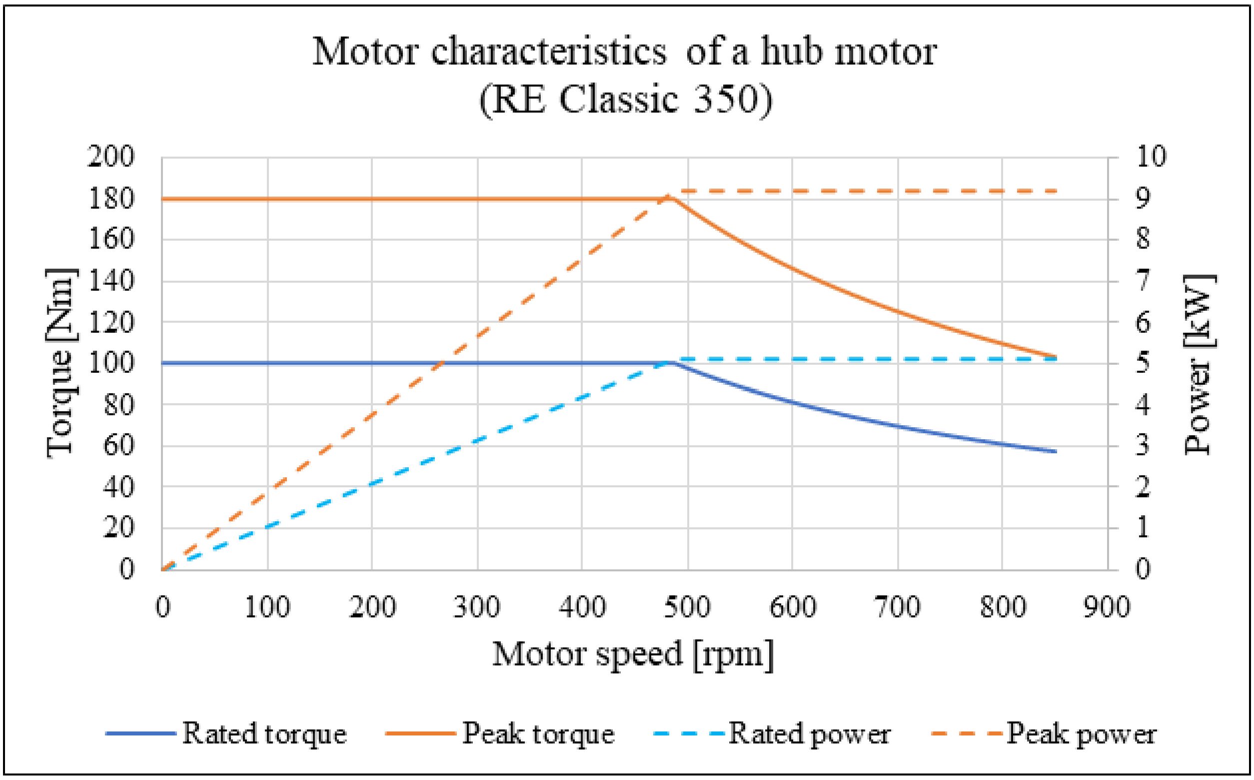


Figure 8.16: Motor characteristics of a hub motor derived from the drive cycle analysis of a RE Classic 350

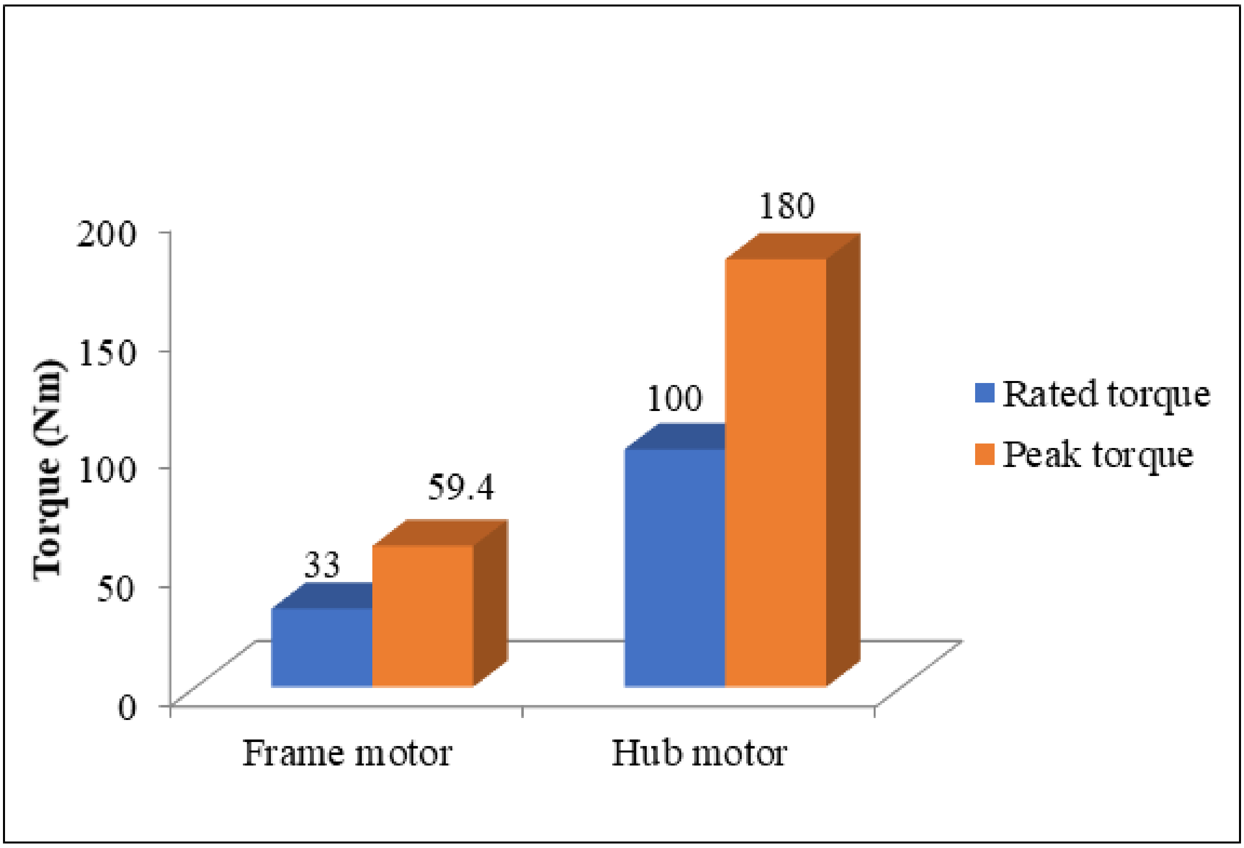


Figure 8.17: Torque ratings of frame and hub motors derived from the drive cycle analysis of a RE Classic 350

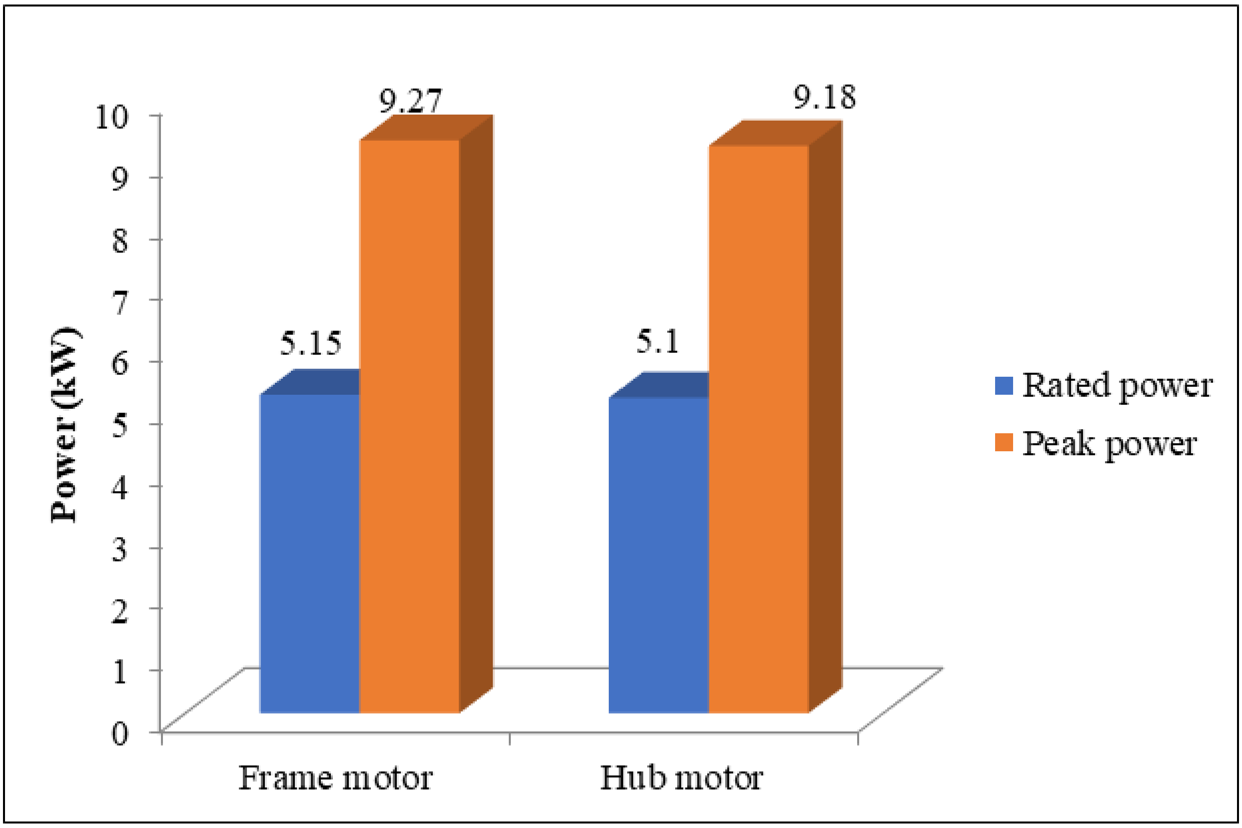


Figure 8.18: Power ratings of frame and hub motor derived from the drive cycle analysis of RE Classic 350

8.1.3 Commute scooter:

In this section, two different drive cycles of Honda Activa are considered. Honda activa 01 and Honda Activa 02 refer to the Renukoot drive cycle and Hyderabad drive cycle.

8.1.3.1 Honda Activa 01

The frame motor's rated torque and peak torques are 18 Nm and 32.4 Nm, respectively, whereas the hub motor's is 77 Nm and 138.6 Nm, respectively, as shown in Figure 8.23. The rated power of the frame motor is 2.16 kW, and that of the hub motor is 2.05 kW. One of the hub motor features, i.e., high torque at comparatively low power, is demonstrated again in this drive cycle.

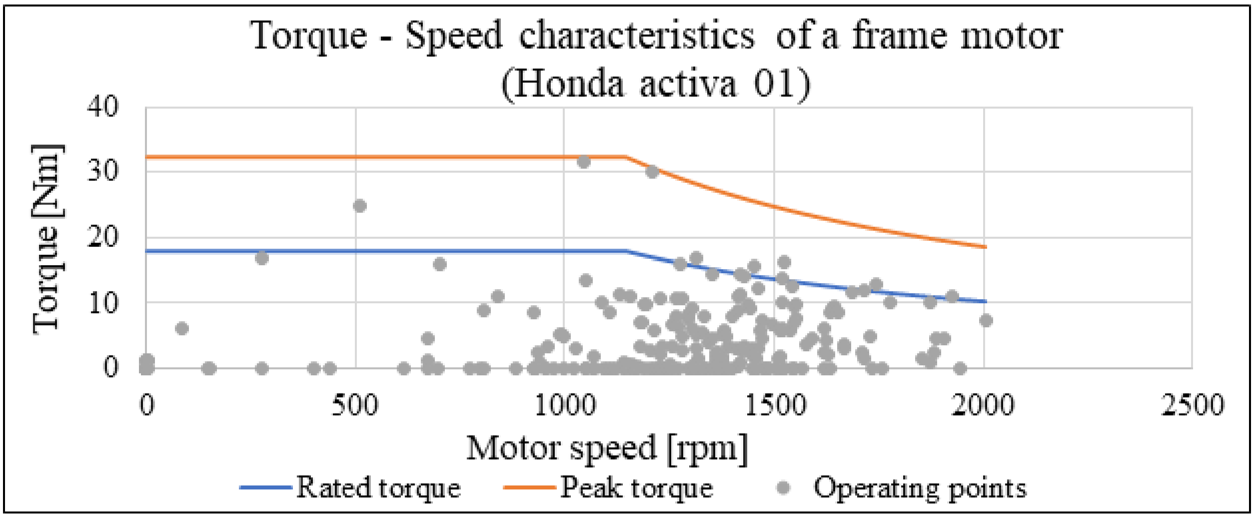


Figure 8.19: Torque speed characteristics of a frame motor derived from the drive cycle analysis of Honda activa 01

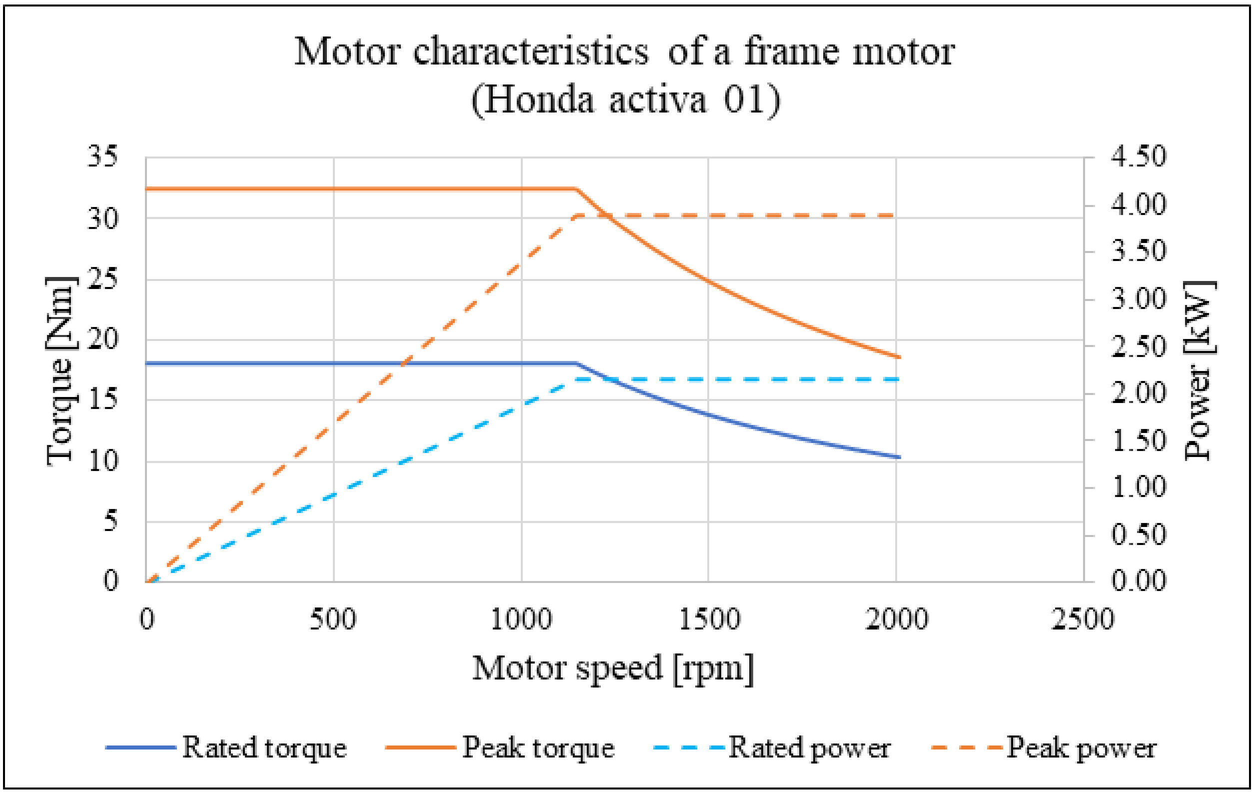


Figure 8.20: Motor characteristics of a frame motor derived from the drive cycle analysis of Honda activa 01

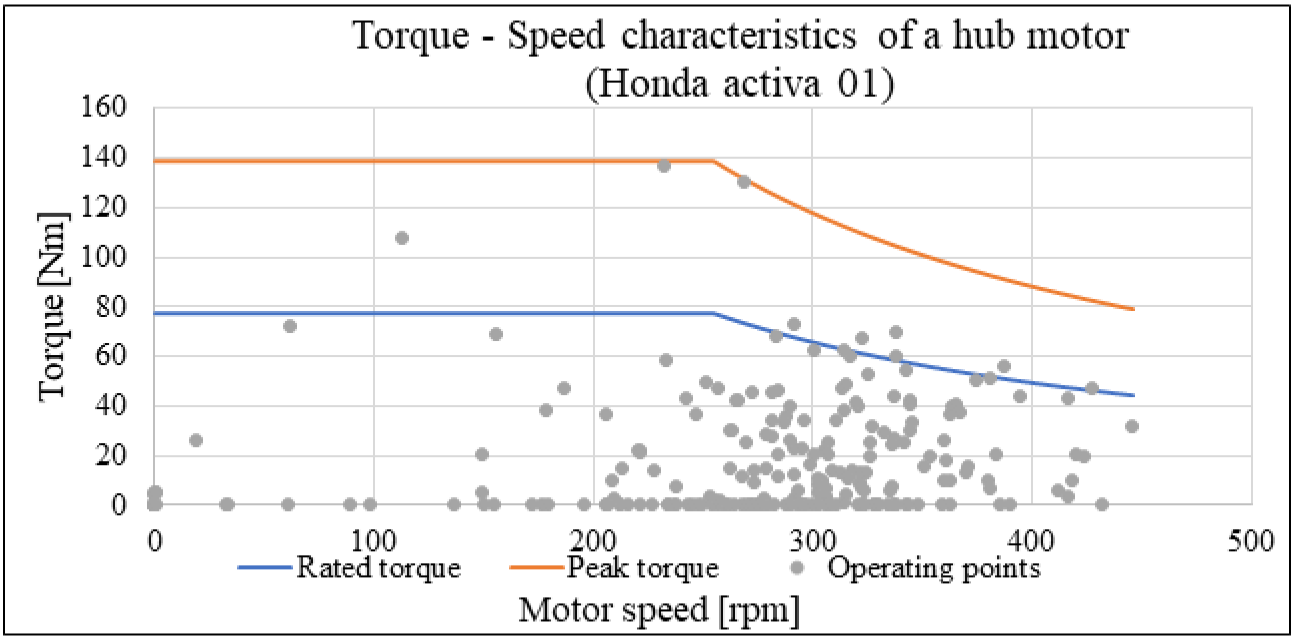


Figure 8.21: Torque speed characteristics of a hub motor derived from the drive cycle analysis of Honda activa 01

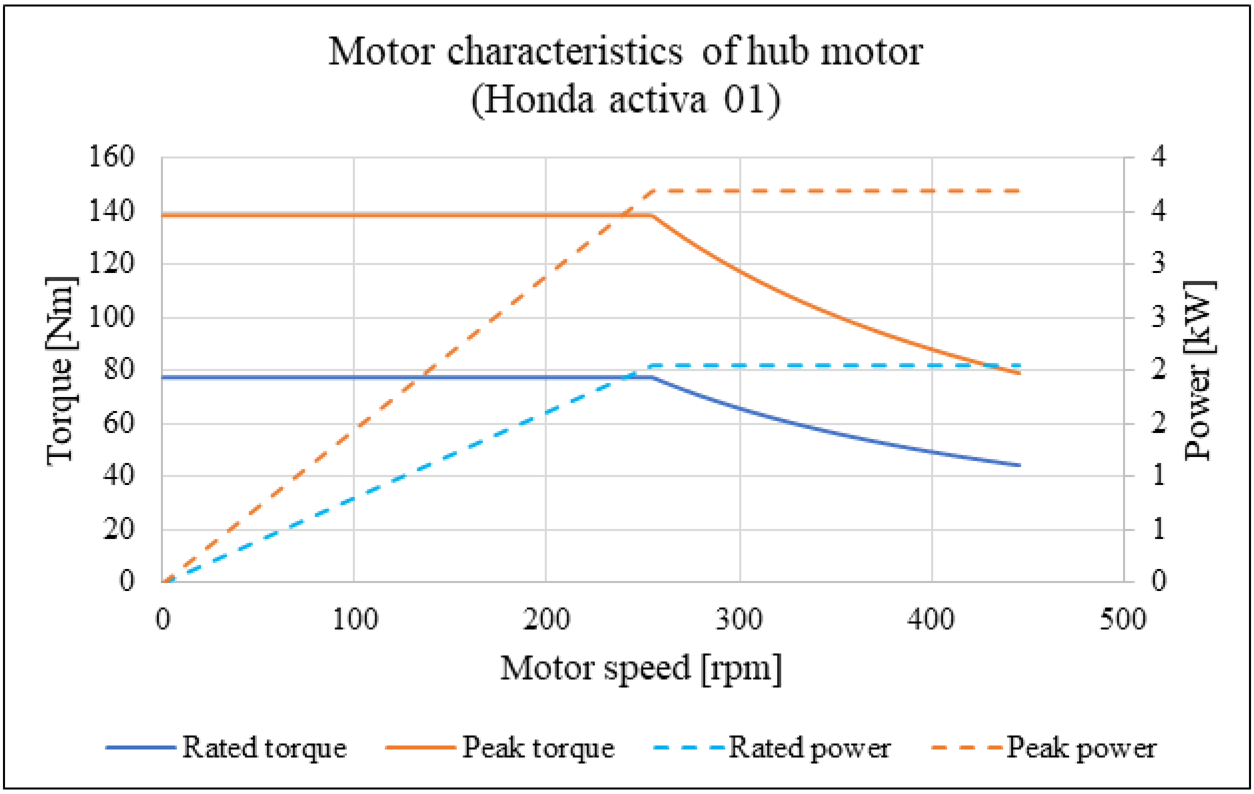


Figure 8.22: Motor characteristics of a hub motor derived from the drive cycle analysis of Honda activa 01

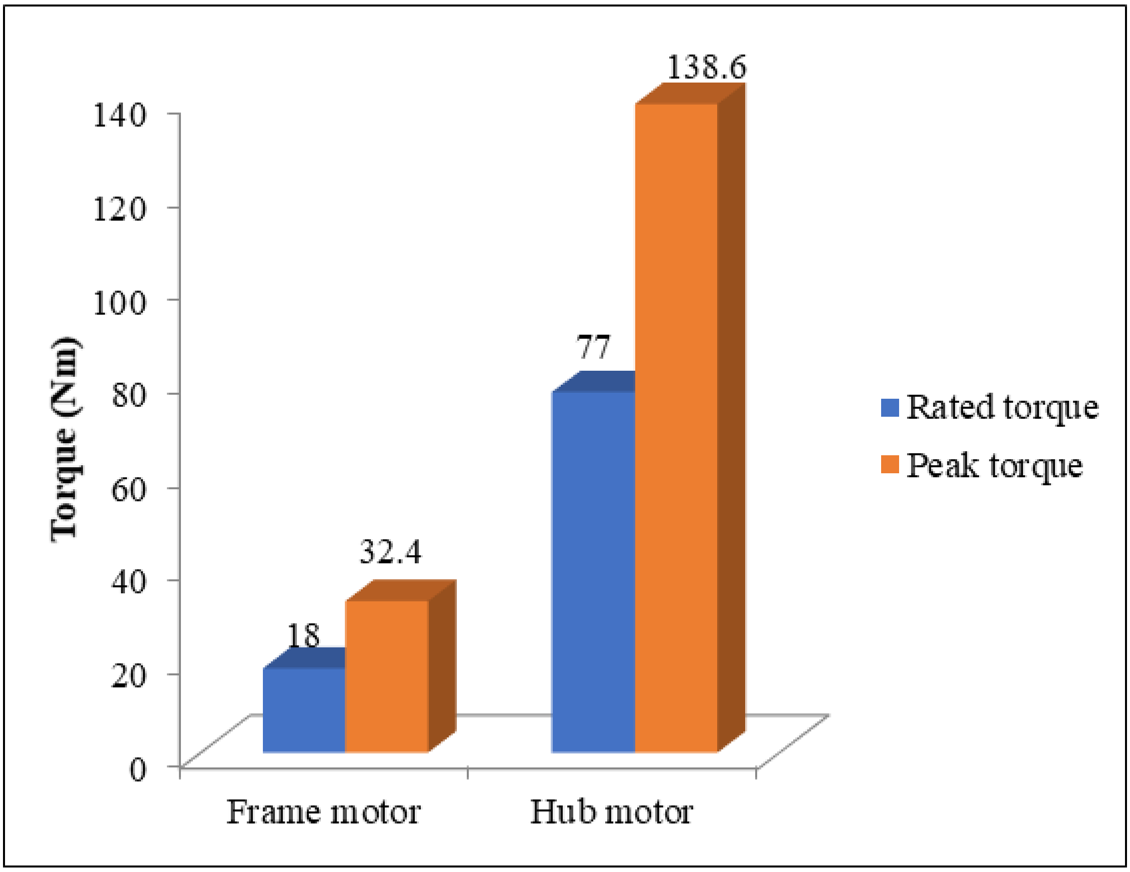


Figure 8.23: Torque ratings of frame and hub motors derived from drive cycle analysis of Honda Activa 01

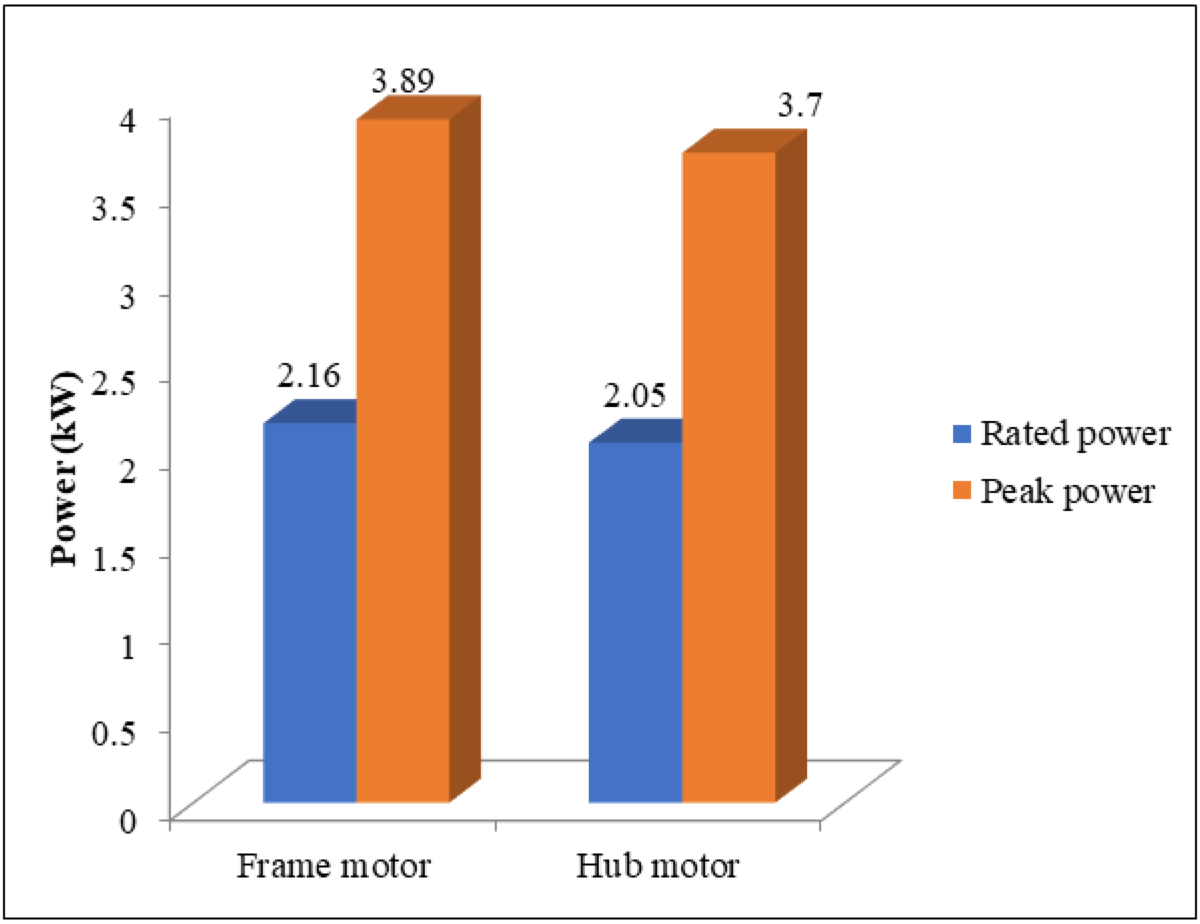


Figure 8.24: Power ratings of frame and hub motors derived from the drive cycle analysis of Honda Activa 01

8.1.3.2 Honda Activa 02

The torque-speed and motor characteristics derived from the drive cycle of Honda activa 02 shown in Figure 8.25, Figure 8.26, Figure 8.27, and Figure 8.28 are similar to that of Honda Activa 1. The slight variation in the power ratings of motors derived from the drive cycle of Honda activa 01 and Honda activa 02 in Figure 8.24 and Figure 8.30 is attributed to the difference in drive cycles. The rated and peak torque of the frame motor is 19 Nm and 34.2 Nm, respectively; the rated and peak torque of the hub motor are 82 Nm and 147.6 Nm. The corresponding power ratings are 3.97 kW and 7.14 kW, respectively, whereas the hub motors are 3.8 kW and 6.85 kW, respectively.

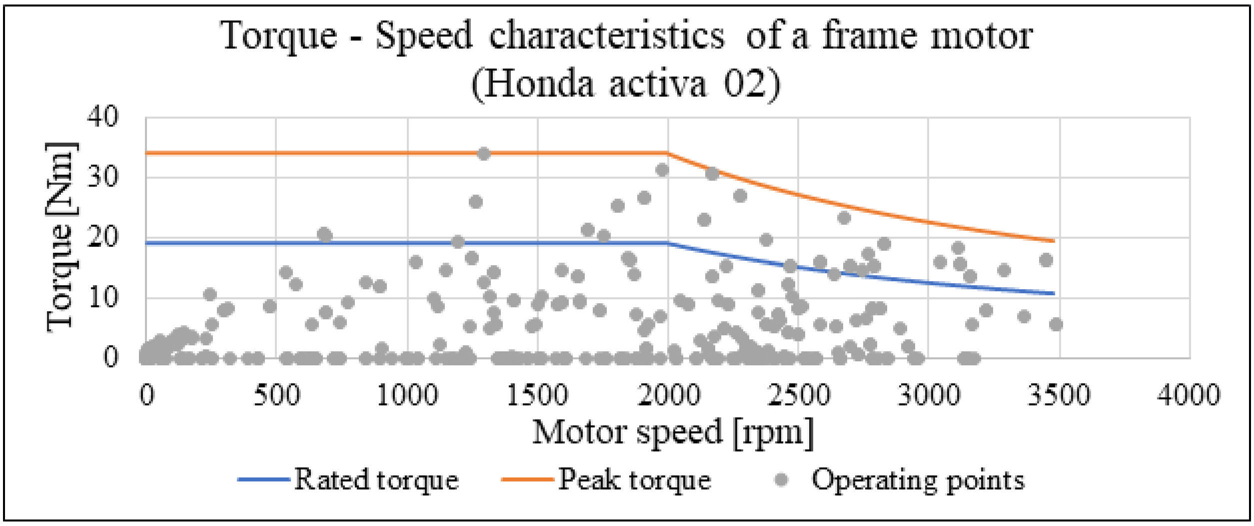


Figure 8.25: Torque speed characteristics of a frame motor derived from the drive cycle analysis of Honda activa 02

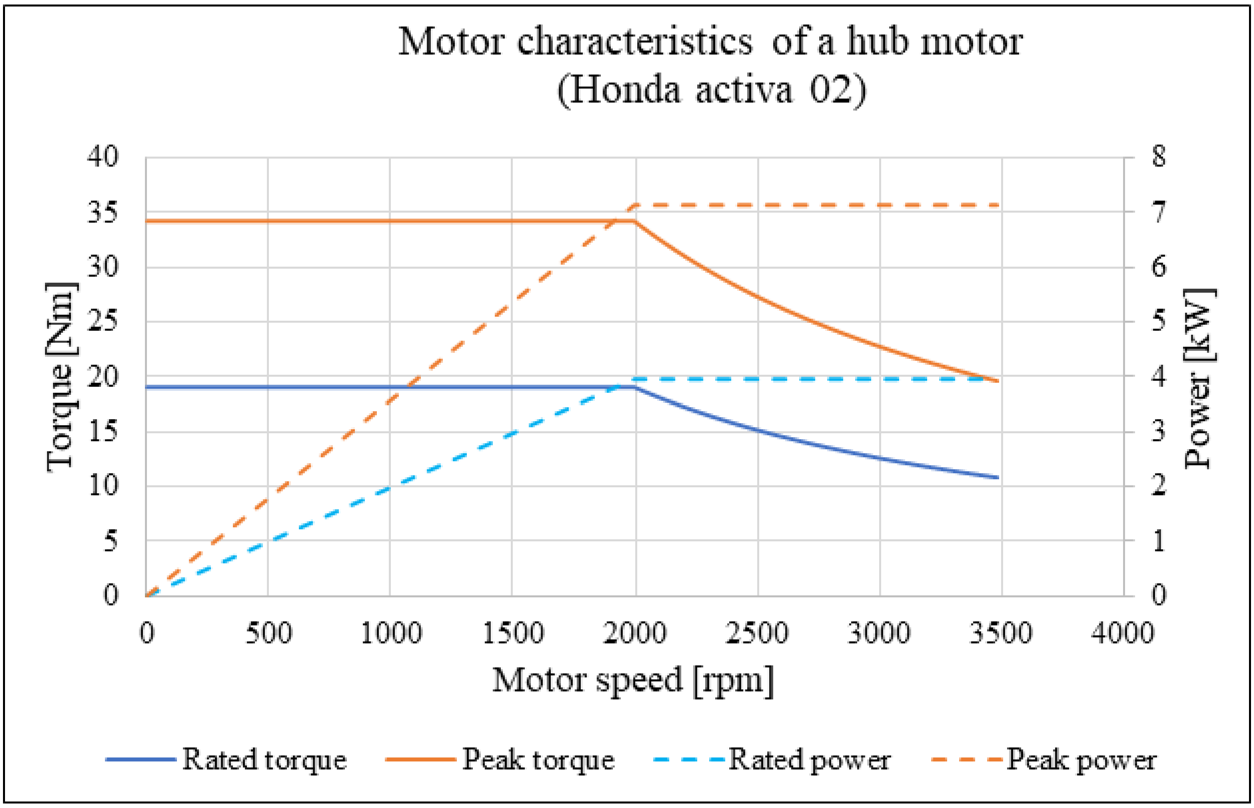


Figure 8.26: Motor characteristics of a frame motor derived from the drive cycle analysis of Honda activa 02

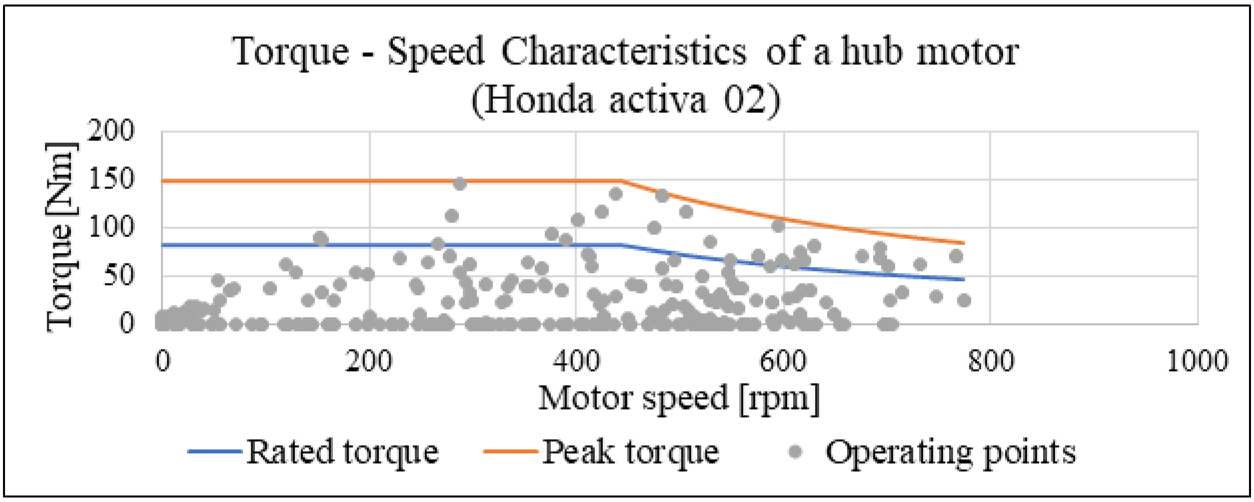


Figure 8.27: Torque speed characteristics of a hub motor derived from the drive cycle analysis of Honda activa 02

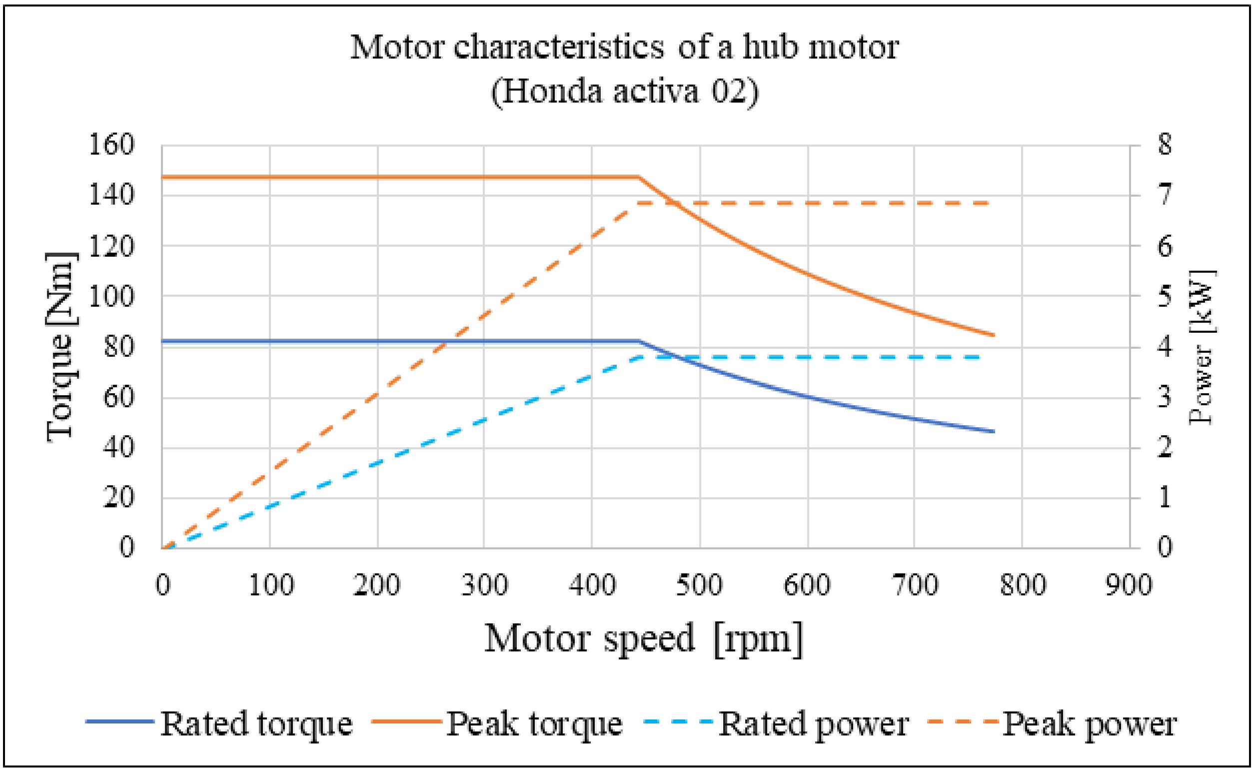


Figure 8.28: Motor characteristics of a hub motor derived from the drive cycle analysis of Honda activa 02

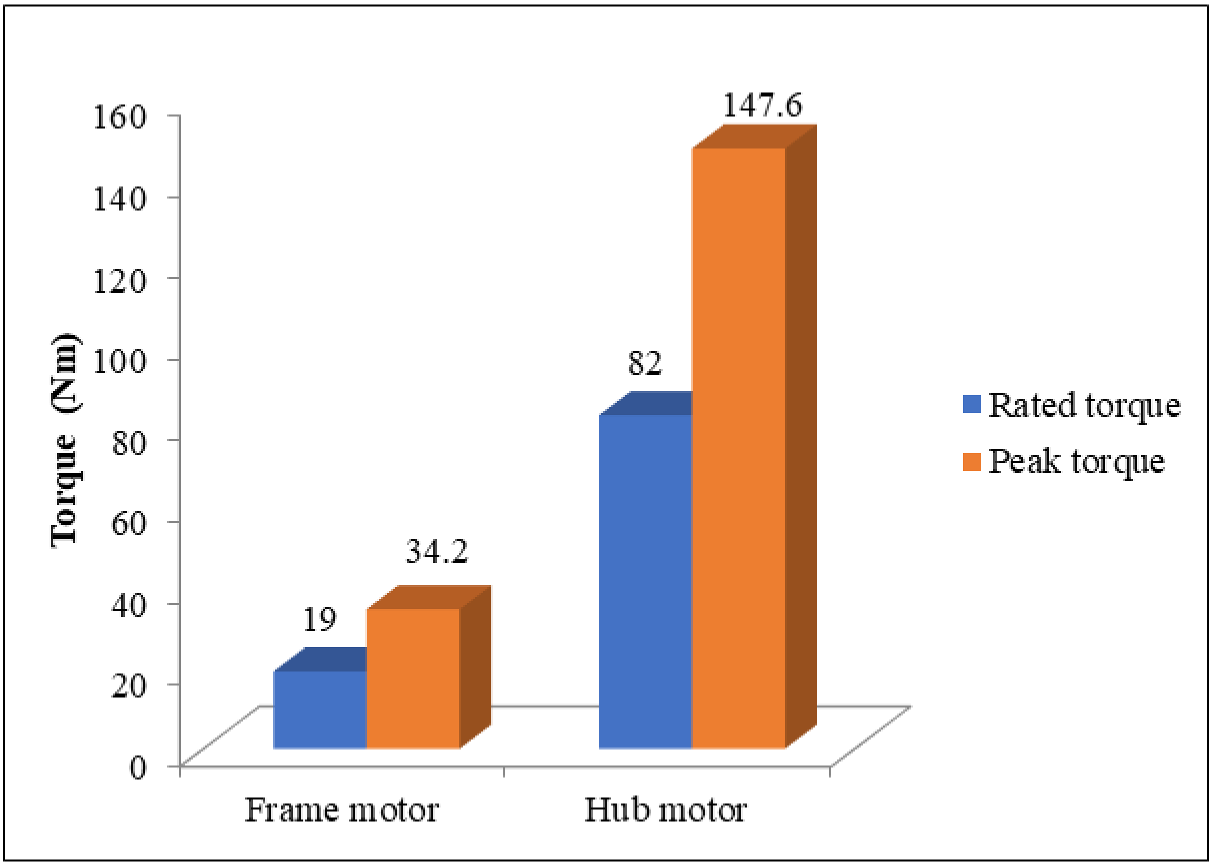


Figure 8.29: Torque ratings of frame and hub motors derived from drive cycle analysis of Honda Activa 02

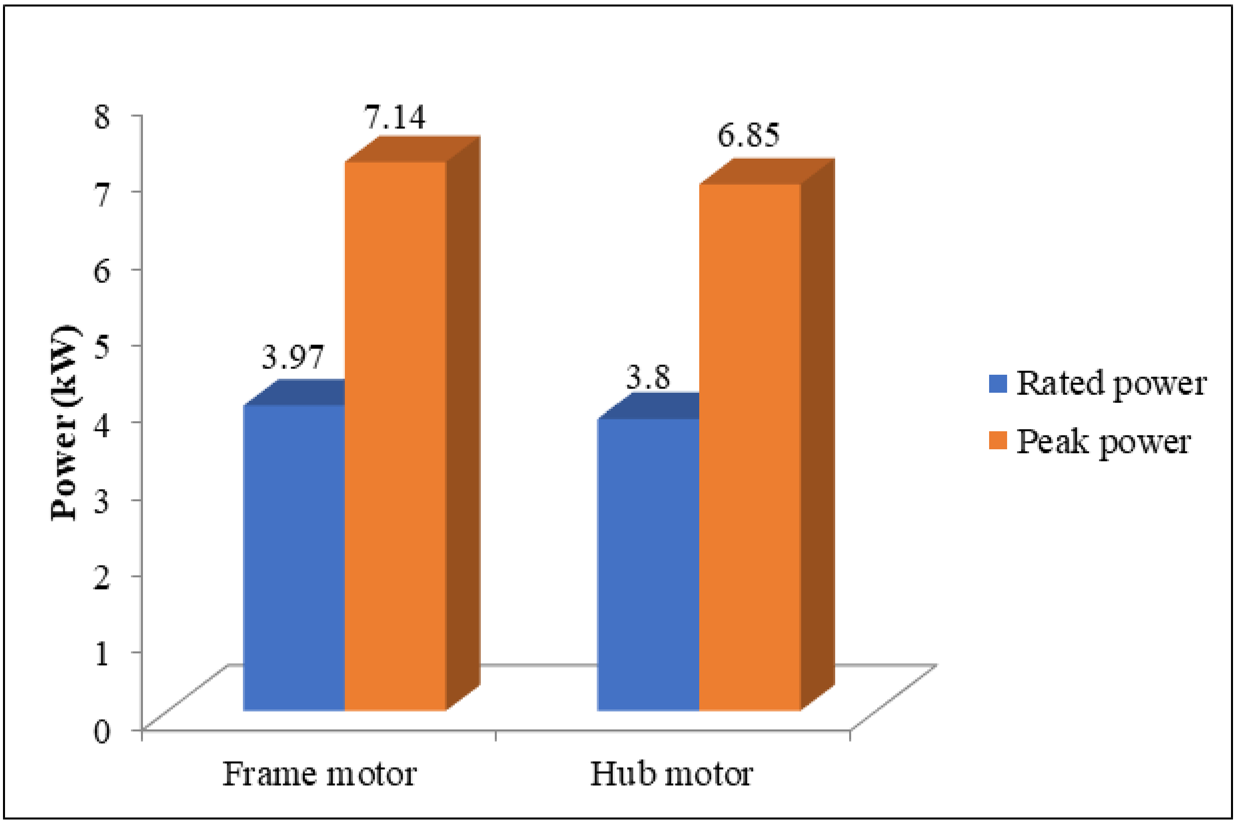


Figure 8.30: Power ratings of frame and hub motors derived from the drive cycle analysis of Honda Activa 02

8.1.4 Mid range bikes

The drive cycles of two different mid-range bikes, a Hero Honda Splender Plus and a Hero Honda Passion Pro are analyzed in this section.

8.1.4.1 Hero Honda Splender Plus

From Figure 8.35, it is inferred that the torque developed by the hub motor is significantly higher than that of frame motors. The rated torque and peak torque of the frame motor is 12.1 Nm and 21.78 Nm, respectively; the corresponding ratings of the hub motor are 53 Nm and 95.4 Nm. Among the drive cycles of different two-wheelers considered in this study, this particular drive cycle requires motors of smaller rating; 1.43 kW hub motor and 1.53 kW frame motor, as shown in Figure 8.36.

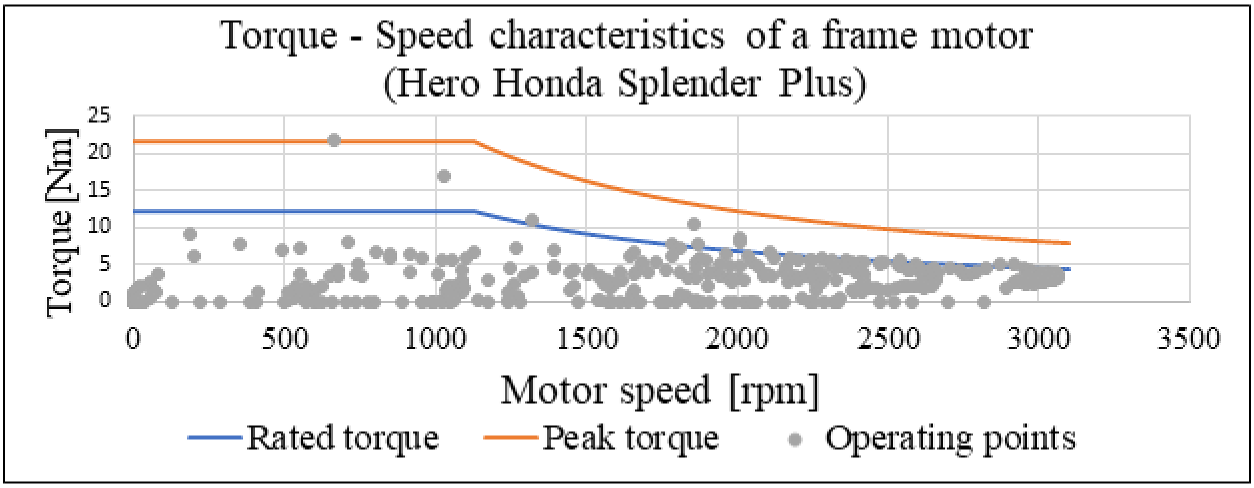


Figure 8.31: Torque speed characteristics of a frame motor derived from the drive cycle analysis of Hero Honda Splender Plus

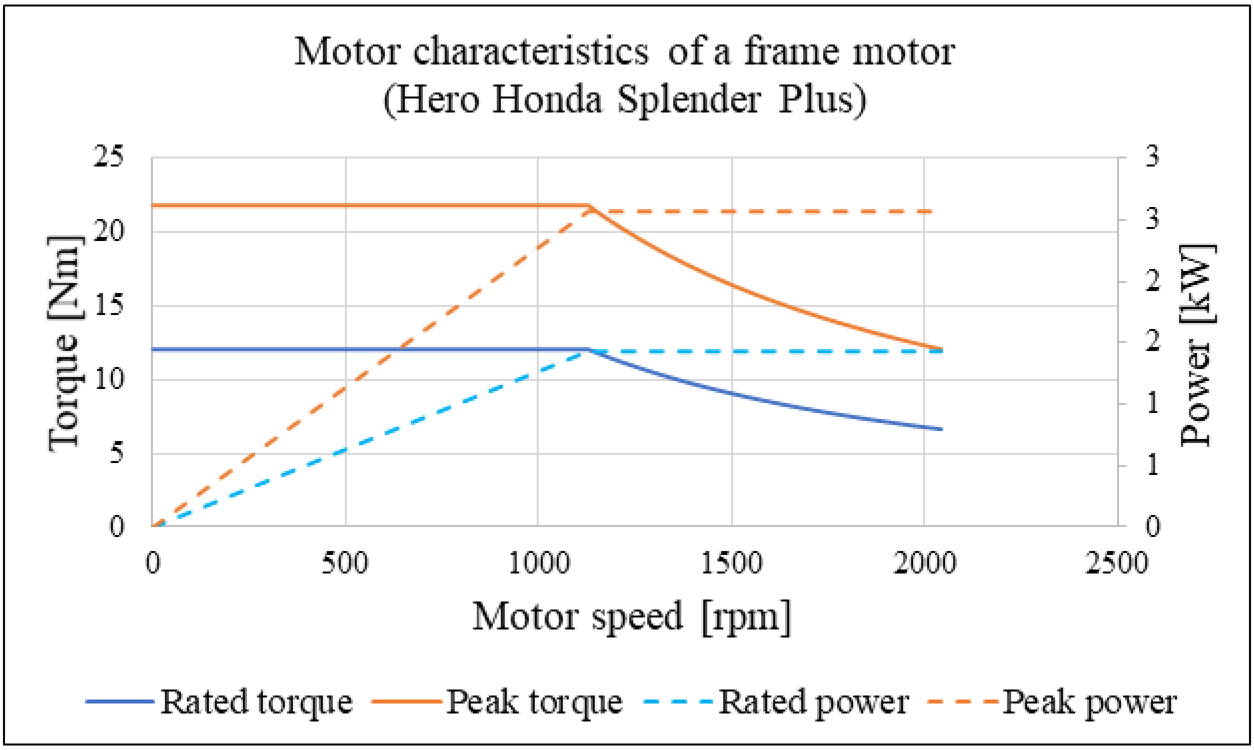


Figure 8.32: Motor characteristics of a frame motor derived from the drive cycle analysis of Hero Honda Splender Plus

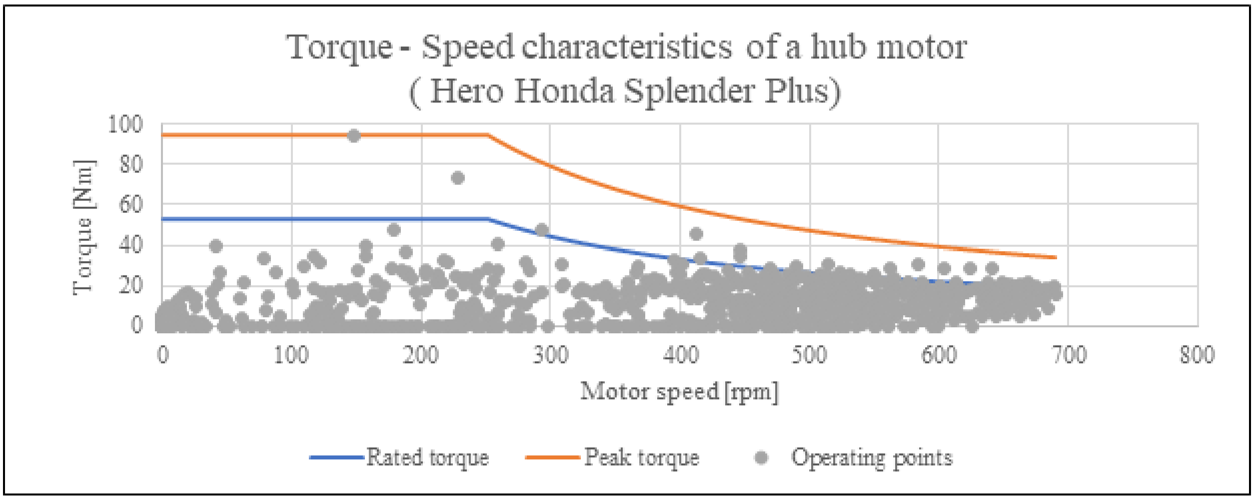


Figure 8.33: Torque speed characteristics of a hub motor derived from the drive cycle analysis of Hero Honda Splender Plus

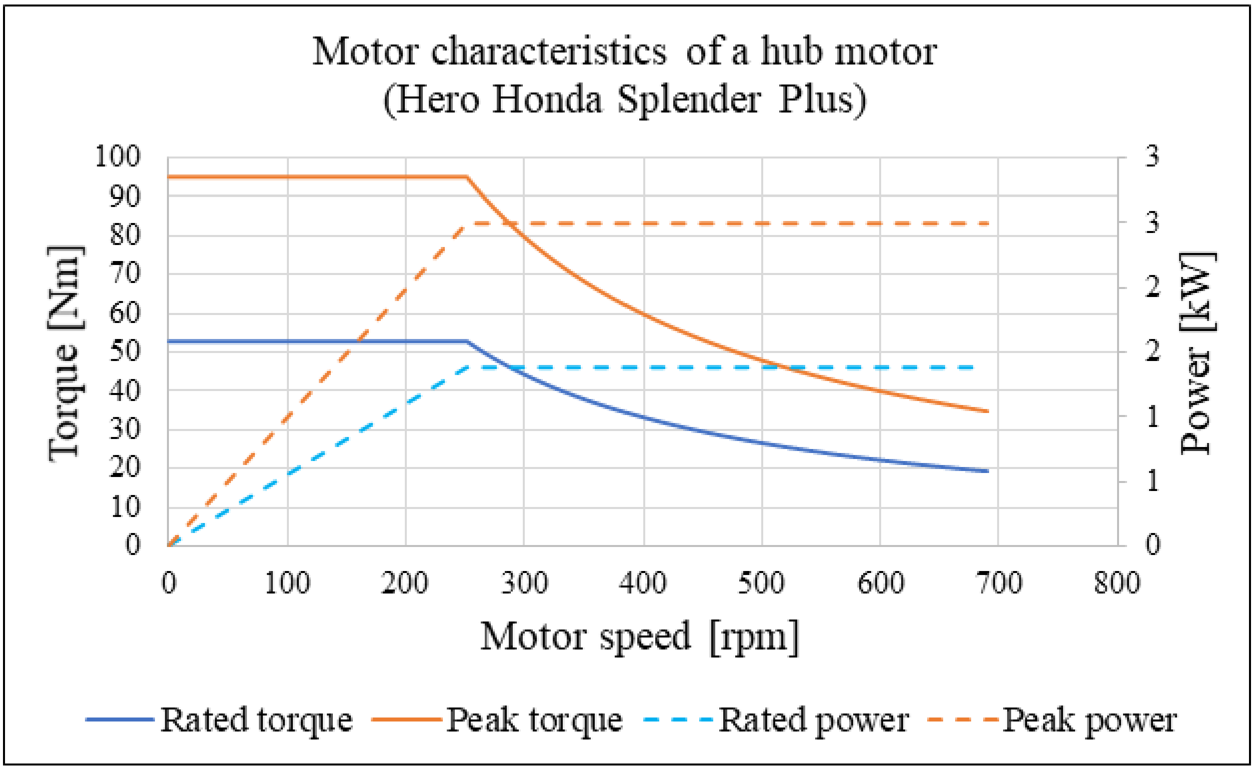


Figure 8.34: Motor characteristics of a hub motor derived from the drive cycle analysis of Hero Honda Splender Plus

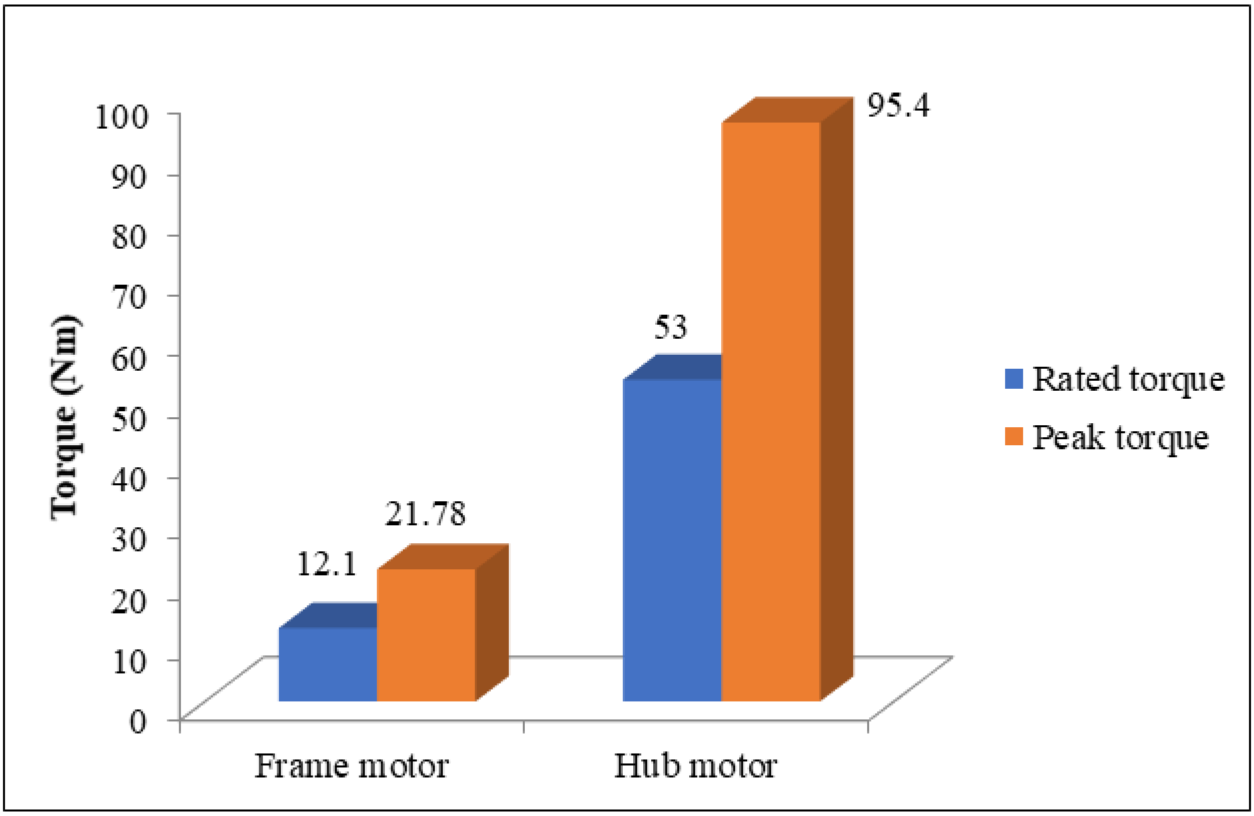


Figure 8.35: Torque ratings of frame and hub motors derived from drive cycle analysis of Hero Honda Splender Plus

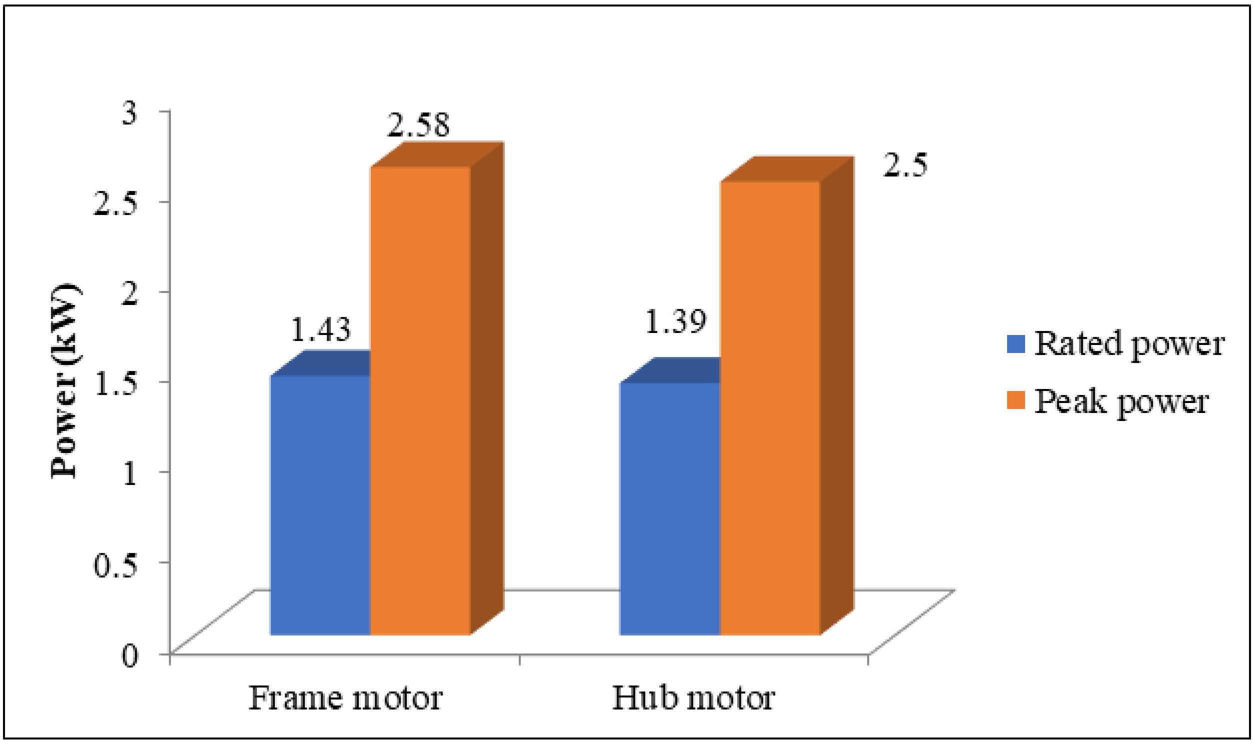


Figure 8.36: Power ratings of frame and hub motors derived from the drive cycle analysis of Hero Honda Splender Plus

8.1.4.2 Hero Honda Passion Pro

The rated torque and peak torque of a frame motor are 18 Nm and 32.4 Nm respectively whereas that of hub motor are 77 Nm and 138.6 Nm as shown in Figure 8.41. The torque of hub motors is 4 times as that of frame motor. However, the difference in power ratings of the two motors is only 200W (rated power of frame motor is 4.45 kW and rated power of hub motor is 4.23 kW).

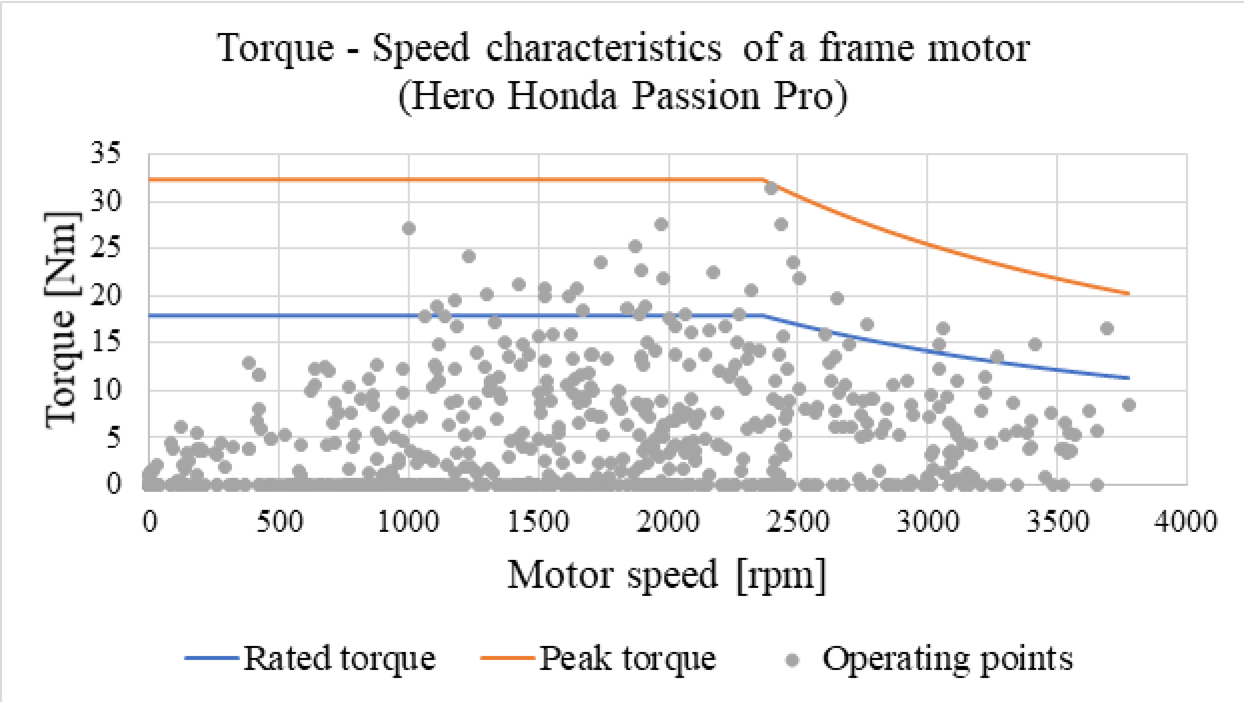


Figure 8.37: Torque speed characteristics of a frame motor derived from the drive cycle analysis of Hero Honda Passion Pro

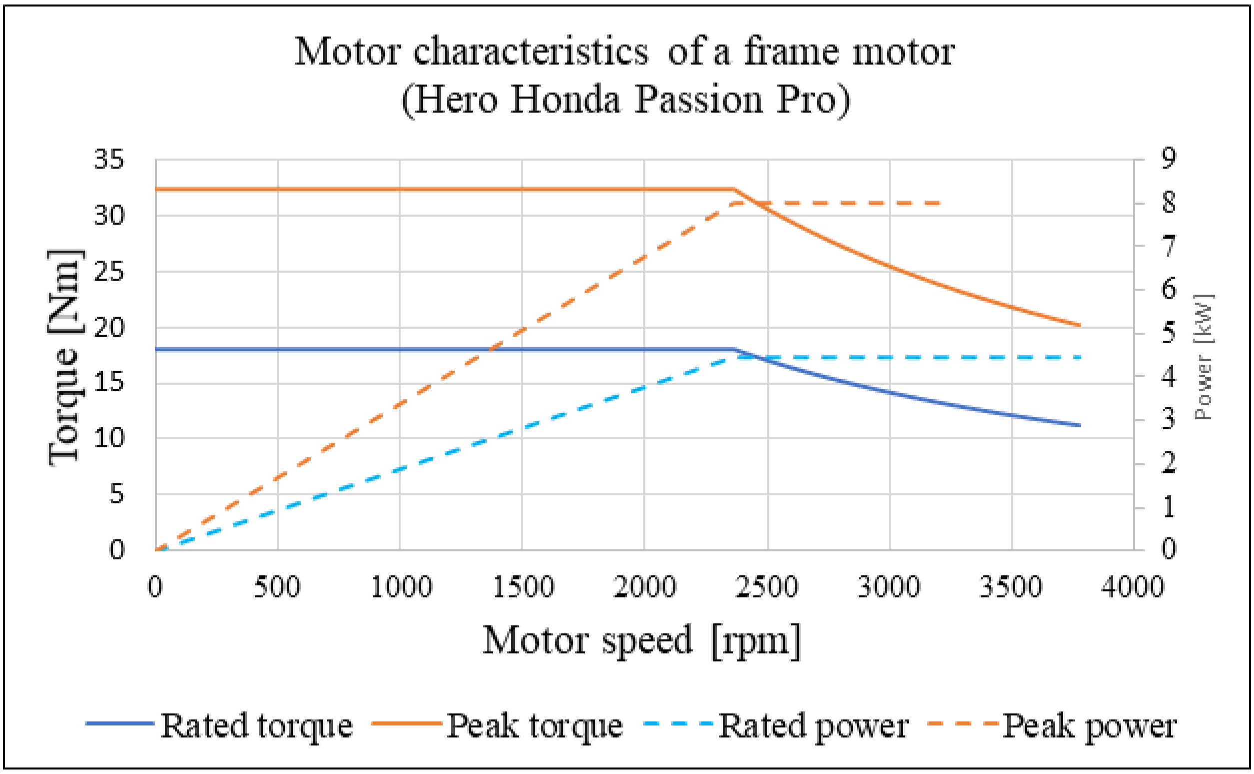


Figure 8.38: Motor characteristics of a frame motor derived from the drive cycle analysis of Hero Honda Passion Pro

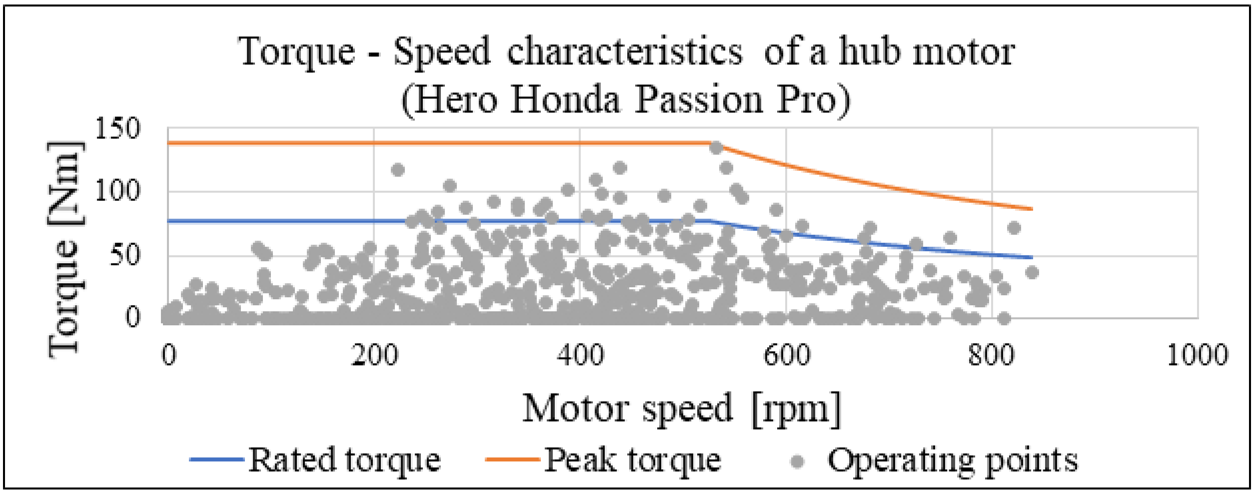


Figure 8.39: Torque speed characteristics of a hub motor derived from the drive cycle analysis of Hero Honda Passion Pro

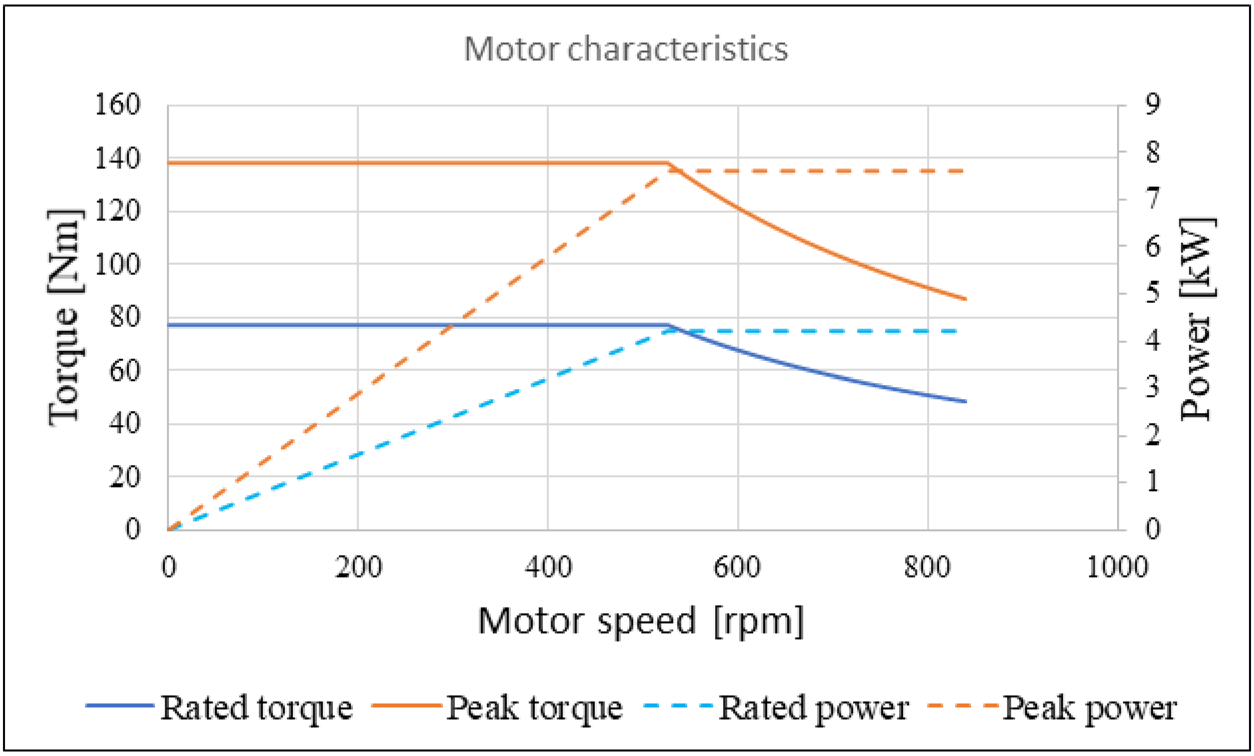


Figure 8.40: Motor characteristics of a hub motor derived from the drive cycle analysis of Hero Honda Passion Pro

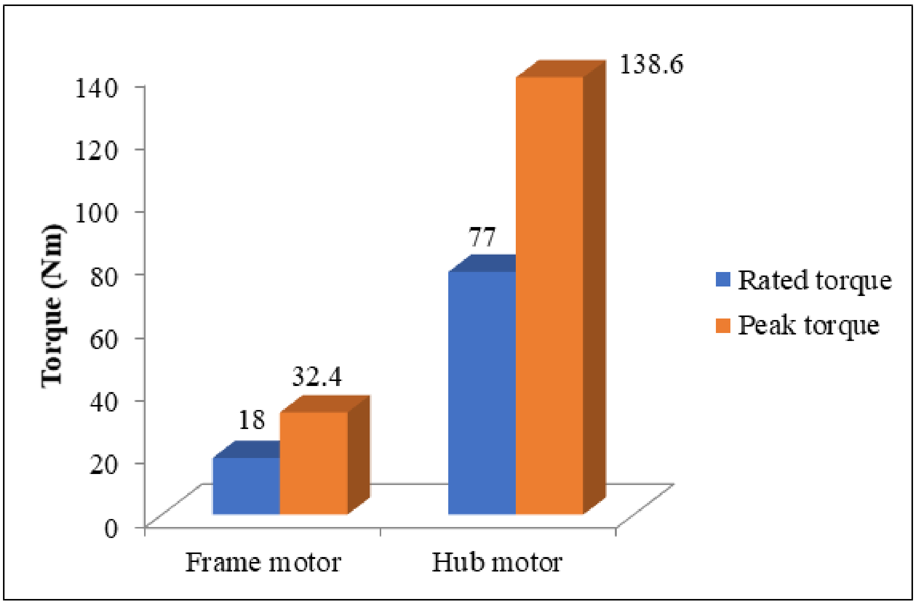


Figure 8.41: Torque ratings of frame and hub motors derived from drive cycle analysis of Hero Honda Passion Pro

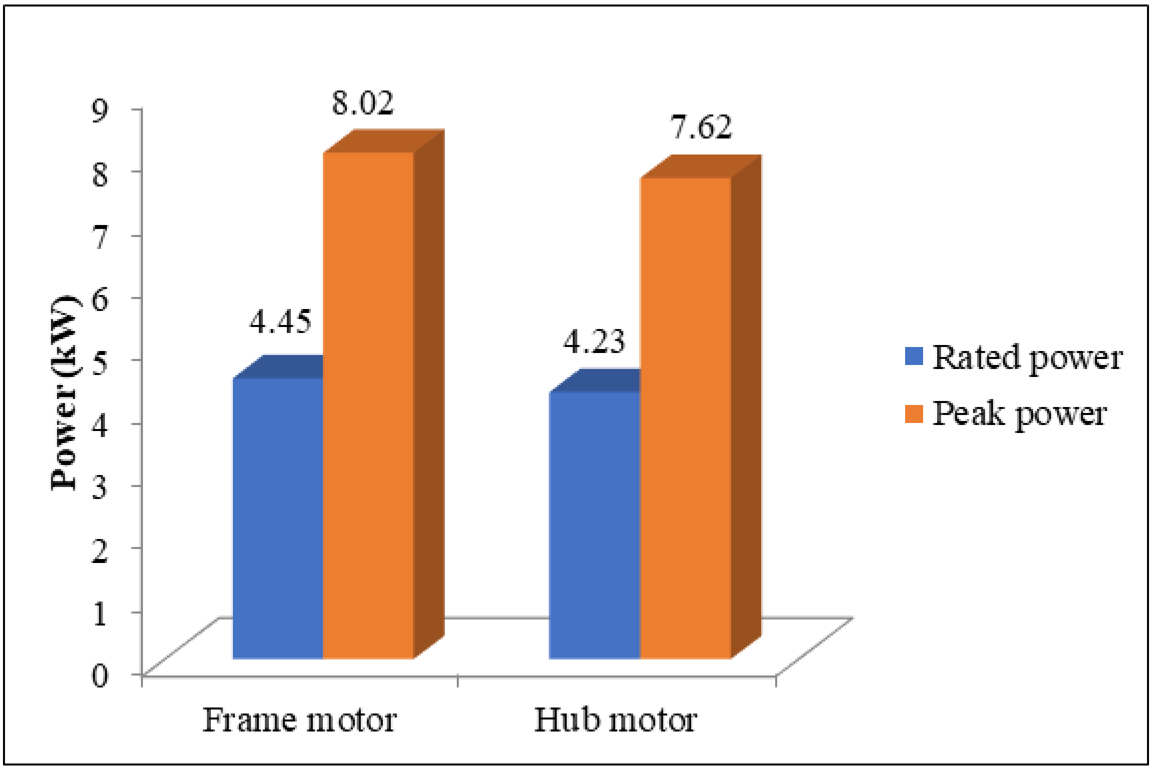


Figure 8.42: Power ratings of frame and hub motors derived from the drive cycle analysis of Hero Honda Passion Pro

From Figure 8.36 and Figure 8.42, it is inferred that the power ratings of Hero Honda Passion Pro (4.45kW and 4.23 kW for frame and hub motor, respectively) are higher than that of Hero Honda Splender Plus (1.39 kW and 2.5 kW for the frame and hub motor respectively).

8.2 Motor peak and rated power ratings

This section elucidates a scenario when frame and hub motors would replace conventional internal combustion engines in two-wheelers. Power rating requirements of motors for various categories of two-wheelers, i.e., sports bikes, retro bikes, commute scooters, and mid-range bikes, will be discussed in particular. Except for Hero Honda Splender Plus, the power rating requirements are lower in the case of hub motors, irrespective of the two-wheeler type.

8.2.1 Sports bikes

From Figure 8.43 and Figure 8.44, it is seen that Bajaj Discover requires a smaller motor (2.13 kW and 2.04 kW for frame and hub motor, respectively) as compared to Honda CB Shine (4.07 kW and 3.62 kW for the frame and hub motor, respectively). In addition, it is observed that the power required to run hub motors is lesser than frame motors in both vehicles.

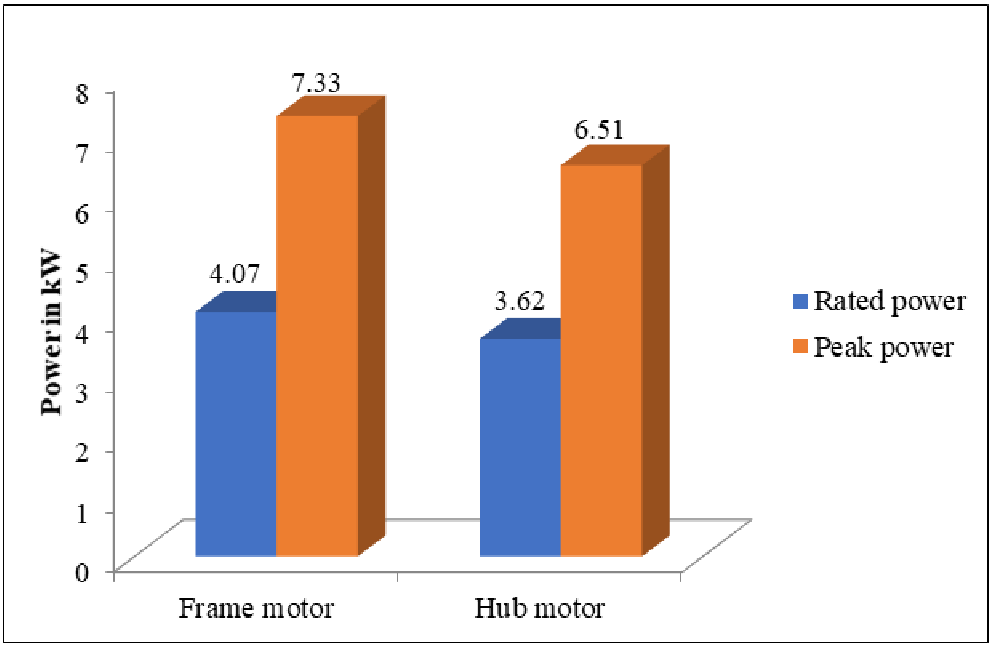


Figure 8.43: Power ratings of frame and hub motor for a Honda CB Shine

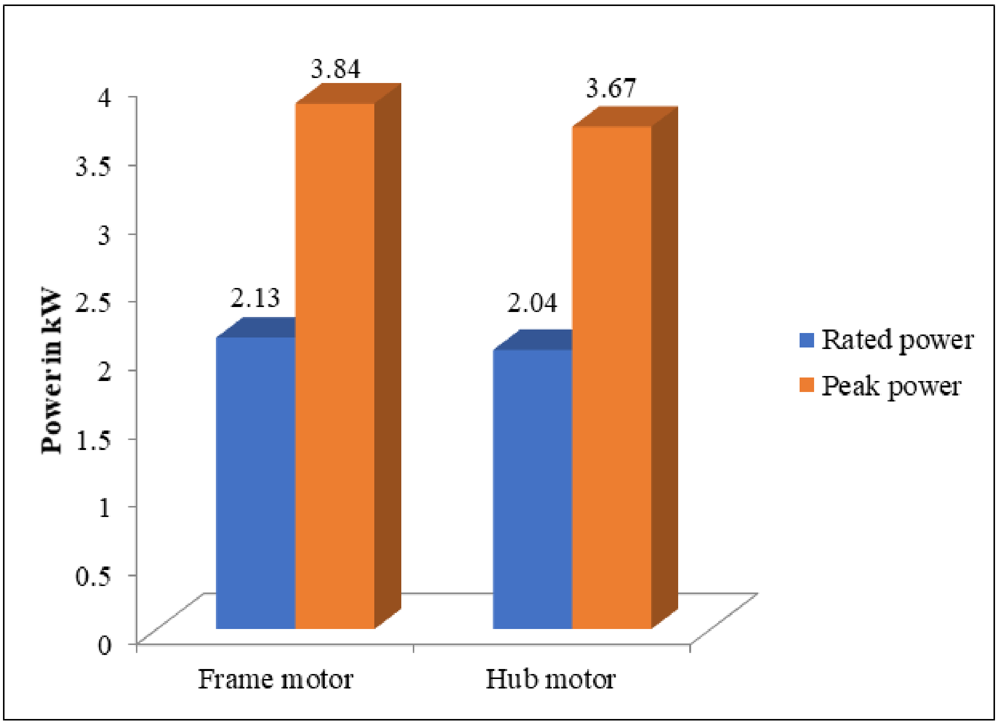


Figure 8.44: Power ratings of the frame and hub motor for a Bajaj Discover

8.2.2 Retro bikes

From Figure 8.45, it is observed that the power ratings of the motor for a RE Classic 350 are higher than all other two-wheeler types considered in this study. It is also observed that the difference in power requirements of frame and hub motors is very minimal (5.15 kW for frame motors and 5.1 kW for hub motors).

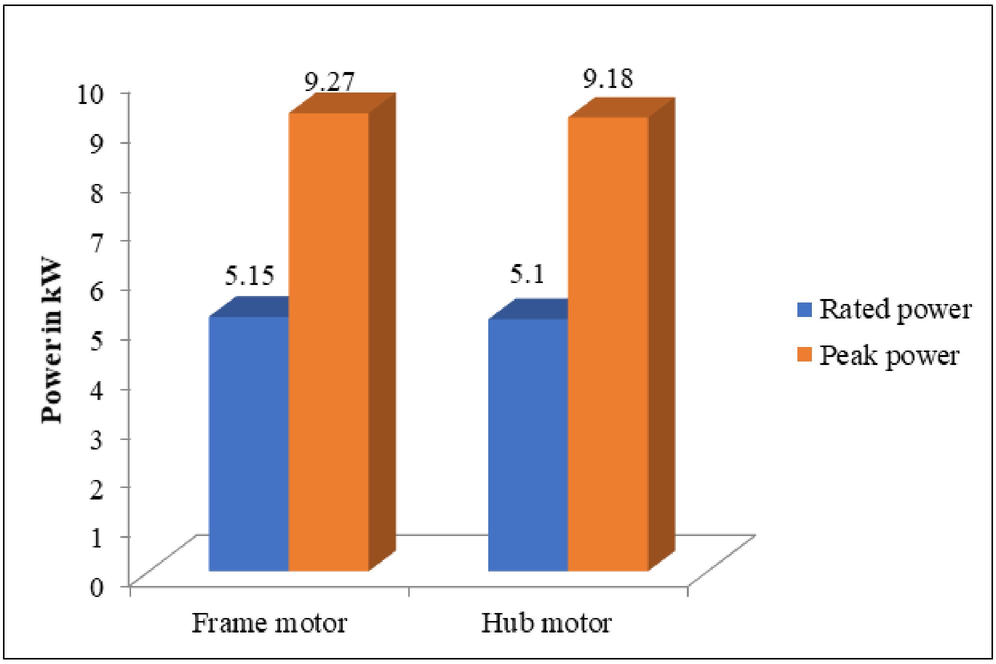


Figure 8.45: Power ratings of the frame and hub motor for a RE Classic 350

8.2.3 Commute scooter

In this study, the power ratings of the motors are dependent on the drive cycle, which is different for the two Honda Activas. The slight variation observed in the power ratings between the two vehicles in Figure 8.46 and Figure 8.47 is ascribed to the difference in drive cycles.

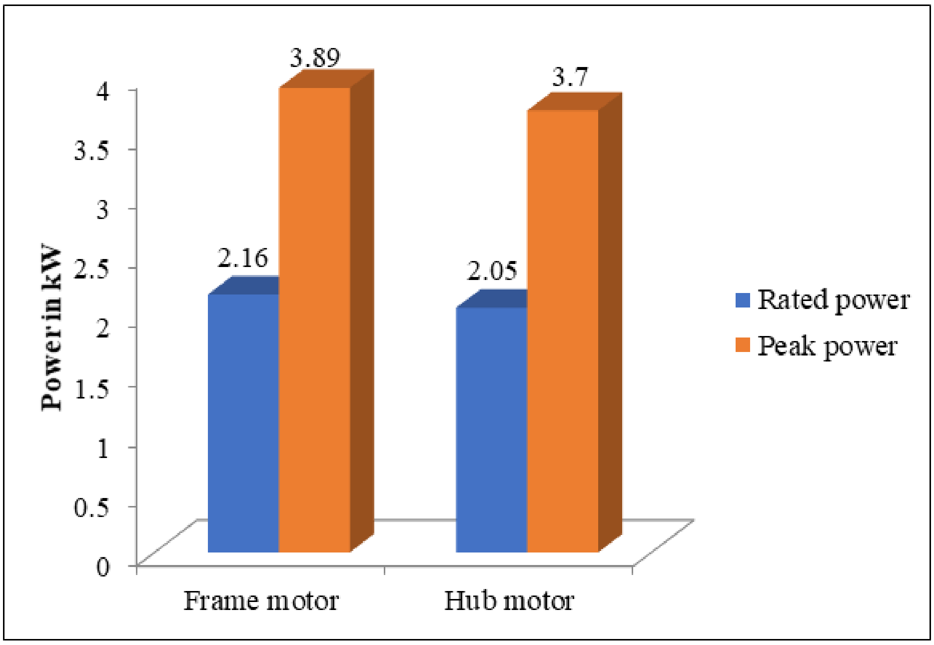


Figure 8.46: Power ratings of the frame and hub motor for a Honda Activa 01

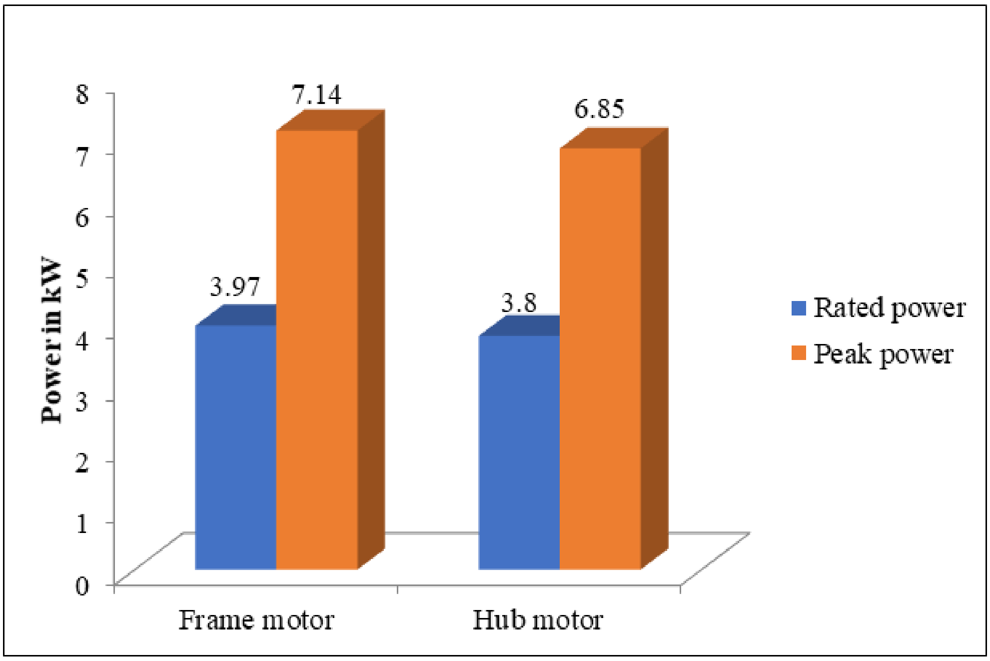


Figure 8.47: Power ratings of the frame and hub motor for a Honda Activa 02

8.2.4 Mid-range bikes

This study considers two different mid-range bikes, a Hero Honda Splender Plus and a Hero Honda Passion Pro. The power ratings of Hero Honda Passion

Pro (4.45kW and 4.23 kW for the frame and hub motor, respectively) are higher than that of Hero Honda Splender Plus (1.43 kW and 1.53 kW for the frame and hub motor, respectively), as seen from Figure 8.48 and Figure 8.49. Unlike other two-wheeler types, the power ratings of hub motors for a Hero Honda Splender Plus are higher than that of frame motors.

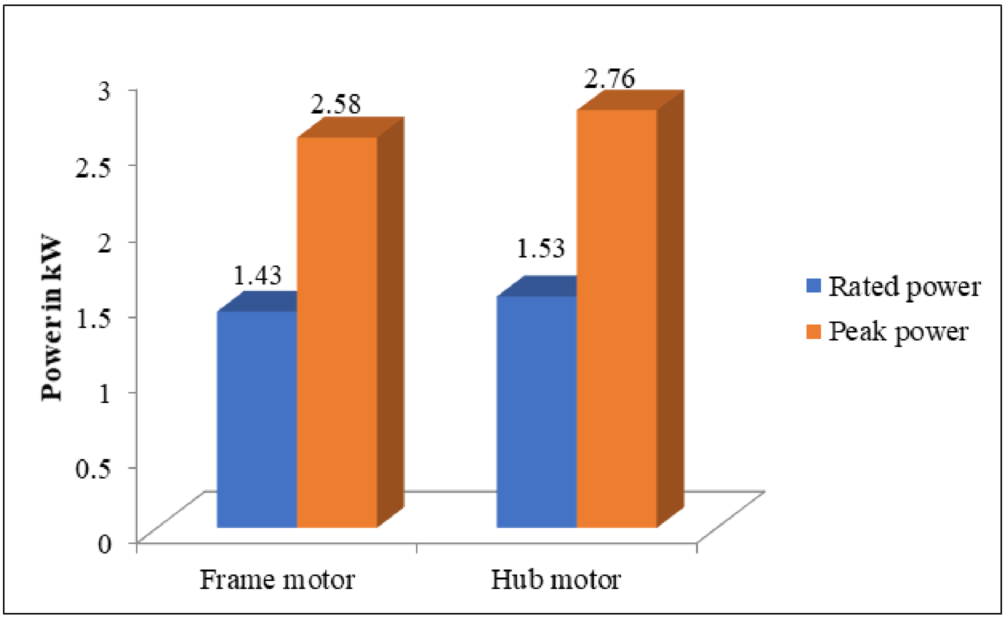


Figure 8.48: Power ratings of the frame and hub motor for a Hero Honda Splender Plus

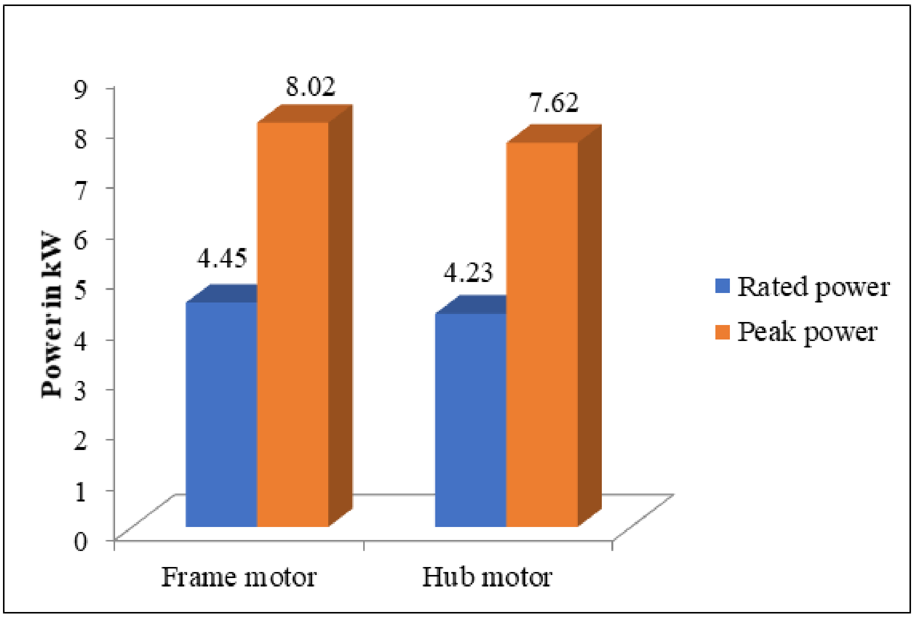


Figure 8.49: Power ratings of the frame and hub motor for a Hero Honda Passion Pro

8.3 Gradeability analysis

In this chapter, the performance characteristics of the motor or analysis of the torque requirement of the motor for the different categories of bikes due to varying road gradients will be discussed. The upgradient of the road offers gradient resistance which increases the motor torque to maintain the acceleration. This leads to more energy consumption and emissions. There can be a trade-off between acceleration and the motor's energy consumption, which will be discussed in this chapter. The torque-gradient characteristics can be analyzed under two conditions: constant acceleration and constant velocity. The analysis is carried out for all four categories of bikes. Three upgradient conditions like 5%, 10%, and 15%, which have gradient angles of $2.86°$, $5.71°$, and $8.53°$, respectively, are considered here. For analysis, three sets of constant acceleration for various bike categories are selected, and an assumed constant velocity of 30kmph, 40kmph, and 50kmph for all bike categories.

8.3.1 Retro bikes

The first bike category is Retro bike, with Royal Enfield Classic 350 for analysis. The torque gradient characteristics graph for different constant accelerations and velocities is given in Figures 8.50 and 8.51.

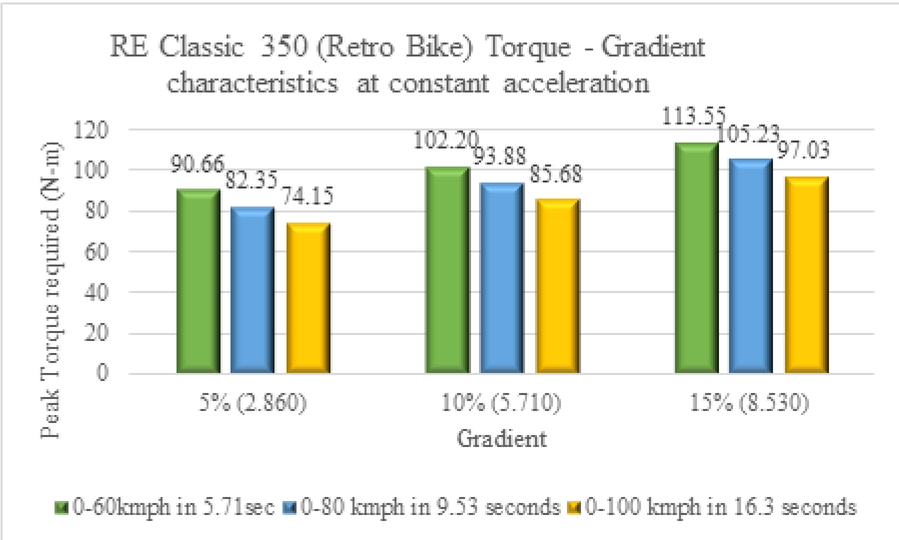


Figure 8.50: Torque-Gradient characteristics for RE Classic 350 at constant accelerations.

Here three constant accelerations considered are 0-60kmph in 5.71 seconds, 0-80kmph in 9.53 seconds and 0-100kmph in 16.3 seconds which has an acceleration value of 2.9188 m/s2, 2.3318 m/s2 and 1.7041 m/s2 respectively. The torque required at 0% gradient is 59.4Nm. The graph clearly shows that with increased gradient, peak torque requirement increases from 59.4N-m to 113.55N-m, approximately 90% more. This high torque demands the overdesigning of the motor and decreased motor efficiency under normal running conditions. A solution to this problem can be achieved by compromising on the acceleration. With a reduced acceleration of 1.7041 m/s2 (0-100kmph in 16.3 seconds), the peak torque required at 15% gradient gets reduced by 27% to 97.03N-m, which is nearly 63% of normal condition peak torque.

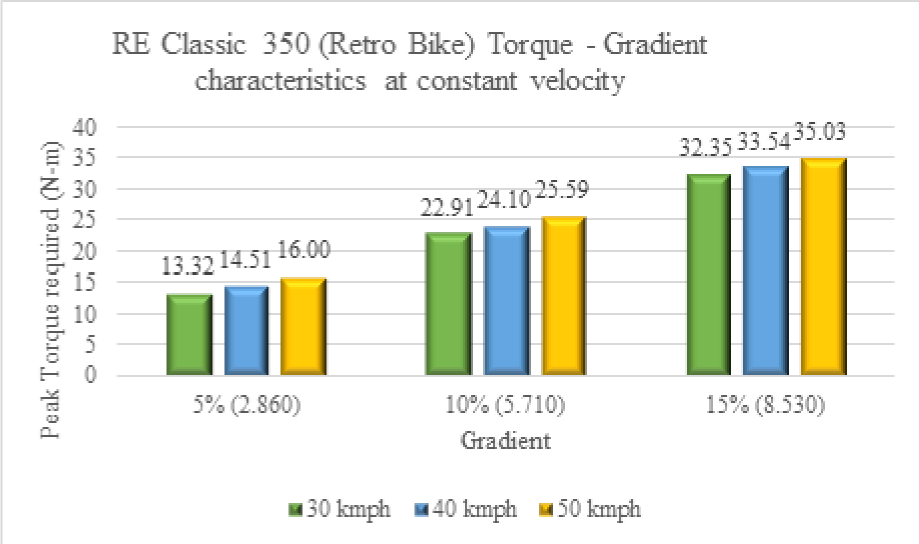


Figure 8.51: Torque-Gradient characteristics for RE Classic 350 at constant velocity.

The above torque-gradient characteristics at constant velocity show that the required peak torque keeps increasing with an increase in speed and gradient value.

8.3.2 Sports bike

In this category, two bikes, Honda CB Shine and Bajaj Discover have driven in rural and urban environments, respectively, are analyzed. The torque-gradient characteristics of CB shine are given in Figures 8.52 and 8.53.

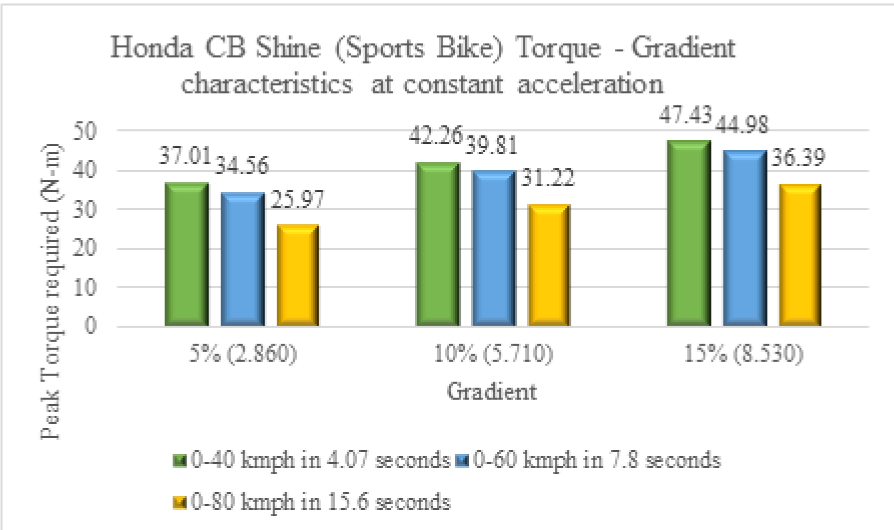


Figure 8.52: Torque-Gradient characteristics for Honda CB Shine at constant accelerations.

The above graph shows that the peak torque requirement increases to 47.43Nm (at 15% gradient) from 27Nm (0% gradient), which is a 76% increase. With a compromised reduced acceleration of 1.424 m/s2 at 0-80kmph in 15.6 seconds, the required peak torque can be reduced to 36.39Nm, which is 35% more than 0% gradient peak torque.

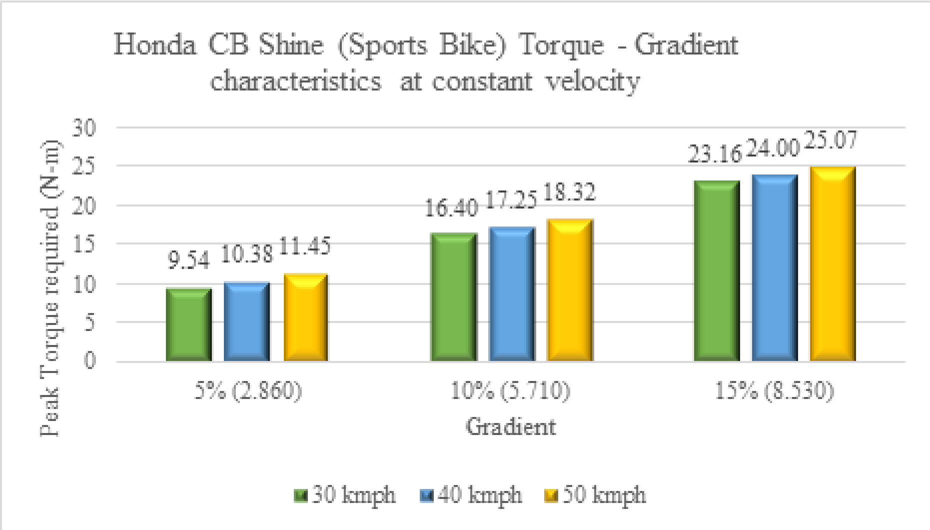


Figure 8.53: Torque-Gradient characteristics for Honda CB Shine at constant velocity

Similarly, with the constant velocity, it can be found that with increasing gradient and velocity, peak torque requirement rises.

Another sports bike, Bajaj Discover, has driven in urban conditions; its torque-gradient characteristics are plotted in Figures 8.54 and 8.55, respectively, for constant acceleration and velocity.

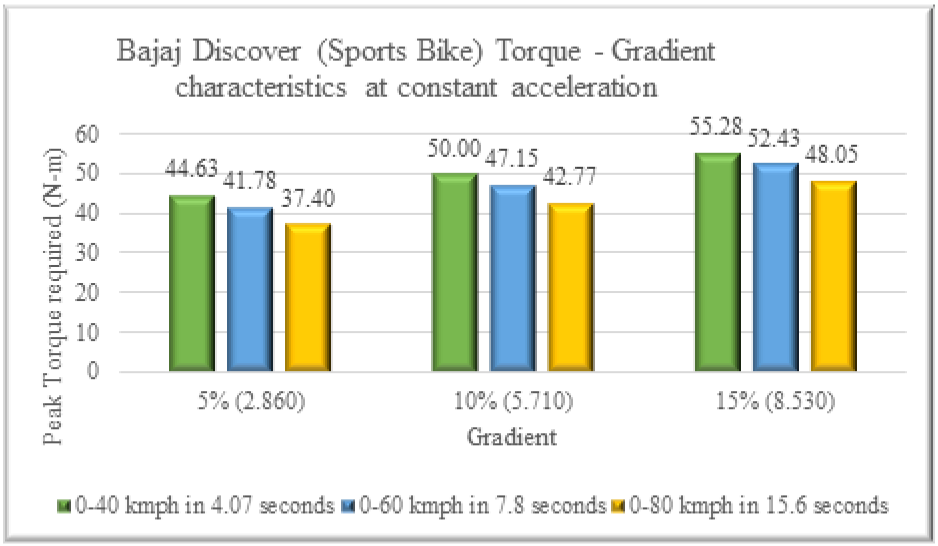


Figure 8.54: Torque-Gradient characteristics for Bajaj Discover at constant accelerations.

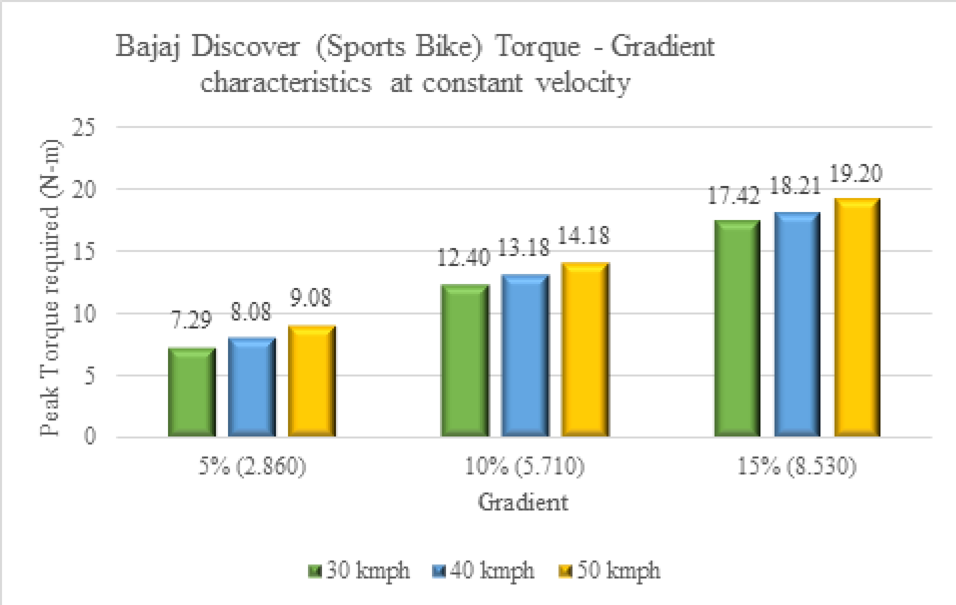


Figure 8.55: Torque-Gradient characteristics for Bajaj Discover at constant velocity

Observing figure 8.54, it is evident that the peak torque at 15% gradient increases to 55.28Nm from 23.40Nm at 0%gradient with an increase in gradient. This increase is about 136%. And it can be reduced by 31% using the compromised acceleration of 2.116m/s2 at 0-80kmph in 15.6 seconds, where the peak torque reduces to 48.05Nm, i.e., 105% more of the average torque value. Also, observing the torque gradient characteristics with a constant velocity plot, it is clear that increased velocity and gradient peak torque increases.

Comparing the two-sports bike considered, as Honda CB Shine was driven at the rural condition and its rated peak torque is slightly more than Bajaj Discover, over designing of the motor peak torque requirement at 15% gradient is much lower (35%) compared to Bajaj Discover (105%).

8.3.3 Mid-range bike

In this section, two bikes of Hero Honda make Splendor Plus and Passion pro, which are driven in rural and urban environments, respectively. The torque-gradient characteristics of Splendor Plus are shown in Figures 8.56 and 8.57.

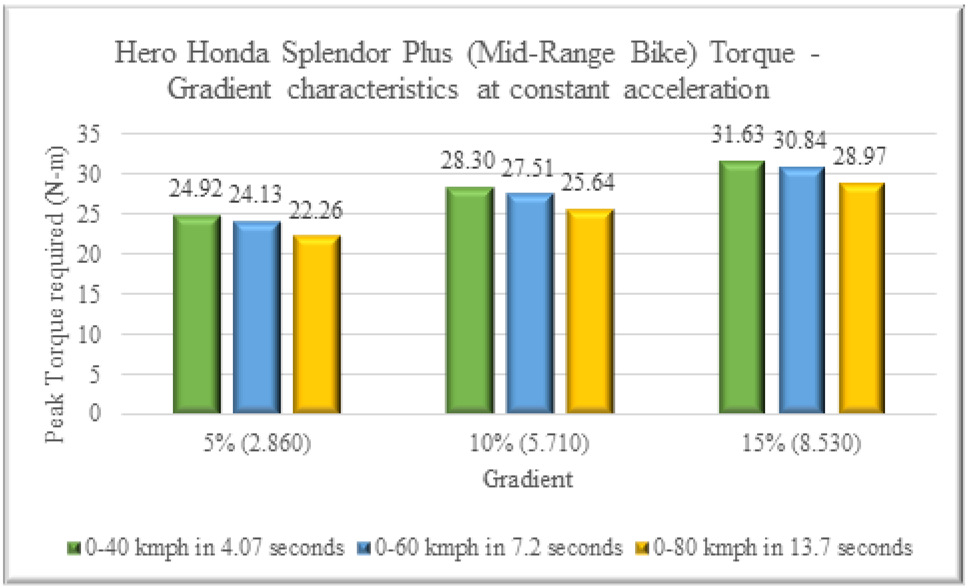


Figure 8.56: Torque-Gradient characteristics forHero Honda Splendor Plus at constant accelerations.

Observing figure 8.56, it is evident that with an increase in gradient, the peak torque at 15% gradient increases to 31.63Nm from 21.60Nm at 0% gradient. This increase is about 46%. And it can be reduced by 12% using the compromised acceleration of 1.622m/s2 at 0-80kmph in 13.7seconds where the peak torque reduces to 28.97Nm, i.e., 34% more of average torque value. Also, observing the torque gradient characteristics with a constant velocity plot, it is clear that increased velocity and gradient peak torque increases.

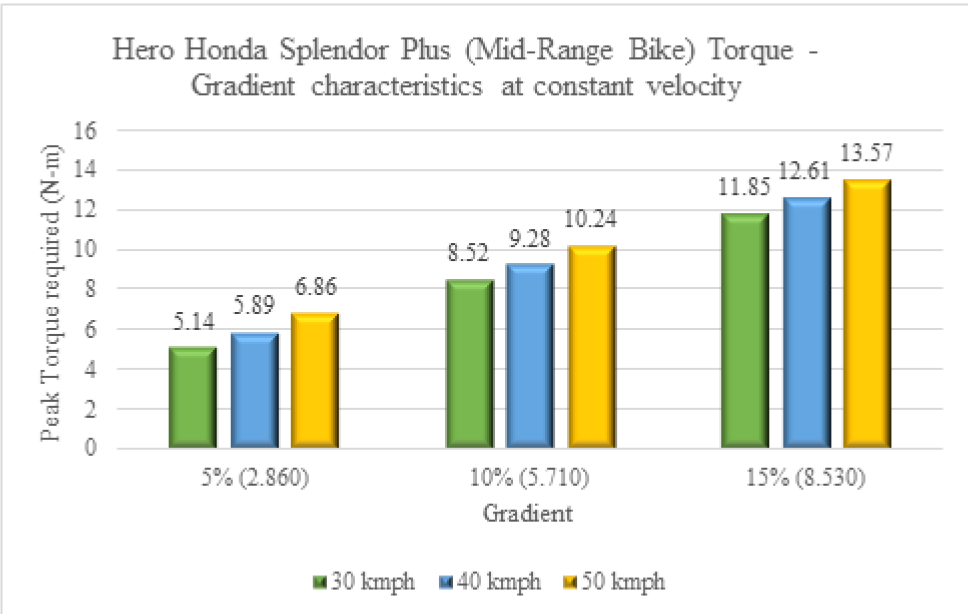


Figure 8.57: Torque-Gradient characteristics for Hero Honda Splendor Plus at constant velocity

Another mid-range bike, Hero Honda Passion Pro, is driven in urban conditions; its torque-gradient characteristics are plotted in Figures 8.57 and 8.58, respectively, for constant acceleration and velocity.

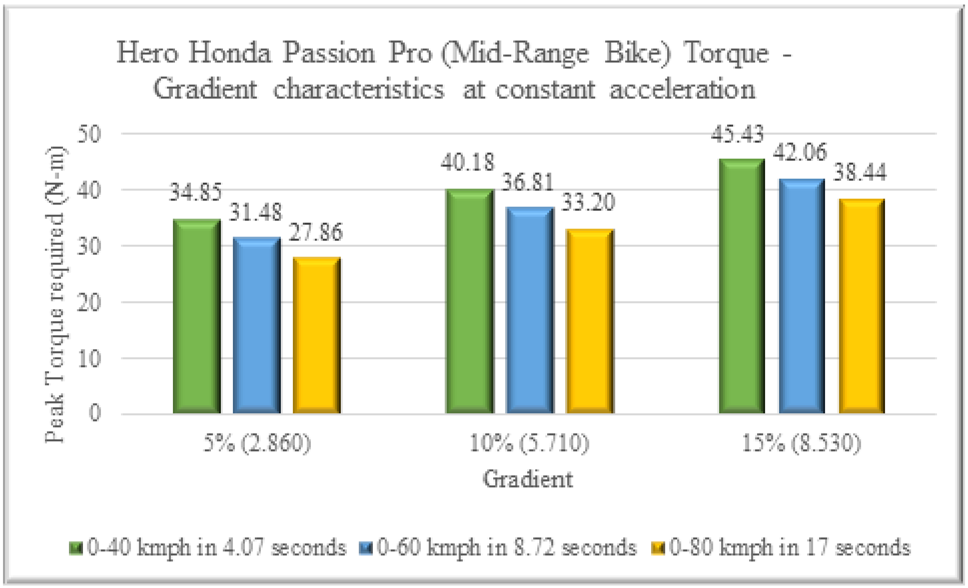


Figure 8.58: Torque-Gradient characteristics for Hero Honda Passion Pro at constant accelerations.

The above graph shows that the peak torque requirement increases to 45.43Nm (at 15% gradient) from 32.40Nm (0% gradient), which is a 40% increase. With a compromised reduced acceleration of 1.307 m/s2 at 0-80kmph in 17 seconds, the required peak torque can be reduced to 38.44Nm, which is 19% more than the 0% gradient peak torque

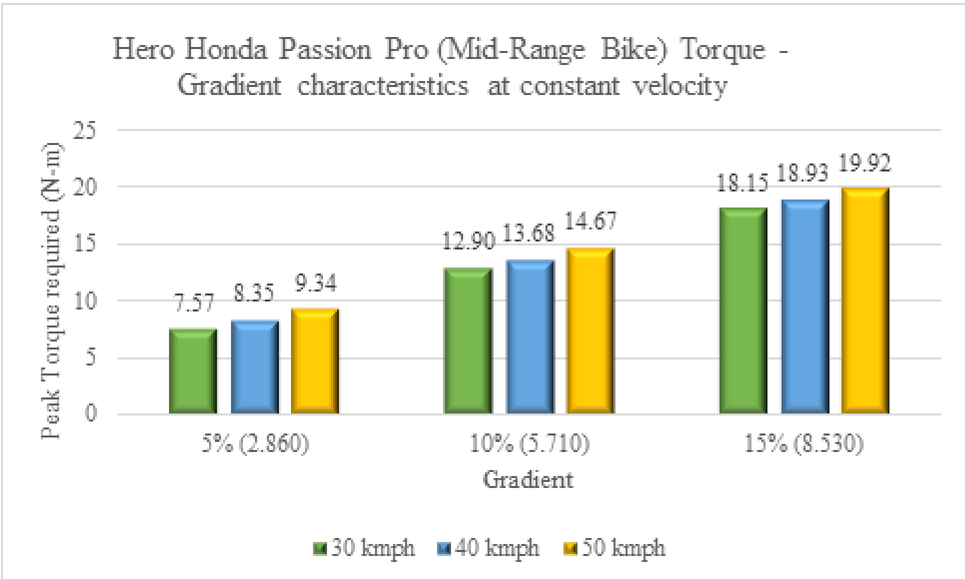


Figure 8.59: Torque-Gradient characteristics for Hero Honda Passion Pro at constant velocity

Similarly, with the constant velocity, it is found that with increasing gradient and velocity, peak torque requirement rises.

Comparing the mid-range bikes considered, Hero Honda Splendor Plus was driven in rural conditions. Its rated peak torque is slightly more than Hero Honda Passion Pro. Over designing the motor, peak torque requirement at

15% gradient is much higher (34%) than Hero Honda Passion Pro. (19%).

8.3.4 Commute scooters

Two Honda Activa bikes, both driven by an urban environment, are considered for analysis in this category. The torque-gradient characteristics of Honda Activa 01 are given in Figures 8.60 and 8.61.

The above graph shows that the peak torque requirement increases to 47.50Nm (at 15% gradient) from 34.2Nm (0% gradient), which is a 39% increase. With a compromised reduced acceleration of 1.646 m/s2 at 0-80kmph in 15.6 seconds, the required peak torque can be reduced to 41.10Nm, 20% more than 0% gradient peak torque.

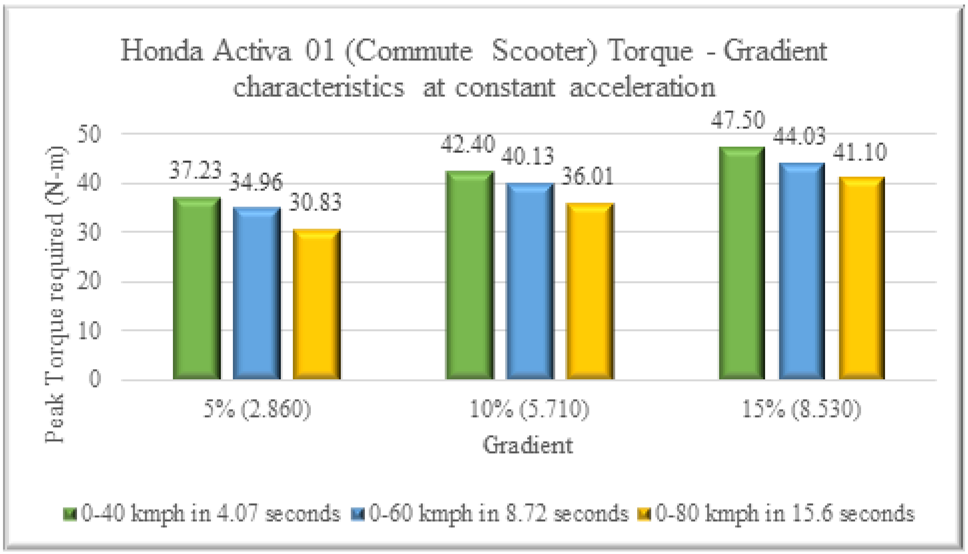


Figure 8.60: Torque-Gradient characteristics for Honda Activa 01 at constant accelerations.

Similarly, with constant velocity, it is found that with increasing gradient and speed, peak torque requirement rises.

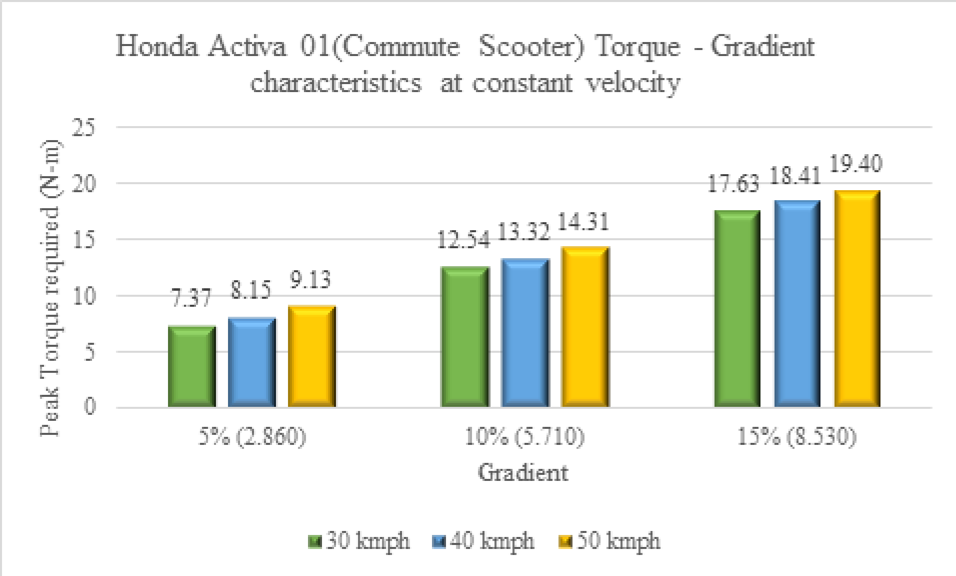


Figure 8.61: Torque-Gradient characteristics for Honda Activa 01 at constant velocity

Another commute scooter Honda Activa 02, driven in urban condition, its torque-gradient characteristics are plotted in Figures 8.62 and 8.63, respectively, for constant acceleration and velocity.

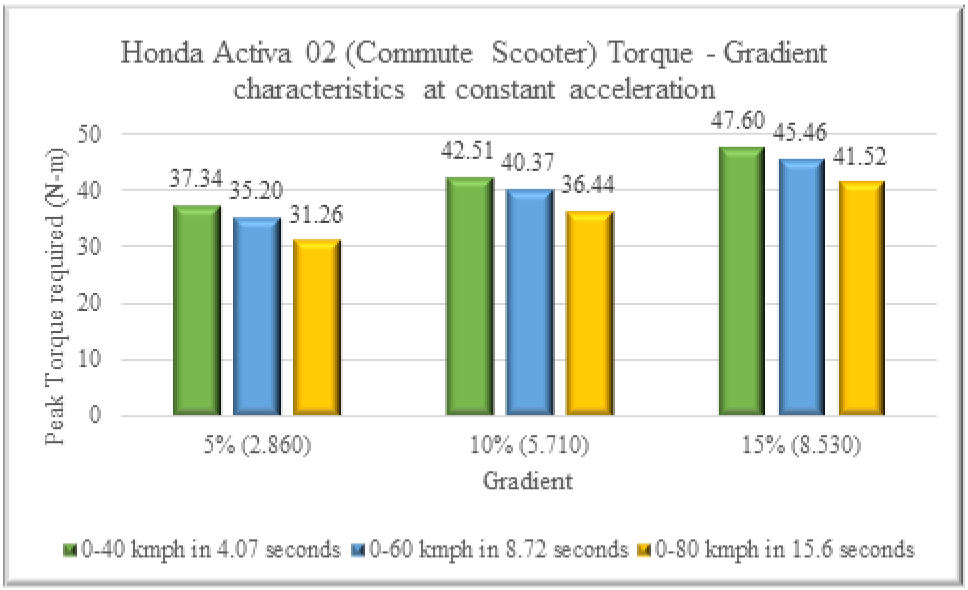


Figure 8.62: Torque-Gradient characteristics for Honda Activa 01 at constant accelerations.

Observing figure 8.62, we can depict that the peak torque at 15% gradient increases to 47.60Nm from 34.2Nm at 0%gradient with an increase in gradient. This increase is about 39%. And it can be reduced by 19% using the compromised acceleration of 1.646m/s2 at 0-80kmph in 15.6 seconds, where the peak torque reduces to 41.52 Nm, which is 21% more of average torque value.

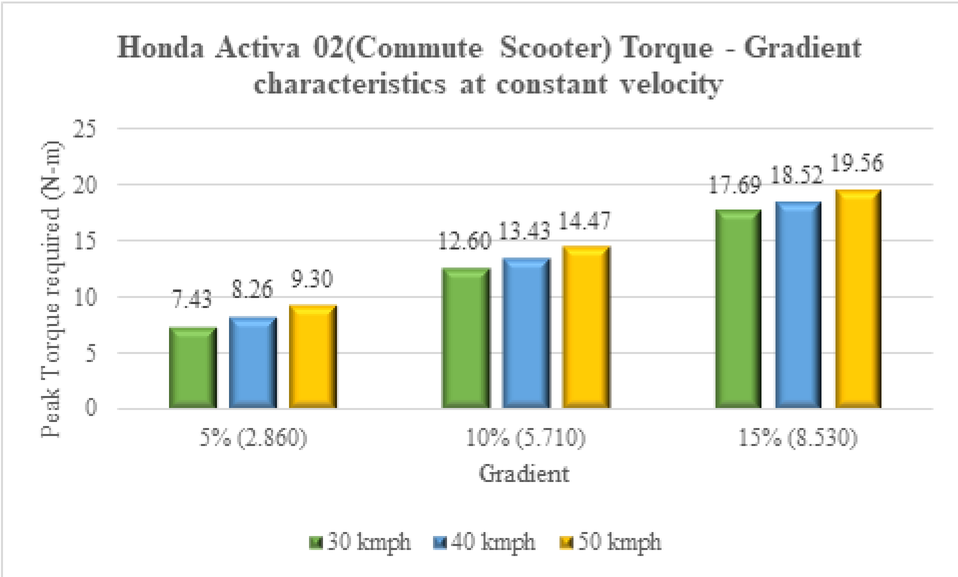


Figure 8.63: Torque-Gradient characteristics for Honda Activa 01 at constant velocity

Observing fig. 8.63, we can say that with constant velocity, increasing gradient and velocity peak torque requirement increases.

Summarising the above analysis, a graph is plotted as shown below in figure 8.64, which shows the percentage increase in the peak torque at 15% gradient and peak torque required with reduced acceleration.

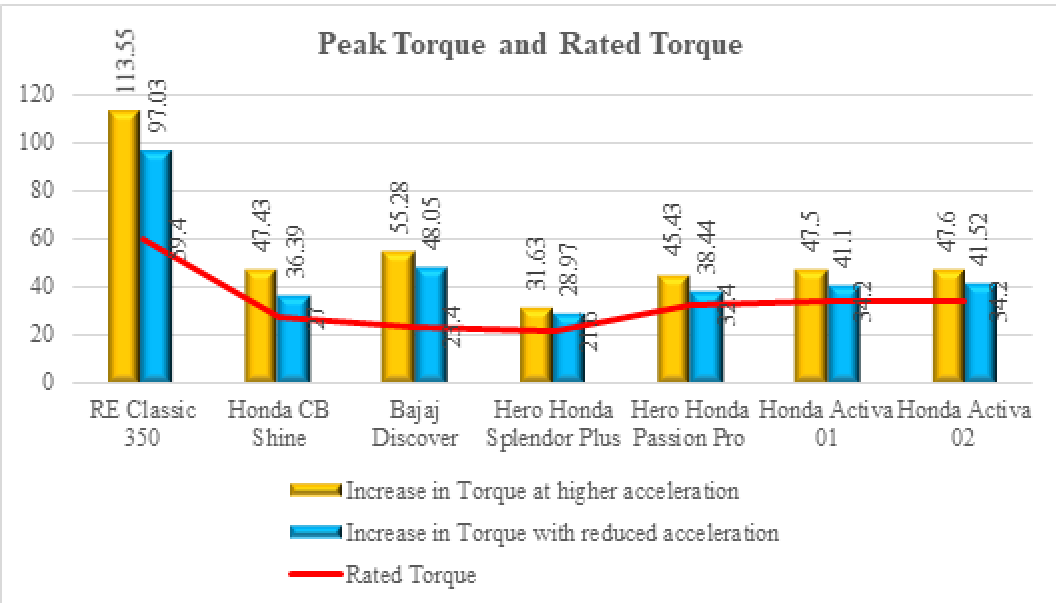


Figure 8.64: Summary of peak torque requirement with different accelerations.

It is observed that in every bike category with a reduced acceleration profile, the required peak torque value gets reduced. The Red line shows the rated torque requirement for normal running conditions. So, with reduced acceleration, the motor rating can be diminished, and the motor's efficiency will increase.

8.4 Acceleration analysis

8.4.1 Selection of acceleration profile

In this section, the acceleration profile of all four bike categories is discussed. This analysis gives a clear idea of the frequency or number of times the bike has reached a specific acceleration or deceleration range over the entire drive cycle.

The acceleration groups for retro bikes, i.e., RE Classic 350, are shown in figure 8.65. It is observed that 41.07% of times acceleration happens in the 0 to 0.5 m/s2 range. This bike is driven in city limits with less traffic density, so higher acceleration frequency is shallow. Also, the deceleration rate is less due to smooth braking in a low traffic density environment. So, with these kinds of acceleration profiles, one can go with the economy mode of operation with reduced acceleration and torque requirement and can operate the motor at higher efficiency.

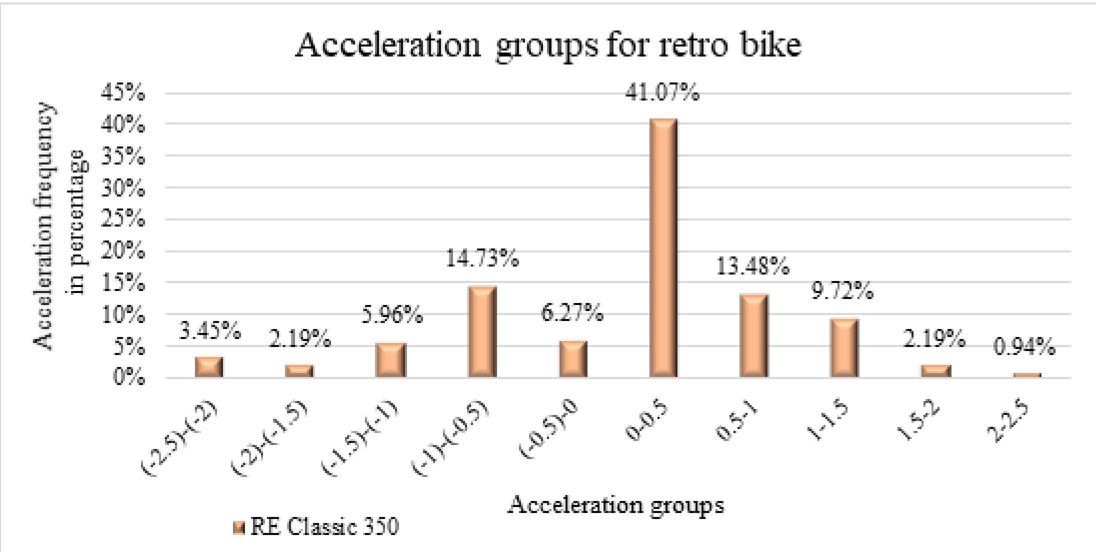


Figure 8.65: Acceleration groups for retro bikes

The acceleration groups of the second category of bike, i.e., sports bike, are shown in figure 8.66. All three bikes, Honda CB Shine, TVS Radeon, and Bajaj Discover, have their acceleration groups at 0 to 0.5 m/s2 range and deceleration at -0.5 to 0 m/s2 range. Maximum acceleration and deceleration frequency are low for all the bikes except Honda CB Shine. So there is a lot of scopes to operate these bikes at reduced acceleration mode and improve the bikes' energy efficiency.

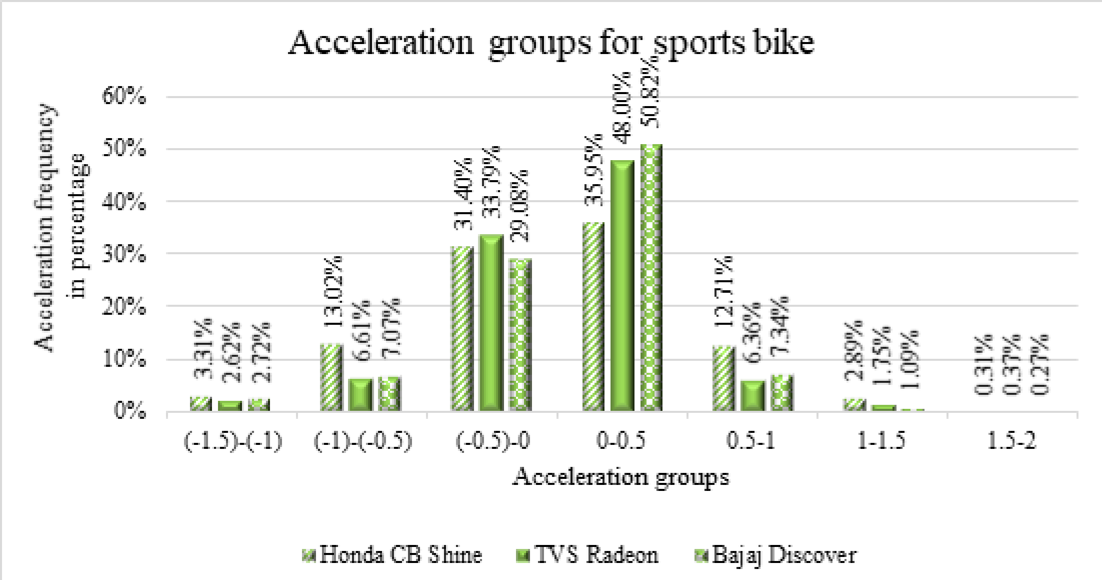


Figure 8.66: Acceleration groups for sports bikes

In the mid-range bike category, we have considered four bikes out of which splendor plus and CD Delux and driven in a rural environment. In contrast, Star City and Passion pro are driven in the city environment. Their acceleration profiles are shown in figure 8.67 below.

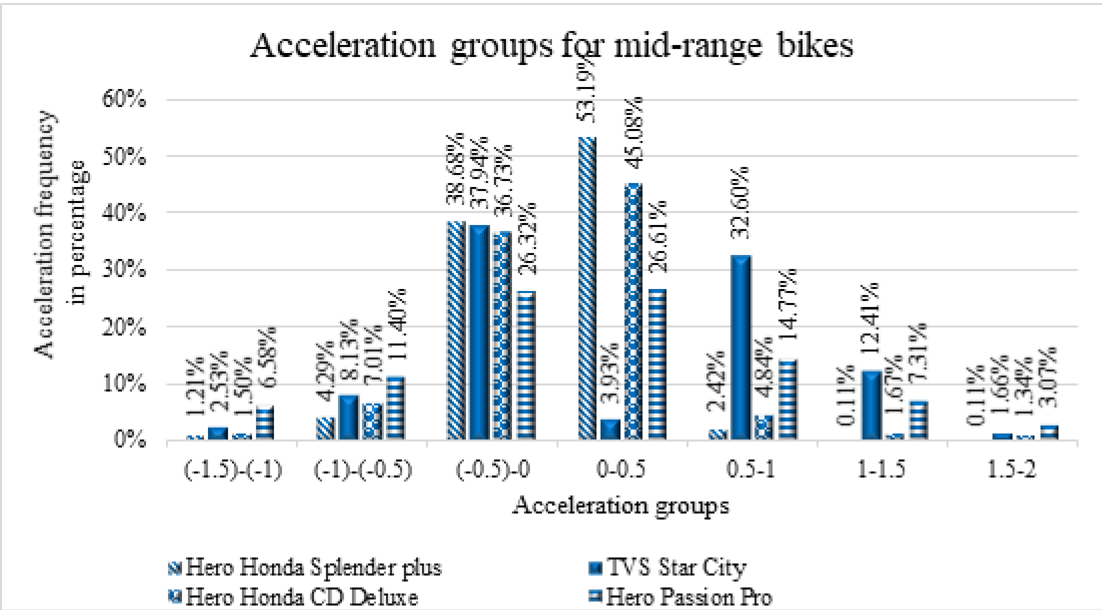


Figure 8.67: Acceleration groups for mid-range bikes

It can be observed that splendor plus and CD Delux, which are rurally driven, have their acceleration group in the 0 to 0.5 m/s2 range. But for Star City, the acceleration rate is higher in the 0.5 to 1 m/s2 range. This is due to high-density city traffic conditions. For Passion pro, the acceleration group is not increased as other bikes in the 0 to 0.5 m/s2 range; instead, it has shared it also in the 0.5 to 1 m/s2 range, which also reflects the high city traffic condition. The deceleration profile shows that all the bikes have a maximum frequency at -0.5 to 0 m/s2 range.

The last category, i.e., commute scooter's acceleration group, is plotted below in figure 8.68. Here two Honda Activa scooters are driven urban conditions.

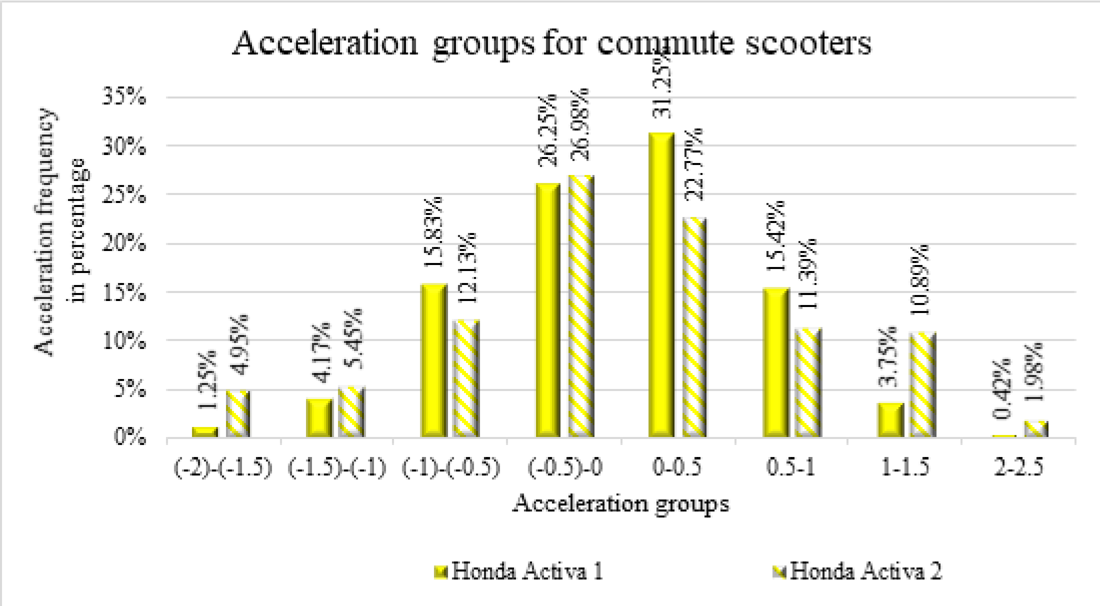


Figure 8.68: Acceleration groups for commute bikes

Both the bikes have a maximum acceleration frequency at 0 to 0.5 m/s2 range. But, a considerable amount of acceleration can also be found at 0.5 to 1 m/s2 and 1 to 1.5 m/s2 range. This clearly shows that sudden high accelerations are required for high traffic density city conditions. Also, though deceleration is maximum at -0.5 to 0 m/s2 range, there is a considerable amount of deceleration at other fields, suggesting the traffic condition requires sudden braking.

8.4.2 Acceleration torque calculations

This section analyzes the torque required for different bike categories with frame induction motor and hub motor. The analysis also considers two different acceleration rates, namely sports mode and economy mode. In sports mode, the acceleration rate is considered per the actual values derived from the drive cycle data. Whereas the economy mode values are proposed values compromising with acceleration rates to reduce the motor torque requirements and improve the efficiency of the motor operation. A graph is plotted to understand and analyze the same, as shown in figure 8.69 below.

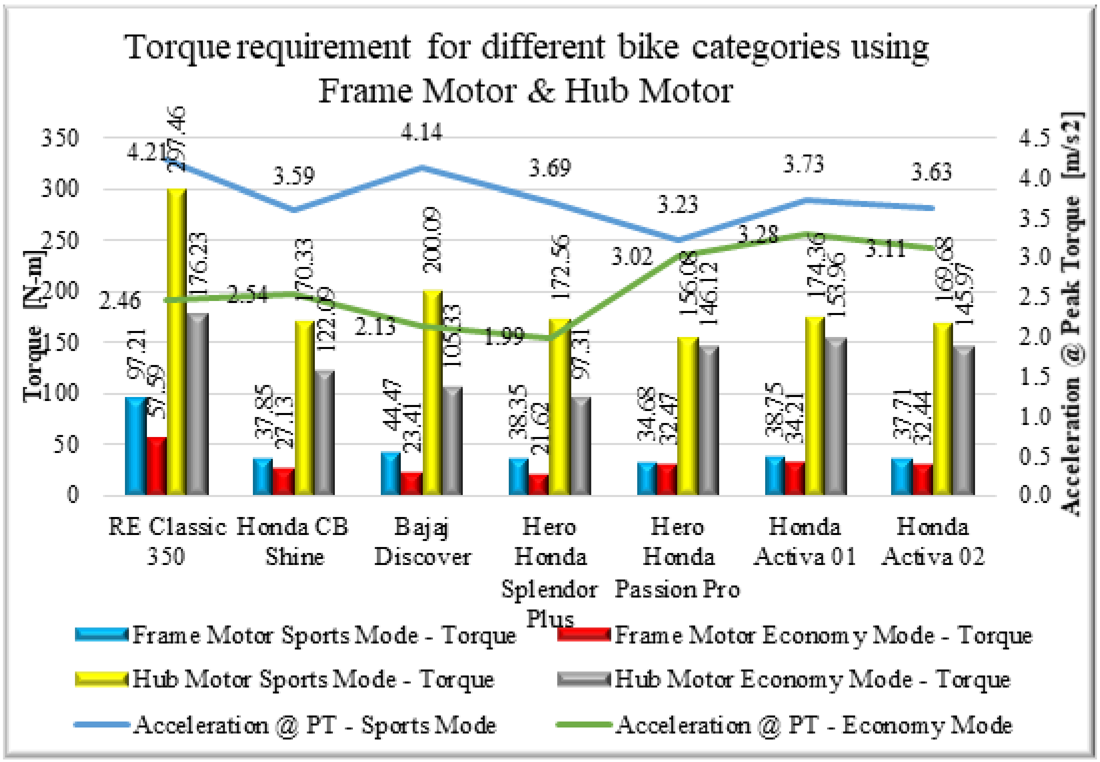


Figure 8.69: Torque requirements using Frame and Hub motor at sports and economy acceleration mode.

It is very much evident from the graph that the frame motor requires lesser peak torque compared to the hub motor. Also, the Torque requirement for economy mode with reduced acceleration requires a lower peak torque than sports mode acceleration, so the motor's efficiency also increases. This can highly benefit the electric bikes to have relatively small motors, which will improve the driving range of the bikes.

Observing the graph more clearly, retro and sports bikes have a significant difference in the acceleration values in sports and economy mode. So, there is a considerable difference in torque values in sports and economy mode in these two bike categories. In comparison, this difference is negligible in mid-range and commute scooters though they are driven both in urban and rural environments. So huge potential is found in the retro and sports bike category on energy saving.

8.5 Summary

This chapter discusses torque-speed characteristics and motor characteristics of hub and frame motors derived from the drive cycle analysis of different categories of two-wheelers. The speed of hub motors is low due to the absence of a gear box. As a result of the inverse relationship between speed and torque, hub motors deliver significantly higher torque than frame motors. This feature of hub motors is demonstrated in this chapter.

This chapter also contains the discussion on the power rating requirements of hub motors which is lower than that of frame motors for the same drive cycle irrespective of the type of two-wheelers. The variation in power requirements with variation in drive cycle is seen from the drive cycle analysis of Honda active 01 and Honda Activa 02. The power requirement for the former is 2.16 kW (frame motor) and 2.05 kW (hub motor), whereas that of the latter is 3.97 kW for frame motor and 3.8 kW for hub motor. Among the drive cycles of different two-wheelers considered, the most significant motor rated 5.15 kW corresponds to the drive cycle of RE Classic 350, and the smallest with the rating of 1.43 kW corresponds to that of Hero Honda Splender Plus.

9 Battery sizing

9.1 Introduction

The rise in the price of fossil fuels and increasing concerns over global warming have shifted focus towards electric vehicles and accelerated research on batteries in the last couple of years. This chapter addresses the battery requirements for various types of two wheelers consisting of different motor combinations. This study categorised the two wheelers as sports bikes, retro bikes, daily commute scooters, and mid-range bikes. Battery parameters such as battery size, optimal power, weight and capacity are compared for a sports bike, retro bike, commute scooter and mid-range bike. Following battery specifications are considered for calculation: Nominal voltage = 72V, Specific energy = 200 W/kg, battery utilization factor = 0.8. The different motor types under consideration are induction motor (IM), hub induction motor (IM Hub), permanent magnet synchronous motor (PMSM), permanent magnet synchronous hub motor (PMSM Hub), synchronous reluctance motor (Sync Rel), synchronous reluctance hub motor (Sync Rel Hub)

9.2 Battery pack calculations

For analysis, efficiency maps of three different motors, Induction Motor (IM), Permanent Magnet Synchronous Motor (PMSM) and Synchronous Reluctance Motor (Sync.Rel) are considered. The efficiency maps of these motors are shown in chapter 10. From the efficiency maps, the entire drive train efficiencies such as Motor efficiency and converter efficiency at corresponding operating points of the vehicle are calculated.

9.2.1 Force calculation

With the obtained drive-train efficiencies, both inverter and motor input powers are calculated. As inverter input is the battery output, the total energy consumption (in kWh) is obtained by calculating individual energy consumption at every operating point in the drive cycle considering the converter and motor efficiencies.

Battery pack weight (in kg) and size (in kWh) can then be calculated with the obtained energy consumption (in kWh) for the drive cycle considered by assuming specific power (in W/kg) and for a fixed nominal voltage (in V) of the battery pack.

$$F_w = \frac{1}{2} A_f C_D r v^2$$

Where, 'A_f' is the frontal area of the vehicle in 'm^2', 'C_D' is the aerodynamic drag coefficient of the vehicle, r is the radius of wheel in 'm' and 'v' is speed of the vehicle in 'm/s'

$$F_g = Mg \sin(\alpha)$$

Where, ‘M’ is the total mass of the vehicle including kerb weight and payload weight in ‘kg’, ’g’ is Gravitation acceleration constant in ‘m/s^2’, ‘α’ is the road angle in degree.

$$F_a = Ma$$

Where, ‘M’ is the total mass of the vehicle including kerb weight and payload weight in ‘kg’, ‘a’ is the acceleration of the vehicle.

$$F_r = f_r Mg \cos(\alpha)$$

Where, ‘f_r’ is the coefficient of rolling resistance, ‘M’ is the total mass of the vehicle including kerb weight and payload weight in ‘kg’, ’g’ is Gravitation acceleration constant in ‘m/s^2’, ‘α’ is the road angle in degree.
The total force can then be calculated as

$$F = F_w + F_g + F_a + F_r$$

9.2.2 Energy consumption calculation

From the force obtained, the torque at the wheel is calculated as follows.

$$T_{wheel} = Fr$$

Where ‘F’ is the total force acting on the vehicle in ‘N’ and ’r’ is the radius of wheel in ‘m’. The torque and speed at the motor is then calculated considering the gear ratio (G.R) and gear efficiency ‘η_g’.

$$T_{motor} = \frac{T_{wheel}}{G.R \times \eta_g}$$

$$\omega_{motor} = \omega_{wheel} \times G.R$$

The output powers of Motor, Inverter and Battery are then calculated considering the weighted mean efficiencies of Motor and Inverter.

$$P_{motor} = T_{motor} \times \omega_{motor}$$

$$P_{inv} = \frac{P_{motor}}{\eta_{motor}}$$

$$P_{batt} = \frac{P_{inv}}{\eta_{inv}}$$

Total energy consumption is then calculated by summation of energy consumptions at individual operating points in 'kWh'.

$$E_{total}\,(kWh) = \sum \frac{P_{batt}(W)}{1000 \times 3600}$$

9.2.3 Battery attributes calculations

With the calculated total energy consumption and assumed battery utilization factor (U.F), various parameters like mileage (kWh/km), battery size (kWh), battery weight (kg), battery capacity (Ah) and usable battery capacity (Ah) can be obtained.

$$Mileage(kWh/km) = \frac{E_{total}}{Length\ of\ drive\,cycle(km)}$$

$$Battery\,Size(kWh) = Mileage(kWh/km) \times Range(km)$$

$$Optimal\,battery\,power(kW) = Battery\,size(kWh) \times Optimal\,C - rate$$

$$Battery\,weight(kg) = \frac{Optimal\,battery\,power(W)}{Specific\,energy\,of\,battery(W/kg)}$$

$$Battery\,capacity(Ah) = \frac{Battery\,size(kWh)}{Battery\,voltage(V)}$$

$$Usable\,capacity(Ah) = Battery\,capacity\,(Ah) \times U.F$$

9.3 Sports bike

This section considers a scenario where the ICE of a Honda CB Shine 125 cc and Bajaj Discover are replaced by different motor types mentioned above. From the graphs below, it is inferred that among different motor types considered here, a PMSM would require the smallest battery, whereas an IM Hub would require the largest battery to meet the same range requirements.

9.3.1 Honda CB Shine 125 cc

The battery requirement for various motor types in increasing order is as follows: PMSM > Sync Rel > PMSM Hub > Sync Rel Hub> IM > IM Hub i.e., a PMSM with a 4.85kW battery weighing about 24.27kg would run a Honda CB Shine for 100 km on a single charge, whereas an IM Hub would require a 5.66 kW battery which weighs around 28.28 kg to meet the same requirement.

Figure 9.1: Battery pack ratings (in kWh) for various motor configurations at different range requirements - Honda CB Shine 125 cc

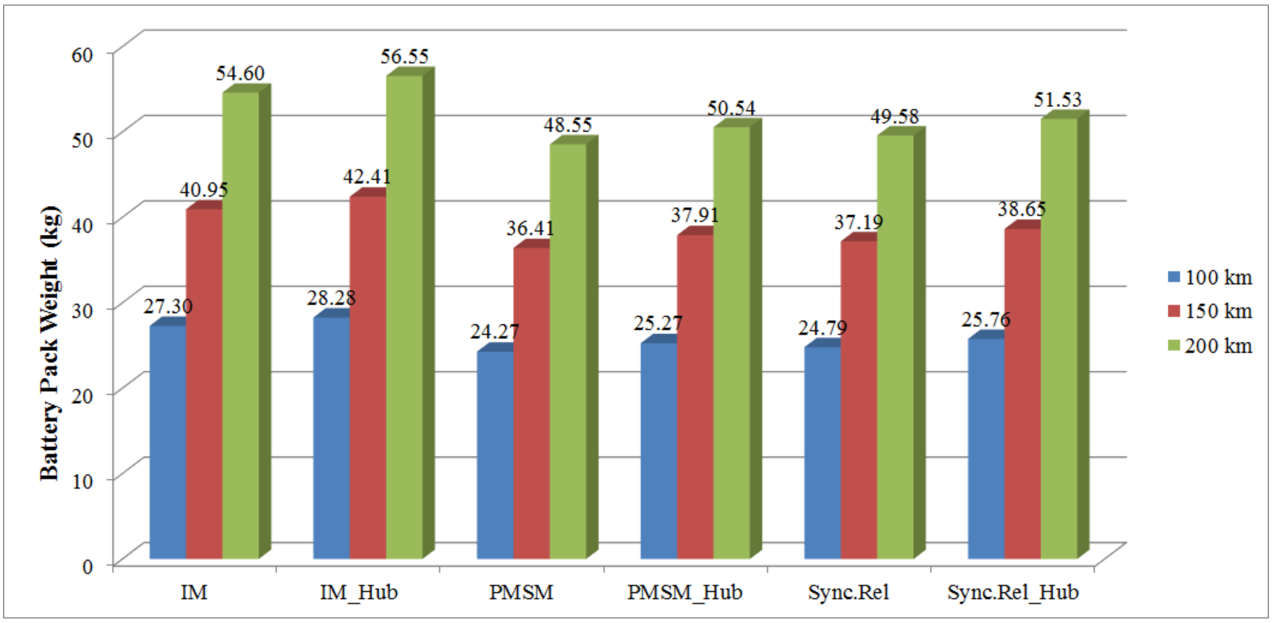


Figure 9.2: Battery pack weight (in kg) for various motor configurations at different range requirements - Honda CB Shine 125 cc

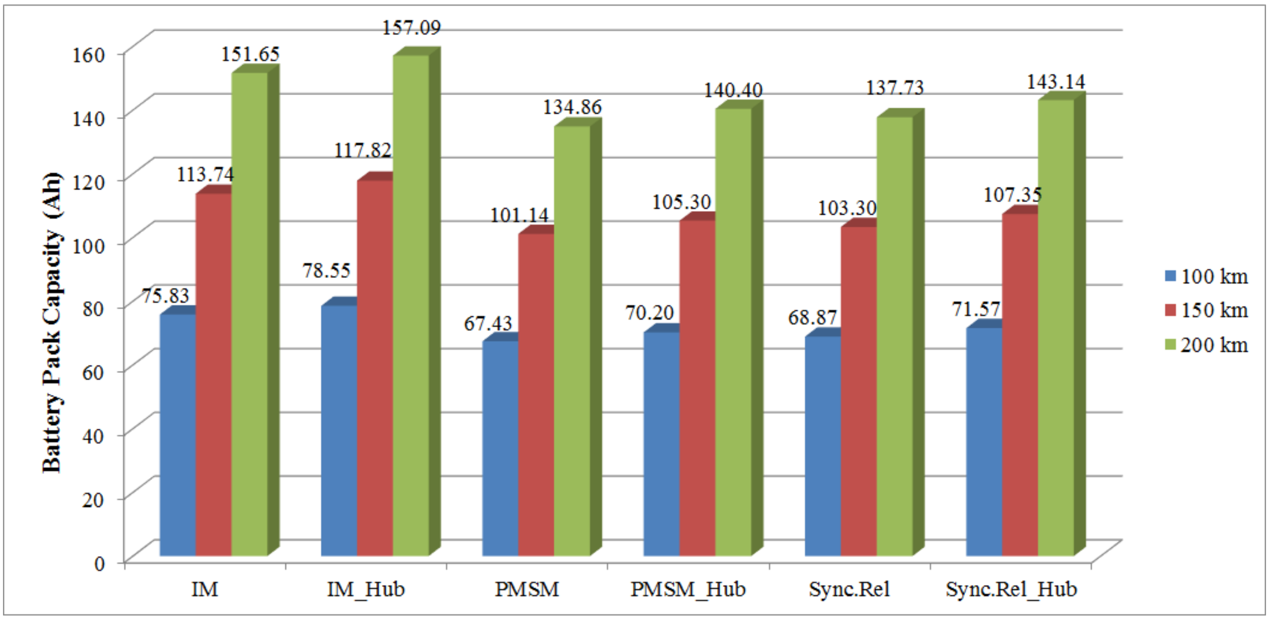


Figure 9.3: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Honda CB Shine 125 cc

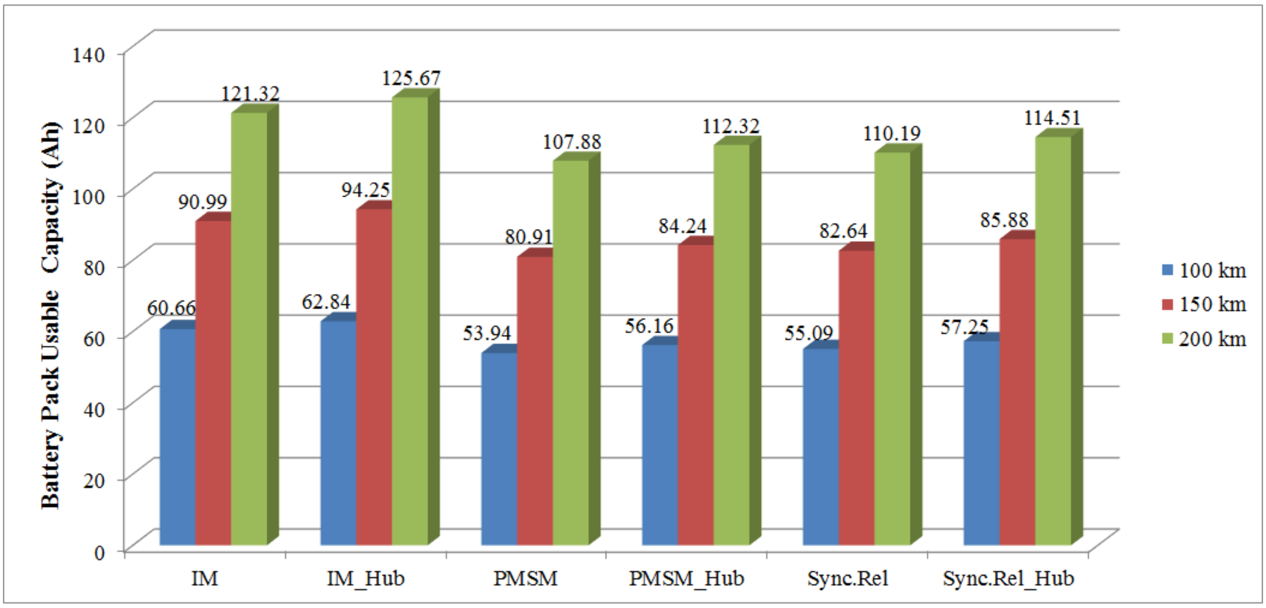


Figure 9.4: Battery pack usable capacity (in Ah) for various motor configurations at different range requirements - Honda CB Shine 125 cc

9.3.2 Bajaj Discover

The order of battery requirement for different motors remains the same as above i.e, PMSM driven two wheeler requires a smaller battery compared to all other motor types. Overall, a Bajaj Discover requires a slightly smaller battery as compared to a Honda CB Shine.

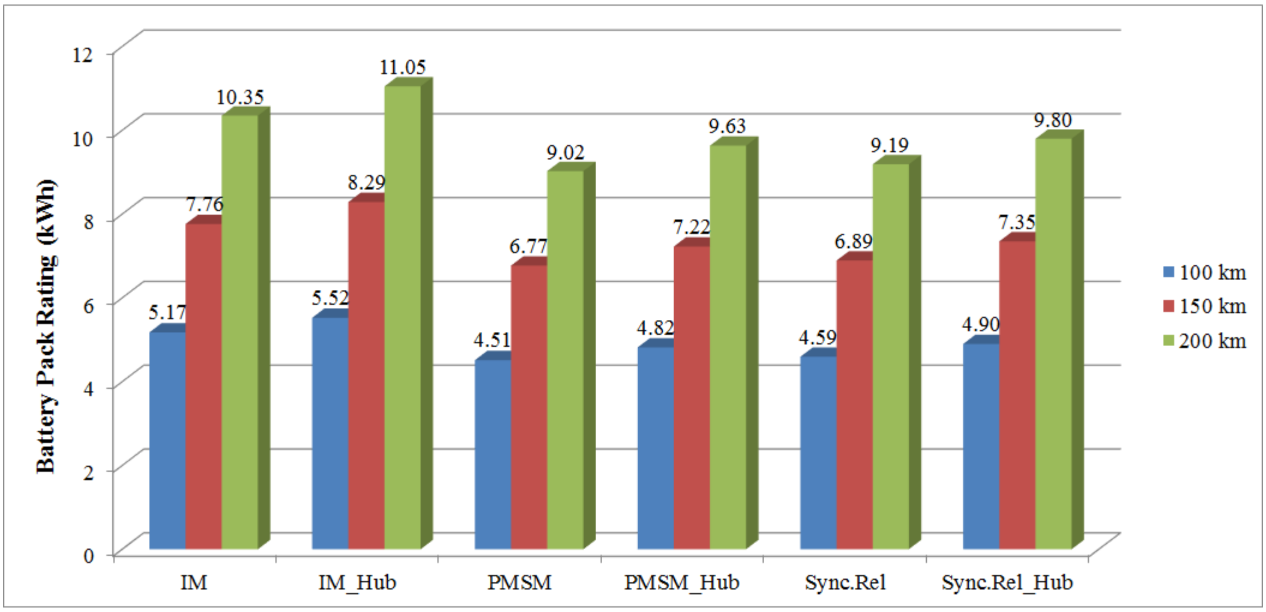


Figure 9.5: Battery pack ratings (in kWh) for various motor configurations at different range requirements - Bajaj Discover

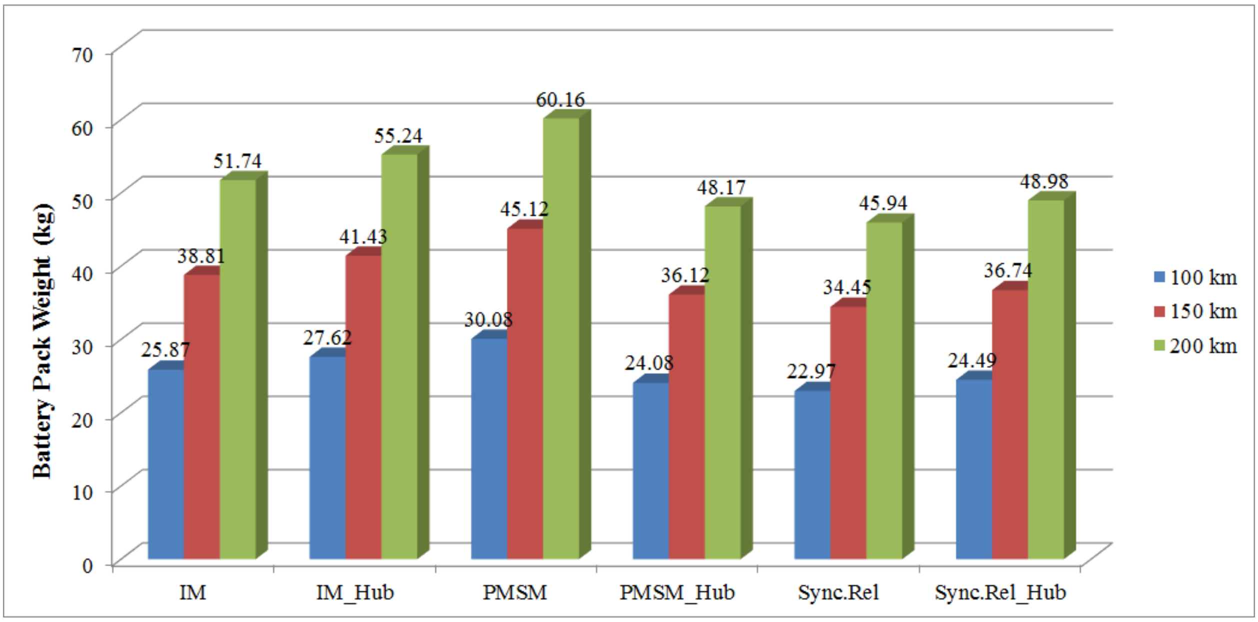


Figure 9.6: Battery pack weight (in kg) for various motor configurations at different range requirements - Bajaj Discover

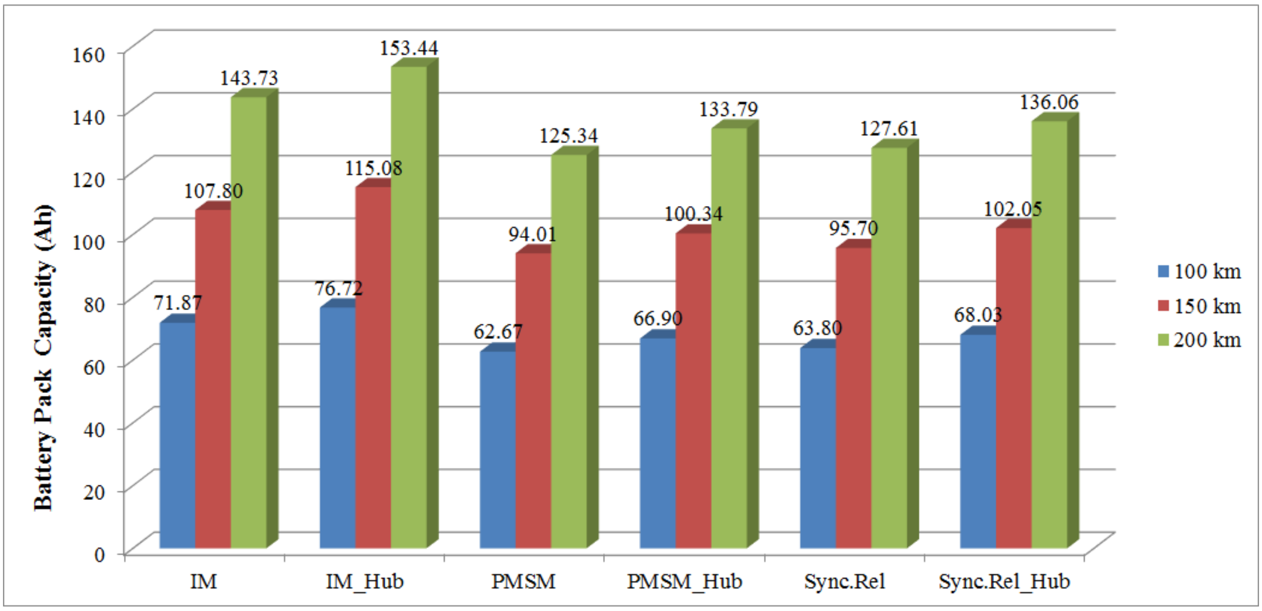


Figure 9.7: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Bajaj Discover

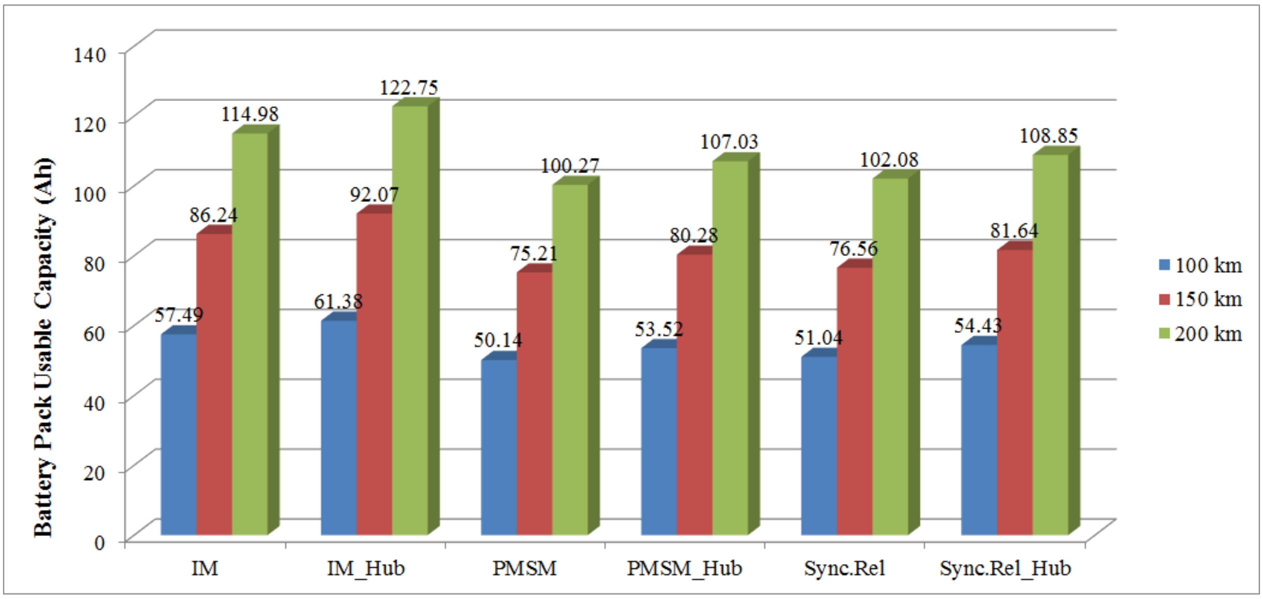


Figure 9.8: Battery pack usable capacity (in Ah) for various motor configurations at different range requirements - Bajaj Discover

9.4 Retro bike

Here, the two wheeler under consideration is a RE Classic 350. The battery requirements for different motors in increasing order are as follows: PMSM Hub > IM Hub > Sync Rel > PMSM >Sync.rel Hub > IM From the various graphs below, it can be inferred that a retro bike fitted with hub motors (PMSM Hub or IM Hub) requires a smaller battery as compared to other motor types; the smallest battery being a 10.10 kW, 140.32 Ah, weighing about 47.19 kg for a PMSM Hub to cover a range of 100km on a single charge. However, among various vehicle types analysed this study, a RE Classic 350requires largest of the batteries to meet the same range requirements.

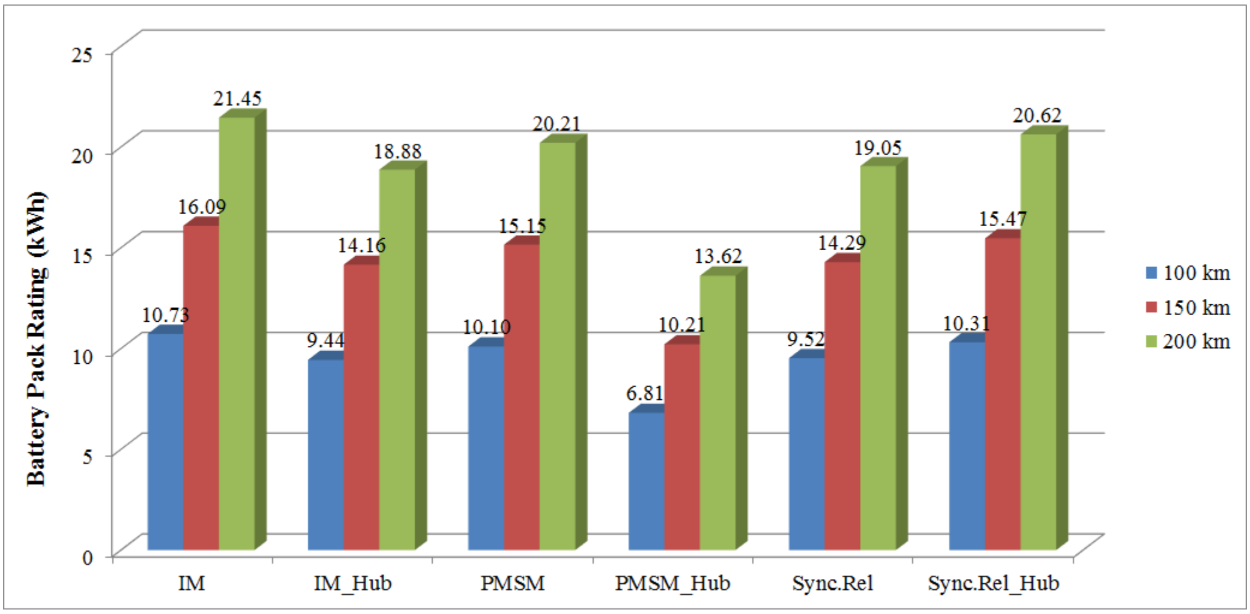


Figure 9.9: Battery Pack Ratings (in kWh) for various motor configurations at different range requirements - Retro bike

Figure 9.10: Battery pack weight (in kg) for various motor configurations at different range requirements - Retro bike

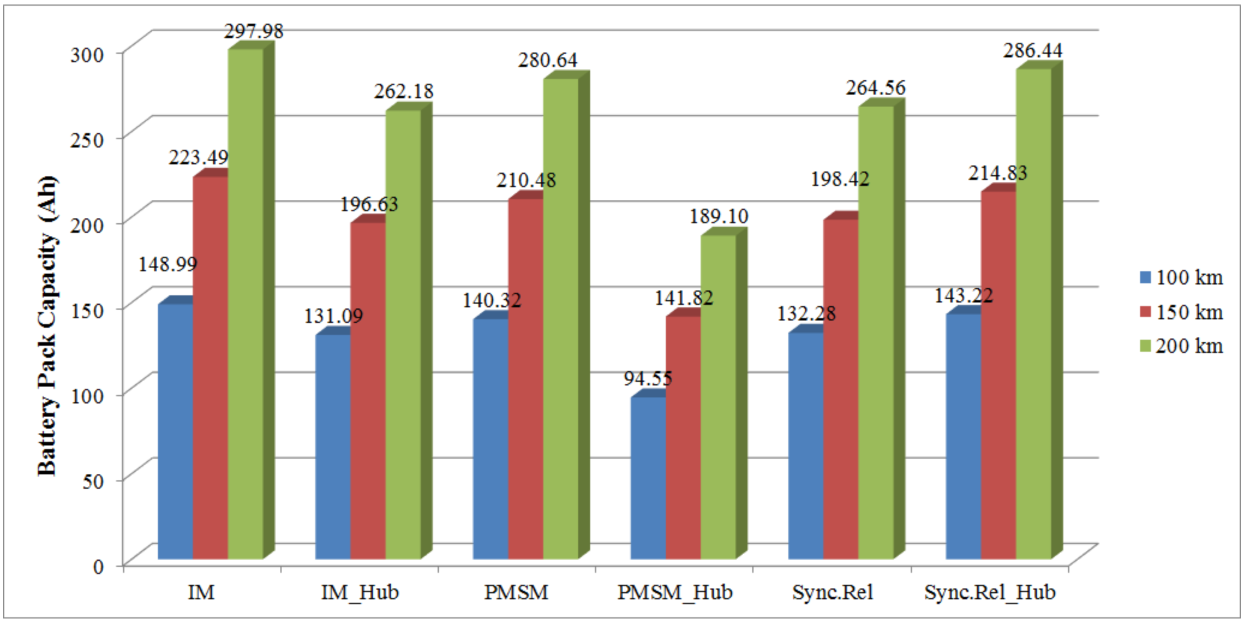


Figure 9.11: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Retro bike

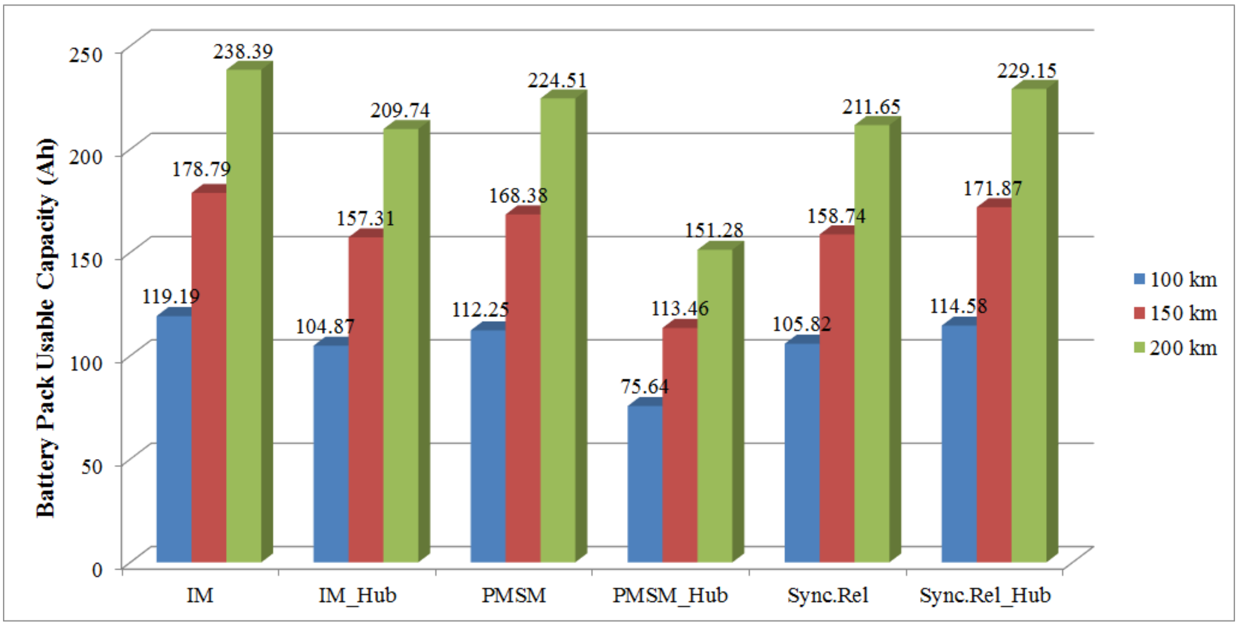


Figure 9.12: Battery Pack usable capacity (in Ah) for various motor configurations at different range requirements - Retro bike

9.5 Commute scooter

Battery requirements of a Honda Activa are analysed in this section. The order of battery requirement for various motors remains the same as a sports bike, i.e., PMSM > Sync Rel > PMSM Hub > Sync Rel Hub > IM > IM Hub. However, a commuting scooter would require a battery of higher rating as compared to a sports bike to meet the same range requirement. For example, a PMSM driven sports bike would require a battery rated 4.85kW, 67.43 Ah to cover a distance of 100 km on a single charge, whereas a commuting scooter with a PMSM motor would require a battery rated 5.70 kW, 79.23 Ah to meet the same range requirement.

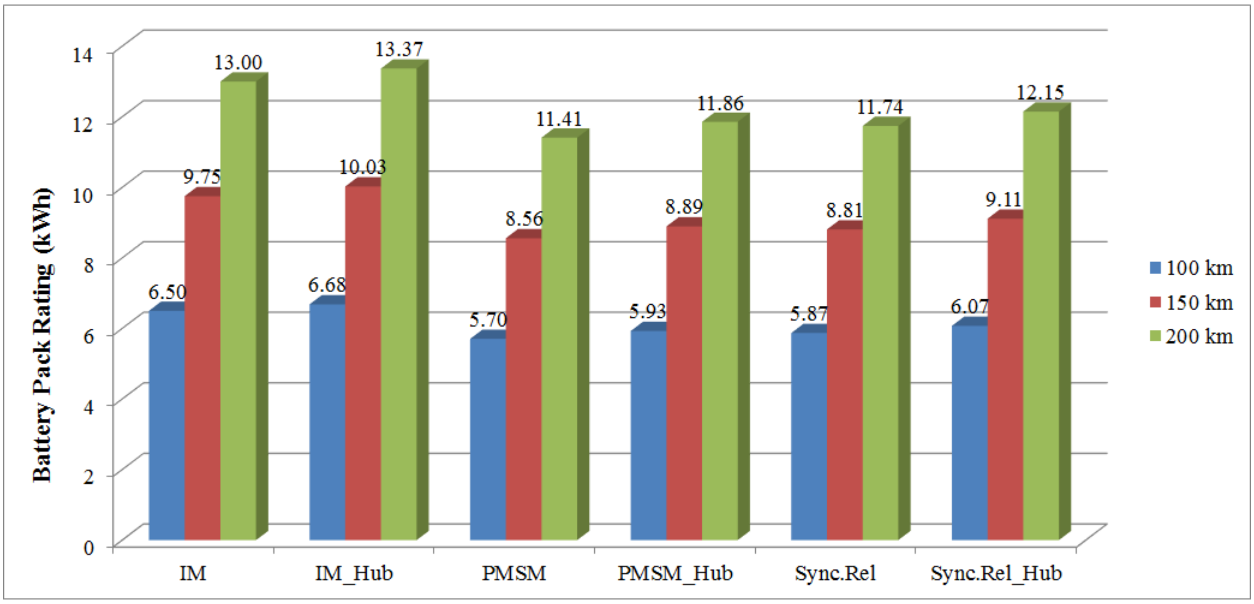


Figure 9.13: Battery pack ratings (in kWh) for various motor configurations at different range requirements - Commute scooter

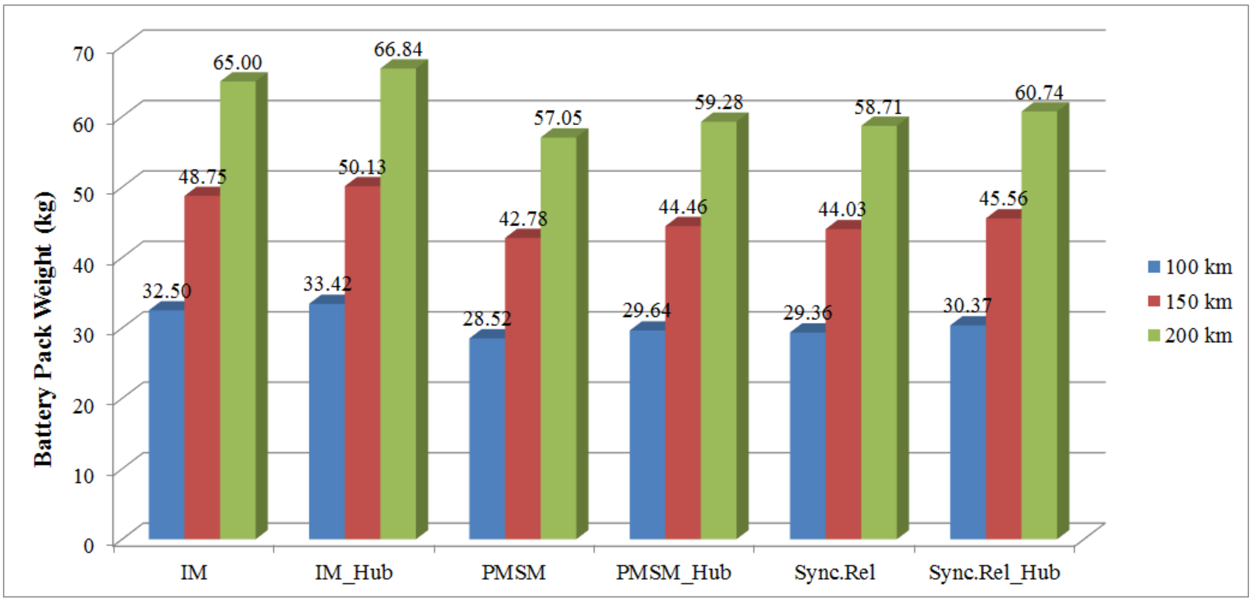


Figure 9.14: Battery pack weight (in kg) for various motor configurations at different range requirements - Commute scooter

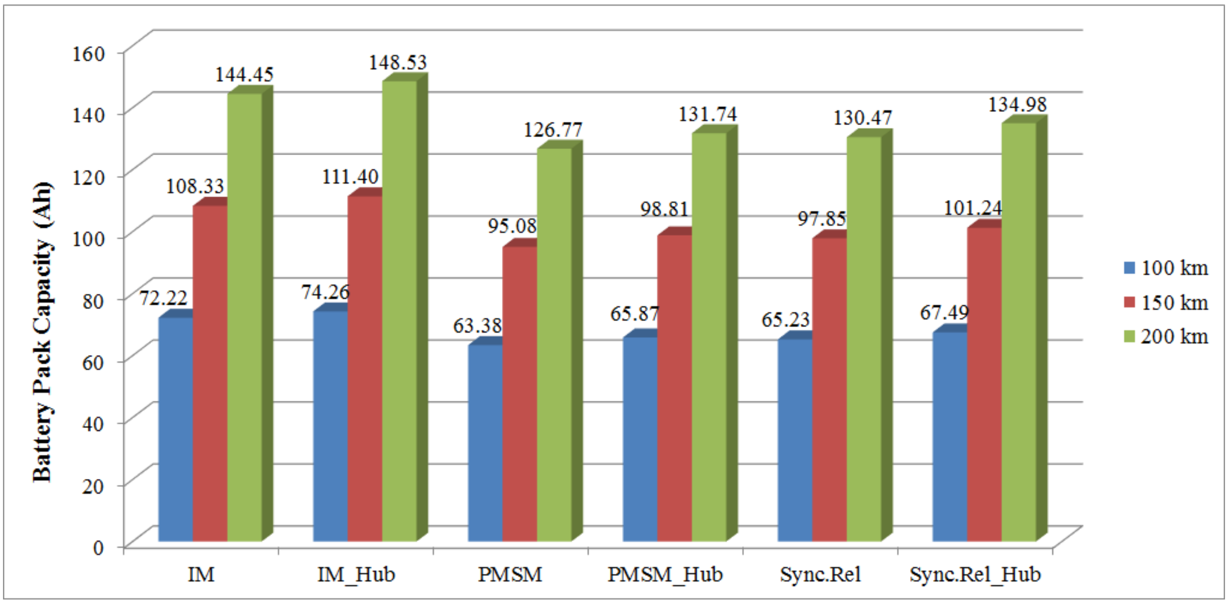


Figure 9.15: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Commute scooter

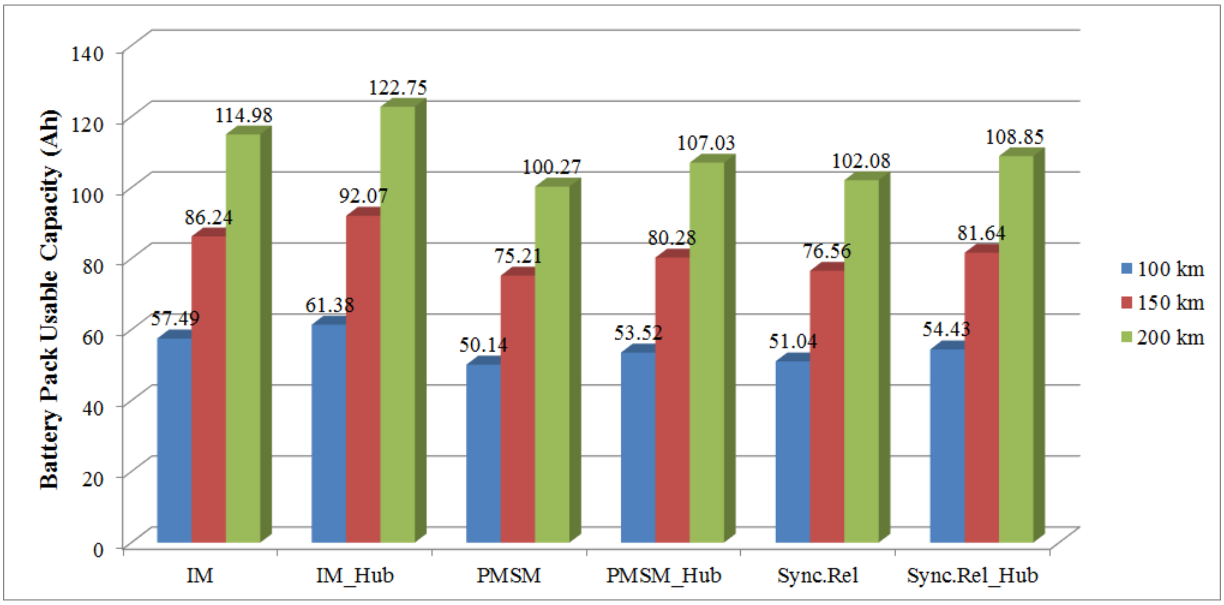


Figure 9.16: Battery Pack Usable Capacity (in Ah) for various motor configurations at different range requirements - Commute scooter

9.6 Mid-range bike

The order of battery requirement for two different types of mid-range bikes, a Hero Honda (Splender Plus) and a Hero Passion Pro, remain the same as the sports bikes and the commute scooter considered in this study.

9.6.1 Hero Honda (Splendor Plus)

Among the different vehicle and motor types considered in this study, a mid-range Hero Honda Splender Plus requires a comparatively smaller battery; the smallest battery rated at 4.15 kW, 57.64 Ah, weighing about 20.75 kg.

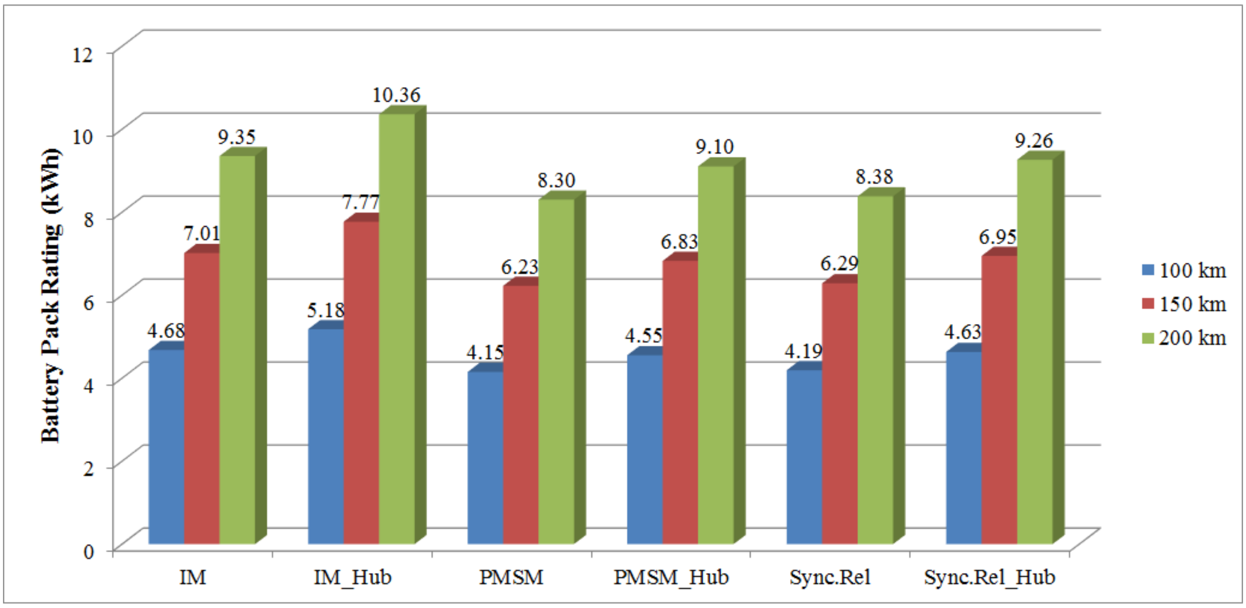


Figure 9.17: Battery pack ratings (in kWh) for various motor configurations at different range requirements - Hero Honda (Splendor Plus)

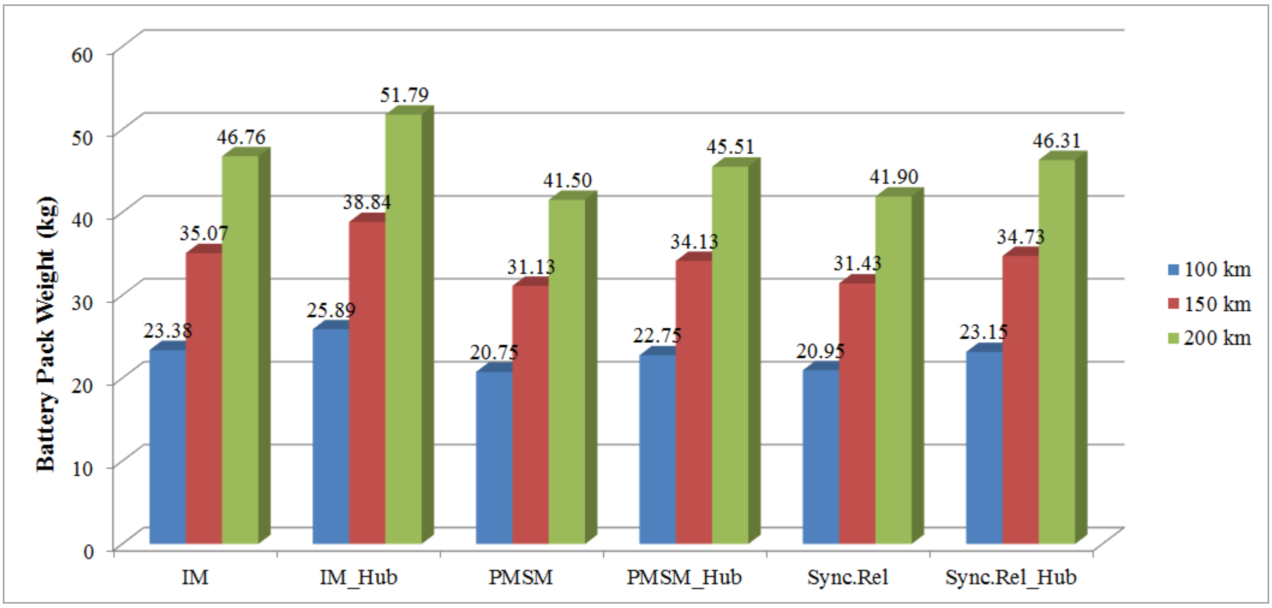


Figure 9.18: Battery pack weight (in kg) for various motor configurations at different range requirements - Hero Honda (Splendor Plus)

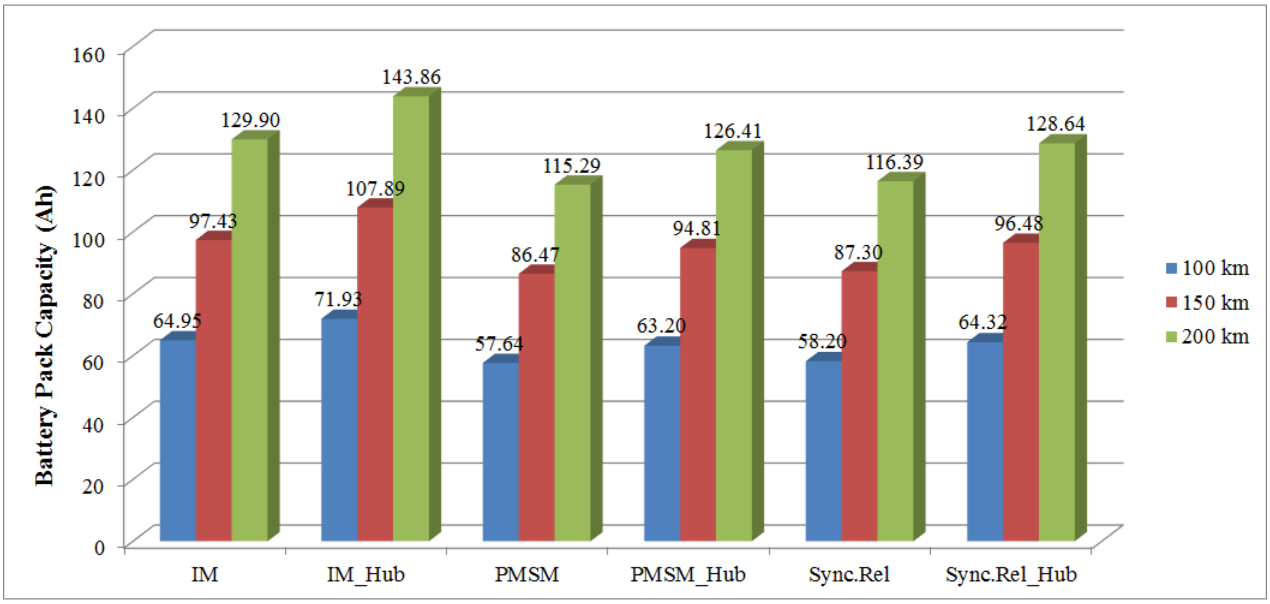


Figure 9.19: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Hero Honda (Splendor Plus)

Figure 9.20: Battery pack usable capacity (in Ah) for various motor configurations at different range requirements - Hero Honda (Splendor Plus)

9.6.2 Hero Passion Pro

A Hero Passion Pro requires a much larger battery as compared to most of the other types of two wheelers considered in this study. The smallest batteries that could power a PMSM for 100 km on a single charge would need to be rated at 7.18kW, over 79 Ah usable capacity and weigh about 35.91 kg. A range of 200 km on single charge would require a much larger battery; the specifications of the largest battery would be about 16.89 kW, over 187 Ah of usable capacity and weigh about 84.45 kg for an IM Hub.

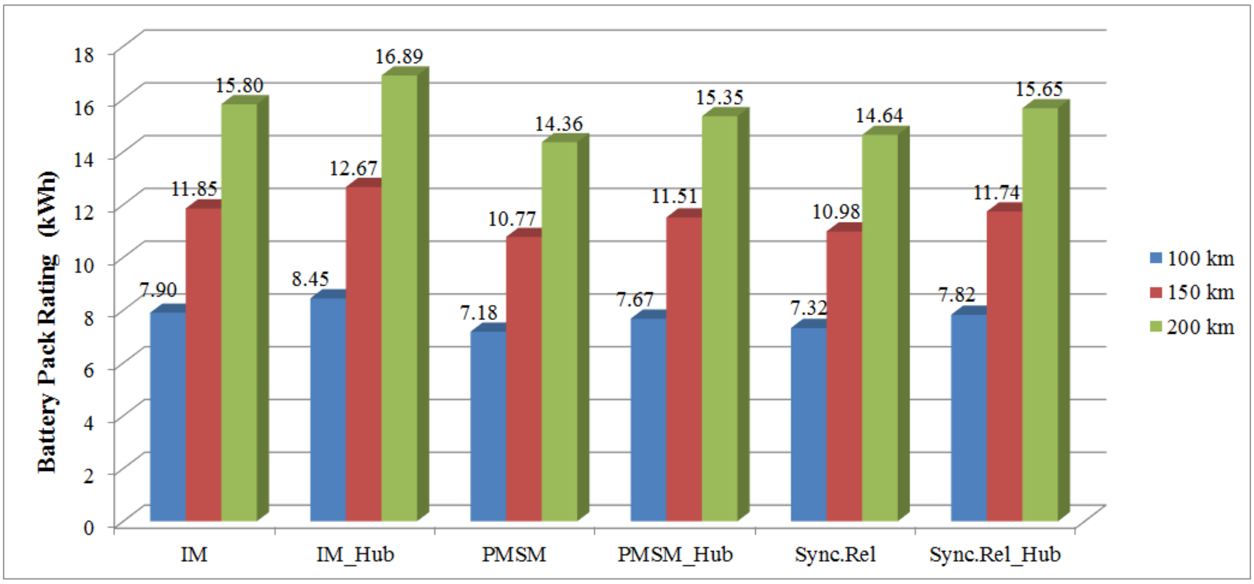


Figure 9.21: Battery pack ratings (in kWh) for various motor configurations at different range requirements - Hero Passion Pro

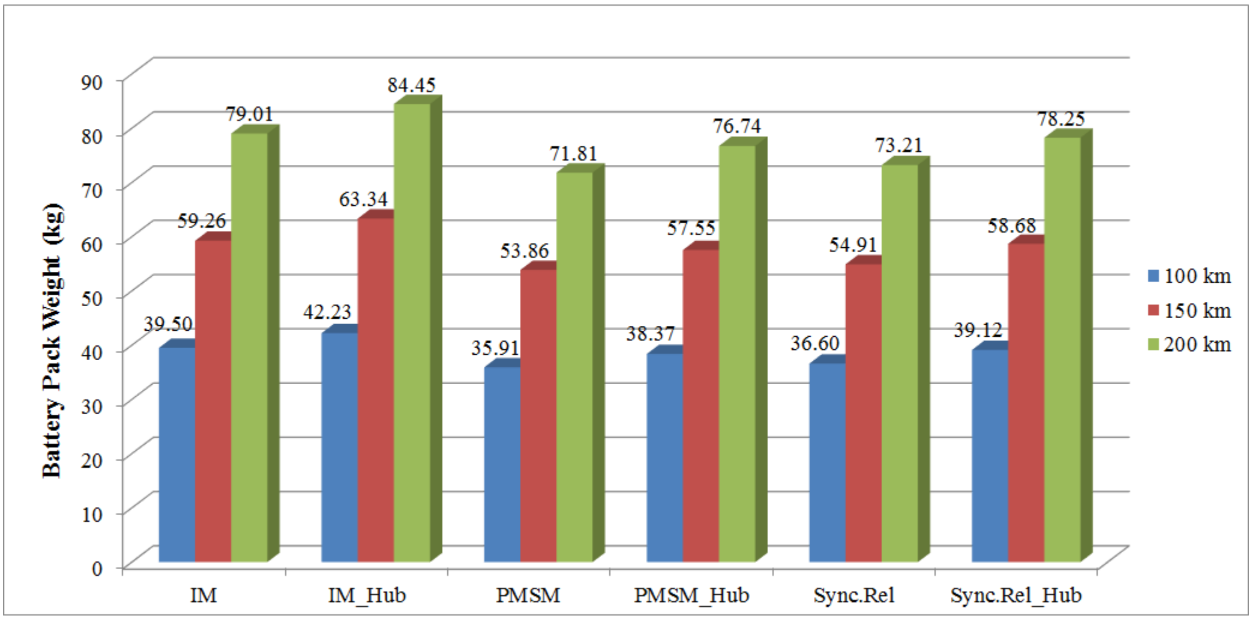


Figure 9.22: Battery pack weight (in kg) for various motor configurations at different range requirements - Hero Passion Pro

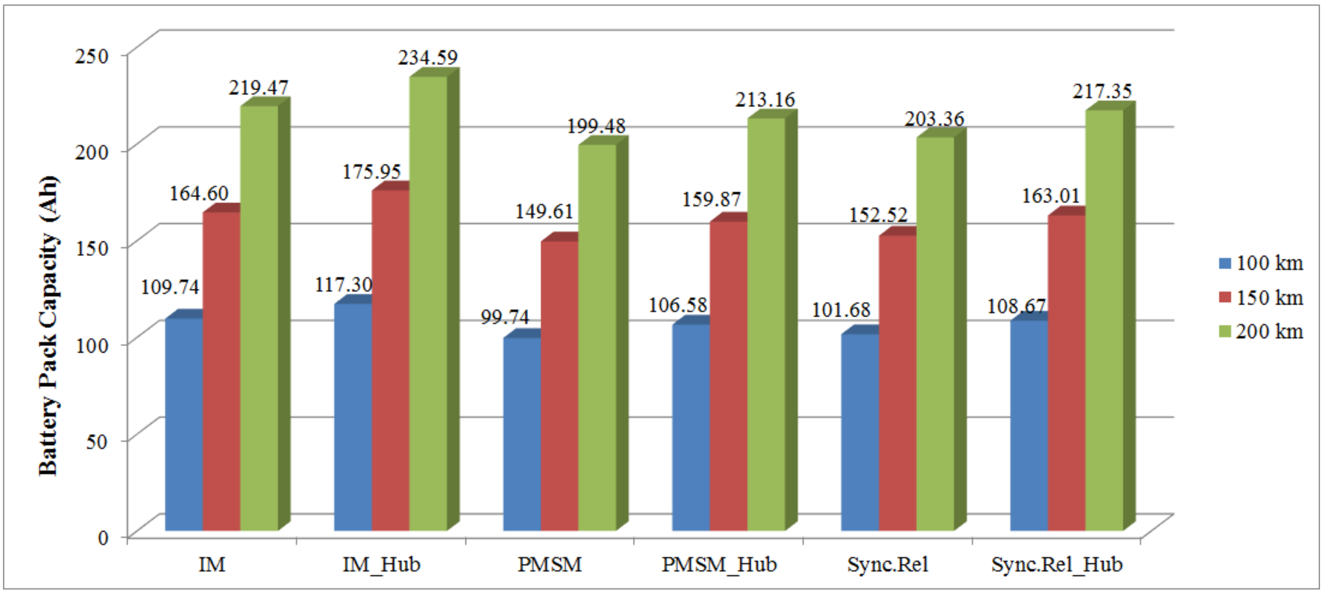


Figure 9.23: Battery pack capacity (in Ah) for various motor configurations at different range requirements - Hero Passion Pro

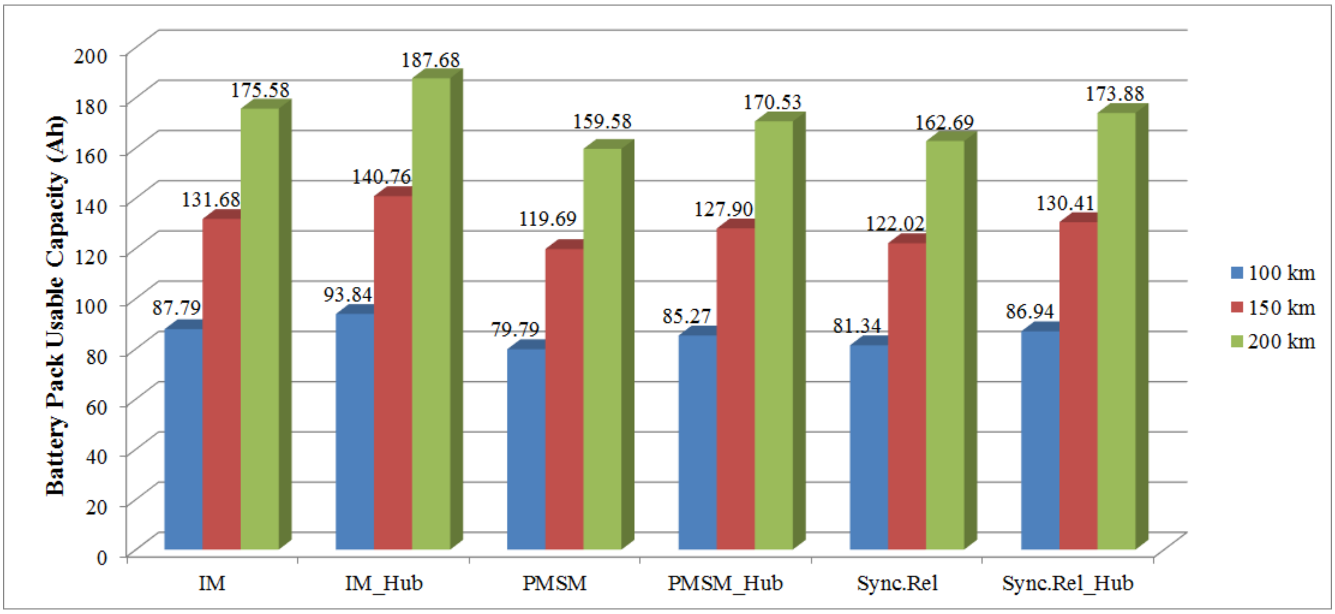


Figure 9.24: Battery pack usable capacity (in Ah) for various motor configurations at different range requirements - Hero Passion Pro

9.7 Insight and analysis

Battery requirements for different types of two wheelers propelled by various combinations of motors are discussed in the chapter. With the exception of a retro bike, the size of the batteries for all other types of two wheelers considered in this study follow the following order: PMSM > Sync Rel > PMSM Hub > Sync Rel Hub > IM > IM Hub i.e., an induction hub motor is driven two wheeler would require a battery with higher ratings to meet the same range requirements, whereas permanent magnet synchronous motors require smaller batteries to meet the same range requirements. The size of the battery for a retro bike fit with various motors would be as follows: PMSM Hub> IM Hub >

Sync Rel > PMSM > Sync Rel Hub > IM In addition, to cover the same distance, the retro bike in this study requires batteries of larger size as compared to other types of two wheelers regardless of the type of motor used. In general, the sizes of batteries for different types of two wheelers follow the following order irrespective of the motor type: Mid-range bike > Sports bike > Commute scooter > Retro bike

10 Drivetrain system integration

10.1 Drivetrain efficiencies analysis:

10.1.1 Motor optimized for driving (economy mode):

1. Rural Drive Cycle:

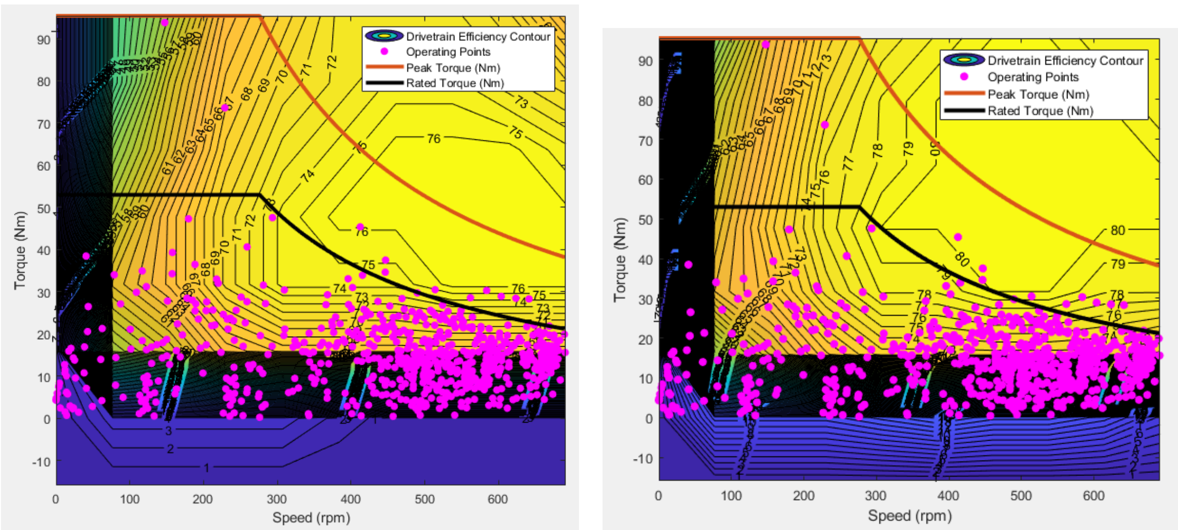
   a. Hub motor:

   From the table 10.1, it is depicted that PMSM hub motors have a higher cyclic motor efficiency whereas induction hub motors have the least cyclic efficiency values, while synchronous reluctance motors lie in the middle of the other two motors cyclic efficiency values.

Table 10.1: Cyclic efficiencies of hub motor - Rural - Hero Honda (splender plus)

Vehicle Name	**Cyclic Efficiency (%)**		
Hero Honda (splender plus)	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	48	59	54

PMSM-Hub motor has the highest efficiency of 59%, whereas induction motor hub provides the lowest efficiency of 48%.



(a) (b)

Figure 10.1: Efficiency Map for motor optimized for driving (a) IM Hub (b) PMSM Hub

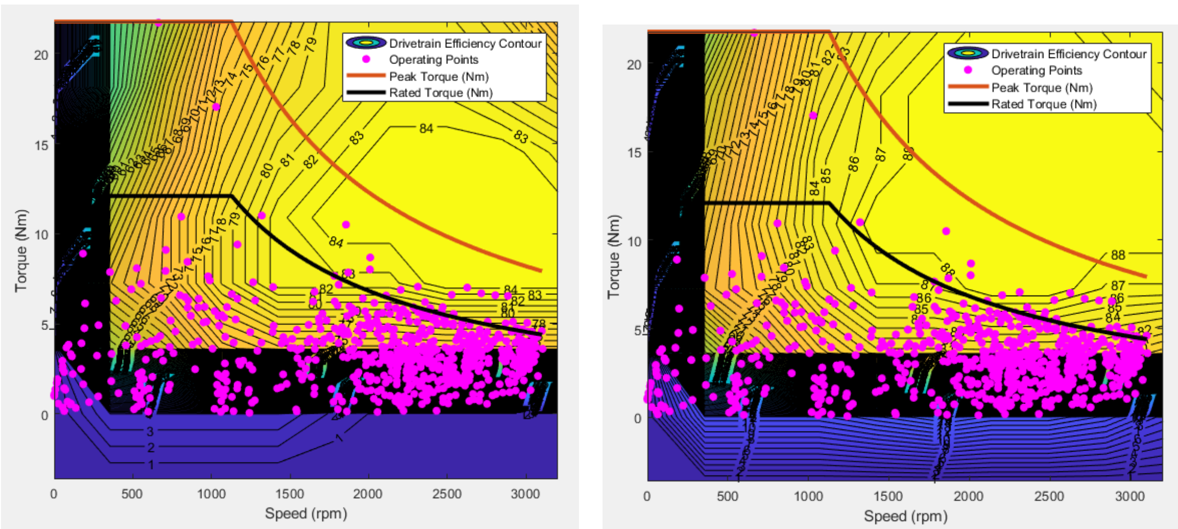
   b. Belt driven motors:

   Alike to the case of hub motors in rural areas, PMSM motors dominate in providing higher motor efficiencies than the other two motors, which in turn leads to lesser emissions to the environment and reduces the load on the grids, although the difference between the efficiencies of PMSM motors and Synchronous reluctance motors is very small, but the IM efficiency lags behind the PMSM efficiency by a more significant margin.

Table 10.2: Cyclic efficiencies of belt driven motor - Rural Drive Cycle - Hero Honda (splender plus)

Vehicle Name	**Cyclic Efficiency (%)**		
Hero Honda (splender plus)	IM	PMSM	Syn. Rel
	56	63	62

Induction motor lags behind the other two types of the motor as it provides 56% efficiency.



(a) (b)

Figure 10.2: Efficiency Map for motor optimized for driving (a) IM (b) PMSM

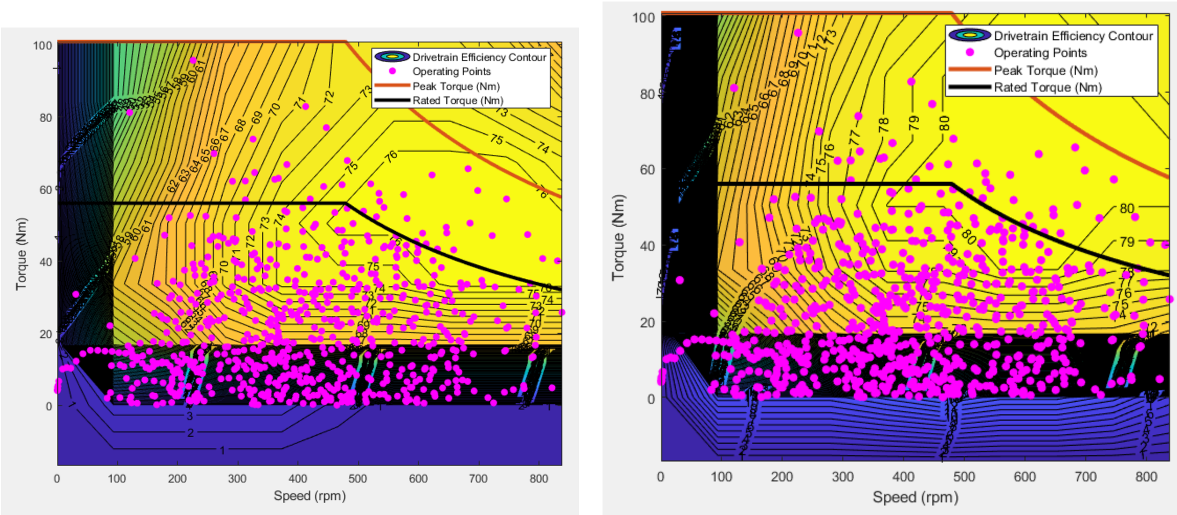
2. Urban Drive Cycle:

   a. Hub motor:
   From the table 10.3, it is depicted that induction hub motors have the lowest cyclic motor efficiency whereas PMSM hub motors have the highest cyclic efficiency values. In contrast, synchronous reluctance motors lie in the middle of the other two motors cyclic efficiency values.

Table 10.3: Cyclic efficiencies of hub motor- Urban Drive Cycle - TVS star city

Vehicle Name	**Cyclic Efficiency (%)**		
TVS star city	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	47	53	53

In the urban area drive cycle, IM-Hub give the efficiency of 47% while PMSM-Hub and Syn.Rel-Hub of 53%



(a) (b)

Figure 10.3: Efficiency Map for motor optimized for driving (a) IM Hub (b) PMSM Hub

b. Belt driven motors:
Alike to the case of hub motors in urban areas, PMSM motors dominate in providing higher motor efficiencies than the other two motors, which in turn leads to lesser emissions to the environment and have a larger value of mileage, although the difference between the efficiencies of PMSM motors and Synchronous reluctance motors is minimal, but the IM efficiency lags behind the PMSM efficiency by a more considerable margin.

Table 10.4: Cyclic efficiencies of belt driven motor - Urban Drive Cycle - TVS star city

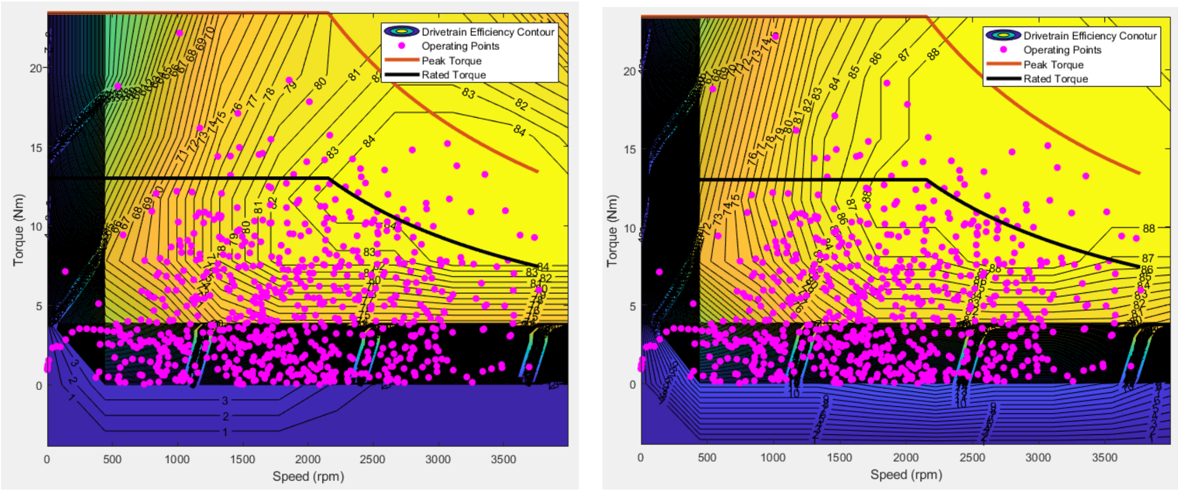
Vehicle Name	**Cyclic Efficiency (%)**		
TVS star city	IM	PMSM	Syn. Rel
	53	60	59

The difference is significantly less between Syn. Rel and PMSM motor efficiency, whereas the efficiency of IM is 53%.

10.1.2 Motor optimized for acceleration mode (sports mode):

Looking at the tables 10.5 to 10.8, it can be derived that the sports mode would be consuming a higher amount of fuel per kilometre distance than the economy mode hence delivering efficiency as the efficiency and performance of the motor goes on inversely.

1. Rural Drive Cycle:



(a) (b)

Figure 10.4: Efficiency Map for motor optimized for driving (a) IM (b) PMSM

a. Hub motors:
   It is observed that IM motors provide the lowest efficiency value while the PMSM motors show the highest efficiency value; hence, hub motor efficiency in sports mode follows a similar fashion as hub motors in economy mode.

Table 10.5: Cyclic efficiencies of hub motor - Rural Drive Cycle - Hero Honda (Splender Plus)

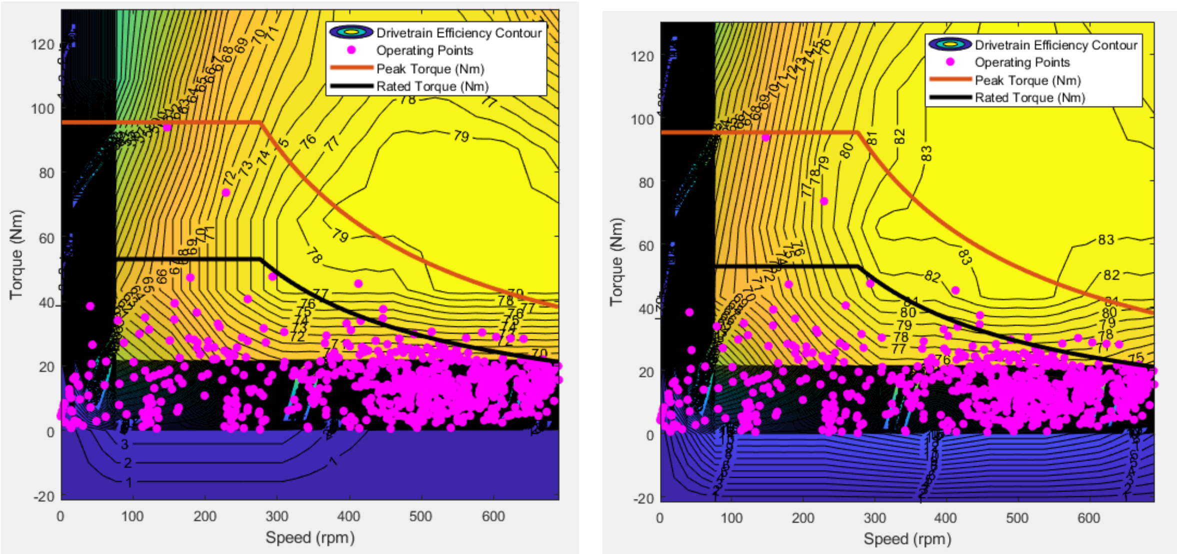
Vehicle Name	**Cyclic Efficiency (%)**		
Hero Honda (Splender Plus)	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	40	47	46

PMSM-Hub motor and synchronous reluctance -hub motor has a similar efficiency value of 47%, whereas IM-Hub provides 40% efficiency.

b. Belt driven motors:
   The PMSM motors leads the other two motors by delivering a higher efficiency value. PMSM and Synchronous reluctance motors efficiencies differ by a tiny value, but there is an observable difference between efficiency of PMSM and IM.

Table- 10.6 Cyclic efficiencies of belt driven motor - Rural Drive Cycle - Hero Honda (Splender Plus)

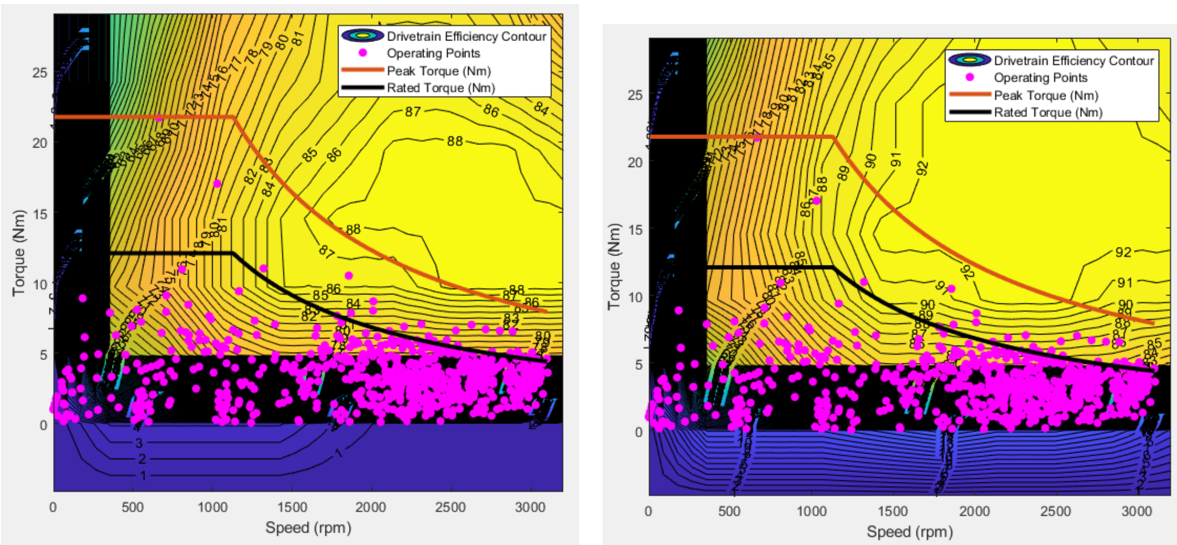
Vehicle Name	**Cyclic Efficiency (%)**		
Hero Honda (Splender Plus)	IM	PMSM	Syn. Rel
	46	54	53



(a) (b)

Figure 10.5: Efficiency Map for motor optimized for driving (a) IM Hub (b) PMSM Hub

PMSM-Hub motor outperforms the other two hub motors by providing the efficiency 54



(a) (b)

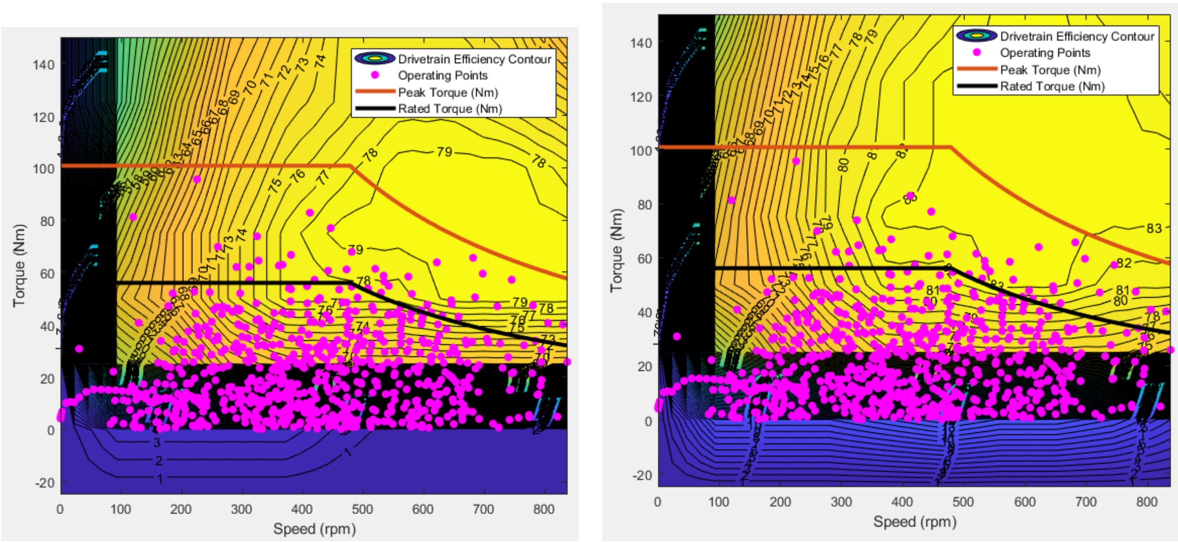
Figure 10.6: Efficiency Map for motor optimized for driving (a) IM (b) PMSM

2. Urban Drive Cycle:

   a. Hub motors:
   It is observed that PMSM motors provide the highest value of efficiency while the IM motors show the lowest efficiency value hence hub motors efficiency in sports mode follows a similar fashion as of hub motors in economy mode.

Table 10.7: Cyclic efficiencies of hub motor- Urban Drive Cycle - TVS star city

Vehicle Name	**Cyclic Efficiency (%)**		
	IM-Hub	PMSM-Hub	Syn. Rel-Hub
TVS star city	43	49	49



(a) (b)

Figure 10.7: Efficiency Map for motor optimized for driving (a) IM Hub (b) PMSM Hub

The IM-Hub provide the least efficiency of 43

b. Belt driven motors:
The IM motors lags behind the other two motors by having a lower efficiency value. PMSM and Synchronous reluctance motors efficiencies vary by a tiny value, but there is an observable difference between the efficiency of PMSM and IM.

Table 10.8: Cyclic efficiencies of belt driven motor- Urban Drive Cycle - TVS star city

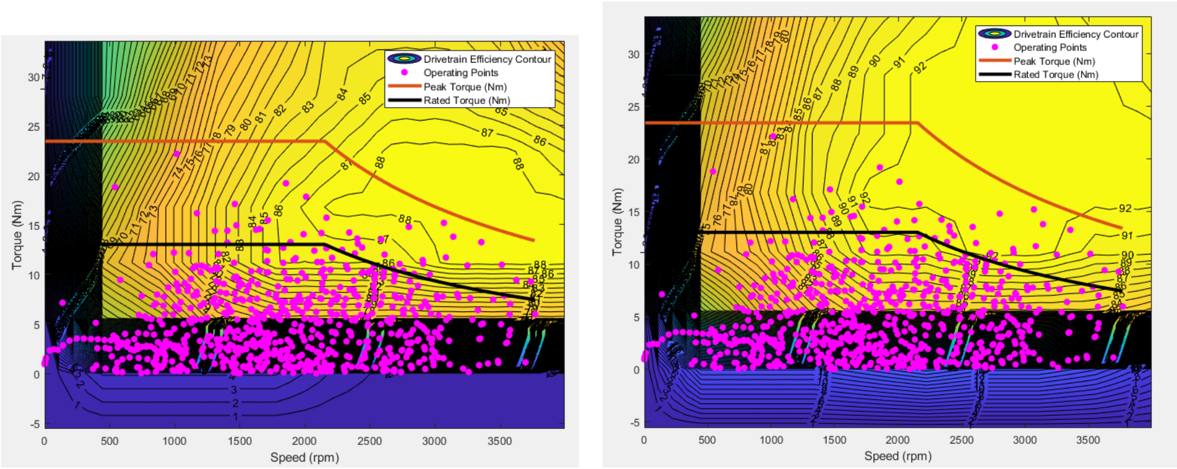
Vehicle Name	**Cyclic Efficiency (%)**		
	IM	PMSM	Syn. Rel
TVS star city	49	56	55

IM has the lowest efficiency of 49

10.2 CVT (Continuously Variable Transmission)

10.2.1 An introduction to CVT.

A Continuously Variable Transmission (CVT) is an automatic transmission that allows seamless change of gear ratios over a continuous range (WIKIPEDIA). The advantage of CVT is that it enables the engine to run at Constant Speed whether the output at different speeds at the wheel can be achieved. In an



(a) (b)

Figure 10.8: Efficiency Map for motor optimized for driving (a) IM (b) PMSM

ICE based vehicle where the engine has a very narrow operating point, by using CVT, performance can be significantly improved. Nonetheless, the same concept can be applied in EVs.

By using CVT, it is possible to vary the gear ratios without interruption of operating torque. Hence, an infinite number of gear ratios (within a range) is possible.

CVT can be of different constructions. The basic one is the 'Pulley-based' design. There is a belt that runs between two variable-diameter cone-shaped pulleys. The transmission ratio between the engine and the wheels changes smoothly with the variable axial gap between the pulleys.

10.2.2 CVT performance characteristics and Efficiency curves

10.2.2.1 Motor and CVT coupling, its advantages and potential of improving the overall efficiency of the drivetrain

In contrast with the traditional gear shifting technique used in two-wheelers, CVT enables the engine/motor to operate at better efficient points. As a result, for the same output, power consumption(input) of the motor could be made to be less. Hence, there will be an overall savings of energy. That leads to the mileage improvement of the vehicle.

The idea is to use a control algorithm along with a control board that will continuously sense the required speed at wheel level and adjust the gear ratio to achieve an optimal operating point at the motor terminal. This phenomenon is to be called "Rule-Based CVT".

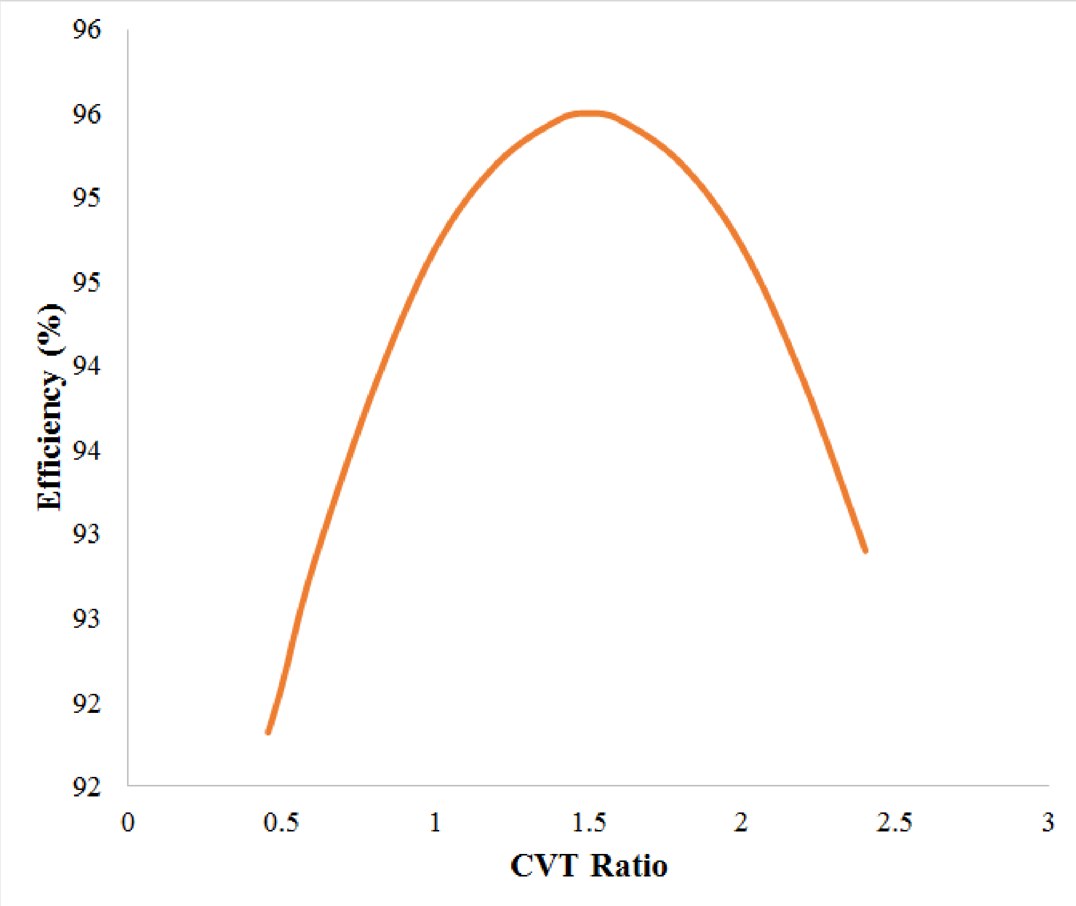


Figure 10.9: Efficiency vs CVT Ratio

10.2.3 Analysis of different drive cycles and different drivetrains.

After running the algorithm, the following results have been achieved. In line with Fig. 1, an algorithm has been developed which provides a continuous range of gear ratios from 0.4 to 2.4.

1. Motor Optimized for Driving:
   The objective of this mode is to achieve zero to the maximum speed of the vehicle as quickly as possible but not to overload the motor. Technically, it is to be completed by keeping the operating torque of the motor below the maximum allowed torque of that motor.

   In this mode, first, the calculation was done for the cyclic efficiencies on all the test vehicles, keeping the gear ratios to be fixed - "Constant Gear Ratio". Then the same operating points have been achieved by using the technique discussed earlier - "Rule-Based CVT".

   a. Sports Bike:
      In this section, the ICE of sports bikes has been replaced by different types of motors, and further analysis has been processed.

- Honda CB Shine 125cc:
  Here, analysis has been done on the drive cycle recorded from Honda CB Shine 125cc. Looking at the following table 10.9, it's evident that there is almost 22% improvement, in the case of PMSM configuration, of the cyclic efficiencies while moving from "Constant Gear Ratio" to "Rule-Based CVT". For the other two types of motor (IM and Syn. Rel), there is almost no improvement recorded by using this algorithm.

Table 10.9: CVT profile of Honda CB Shine 125cc

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
Honda CB Shine	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	52.3667	46.6007	58.1951	51.8635	56.8376	50.9968

- TVS Radeon:
  In this section, analysis has been done on the drive cycle recorded from TVS Radeon. Looking at the following table 10.10, it's clear that there is almost 14.59% improvement of the cyclic efficiencies in the case of IM configuration while moving from "Constant Gear Ratio" to "Rule-Based CVT". For the other two types of motor (PMSM and Syn. Rel), there is an improvement of 11.2% and 8.8%, respectively.

Table 10.10: CVT profile of TVS Radeon

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
TVS Radeon	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	44.227	48.7876	48.8516	50.6809	54.2581	53.1764

b. Retro Bike – RE Classic 350:
   In this section, the ICE of a retro bike has been replaced by different motors, and further analysis has been processed. For this, let's discuss RE Classic 350. It's clear from the following table 10.11 that there is a significant improvement of cyclic efficiencies for all three categories of the motor. To give the perspective, these are around 14%, 11% and 10%, respectively.

Table 10.11: CVT profile of RE Classic 350

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
RE Classic 350	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	64	71	70	74	79	77

c. Mid-Range Bike – Hero Passion Pro:
   In this section, the ICE of a mid-range bike has been replaced by different motors, and further analysis has been processed. Taking an

example of Hero Passion Pro, another section has been discussed. It's apparent from the following table 10.12 that there is a significant improvement of cyclic efficiencies for all three categories of the motor. To give the perspective, these are around 10%, 8% and 7%, respectively.

Table 10.12: CVT profile of Hero Passion Pro

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
Hero Passion Pro	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	62	67	66	68	73	71

2. Motor Optimized for Acceleration:
   The objective of this mode is to achieve zero to the maximum speed of the vehicle as quickly as possible. However, the motor could be overloaded for a fraction of time in this case.

   Like before, the same calculation was done on the operating points, and the cyclic efficiencies had been figured out.

   a. Sports Bike:
      In this section, the ICE of two sports bikes has been replaced by different motors, and further analysis has been processed.

      - Honda CB Shine 125cc:
        In this section, analysis has been done on the drive cycle recorded from Honda CB Shine 125cc. Referring to the following 10.13, it's evident that there is a significant improvement of the cyclic efficiencies for all three types of motor configuration while moving from "Constant Gear Ratio" to "Rule-Based CVT". To give a quantitative approximation, there are 29%, 20% and 20% improvements for IM, PMSM and Syn. Rel respectively.

Table 10.13: CVT profile of Honda CB Shine 125cc

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
Honda CB Shine	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	49.1163	56.7324	55.7225	63.7631	68.5231	66.9109

- TVS Radeon:
  In this section, analysis has been done on the drive cycle recorded from TVS Radeon. Looking at the following table 10.14, it's evident that there is almost 31.29% improvement of the cyclic efficiencies in the case of IM configuration while moving from "Constant Gear Ratio" to "Rule-Based CVT". For the other two types

of motor (PMSM and Syn. Rel), there is an improvement of 22.7% and 17.44%, respectively.

Table 10.14: CVT profile of TVS Radeon

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
TVS Radeon	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	34.234	39.296	40.2567	44.9465	48.2463	47.2783

b. Retro Bike – RE Classic 350:
In this section, the ICE of a retro bike has been replaced by different motors, and further analysis has been processed. For this, let's discuss RE Classic 350. It's clear from the following table 10.15 that there is a significant improvement of cyclic efficiencies for all three categories of the motor. To give the perspective, these are around 31%, 22% and 22%, respectively.

Table 10.15: CVT profile of RE Classic 350

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
RE Classic 350	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	52	60	59	69	74	72

c. Mid-Range Bike – Hero Passion Pro:
In this section, the ICE of a mid-range bike has been replaced by different motors, and further analysis has been processed. Taking an example of Hero Passion Pro, a further section has been discussed. It's apparent from the following table 10.16 that there is a significant improvement of cyclic efficiencies for all three categories of the motor. To give the perspective, these are around 13%, 9.8% and 8.8%, respectively.

Table 10.16: CVT profile of Hero Passion Pro

Vehicle Name	**Fixed Gear Ratio - 2.4**			**Rule-Based CVT**		
Hero Passion Pro	IM	PMSM	Syn. Rel	IM	PMSM	Syn. Rel
	59	65	64	67	72	70

10.2.4 Conclusions

In a nutshell, there is an average 16.35% improvement for the mode of "Motor Optimized for Driving" and 24.88% improvement for the mode of "Motor Optimized for Acceleration".

For both two cases, the values were calculated theoretically. Even though there will be a lot of limitations on the mechanical gear transmission device and other control devices in practice, the astonishing number of efficiencies improvement suggests at least for observation.

10.3 Fuel consumption analysis:

The distance travelled by the vehicle per unit amount of fuel is called the mileage (WIKIPEDIA). In the case of an electric vehicle, the fuel is electrical energy hence the definition of mileage would be kilometre travelled per kilowatt-hour. Suppose the mileage of the hub and the belt-driven motor is considered irrespective of its type. In that case, it is evident that hub motor has lower mileage than the belt-driven motor, which is due to the fact that fuel consumed in the hub motor is more than belt-driven motor. Here the mileage is recorded for two payloads that are 70kgs and 150 kgs.

10.3.1 Motor optimized for driving (economy mode):

Here the driving mode means the parameters of the motor are optimized in such a manner that it gives a higher mileage or a lower fuel consumption values; for example: in the case of a sports bike for 150 kg payload, the motor must achieve 40 kmph speed in 6.2 seconds, while it must 11.1 seconds to achieve a speed of 60 kmph.

1. Rural Drive Cycle:

   a. Hub motor:

   - 70 kg payload:

Table 10.17: Fuel Consumption of hub motor - Rural Drive Cycle - 70 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0282	.0251	.0257

In the case of hub motors mileage decreases by almost 6.6% as compared to frame motors. In comparison, among hub motors PMSM hub motors outperform the other two motor types by providing the maximum mileage which is about 14.05% higher than Induction hub motors. In contrast, Synchronous reluctance hub motors provide mileage which is 12.20% higher than Induction hub motor.

   - 150 kg payload:

Table 10.18: Fuel Consumption of hub motor - Urban Drive Cycle - 150 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0397	.0350	0.0359

From the table 10.18, it can be seen clearly that Permanent magnet synchronous motors have a lower value of fuel consumption. Therefore, it can be said that PMSM hub motors have higher mileage values. In contrast, Induction hub motors provide lower mileage as their fuel consumption per kilometre is highest than the other two motors.

b. Belt driven motors:
Analysis has been done on the drive cycle recorded from Honda CB Shine 125cc. Clearly, it can be seen from the table 10.19 data that there is almost a 12.235 % improvement in mileage, in the case of PMSM configuration than IM is recorded, while for the Syn. Rel motor, there is nearly 5.94% mileage improvement than Induction motor.

- 70 kg payload:

Table 10.19: Fuel Consumption of belt driven motor - Rural Drive Cycle - 70 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM	PMSM	Syn. Rel
	.0266	.0237	.0247

- 150 kg payload:

Table 10.20: Fuel Consumption of belt driven motor - Rural Drive Cycle - 150 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM	PMSM	Syn. Rel
	0.383	.0335	.0343

Similar to the case of hub motors, PMSM motors dominate in the mileage over the other two motors. However, the difference in the mileages of PMSM motors and Synchronous reluctance motors is very small, but the IM mileage lags behind the PMSM mileage by a larger margin.

2. Urban Drive Cycle:

a. Hub motor:
In the case of HUB, Motors mileage decreases by almost 5.3% as compared to Frame motors. In comparison, among Hum motors, the PMSM hub motor provides the maximum mileage of about 12.3% higher than Induction Hub motors. In contrast, Syn. reluctance hub motor provides mileage 9.72% higher than Induction hub motor.

- 70 kg payload:

Table 10.21: Fuel Consumption of hub motor-Urban-70 kg payload-Bajaj Discover 100cc

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0282	.0251	.0257

Table 10.22: Fuel Consumption of hub motor-Urban-150 kg payload-Bajaj Discover 100cc

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0406	.0346	.0351

- 150 kg payload:
  The table 10.22 clearly shows that Permanent magnet synchronous motors have a lower fuel consumption value. Hence PMSM hub motors have higher mileage values, while Induction hub motors provide lower mileage as their fuel consumption per kilometre is highest than the other two motors.

b. Belt driven motors:

- 70 kg payload:

Table 10.23: Fuel Consumption of belt driven motor-Urban-70 kg payload-Bajaj Discover 100cc

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM	PMSM	Syn. Rel
	.0258	.0227	.0230

Here, analysis has been done on the drive cycle recorded from Bajaj Discover 100cc. Looking at the following table 10.23, it's evident that there is almost a 13.65% improvement in mileage, in the case of PMSM configuration than IM is recorded, while for the Syn. Rel motor, there is nearly 12.17% mileage improvement than Induction motor.

- 150 kg payload:

Table 10.24: Fuel Consumption of belt driven motor-Urban-150 kg payload-Bajaj Discover 100cc

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM	PMSM	Syn. Rel
	.0380	.0324	.0329

Similar to the case of hub motors in urban areas, PMSM motors dominate in providing greater mileage than the other two motors. However, the difference between the mileages of PMSM motors and Synchronous reluctance motors is minimal, but the IM mileage lags behind the PMSM mileage by a more significant margin.

10.3.2 Motor optimized for acceleration mode (sports mode):

The motor parameters in this mode are altered such that 40 kmph is achieved in 3.4 seconds while it takes 6.2 seconds to achieve a speed of 60 kmph. From the data, it can be inferred clearly that the sports mode would be consuming a higher amount of fuel per kilometre distance than the economy mode hence delivering a lower mileage value.

1. Rural Drive Cycle:

   a. Hub motors:

   - 70 kg payload:

Table 10.25: Fuel Consumption of hub motor - Rural Drive Cycle - 70 kg payload-Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0353	.0295	.0201

Hub motors in acceleration mode have a higher fuel consumption than economy mode. In addition, IM-Hub consumes the highest amount of fuel per km distance, thus giving the least mileage.

   - 150 kg payload:

Table 10.26: Fuel Consumption of hub motor - Rural Drive Cycle - 150 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0494	.0408	.0417

The table 10.26 data shows that PMSM motors provide the lowest value of fuel consumption while the IM motors consume the highest amount of energy. Hence, the mileage of hub motors follows a similar trend as hub motors in economy mode.

   b. Belt driven motors:

   - 70 kg payload:
     Frame motors consume a lesser amount of fuel than hub motor, and out of all the frame motors, PMSM motor gives the most negligible value of fuel consumption, i.e .0275kwh/km.

Table 10.27: Fuel Consumption of belt driven motor - Rural Drive Cycle - 70 kg payload-Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM	PMSM	Syn. Rel
	.0383	.0275	.0280

- 150 kg payload:

Table 10.28: Fuel Consumption of belt driven motor - Rural Drive Cycle - 150 kg payload/Honda CB Shine 125cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Honda CB Shine 125cc	IM	PMSM	Syn. Rel
	.0453	.0376	.0385

The PMSM motors outperform the other two motors by giving a mileage higher than IM and Synchronous reluctance motors. However, mileage of synchronous reluctance motors lags behind the PMSM motors by a small value, but there is a significant difference between mileages of PMSM and IM.

2. Urban Drive Cycle:

From the data, it can be concluded that the sports mode would be consuming a higher amount of fuel per kilometre distance than the economy mode hence delivering a lower mileage value.

a. Hub motors:

- 70kg payload:

Table 10.29: Fuel Consumption of hub motor - Urban Drive Cycle - 70kg payload/Bajaj Discover 100cc

Vehicle Name	**Fuel Consumption (kWh/km)**		
Bajaj Discover 100cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0462	.0355	.0360

From acceleration mode to driving mode, fuel consumption is more, leading to a lower mileage value. i.e. 28km/kWh in PMSM-Hub motor.

- 150kg payload:

Table 10.30: Fuel Consumption of hub motor - Urban Drive Cycle - 150kg payload/Bajaj Discover 100cc

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM-Hub	PMSM-Hub	Syn. Rel-Hub
	.0563	.0440	.0446

The table 10.30 shows that PMSM motors provide the lowest value of fuel consumption while the IM motors consume the highest amount of energy; hence hub motors mileage follows a similar fashion as of hub motors in economy mode.

b. Belt driven motors:

- 70kg payload:

Table 10.31: Fuel Consumption of belt driven motor - Urban Drive Cycle - 70kg payload/Bajaj Discover 100ccmotors

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM	PMSM	Syn. Rel
	.0423	.0328	.0332

IM have the highest amount of fuel consumption, i.e. 0.0423 kWh/km, giving the least mileage.

- 150kg payload:

Table 10.32: Fuel Consumption of belt driven motor - Urban Drive Cycle - 150kg payload/Bajaj Discover 100ccmotors

Vehicle Name	Fuel Consumption (kWh/km)		
Bajaj Discover 100cc	IM	PMSM	Syn. Rel
	.0511	.0403	.0409

The PMSM motors lead the other two motors by delivering a higher mileage than IM and Synchronous reluctance motors even if the mileage of synchronous reluctance motors lags behind the PMSM motors by a tiny value. Still, there is an observable difference between mileages of PMSM and IM.

10.4 Well to Wheel Analysis

Eventually, the energy required to drive an electric vehicle for a particular distance has to be carried out through various mediums from the well (Source/ Power Plant) to the wheel of the electric vehicle. As the energy gets carried through these mediums, it's encountered some losses. Hence, it becomes essential to do 'Well to Wheel' calculations.

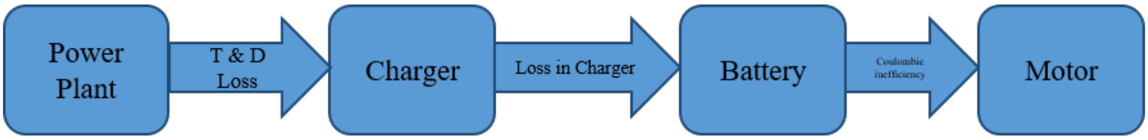


Figure 10.10: Energy Flow

In a nutshell, the energy that is to be produced at the power plant to drive an electric bike for a distance of 1 km has to be figured out in figure 10.10.

The following points are to be considered for this calculation.

1. Electrical energy, when flows from a power plant to the consumer, encounters transmission and distribution losses. For a typical system, the efficiency turns out to be around 95%.

2. At the consumer, there will be a charger to charge the battery of the electric vehicle. That will have certain power electronics components. The overall efficiency of this system turns out to be around 88

3. At last, the battery has a Coulombic efficiency. Taking that to be around 95%, further calculations are proceeded.

Hence the overall system efficiency of electric energy delivery from the well to the wheel comes out to be 79.42%. For this illustration, let's take any test vehicle with its operating points for a particular drive cycle. Analysis has been done, imagining the vehicle is fitted with a Permanent Magnet Synchronous Motor (PMSM).

Table 10.33: Illustration of test vehicle

Vehicle	**Motor**	**Payload**
RE Classic 350	PMSM	150 kg

From table 10.34, it is evident that to drive the vehicle for 1km, and the motor will consume 56.6Wh of electrical energy. For that, the power plant has to produce 71.3Wh of electrical energy.

10.5 Emission Analysis

Table 10.34: Well to Wheel Calculation

Motor Optimized for Driving		**Motor Optimized for Acceleration**	
Fuel Consumption (kWh/km)	**Energy Generation at Power Plant (kWh/km)**	**Fuel Consumption (kWh/km)**	**Energy Generation at Power Plant (kWh/km)**
0.0566	0.0713	0.0667	0.084

10.5.1 Overview

Conventional ICE vehicles cause direct and indirect emissions at the time of manufacturing and use of the vehicle. In contrast, EVs cause mostly indirect emissions that include the proportion at manufacturing as well as energy generation for the vehicle. A study from the Massachusetts Institute of Technology Energy Initiative found that EV production leads to more emissions than ICE vehicles, which is mostly from battery production. The production of batteries (mostly lithium-ions) includes extensive use of rare earth materials that facilitate effective energy use from burning fossil fuel. Considering the limited supply of the materials used in the production of batteries, most battery manufacturers will start working on battery recycling rather than producing a new cell. If that continues, in a couple of years, the emission due to EVs production will reduce significantly. Hence, we will be left with only the emission caused by the energy generation to drive the vehicle.
In this section, our primary aim is to estimate the total emission from generating power plants to generate energy consumption by driving for 1 km. Thereby, we have not considered the emissions due to the production phase of EVs. India's energy generation scenarios will help examine the available energy support, as shown in figure 10.11.

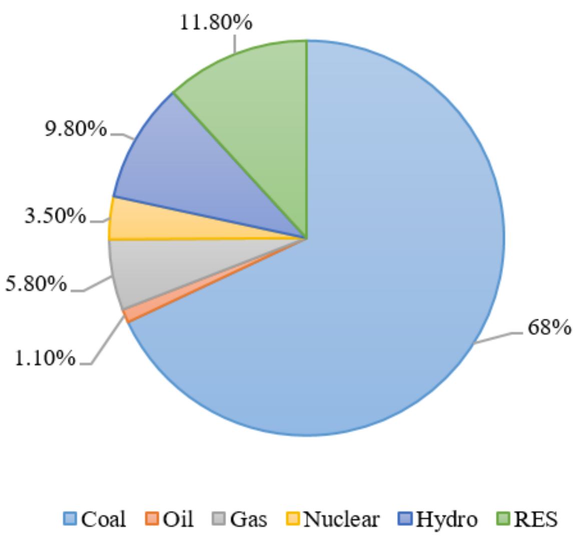


Figure 10.11: Energy generation scenario (percentage contribution from fuel mix)

There are various air pollutants produced by fossil fuel-based power plants, as shown in table 10.35. These pollutants are of different types and have a range of negative impacts on ambient air quality and correspondingly on human health and the environment. CO2, NOx, SOx, and PM2.5 are the critical air pollutants of concern from generating power plants. This section primarily discusses the pollution caused by individual fuel mixes per KWh energy generation. Table 10.35 presents the air pollutants from fuel mixes for annual energy generation in the present years of the coal dominant scenario.

The literature shows that coal is the core fuel for India and will remain so for India's electricity mix in the years to come. Therefore, more efficient use of coal is essential to ensure a clean environment for India. In all the cases, the contribution of CO2 is the highest among the other pollutants.

Table 10.35: Pollutants(gm/KWh) in case of coal dominant scenario

Power Plants	**% generation**	$EM_{CO_2}^{kWh}$	$EM_{NO_x}^{kWh}$	$EM_{SO_x}^{kWh}$	$EM_{PM_{2.5}}^{kWh}$
Coal	68	617.3117	2.720529	4.673376	1.255319
Oil	1.1	11.38068	0.023577	0.124209	0.020127
Gas	5.8	27.54687	0.209891	0.017826	0
Nuclear	3.5	1.100633	0.001725	0.001725	0.002875
Hydro	9.8	2.601495	0.00575	0.002875	5.75E-05
RES	11.8	7.967223	0.037378	0.027027	0.000575
$\sum EM_{Pollu\tan t_{(FM)}}^{kWh}$		667.9086	2.99885	4.847039	1.278953
Total emissions(Kg/KWh)		0.67703341			

$EM_{CO_{2(FM)}} = E_{req(GP)} * EM_{CO_2}^{kWh}$

$EM_{CO_{2(FM)}}, EM_{NO_{x(FM)}}, EM_{SO_{x(FM)}}, EM_{PM_{2.5(FM)}}$ are the $CO_2, NO_x, SO_x, PM_{2.5}$ emissions from the fuel mix, respectively.

$EM_{CO_{2(FM)}} = E_{req(GP)} * EM_{CO_{2(FM)}}^{kWh}$

$EM_{NO_{x(FM)}} = E_{req(GP)} * EM_{NO_{x(FM)}}^{kWh}$

$EM_{NO_{x(FM)}} = E_{req(GP)} * EM_{NO_{x(FM)}}^{kWh}$

$EM_{PM_{2.5(FM)}} = E_{req(GP)} * EM_{PM_{2.5(FM)}}^{kWh}$

where,

$EM_{CO_{2(FM)}}^{kWh}, EM_{NO_{x(FM)}}^{kWh}, EM_{PM_{2.5(FM)}}^{kWh}\, and\, EM_{SO_{x(FM)}}^{kWh}$ are the respective emissions for producing 1 kWh from the fuel mixes and, E(req(GP)) is the energy of generating power plants to drive a vehicle for 1 km.

EM_{GP} is the total emission from generating power plant to generate energy consumption by the vehicle to drive for 1 km, is calculated as:

$EM_{GP} = \Sigma(EM_{CO_{2(FM)}} + EM_{NO_{x(FM)}} + EM_{SO_{x(FM)}} + EM_{PM_{2.5(FM)}})$

Referring to the fuel consumption from tables 10.36 to 10.39 , the emissions that would happen to drive the vehicle for 1km are shown below from table 10.40 to table 10.55. Hence, to drive these vehicles for a distance of 1km, a total of emissions are presented in tables 10.56 to 10.59 .

Table 10.36: Fuel Consumption (kWh/km) – motor optimized for driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Driving					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0797	0.0858	0.0713	0.0764	0.0728	0.0780
2	Hero Honda (splender plus)	0.0428	0.0475	0.0373	0.0408	0.0377	0.0416
3	TVS star city	0.0497	0.0533	0.0431	0.0465	0.0440	0.0473
4	Honda Activa	0.0548	0.0543	0.0471	0.0473	0.0485	0.0484
5	Hero Honda CD Deluxe	0.0529	0.0570	0.0413	0.0451	0.0424	0.0455
6	Hero Passion Pro	0.0748	0.0799	0.0673	0.0719	0.0688	0.0733
7	Honda Activa	0.0779	0.0833	0.0692	0.0740	0.0709	0.0755
8	Honda CB Shine 125cc	0.0483	0.0500	0.0422	0.0441	0.0432	0.0452
9	TVS Radeon	0.0605	0.0613	0.0537	0.0551	0.0534	0.0548
10	Bajaj discover	0.0479	0.0511	0.0408	0.0435	0.0414	0.0441

Table 10.37: Fuel Consumption (kWh/km) – motor optimized for acceleration

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.1001	0.1088	0.0840	0.0906	0.0860	0.0927
2	Hero Honda (splender plus)	0.0533	0.0585	0.0439	0.0476	0.0446	0.0489
3	TVS star city	0.0547	0.0594	0.0460	0.0502	0.0469	0.0508
4	Honda Activa	0.0558	0.0593	0.0477	0.0500	0.0491	0.0514
5	Hero Honda CD Deluxe	0.0590	0.0637	0.0444	0.0486	0.0457	0.0490
6	Hero Passion Pro	0.0767	0.0828	0.0686	0.0738	0.0700	0.0751
7	Honda Activa	0.0784	0.0846	0.0696	0.0748	0.0712	0.0763
8	Honda CB Shine 125cc	0.0571	0.0623	0.0474	0.0514	0.0485	0.0525
9	TVS Radeon	0.0710	0.0774	0.0606	0.0657	0.0593	0.0639
10	Bajaj discover	0.0644	0.0709	0.0507	0.0554	0.0515	0.0561

Table 10.38: Fuel Consumption (kWh/km) – motor optimized for driving

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0815	0.0731	0.0747	0.0736	0.0680	0.0704
2	Hero Honda (splender plus)	0.0452	0.0392	0.0395	0.0344	0.0324	0.0333
3	TVS star city	0.0480	0.0425	0.0434	0.0415	0.0390	0.0401
4	Honda Activa	0.0467	0.0416	0.0425	0.0421	0.0397	0.0406
5	Hero Honda CD Deluxe	0.0445	0.0362	0.0373	0.0259	0.0242	0.0250
6	Hero Passion Pro	0.0749	0.0678	0.0693	0.0688	0.0643	0.0659
7	Honda Activa	0.0754	0.0666	0.0682	0.0716	0.0669	0.0686
8	Honda CB Shine 125cc	0.0479	0.0424	0.0435	0.0421	0.0391	0.0406
9	TVS Radeon	0.0469	0.0424	0.0425	0.0439	0.0399	0.0413
10	Bajaj discover	0.0455	0.0387	0.0393	0.0382	0.0353	0.0366

Table 10.39: Fuel Consumption (kWh/km) – motor optimized for acceleration

S.No	Vehicle Name	Motor Optimized for Acceleration					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.1013	0.0855	0.0875	0.0750	0.0704	0.0727
2	Hero Honda (splender plus)	0.0535	0.0446	0.0450	0.0361	0.0337	0.0346
3	TVS star city	0.0555	0.0469	0.0478	0.0446	0.0414	0.0423
4	Honda Activa	0.0476	0.0421	0.0431	0.0423	0.0398	0.0408
5	Hero Honda CD Deluxe	0.0583	0.0433	0.0449	0.0304	0.0278	0.0283
6	Hero Passion Pro	0.0776	0.0696	0.0710	0.0692	0.0649	0.0664
7	Honda Activa	0.0763	0.0672	0.0688	0.0717	0.0671	0.0688
8	Honda CB Shine 125cc	0.0578	0.0483	0.0494	0.0436	0.0407	0.0421
9	TVS Radeon	0.0587	0.0503	0.0494	0.0464	0.0425	0.0437
10	Bajaj discover	0.0634	0.0495	0.0502	0.0398	0.0370	0.0382

Table 10.40: CO2 Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Driving					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0532	0.0573	0.0476	0.0511	0.0486	0.0521
2	Hero Honda (splender plus)	0.0286	0.0317	0.0249	0.0273	0.0252	0.0278
3	TVS star city	0.0332	0.0356	0.0288	0.0311	0.0294	0.0316
4	Honda Activa	0.0366	0.0363	0.0314	0.0316	0.0324	0.0323
5	Hero Honda CD Deluxe	0.0353	0.0380	0.0276	0.0301	0.0283	0.0304
6	Hero Passion Pro	0.0499	0.0534	0.0450	0.0480	0.0459	0.0490
7	Honda Activa	0.0520	0.0557	0.0462	0.0494	0.0473	0.0504
8	Honda CB Shine 125cc	0.0322	0.0334	0.0282	0.0295	0.0289	0.0302
9	TVS Radeon	0.0404	0.0409	0.0359	0.0368	0.0357	0.0366
10	Bajaj discover	0.0320	0.0342	0.0272	0.0291	0.0276	0.0295

Table 10.41: CO2 Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0669	0.0727	0.0561	0.0605	0.0574	0.0619
2	Hero Honda (splender plus)	0.0356	0.0391	0.0293	0.0318	0.0298	0.0326
3	TVS star city	0.0365	0.0397	0.0307	0.0335	0.0313	0.0339
4	Honda Activa	0.0373	0.0396	0.0318	0.0334	0.0328	0.0343
5	Hero Honda CD Deluxe	0.0394	0.0425	0.0296	0.0325	0.0305	0.0327
6	Hero Passion Pro	0.0512	0.0553	0.0458	0.0493	0.0467	0.0502
7	Honda Activa	0.0524	0.0565	0.0465	0.0499	0.0476	0.0510
8	Honda CB Shine 125cc	0.0381	0.0416	0.0317	0.0343	0.0324	0.0351
9	TVS Radeon	0.0474	0.0517	0.0405	0.0439	0.0396	0.0427
10	Bajaj discover	0.0430	0.0474	0.0339	0.0370	0.0344	0.0375

Table 10.42: CO2 Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0544	0.0488	0.0499	0.0492	0.0454	0.0470
2	Hero Honda (splender plus)	0.0302	0.0262	0.0264	0.0230	0.0216	0.0223
3	TVS star city	0.0320	0.0284	0.0290	0.0277	0.0260	0.0268
4	Honda Activa	0.0312	0.0278	0.0284	0.0281	0.0265	0.0271
5	Hero Honda CD Deluxe	0.0297	0.0242	0.0249	0.0173	0.0162	0.0167
6	Hero Passion Pro	0.0500	0.0453	0.0463	0.0459	0.0429	0.0440
7	Honda Activa	0.0504	0.0445	0.0456	0.0478	0.0447	0.0458
8	Honda CB Shine 125cc	0.0320	0.0283	0.0290	0.0281	0.0261	0.0271
9	TVS Radeon	0.0314	0.0283	0.0284	0.0293	0.0266	0.0276
10	Bajaj discover	0.0304	0.0259	0.0263	0.0255	0.0236	0.0244

Table 10.43: CO2 Emissions (kg/km) - motor optimized for acceleration

S.No	Vehicle Name	Motor Optimized for Acceleration					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0677	0.0571	0.0584	0.0501	0.0470	0.0485
2	Hero Honda (splender plus)	0.0357	0.0298	0.0300	0.0241	0.0225	0.0231
3	TVS star city	0.0371	0.0313	0.0319	0.0298	0.0277	0.0283
4	Honda Activa	0.0318	0.0281	0.0288	0.0283	0.0266	0.0272
5	Hero Honda CD Deluxe	0.0389	0.0289	0.0300	0.0203	0.0186	0.0189
6	Hero Passion Pro	0.0518	0.0465	0.0474	0.0463	0.0433	0.0444
7	Honda Activa	0.0510	0.0449	0.0459	0.0479	0.0448	0.0459
8	Honda CB Shine 125cc	0.0386	0.0322	0.0330	0.0291	0.0272	0.0281
9	TVS Radeon	0.0392	0.0336	0.0330	0.0310	0.0284	0.0292
10	Bajaj discover	0.0424	0.0331	0.0335	0.0266	0.0247	0.0255

Table 10.44: NOx Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Driving					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
2	Hero Honda (splender plus)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	TVS star city	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
7	Honda Activa	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
8	Honda CB Shine 125cc	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
10	Bajaj discover	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001

Table 10.45: NOx Emissions (kg/km) - motor optimized for acceleration

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
2	Hero Honda (splender plus)	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
3	TVS star city	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002
4	Honda Activa	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002
5	Hero Honda CD Deluxe	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
7	Honda Activa	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
8	Honda CB Shine 125cc	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002
9	TVS Radeon	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
10	Bajaj discover	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

Table 10.46: NOx Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
2	Hero Honda (splender plus)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	TVS star city	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
7	Honda Activa	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
8	Honda CB Shine 125cc	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

Table 10.47: NOx Emissions (kg/km) - motor optimized for acceleration

S.No	Vehicle Name	Motor Optimized for Acceleration					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
2	Hero Honda (splender plus)	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
3	TVS star city	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
7	Honda Activa	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
8	Honda CB Shine 125cc	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001

Table 10.48: SOx Emissions (kg/km) - motor optimized for driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Driving					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0004	0.0004	0.0003	0.0004	0.0004	0.0004
2	Hero Honda (splender plus)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
3	TVS star city	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
4	Honda Activa	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
5	Hero Honda CD Deluxe	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
6	Hero Passion Pro	0.0004	0.0004	0.0003	0.0003	0.0003	0.0004
7	Honda Activa	0.0004	0.0004	0.0003	0.0004	0.0003	0.0004
8	Honda CB Shine 125cc	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
9	TVS Radeon	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
10	Bajaj discover	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

Table 10.49: SOx Emissions (kg/km) - Motor optimized for Acceleration

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004
2	Hero Honda (splender plus)	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
3	TVS star city	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
4	Honda Activa	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
5	Hero Honda CD Deluxe	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
6	Hero Passion Pro	0.0004	0.0004	0.0003	0.0004	0.0003	0.0004
7	Honda Activa	0.0004	0.0004	0.0003	0.0004	0.0003	0.0004
8	Honda CB Shine 125cc	0.0003	0.0003	0.0002	0.0002	0.0002	0.0003
9	TVS Radeon	0.0003	0.0004	0.0003	0.0003	0.0003	0.0003
10	Bajaj discover	0.0003	0.0003	0.0002	0.0003	0.0002	0.0003

Table 10.50: SOx Emissions (kg/km) - Motor optimized for driving

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003
2	Hero Honda (splender plus)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
3	TVS star city	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	Honda Activa	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
5	Hero Honda CD Deluxe	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003
7	Honda Activa	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003
8	Honda CB Shine 125cc	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
9	TVS Radeon	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
10	Bajaj discover	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

Table 10.51: SOx Emissions (kg/km) - Motor optimized for acceleration

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0005	0.0004	0.0004	0.0004	0.0003	0.0004
2	Hero Honda (splender plus)	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
3	TVS star city	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
4	Honda Activa	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
5	Hero Honda CD Deluxe	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003
7	Honda Activa	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003
8	Honda CB Shine 125cc	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
9	TVS Radeon	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
10	Bajaj discover	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002

Table 10.52: PM2.5 Emissions (kg/km) - Motor optimized for Driving

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Driving					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	Hero Honda (splender plus)	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001
3	TVS star city	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
7	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
8	Honda CB Shine 125cc	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

Table 10.53: PM2.5 Emissions (kg/km) - Motor optimized for Acceleration

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	Hero Honda (splender plus)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	TVS star city	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
6	Hero Passion Pro	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
7	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
8	Honda CB Shine 125cc	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

Table 10.54: PM2.5 Emissions (kg/km) - Motor optimized for Driving

S.No	**Vehicle Name**	**Motor Optimized for Driving**					
		Fixed Gear Ratio - 2.4			**Rule Based CVT**		
		IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
1	RE CLASSIC 350	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	Hero Honda (splender plus)	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
3	TVS star city	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
6	Hero Passion Pro	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
7	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
8	Honda CB Shine 125cc	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000

Table 10.55: PM2.5 Emissions (kg/km) - Motor optimized for Acceleration

S.No	**Vehicle Name**	**Motor Optimized for Driving**					
		Fixed Gear Ratio - 2.4			**Rule Based CVT**		
		IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
1	RE CLASSIC 350	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	Hero Honda (splender plus)	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
3	TVS star city	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
5	Hero Honda CD Deluxe	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
6	Hero Passion Pro	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
7	Honda Activa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
8	Honda CB Shine 125cc	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
9	TVS Radeon	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
10	Bajaj discover	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000

Table 10.56: Total Emissions (kg/km) - Motor optimized for driving

S.No	**Vehicle Name**	**Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)**					
		Motor Optimized for Driving					
		IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
1	RE CLASSIC 350	0.0540	0.0581	0.0483	0.0517	0.0493	0.0528
2	Hero Honda (splender plus)	0.0290	0.0322	0.0252	0.0277	0.0255	0.0282
3	TVS star city	0.0336	0.0361	0.0292	0.0315	0.0298	0.0320
4	Honda Activa	0.0371	0.0368	0.0319	0.0320	0.0328	0.0328
5	Hero Honda CD Deluxe	0.0358	0.0386	0.0280	0.0305	0.0287	0.0308
6	Hero Passion Pro	0.0506	0.0541	0.0456	0.0487	0.0466	0.0496
7	Honda Activa	0.0527	0.0564	0.0469	0.0501	0.0480	0.0511
8	Honda CB Shine 125cc	0.0327	0.0339	0.0286	0.0299	0.0293	0.0306
9	TVS Radeon	0.0410	0.0415	0.0364	0.0373	0.0361	0.0371
10	Bajaj discover	0.0324	0.0346	0.0276	0.0295	0.0280	0.0299

Table 10.57: Total Emissions (kg/km) - Motor optimized for acceleration

S.No	Vehicle Name	Fixed Gear Ratio - 4.5 (3.06 for RE Classic 350)					
		Motor Optimized for Acceleration					
		IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
1	RE CLASSIC 350	0.0678	0.0737	0.0569	0.0614	0.0582	0.0628
2	Hero Honda (splender plus)	0.0361	0.0396	0.0297	0.0322	0.0302	0.0331
3	TVS star city	0.0370	0.0402	0.0312	0.0340	0.0318	0.0344
4	Honda Activa	0.0378	0.0401	0.0323	0.0339	0.0333	0.0348
5	Hero Honda CD Deluxe	0.0400	0.0431	0.0300	0.0329	0.0309	0.0332
6	Hero Passion Pro	0.0519	0.0561	0.0464	0.0500	0.0474	0.0509
7	Honda Activa	0.0531	0.0572	0.0471	0.0506	0.0482	0.0516
8	Honda CB Shine 125cc	0.0386	0.0422	0.0321	0.0348	0.0328	0.0355
9	TVS Radeon	0.0481	0.0524	0.0410	0.0445	0.0402	0.0433
10	Bajaj discover	0.0436	0.0480	0.0343	0.0375	0.0348	0.0380

Table 10.58: Total Emissions (kg/km) - Motor optimized for driving

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0552	0.0495	0.0505	0.0499	0.0460	0.0477
2	Hero Honda (splender plus)	0.0306	0.0266	0.0267	0.0233	0.0219	0.0226
3	TVS star city	0.0325	0.0287	0.0294	0.0281	0.0264	0.0272
4	Honda Activa	0.0316	0.0282	0.0288	0.0285	0.0268	0.0275
5	Hero Honda CD Deluxe	0.0301	0.0245	0.0253	0.0176	0.0164	0.0170
6	Hero Passion Pro	0.0507	0.0459	0.0469	0.0466	0.0435	0.0446
7	Honda Activa	0.0510	0.0451	0.0462	0.0485	0.0453	0.0465
8	Honda CB Shine 125cc	0.0324	0.0287	0.0294	0.0285	0.0265	0.0275
9	TVS Radeon	0.0318	0.0287	0.0288	0.0297	0.0270	0.0279
10	Bajaj discover	0.0308	0.0262	0.0266	0.0259	0.0239	0.0248

Table 10.59: Total Emissions (kg/km) - Motor optimized for acceleration

S.No	Vehicle Name	Motor Optimized for Driving					
		Fixed Gear Ratio - 2.4			Rule Based CVT		
		IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
1	RE CLASSIC 350	0.0686	0.0579	0.0592	0.0508	0.0476	0.0492
2	Hero Honda (splender plus)	0.0362	0.0302	0.0305	0.0245	0.0228	0.0234
3	TVS star city	0.0376	0.0317	0.0323	0.0302	0.0280	0.0287
4	Honda Activa	0.0322	0.0285	0.0292	0.0286	0.0270	0.0276
5	Hero Honda CD Deluxe	0.0394	0.0293	0.0304	0.0206	0.0188	0.0192
6	Hero Passion Pro	0.0526	0.0471	0.0481	0.0469	0.0439	0.0450
7	Honda Activa	0.0517	0.0455	0.0466	0.0486	0.0454	0.0466
8	Honda CB Shine 125cc	0.0391	0.0327	0.0335	0.0295	0.0276	0.0285
9	TVS Radeon	0.0397	0.0341	0.0334	0.0314	0.0288	0.0296
10	Bajaj discover	0.0429	0.0335	0.0340	0.0269	0.0250	0.0259

10.5.2 Motor Optimized for Driving

In this section, the emissions for each vehicle, when they are configured with an equivalent electric motor, are discussed. The idea of this mode is already discussed in the previous chapter. In this section, the vehicle's emissions, when driven in this mode, are presented.

1. Sports Bike
   In this section, the ICE of sports bikes has been replaced by different types of motors and further analysis has been processed.

   a. Honda CB Shine
   The emissions analysis has been done for the vehicle configuration similar to 'Honda CB Shine'.

Table 10.60: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 4.5					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.032248328	0.03342	0.02818	0.02945206	0.02889	0.030166054
NOx Emission	0.000144792	0.00015	0.00013	0.000132237	0.00013	0.000135443
SOx Emission	0.000234027	0.00024	0.0002	0.000213735	0.00021	0.000218916
PM2.5 Emission	6.17511E-05	6.4E-05	5.4E-05	5.63967E-05	5.5E-05	5.77639E-05
Total Emission	0.032688898	0.03388	0.02856	0.029854428	0.02928	0.030578177

Table 10.61: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 2.4			**Rule Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.03201	0.0283	0.02903	0.02814	0.02614	0.02709
NOx Emission	0.00014	0.00013	0.00013	0.00013	0.00012	0.00012
SOx Emission	0.00023	0.00021	0.00021	0.0002	0.00019	0.0002
PM2.5 Emission	6.1E-05	5.4E-05	5.6E-05	5.4E-05	5E-05	5.2E-05
Total Emission	0.03244	0.02869	0.02943	0.02852	0.02649	0.02746

   For induction motor (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.032 kg/km while using constant gear ratio, 0.032 kg/km while using constant gear ratio and 0.028 kg/km while using Rule-Based CVT. From this table, it's clear that the emissions are lower while testing with rule-based CVT.

   b. TVS Radeon
   Here, the emissions analysis has been done for the vehicle configuration similar to 'TVS Radeon'.

   For induction motor (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.040 kg/km while using constant gear ratio, 0.032

Table 10.62: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 4.5					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.040403338	0.04092	0.0359	0.036807296	0.03566	0.036592845
NOx Emission	0.000181407	0.00018	0.00016	0.000165261	0.00016	0.000164299
SOx Emission	0.000293209	0.0003	0.00026	0.000267112	0.00026	0.000265556
PM2.5 Emission	7.73669E-05	7.8E-05	6.9E-05	7.04809E-05	6.8E-05	7.00703E-05
Total Emission	0.040955321	0.04148	0.03639	0.03731015	0.03615	0.03709277

Table 10.63: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 2.4			**Rule-Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.03135	0.02833	0.02838	0.02932	0.02663	0.02756
NOx Emission	0.00014	0.00013	0.00013	0.00013	0.00012	0.00012
SOx Emission	0.00023	0.00021	0.00021	0.00021	0.00019	0.0002
PM2.5 Emission	6E-05	5.4E-05	5.4E-05	5.6E-05	5.1E-05	5.3E-05
Total Emission	0.03178	0.02872	0.02877	0.02972	0.027	0.02794

kg/km while using constant gear ratio and 0.029 kg/km while using rule-based CVT. From this table, it's clear that the emissions are lower while testing with rule-based CVT.

2. Retro Bike – RE Classic 350
In this section, the ICE of a retro bike has been replaced by different types of motors, and further analysis has been processed. For this, let's discuss RE Classic 350.

Table 10.64: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 3.06					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.053245146	0.05734	0.04761	0.051051022	0.04863	0.052114024
NOx Emission	0.000239066	0.00026	0.00021	0.000229215	0.00022	0.000233987
SOx Emission	0.000386402	0.00042	0.00035	0.000370479	0.00035	0.000378194
PM2.5 Emission	0.000101957	0.00011	9.1E-05	9.77557E-05	9.3E-05	9.97912E-05
Total Emission	0.053972572	0.05812	0.04826	0.051748472	0.0493	0.052825996

Table 10.65: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 2.4			**Rule-Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.05445	0.04882	0.04987	0.04918	0.04539	0.04704
NOx Emission	0.00024	0.00022	0.00022	0.00022	0.0002	0.00021
SOx Emission	0.0004	0.00035	0.00036	0.00036	0.00033	0.00034
PM2.5 Emission	0.0001	9.3E-05	9.5E-05	9.4E-05	8.7E-05	9E-05
Total Emission	0.05519	0.04949	0.05055	0.04986	0.04601	0.04768

For induction motor (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.053 kg/km while using constant gear ratio, 0.055 kg/km while using constant gear ratio and 0.049 kg/km while using rule-based CVT. From this table, it's clear that the emissions are lower while testing with rule-based CVT.

3. Mid-Range Bike – Hero Passion Pro
   In this section, the ICE of a mid-range bike has been replaced by different types of motors, and further analysis has been processed. Taking an example of Hero Passion Pro, an additional section has been discussed.

Table 10.66: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 4.5					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.049935879	0.05336	0.04497	0.048032735	0.04593	0.04895277
NOx Emission	0.000224208	0.00024	0.0002	0.000215663	0.00021	0.000219794
SOx Emission	0.000362387	0.00039	0.00033	0.000348575	0.00033	0.000355252
PM2.5 Emission	9.56204E-05	0.0001	8.6E-05	9.19761E-05	8.8E-05	9.37378E-05
Total Emission	0.050618093	0.05409	0.04559	0.048688949	0.04656	0.049621553

Table 10.67: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Driving**					
	Fixed Gear Ratio - 2.4			**Rule-Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.05003	0.04529	0.04628	0.04593	0.04293	0.04405
NOx Emission	0.00022	0.0002	0.00021	0.00021	0.00019	0.0002
SOx Emission	0.00036	0.00033	0.00034	0.00033	0.00031	0.00032
PM2.5 Emission	9.6E-05	8.7E-05	8.9E-05	8.8E-05	8.2E-05	8.4E-05
Total Emission	0.05071	0.04591	0.04691	0.04655	0.04351	0.04465

For induction motor (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.050 kg/km while using constant gear ratio, 0.050 kg/km while using constant gear ratio and 0.04655 kg/km while using rule-based CVT. From this table, it's clear that the emissions are lower while testing with rule-based CVT.

10.5.3 Motor Optimized for Acceleration

The idea of this mode is already discussed in the previous chapter. In this section, the vehicle's emissions, when driven in this mode, are presented.

1. Sports Bike:
   In this section, the ICE of sports bikes has been replaced by different types of motors and further analysis has been processed.

   a. Honda CB Shine:
      Here, the emissions analysis has been done for the vehicle configuration similar to 'Honda CB Shine'.

Table 10.68: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	Motor Optimized for Acceleration					
	Fixed Gear Ratio - 4.5					
	IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
CO2 Emission	0.03811	0.04158	0.03166	0.03430369	0.032396341	0.03505637
NOx Emission	0.00017	0.00019	0.00014	0.000154021	0.000145457	0.0001574
SOx Emission	0.00028	0.0003	0.00023	0.000248943	0.000235102	0.000254405
PM2.5 Emission	7.3E-05	8E-05	6.1E-05	6.56869E-05	6.20346E-05	6.71281E-05
Total Emission	0.03863	0.04215	0.03209	0.03477234	0.032838934	0.035535303

Table 10.69: Total Emissions - CVT based vehicle

Emissions (kg/km)	Motor Optimized for Acceleration					
	Fixed Gear Ratio - 2.4			Rule-Based CVT		
	IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
CO2 Emission	0.03857	0.03224	0.033	0.029144	0.027202	0.028103
NOx Emission	0.00017	0.00014	0.00015	0.000131	0.000122	0.000126
SOx Emission	0.00028	0.00023	0.00024	0.000212	0.000197	0.000204
PM2.5 Emission	7.4E-05	6.2E-05	6.3E-05	5.58E-05	5.21E-05	5.38E-05
Total Emission	0.0391	0.03268	0.03345	0.029542	0.027574	0.028487

For PMSM (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.032 kg/km while using constant gear ratio, 0.032 kg/km while using constant gear ratio and 0.027 kg/km while using rule-based CVT. From this table, it's clear that the emissions are lower while testing with rule-based CVT.

b. TVS Radeon:
Here, the emissions analysis has been done for the vehicle configuration similar to 'TVS Radeon'.

Table 10.70: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	Motor Optimized for Acceleration					
	Fixed Gear Ratio - 4.5					
	IM	IM_Hub	PMSM	PMSM_Hub	Syn.Rel	Syn.Rel_Hub
CO2 Emission	0.04744	0.05171	0.04046	0.043853891	0.039623747	0.042675674
NOx Emission	0.00021	0.00023	0.00018	0.0001969	0.000177907	0.00019161
SOx Emission	0.00034	0.00038	0.00029	0.000318249	0.000287551	0.000309699
PM2.5 Emission	9.1E-05	9.9E-05	7.7E-05	8.39742E-05	7.5874E-05	8.17181E-05
Total Emission	0.04809	0.05242	0.04101	0.044453015	0.04016508	0.043258701

Table 10.71: Total Emissions - CVT based vehicle

Emissions (kg/km)	Motor Optimized for Acceleration					
	Fixed Gear Ratio - 2.4			Rule-Based CVT		
	IM	PMSM	Syn.Rel	IM	PMSM	Syn.Rel
CO2 Emission	0.03921	0.03361	0.03298	0.030965	0.028405	0.029163
NOx Emission	0.00018	0.00015	0.00015	0.000139	0.000128	0.000131
SOx Emission	0.00028	0.00024	0.00024	0.000225	0.000206	0.000212
PM2.5 Emission	7.5E-05	6.4E-05	6.3E-05	5.93E-05	5.44E-05	5.58E-05
Total Emission	0.03975	0.03407	0.03343	0.031388	0.028793	0.029561

For PMSM (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.0002 kg/km while using constant gear ratio, 0.0002 kg/km while using constant gear ratio and 0.0002 kg/km while using rule-based CVT.

2. Retro Bike – RE Classic 350:
   In this section, the ICE of a retro bike has been replaced by different types of motors, and further analysis has been processed. For this, let's discuss RE Classic 350.

Table 10.72: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Acceleration**					
	Fixed Gear Ratio - 3.06					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.06687	0.0727	0.05611	0.060541513	0.057410534	0.061947637
NOx Emission	0.0003	0.00033	0.00025	0.000271826	0.000257768	0.000278139
SOx Emission	0.00049	0.00053	0.00041	0.000439352	0.00041663	0.000449556
PM2.5 Emission	0.00013	0.00014	0.00011	0.000115929	0.000109933	0.000118621
Total Emission	0.06779	0.07369	0.05688	0.06136862	0.058194866	0.062793954

Table 10.73: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Acceleration**					
	Fixed Gear Ratio - 2.4			**Rule-Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.06768	0.05712	0.05842	0.050106	0.046994	0.048542
NOx Emission	0.0003	0.00026	0.00026	0.000225	0.000211	0.000218
SOx Emission	0.00049	0.00041	0.00042	0.000364	0.000341	0.000352
PM2.5 Emission	0.00013	0.00011	0.00011	9.59E-05	9E-05	9.3E-05
Total Emission	0.06861	0.0579	0.05922	0.05079	0.047636	0.049206

For PMSM (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.0568 kg/km while using constant gear ratio, 0.0579 kg/km while using constant gear ratio and 0.04763 kg/km while using Rule-Based CVT.

3. Mid-Range Bike – Hero Passion Pro
   In this section, the ICE of a mid-range bike has been replaced by different types of motors, and further analysis has been processed. Taking an example of Hero Passion Pro, an additional section has been discussed.

Table 10.74: Total Emissions - Fixed gear ratio based vehicle

Emissions (kg/km)	**Motor Optimized for Acceleration**					
	Fixed Gear Ratio - 4.5					
	IM	**IM_Hub**	**PMSM**	**PMSM_Hub**	**Syn.Rel**	**Syn.Rel_Hub**
CO2 Emission	0.05121	0.05532	0.04581	0.049312711	0.046735939	0.050183128
NOx Emission	0.00023	0.00025	0.00021	0.00022141	0.00020984	0.000225318
SOx Emission	0.00037	0.0004	0.00033	0.000357864	0.000339165	0.000364181
PM2.5 Emission	9.8E-05	0.00011	8.8E-05	9.44271E-05	8.94929E-05	9.60938E-05
Total Emission	0.05191	0.05608	0.04644	0.049986412	0.047374437	0.05086872

Table 10.75: Total Emissions - CVT based vehicle

Emissions (kg/km)	**Motor Optimized for Acceleration**					
	Fixed Gear Ratio - 2.4			**Rule-Based CVT**		
	IM	**PMSM**	**Syn.Rel**	**IM**	**PMSM**	**Syn.Rel**
CO2 Emission	0.05185	0.04649	0.04743	0.046251	0.043328	0.044357
NOx Emission	0.00023	0.00021	0.00021	0.000208	0.000195	0.000199
SOx Emission	0.00038	0.00034	0.00034	0.000336	0.000314	0.000322
PM2.5 Emission	9.9E-05	8.9E-05	9.1E-05	8.86E-05	8.3E-05	8.49E-05
Total Emission	0.05256	0.04713	0.04808	0.046883	0.04392	0.044963

For PMSM (taking any of the tested motors) configuration, the total emissions for the drive cycle recorded from this particular test vehicle are 0.0464 kg/km while using constant gear ratio, 0.0471 kg/km while using Constant Gear Ratio and 0.04392 kg/km while using Rule-Based CVT.

11 Comprehensive comparison and analysis

11.1 Retro bike - Royal Enfield Classic 350

11.1.1 Vehicle parameters

One of the team member from E-Mobility Lab (EML), IIT Guwahati rode a Royal Enfield in Kundapura, Karnataka, daily, about three times a day for more than two weeks. This vehicle has the following parameters, as shown in Table 10.1:

Table 11.1: Vehicle Parameters of Royal Enfield

S.No	Parameter name	Symbol	Unit	Value
1	Kerb weight	m	kg	195
2	Aerodynamic drag coefficient of vehicle	Cd	-	0.78
3	Frontal area of vehicle	Af	m2	0.68
4	Radius of the wheel	r	m	0.2413
5	Gear ratio		-	3.06

11.1.2 Drive cycles used

The data obtained above was then converted into a drive cycle, for which the process has been explained in earlier chapters. These drive cycles were obtained from an ICE vehicle. For our analysis, we will replace the prime-mover with different electric motors with belt drive and hub configurations and see how they would perform on the same drive cycle along with WLTC and MoRTH drive cycles.

The table below gives out some performance metrics of the drive cycles used.

Table 11.2: Some performance metrics of the drive cycles used

S.No.	Drive Cycle	Average speed	Max speed	PKE	KI	RPS
		(km/h)	(km/h)	(m/s2)	(1/m)	(m/s2)
1	Kundapura	33.3	64.1	0.5	0.0020	0.036
2	WLTC	24.5	74.7	0.3	0.0010	0.010
3	MoRTH	21.9	42.0	0.4	0.0024	0.015

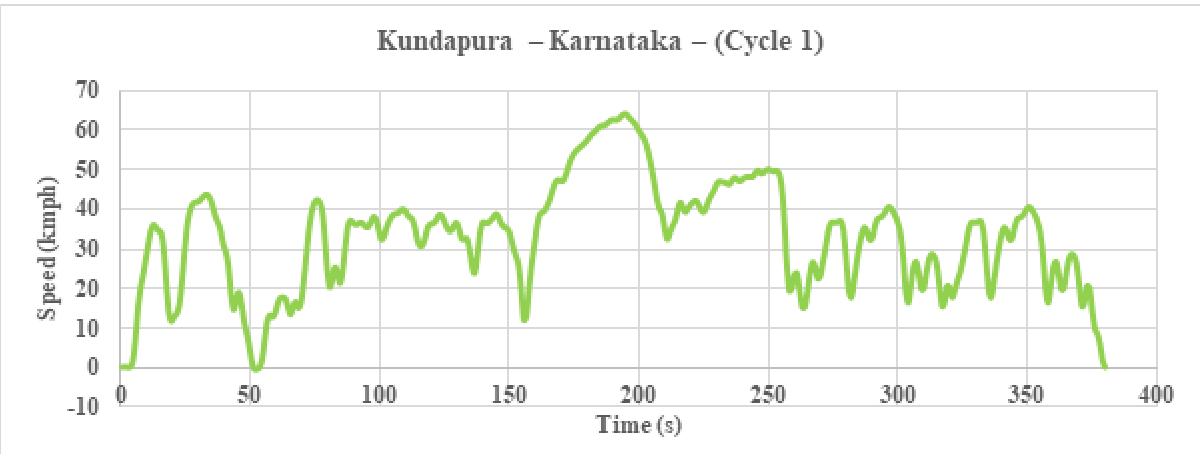


Figure 11.1: Kundapura drive cycle

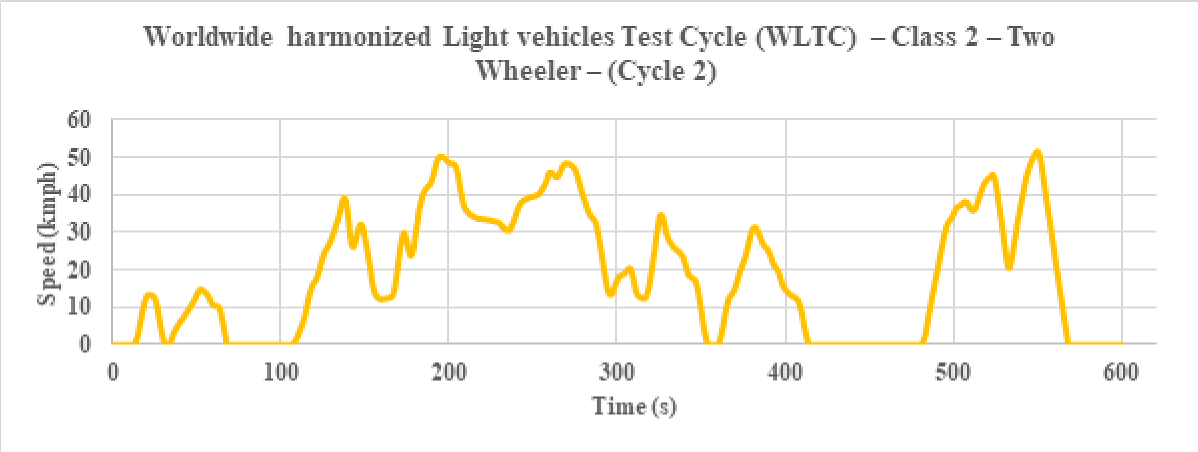


Figure 11.2: WLTC drive cycle for two wheelers

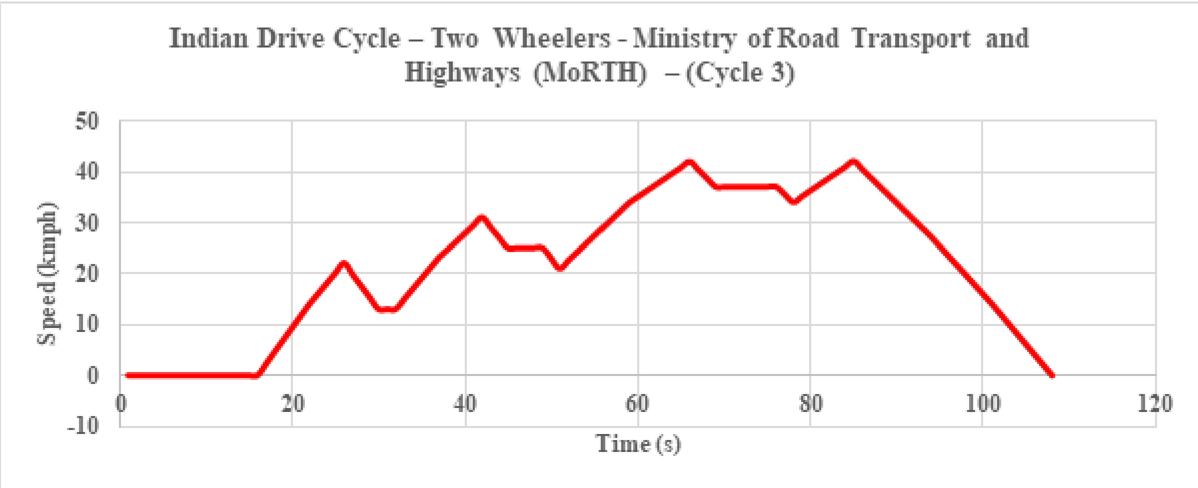


Figure 11.3: Ministry of Road Transport and Highways (MoRTH) drive cycle

11.1.3 Acceleration performance - Kundapura drive cycle

For motor optimized for drive cycle driving with fixed gear ratio:

Table 11.3: Acceleration performance – motor optimized for driving

Speed (km/h)	Time (s)
0-60	9.5
0-80	15.6
0-100	28.8

For motor optimized for acceleration with fixed gear ratio:

Table 11.4: Acceleration performance – motor optimized for acceleration

Speed (km/h)	Time (s)
0-60	5.71
0-80	9.53
0-100	16.3

11.1.4 Motor optimized for driving

11.1.4.1 Fuel consumption analysis

As shown in Table 10.7 and 10.8, the MoRTH drive cycle is the least taxing, followed by WLTC and, finally, the Kundapura cycle. Also, belt drives are consistently better than hub motors, as seen in the table. Comparing the types of motors, PMSM comes out to be the most efficient, after which comes SynRel motor and then Induction motor.

Table 11.5: Fuel consumption (kWh/km) for payload = 70kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.05	0.05	0.05	0.05	0.05	0.05
2	WLTC	0.04	0.04	0.04	0.04	0.04	0.04
3	MoRTH	0.03	0.03	0.03	0.03	0.03	0.03

Table 11.6: Fuel consumption (kWh/km) for payload = 150kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.06	0.07	0.06	0.06	0.06	0.06
2	WLTC	0.05	0.05	0.04	0.05	0.04	0.05
3	MoRTH	0.04	0.04	0.04	0.04	0.04	0.04

Table 11.7: Fuel consumption (kWh/100km) for payload = 70kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	5.0	5.3	4.5	4.8	4.6	4.9
2	WLTC	4.0	4.2	3.7	3.9	3.7	4.0
3	MoRTH	3.2	3.4	3	3.2	3.0	3.0

Table 11.8: Fuel consumption (kWh/100km) for payload = 150kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	6.3	6.8	5.7	6.1	5.8	6.2
2	WLTC	4.6	4.9	4.3	4.5	4.4	4.6
3	MoRTH	3.9	4.2	3.7	3.9	3.8	4.0

11.1.4.2 Power generation required

The next important criteria to look into is the energy required to be generated at the power plant, which is then delivered to our car by transmissions and distribution networks, and hence used to charge the battery. Each part of this journey has its own efficiency. So, every km our vehicle drives may have used 0.03 to 0.05 kWh/km for 70kg from earlier analysis, because of the inefficiencies, this energy will be much more upstream.

The same can be seen from our analysis. When compared to the fuel consumption table, the below table has higher values of kWh/km.

Table 11.9: Energy needed to be generated at the power plant for payload = 70kg–motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.06	0.07	0.06	0.06	0.06	0.06
2	WLTC	0.05	0.05	0.05	0.05	0.05	0.05
3	MoRTH	0.04	0.04	0.04	0.04	0.04	0.04

Table 11.10: Energy needed to be generated at the power plant for payload = 150kg–motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.08	0.09	0.07	0.08	0.07	0.08
2	WLTC	0.06	0.06	0.05	0.06	0.05	0.06
3	MoRTH	0.05	0.05	0.05	0.05	0.05	0.05

11.1.4.3 Emission analysis

For the energy per km in the above table 10.9, assuming that all the powerplants available are coal-based, the following table discusses emissions for all the drive cycles and motor-transmission combinations. As can be seen, the higher the energy consumption was in the previous table, the higher the emissions we get here.

Table 11.11: Emissions for payload = 70kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Kundapura	41.9	44.3	37.9	40.0	38.7	40.8
2	WLTC	33.1	35.3	30.4	32.4	31.1	33.0
3	MoRTH	26.3	28.1	24.8	26.4	25.3	26.9

Table 11.12: Emissions for payload = 150kg – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Kundapura	52.7	56.8	47.1	50.5	48.2	51.6
2	WLTC	38.6	41.1	35.5	37.8	36.3	38.5
3	MoRTH	32.8	35.0	30.8	32.9	31.4	33.5

11.1.5 Motor optimized for acceleration

11.1.5.1 Fuel consumption Analysis

As can be seen from Table 10.11 and 10.12, the MoRTH drive cycle is the least taxing and needs the least energy per km, followed by WLTC and finally, the Kundapura cycle. Also, belt drives are consistently better than hub motors, as seen in the table. Comparing the types of motors, PMSM comes out to be the most efficient, after which comes SynRel motor and then Induction motor.

Table 11.13: Fuel consumption (kWh/km) for payload = 70kg – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.06	0.07	0.05	0.06	0.05	0.06
2	WLTC	0.06	0.06	0.05	0.05	0.05	0.05
3	MoRTH	0.04	0.05	0.04	0.04	0.04	0.04

Table 11.14: Fuel consumption (kWh/km) for payload = 70kg – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.08	0.08	0.07	0.07	0.07	0.07
2	WLTC	0.07	0.08	0.06	0.06	0.06	0.06
3	MoRTH	0.06	0.06	0.05	0.05	0.05	0.05

Table 11.15: Fuel consumption (kWh/100km) for payload = 70kg – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	6.2	6.7	5.2	5.6	5.3	5.7
2	WLTC	5.8	6.4	4.8	5.2	4.8	5.3
3	MoRTH	4.5	5.0	3.9	4.2	3.9	4.2

Table 11.16: Fuel consumption (kWh/100km) for payload = 150kg – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	7.8	8.5	6.5	7.1	6.7	7.2
2	WLTC	7.2	7.9	5.9	6.4	5.9	6.4
3	MoRTH	5.8	6.5	4.9	5.4	5.0	5.5

11.1.5.2 Power generation required

In this part, we report about the power generation needed for our vehicle to then charge and travel a km. Each part of this journey has its efficiency. So, every km our vehicle drives may have used 0.04 to 0.08 kWh/km for 70kg from earlier analysis, because of the inefficiencies, this energy will be much more upstream.

The same can be seen from our analysis. When compared to the fuel consumption table, the below table has higher values of kWh/km.

Table 11.17: Energy needed to be generated at the power plant– motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.08	0.08	0.07	0.07	0.07	0.07
2	WLTC	0.07	0.08	0.06	0.07	0.06	0.07
3	MoRTH	0.06	0.06	0.05	0.05	0.05	0.05

Table 11.18: Energy needed to be generated at the power plant– motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.10	0.11	0.08	0.09	0.08	0.09
2	WLTC	0.09	0.10	0.07	0.08	0.07	0.08
3	MoRTH	0.07	0.08	0.06	0.07	0.06	0.07

11.1.5.3 Emission analysis

For the energy per km in the above table 10.14, assuming that all the powerplants available are coal-based, the following table discusses emissions for all the drive cycles and motor-transmission combinations. As can be seen, the higher the energy consumption was in the previous table, the higher the emissions we get here.

Table 11.19: Total emissions (g/km)– motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Kundapura	51.2	55.5	43.5	46.9	44.5	47.9
2	WLTC	48.4	53.1	39.9	43.4	40.3	43.8
3	MoRTH	37.4	41.4	32.1	35.3	33.2	35.4

Table 11.20: Total emissions (g/km)– motor optimized for acceleration

S.No.	Drive Cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Kundapura	64.9	70.6	54.5	58.8	55.7	60.1
2	WLTC	60.1	66.1	48.7	53.1	49.4	53.6
3	MoRTH	48.6	53.8	41.2	45.3	41.4	45.4

11.1.6 Comparison of fuel consumption

Further expanding on the fuel consumption part, taking 150 kg as the weight of a rider plus a passenger, we can have two cases where motor optimization could be done in a vehicle, for average everyday driving and second for maximum acceleration. Both these cases were evaluated, and the observations are listed below.

Table 11.21: Fuel consumption (kWh/km) comparison (Payload weight = 150 kg)

S.No.	Drive cycle	Motor optimized for driving					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.06	0.07	0.06	0.06	0.06	0.06
2	WLTC	0.05	0.05	0.04	0.05	0.04	0.05
3	MoRTH	0.04	0.04	0.04	0.04	0.04	0.04

Table 11.22: Fuel consumption (kWh/km) comparison (Payload weight = 150 kg)

S.No.	Drive cycle	Motor optimized for acceleration					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.08	0.08	0.07	0.07	0.07	0.07
2	WLTC	0.07	0.08	0.06	0.06	0.06	0.06
3	MoRTH	0.06	0.06	0.05	0.05	0.05	0.05

As can be seen from the data above, a motor optimized for acceleration uses about 25 to 50 percent more fuel than the motor optimized for normal driving. All of this is just for bragging rights. Rarely do people drive like such maniacs where they make use of that acceleration. Instead, that motor could've been optimized for normal driving, the customer could have either bought a cheaper product because of reduced battery size or enjoyed a longer range if the battery were kept the same.

Table 11.23: Fuel consumption (kWh/100 km) comparison (Payload weight = 150 kg)

S.No.	Drive cycle	Motor optimized for driving					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	6.3	6.8	5.7	6.1	5.8	6.2
2	WLTC	4.6	4.9	4.3	4.5	4.4	4.6
3	MoRTH	3.9	4.2	3.7	3.9	3.8	4.0

Table 11.24: Fuel consumption (kWh/100 km) comparison (Payload weight = 150 kg)

S.No.	Drive cycle	Motor optimized for acceleration					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	7.8	8.5	6.5	7.1	6.7	7.2
2	WLTC	7.2	7.9	5.9	6.4	5.9	6.4
3	MoRTH	5.8	6.5	4.9	5.4	5.0	5.5

Similarly, the same can be inferred for 70 kg payload for one rider. Apart from less fuel consumption for normal driving as discussed earlier, one other reason is the environment, which is the second victim. Emissions are directly proportional to fuel consumption. So, the motor optimized for acceleration is also responsible for much more emissions.

Table 11.25: Fuel consumption (kWh/km) comparison (Payload weight = 70 kg)

S.No.	Drive cycle	Motor optimized for driving					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.05	0.05	0.05	0.05	0.05	0.05
2	WLTC	0.04	0.04	0.04	0.04	0.04	0.04
3	MoRTH	0.03	0.03	0.03	0.03	0.03	0.03

Table 11.26: Fuel consumption (kWh/km) comparison (Payload weight = 70 kg)

S.No.	Drive cycle	Motor optimized for acceleration					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Kundapura	0.06	0.07	0.05	0.06	0.05	0.06
2	WLTC	0.06	0.06	0.05	0.05	0.05	0.05
3	MoRTH	0.04	0.05	0.04	0.04	0.04	0.04

11.1.7 Efficiency maps

Three different types of motors are considered for the analysis related to efficiency maps *viz.*, IM, PMSM and SynRel.

The operating points fall in higher efficiency regions for smaller motors, while there are fewer such occurrences for a larger motor. Here smaller motor

Table 11.27: Fuel consumption (kWh/100 km) comparison (Payload weight = 70 kg)

S.No.	Drive cycle	Motor optimized for driving					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	5.0	5.3	4.5	4.8	4.6	4.9
2	WLTC	4.0	4.2	3.7	3.9	3.7	4.0
3	MoRTH	3.2	3.4	3.0	3.2	3.0	3.2

Table 11.28: Fuel consumption (kWh/100 km) comparison (Payload weight = 70 kg)

S.No.	Drive cycle	Motor optimized for acceleration					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Kundapura	6.2	6.7	5.2	5.6	5.3	5.7
2	WLTC	5.8	6.4	4.8	5.2	4.8	5.3
3	MoRTH	4.5	5.0	3.9	4.2	3.9	4.2

will correspond to normal driving conditions used for the optimization of motor, and a larger motor rating will correspond to optimization for acceleration.

11.2 Commute scooter - Honda Activa

11.2.1 Vehicle parameters

A team of three from EML, IITG, drove Honda Activas in their neighbourhoods in Renukoot (Uttar Pradesh), Hyderabad (Telangana) and Guwahati (Assam) completing more than 40 round trips each.

Table 11.29: Vehicle parameters of Honda Activa

S.No	Parameter name	Symbol	Unit	Value
1	Kerb weight	m	kg	110
2	Aerodynamic drag coefficient of vehicle	Cd	-	0.78
3	Frontal area of vehicle	Af	m2	0.68
4	Radius of the wheel	r	m	0.175
5	Gear Ratio		-	4.5

11.2.2 Drive cycles Used

The obtained data was then converted into drive cycles for these cities (the process of which has been explained in earlier chapters).

These drive cycles were obtained from an ICE vehicle. For our analysis, we will replace the prime-mover to different electric motors with belt drive and hub configurations and see how they would perform on the same drive cycles along with WLTC two-wheeler and MoRTH drive cycles.

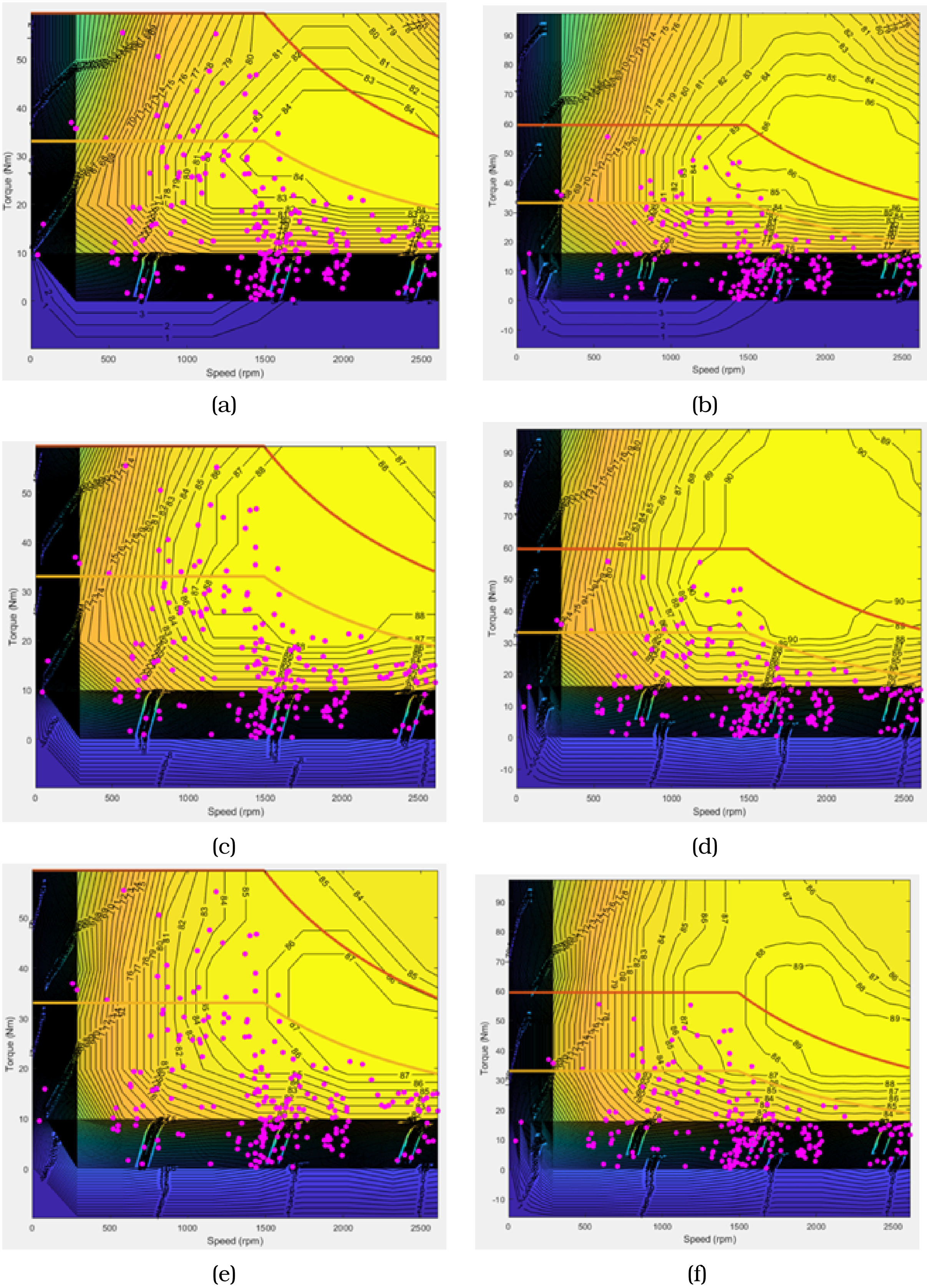


Figure 11.4: Motor optimized for (a) driving IM (b) acceleration IM (c) driving PMSM (d) acceleration PMSM (e) driving SynRel (f) acceleration SynRel

Table 11.30: Some performance metrics of the drive cycles used

Sl. No.	**Drive cycle**	**Average speed [km/h]**	**Max speed [km/h]**	**PKE [m/s^2]**	**KI [1/m]**	**RPA [m/s^2]**
1	Renukoot (U.P.)	20.7	33.5	0.3	0.0048	0.038
2	Hyderabad (Telangana)	23.9	51.0	0.8	0.0046	0.083
3	Guwahati (Assam)	25.1	50.8	0.4	0.0021	0.024
4	WLTC	24.5	74.7	0.3	0.0010	0.010
5	MoRTH	21.9	42.0	0.4	0.0024	0.015

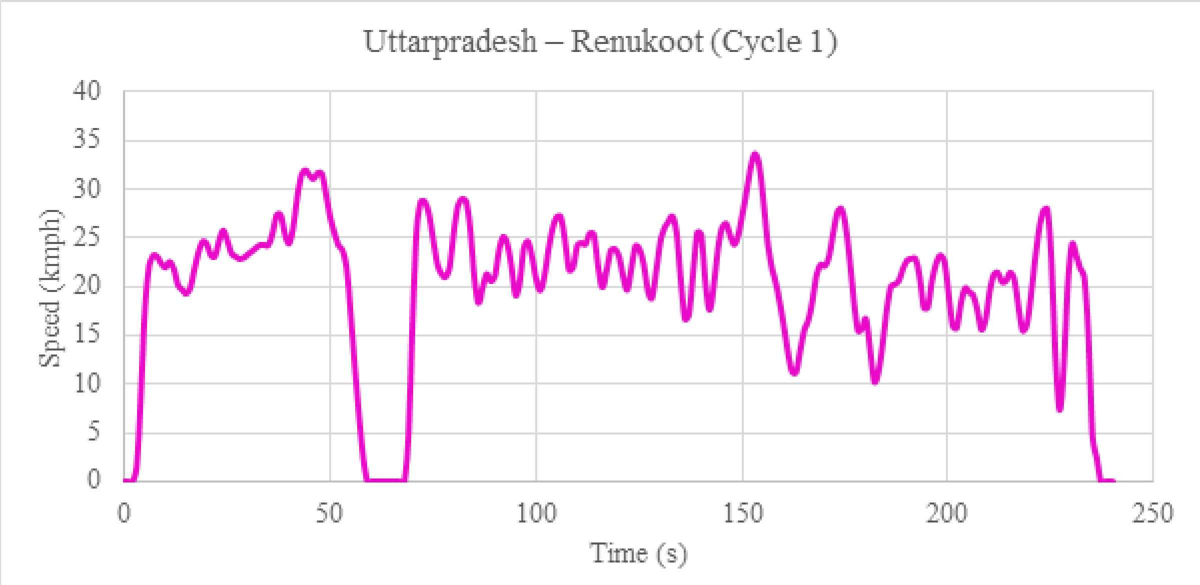


Figure 11.5: Renukoot drive cycle

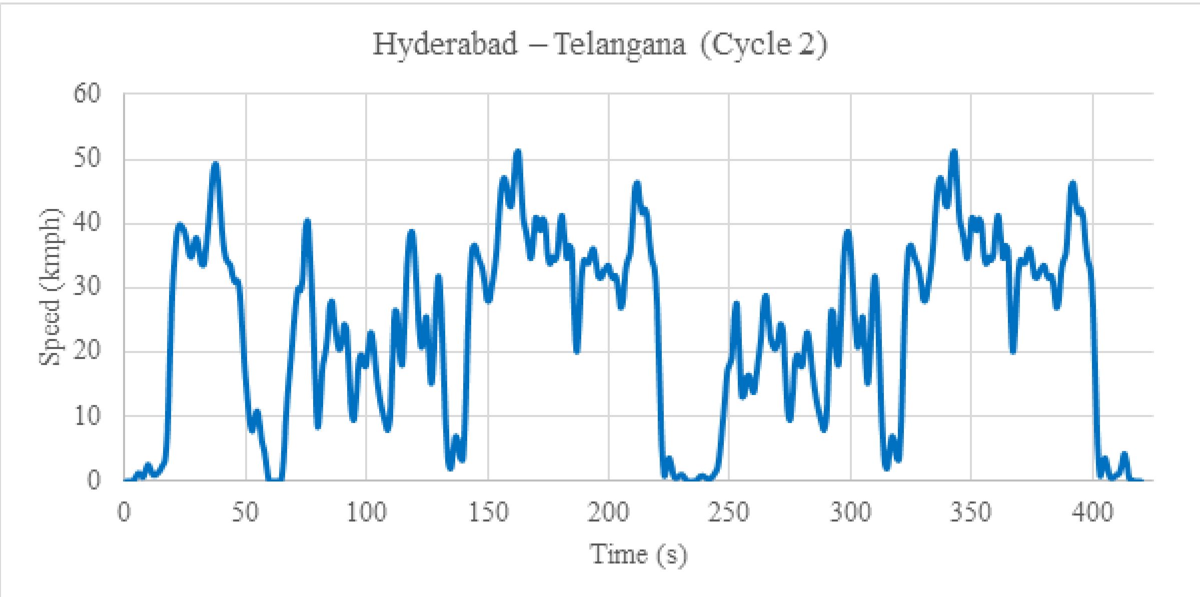


Figure 11.6: Hyderabad drive cycle

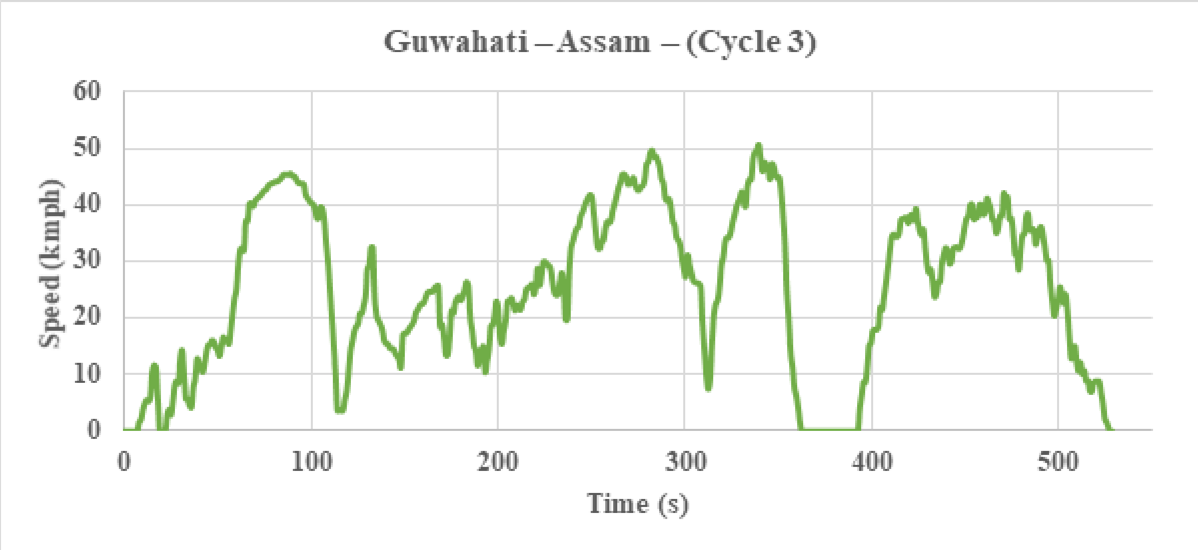


Figure 11.7: Guwahati drive cycle

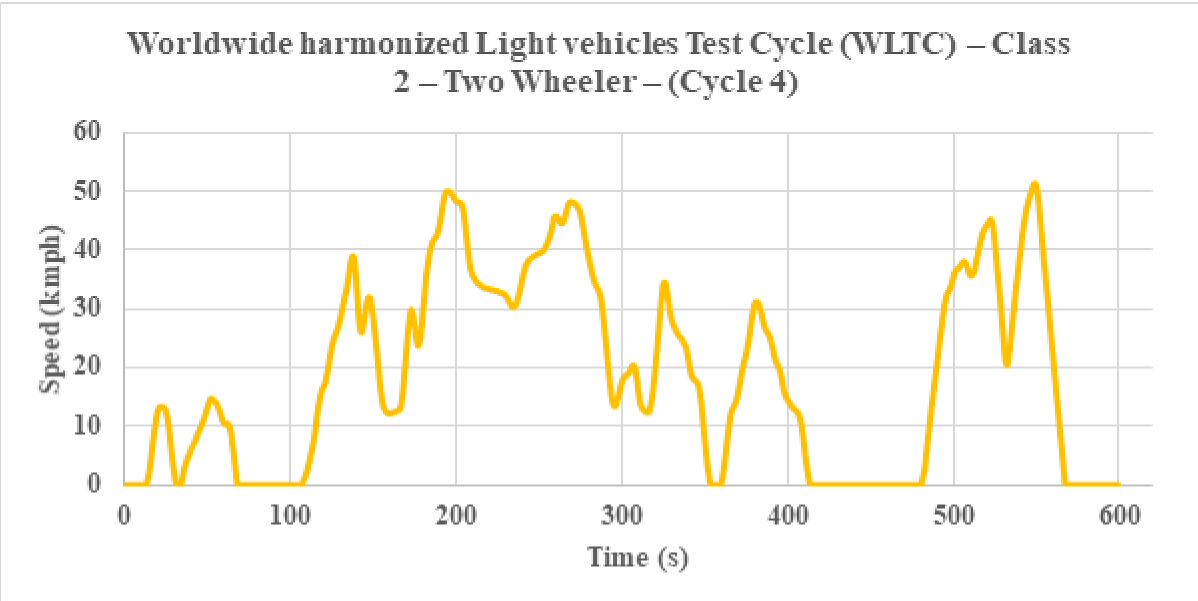


Figure 11.8: WLTC two wheeler drive cycle

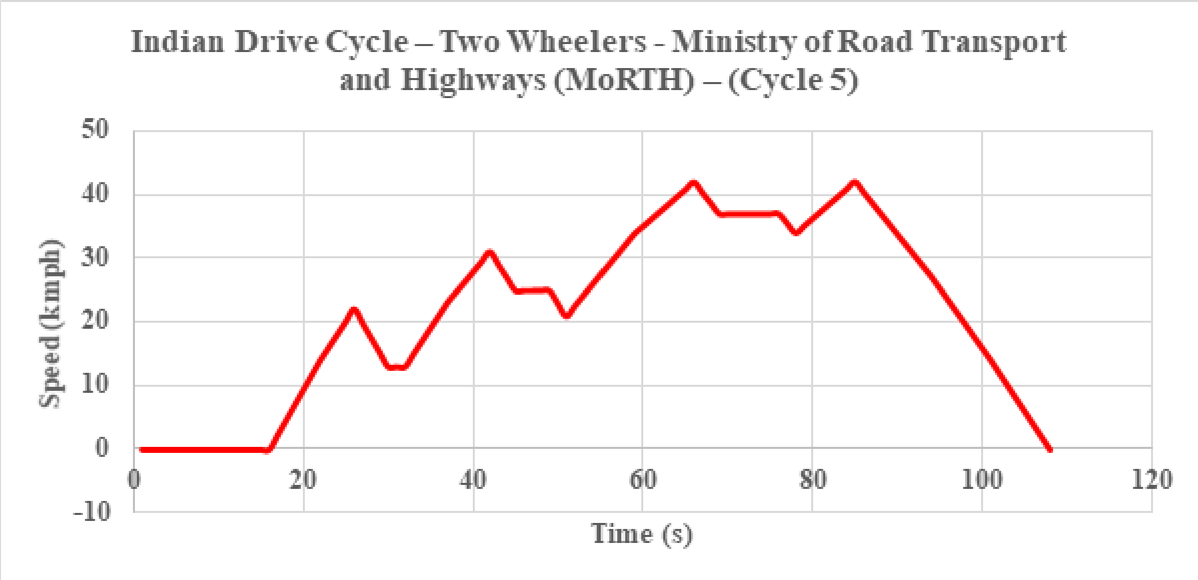


Figure 11.9: MoRTH drive cycle

11.2.3 Acceleration performance - Hyderabad drive cycle

For motor optimized for drive cycle driving with fixed gear ratio:

Table 11.31: Acceleration performance – motor optimized for drive cycle case

Speed [km/h]	Time[s]
0-40	4.2
0-60	7.6
0-80	14.3

For motor optimized for acceleration with fixed gear ratio:

Table 11.32: Table - 20 Acceleration performance – motor optimized for acceleration

Speed [km/h]	Time[s]
0-40	4.07
0-60	7.2
0-80	13.5

11.2.4 Motor optimized for drive cycle

11.2.4.1 Fuel consumption analysis

As can be seen in the fuel consumption tables, the MoRTH drive cycle is the least taxing, followed by Renukoot, then Guwahati, then WLTC and finally Hyderabad cycle. Also, belt drives are consistently better than hub motors, as seen in the table. Comparing between the types of motors, PMSM comes out to be the most efficient, followed by SynRel motor and thereafter induction motor.

Table 11.33: Fuel consumption (kWh/km) – motor optimized for drive cycle

Sl.No	Drive cycle	Load=70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P)	0.032	0.035	0.028	0.030	0.028	0.030
2	Telangana (Hyderabad)	0.044	0.048	0.039	0.043	0.040	0.044
3	Guwahati	0.033	0.035	0.029	0.031	0.030	0.031
4	WLTC	0.035	0.038	0.032	0.034	0.032	0.034
5	MoRTH	0.024	0.024	0.022	0.022	0.023	0.022

Table 11.34: Fuel consumption (kWh/km) – motor optimized for drive cycle

Sl.No	Drive cycle	Load=150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P)	0.043	0.043	0.037	0.038	0.039	0.038
2	Hyderabad (Telangana)	0.062	0.066	0.055	0.059	0.056	0.060
3	Guwahati	0.044	0.046	0.039	0.041	0.039	0.041
4	WLTC	0.043	0.045	0.038	0.041	0.039	0.041
5	MoRTH	0.034	0.036	0.032	0.033	0.032	0.034

Table 11.35: Fuel consumption (kWh/100 km) – motor optimized for drive cycle

Sl.No	Drive cycle	Load=70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh /100km	kWh /100km	kWh /100km	kWh /100km	kWh /100km	kWh /100km
1	Renukoot (U.P)	3.243	3.464	2.772	2.960	2.843	3.034
2	Hyderabad (Telangana)	4.377	4.795	3.910	4.281	4.000	4.366
3	Guwahati	3.294	3.477	2.924	3.089	2.968	3.131
4	WLTC	3.543	3.759	3.172	3.369	3.215	3.404
5	MoRTH	2.384	2.357	2.250	2.226	2.273	2.248

Table 11.36: Fuel consumption (kWh/100 km) – motor optimized for drive cycle

Sl.No	Drive cycle	Load=150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh /100km	kWh /100km	kWh /100km	kWh /100km	kWh /100km	kWh /100km
1	Renukoot (U.P)	4.350	4.313	3.738	3.757	3.851	3.843
2	Hyderabad (Telangana)	6.184	6.618	5.498	5.878	5.627	5.998
3	Guwahati	4.377	4.630	3.851	4.058	3.912	4.116
4	WLTC	4.273	4.544	3.820	4.066	3.881	4.114
5	MoRTH	3.412	3.616	3.156	3.350	3.182	3.376

11.2.4.2 Power generation required

The next criteria to look into is the energy required to be generated at the power plant, which is then delivered to our vehicle by transmissions and distribution networks and hence used to charge the battery. Each part of this journey has its efficiency. So, every km our vehicle drives may have used 0.03 to 0.05 kWh/km for 70kg from earlier analysis, because of the inefficiencies, this energy will be much more upstream.

The same can be seen from our analysis, the below table, when compared to the fuel consumption table, has higher values of kWh/km.

Table 11.37: Energy needed to be generated at the power plant – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	0.041	0.045	0.035	0.038	0.036	0.039
2	Hyderabad (Telangana)	0.056	0.062	0.050	0.055	0.051	0.056
3	Guwahati (Assam)	0.050	0.054	0.042	0.045	0.042	0.046
4	WLTC	0.052	0.057	0.044	0.048	0.045	0.049
5	MoRTH	0.038	0.039	0.033	0.034	0.033	0.034

Table 11.38: Energy needed to be generated at the Power Plant– motor optimized for drive cycle

S.No.	Drive Cycle	Payload Weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot(U.P.)	0.056	0.059	0.048	0.050	0.049	0.051
2	Hyderabad(Telangana)	0.078	0.085	0.070	0.075	0.071	0.076
3	Guwahati(Assam)	0.066	0.072	0.055	0.060	0.066	0.061
4	WLTC	0.067	0.073	0.056	0.061	0.057	0.062
5	MoRTH	0.052	0.057	0.045	0.049	0.045	0.049

11.2.4.3 Emission analysis

For the energy per km in the above table, assuming that all the powerplants available are coal-based, the following table discusses emissions for all the drive cycles and motor-transmission combinations. As can be seen, the higher the energy consumption was in the previous table, the higher the emissions we get here.

Table 11.39: Emissions – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	21.8	23.7	18.5	20.0	19.0	20.5
2	Hyderabad (Telangana)	29.3	32.4	26.1	28.7	26.7	29.3
3	Guwahati (Assam)	26.0	28.3	22.0	23.7	22.3	24.0
4	WLTC	27.2	29.7	23.3	25.3	23.6	25.5
5	MoRTH	19.7	20.3	17.4	17.8	17.5	17.8

11.2.5 Motor optimized for acceleration

11.2.5.1 Fuel consumption analysis

As can be seen in the fuel consumption tables, the MoRTH drive cycle is the least taxing, followed by Renukoot, then Guwahati, then WLTC and finally

Table 11.40: Emissions – motor optimized for drive cycle

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	29.3	31.1	25.0	25.3	25.8	27.0
2	Hyderabad (Telangana)	41.2	44.4	36.5	39.3	37.4	40.1
3	Guwahati (Assam)	34.9	38.0	29.1	31.4	29.5	31.9
4	WLTC	35.2	38.6	29.6	32.2	29.9	32.4
5	MoRTH	29.8	23.7	25.8	23.8	17.5	25.9

Hyderabad cycles. Also, belt drives are consistently better than hub motors, as seen in the table. Comparing between the types of motors, PMSM comes out to be the most efficient, followed by SynRel motor and thereafter induction motor.

Table 11.41: Fuel consumption (kWh/km) – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	0.033	0.036	0.028	0.030	0.029	0.031
2	Hyderabad (Telangana)	0.044	0.049	0.039	0.043	0.040	0.044
3	Guwahati (Assam)	0.039	0.043	0.033	0.036	0.034	0.036
4	WLTC	0.041	0.045	0.035	0.038	0.036	0.039
5	MoRTH	0.030	0.031	0.026	0.027	0.026	0.027

Table 11.42: Fuel consumption (kWh/km) – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	0.044	0.047	0.038	0.040	0.039	0.041
2	Hyderabad (Telangana)	0.062	0.067	0.055	0.059	0.057	0.061
3	Guwahati (Assam)	0.053	0.057	0.044	0.048	0.045	0.048
4	WLTC	0.053	0.058	0.045	0.049	0.045	0.049
5	MoRTH	0.041	0.045	0.036	0.039	0.036	0.039

Table 11.43: Fuel consumption (kWh/100 km) – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Renukoot (U.P.)	3.3	3.6	2.8	3.0	2.9	3.1
2	Hyderabad (Telangana)	4.4	4.9	3.9	4.3	4.0	4.4
3	Guwahati (Assam)	3.9	4.3	3.3	3.6	3.4	3.6
4	WLTC	4.1	4.5	3.5	3.8	3.6	3.9
5	MoRTH	3.0	3.1	2.6	2.7	2.6	2.7

Table 11.44: Fuel consumption (kWh/100 km) – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Renukoot (U.P.)	4.4	4.7	3.8	4.0	3.9	4.1
2	Hyderabad (Telangana)	6.2	6.7	5.5	5.9	5.7	6.1
3	Guwahati (Assam)	5.3	5.7	4.4	4.8	4.5	4.8
4	WLTC	5.3	5.8	4.5	4.9	4.5	4.9
5	MoRTH	4.1	4.5	3.6	3.9	3.6	3.9

11.2.5.2 Power generation required

The next criteria to look into is the energy required to be generated at the power plant, which is then delivered to our vehicle by transmissions and distribution networks and hence used to charge the battery. Each part of this journey has its efficiency. So, every km our vehicle drives may have used 0.03 to 0.05 kWh/km for 70kg from earlier analysis, because of the inefficiencies, this energy will be much more upstream.

The same can be seen from our analysis, the below table, when compared to the fuel consumption table, has higher values of kWh/km.

Table 11.45: Energy needed to be generated at the Power Plant – Motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot(U.P.)	0.041	0.045	0.035	0.038	0.036	0.039
2	Hyderabad(Telangana)	0.056	0.062	0.050	0.055	0.051	0.056
3	Guwahati(Assam)	0.050	0.054	0.042	0.045	0.042	0.046
4	WLTC	0.052	0.057	0.044	0.048	0.045	0.049
5	MoRTH	0.038	0.039	0.033	0.034	0.033	0.034

Table 11.46: Energy needed to be generated at the power plant – motor optimized for acceleration

S.No.	Drive Cycle	Payload Weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot(U.P.)	0.056	0.059	0.048	0.050	0.049	0.051
2	Hyderabad(Telangana)	0.078	0.085	0.070	0.075	0.071	0.076
3	Guwahati(Assam)	0.066	0.072	0.055	0.060	0.056	0.061
4	WLTC	0.067	0.073	0.056	0.061	0.057	0.062
5	MoRTH	0.052	0.057	0.045	0.049	0.045	0.049

11.2.5.3 Emission analysis

The energy per km is the above table, assuming that all the powerplants available are coal-based. The following table discusses emissions for all the drive cycles and motor-transmission combinations. As can be seen, the higher the energy consumption was in the previous table, higher are the emissions that we get here.

Table 11.47: Emissions – motor optimized for acceleration

S.No.	Drive cycle	Payload weight = 70kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Renukoot (U.P.)	21.789	23.718	18.525	20.028	19.007	20.545
2	Hyderabad (Telangana)	29.329	32.369	26.091	28.172	26.683	29.274
3	Guwahati (Assam)	25.999	28.316	21.954	23.724	22.277	24.037
4	WLTC	27.170	29.688	23.337	25.328	23.587	25.499
5	MoRTH	19.719	20.303	17.404	17.768	17.457	17.804

Table 11.48: Emissions – motor optimized for acceleration

S.No.	Drive Cycle	Payload Weight = 150kg					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		g/km	g/km	g/km	g/km	g/km	g/km
1	Renukoot(U.P.)	29.325	31.141	25.028	26.284	25.803	26.971
2	Hyderabad(Telangana)	41.195	44.407	36.548	39.274	37.401	40.065
3	Guwahati(Assam)	34.858	38.005	29.061	31.422	29.526	31.886
4	WLTC	35.199	38.556	29.572	32.152	29.938	32.415
5	MoRTH	27.150	29.798	23.698	25.822	23.788	25.928

11.2.6 Comparison of fuel consumption

Further expanding on the fuel consumption part, taking 150 kg as the weight of a rider plus a passenger, we can have two cases where motor optimization could be done in a vehicle, for normal everyday driving and second for maximum acceleration. Both these cases were evaluated and the observations are listed below.

Table 11.49: Fuel consumption comparison 150 kg (kWh/km) - motor optimized for driving

S.No.	Drive cycle	Fuel consumption (kWh/km)					
		IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	0.043	0.043	0.037	0.038	0.039	0.038
2	Hyderabad (Telangana)	0.062	0.066	0.055	0.059	0.056	0.060
3	Guwahati (Assam)	0.044	0.046	0.039	0.041	0.039	0.041
4	WLTC	0.043	0.045	0.038	0.041	0.039	0.041
5	MoRTH	0.034	0.034	0.032	0.033	0.032	0.034

As can be seen from the data above, motor optimized for acceleration uses far more fuel than the motor optimized for normal driving, about 25 to 50 percent more. This acceleration potential is rarely used except for boasting the vehicle's capability. Instead, if the motor is optimized for normal driving,

Table 11.50: Fuel consumption comparison 150 kg (kWh/km) - motor optimized for acceleration

Sl.No	**Drive cycle**	**IM**		**PM**		**SynRel**	
		Belt drive	**Hub**	**Belt drive**	**Hub**	**Belt drive**	**Hub**
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	**Renukoot (U.P.)**	0.04	0.05	0.04	0.04	0.04	0.04
2	**Hyderabad (Telangana)**	0.06	0.07	0.06	0.06	0.06	0.06
3	**Guwahati (Assam)**	0.05	0.06	0.04	0.05	0.04	0.05
4	**WLTC**	0.05	0.06	0.04	0.05	0.05	0.05
5	**MoRTH**	0.04	0.05	0.04	0.04	0.04	0.04

Table 11.51: Fuel Consumption comparison 150 kg (kWh/100km) - Motor optimized for driving

Sl.No	**Drive Cycle**	**IM**		**PM**		**SynRel**	
		Belt drive	**Hub**	**Belt drive**	**Hub**	**Belt drive**	**Hub**
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	**Renukoot (U.P.)**	4.3	4.3	3.7	3.8	3.9	3.8
2	**Hyderabad (Telangana)**	6.2	6.6	5.5	5.9	5.6	6.0
3	**Guwahati (Assam)**	4.4	4.6	3.9	4.1	3.9	4.1
4	**WLTC**	4.3	4.5	3.8	4.1	3.9	4.1
5	**MoRTH**	3.4	3.6	3.2	3.3	3.2	3.4

Table 11.52: Fuel consumption comparison 150 kg (kWh/100km) - motor optimized for acceleration

Sl.No	**Drive cycle**	**IM**		**PM**		**SynRel**	
		Belt drive	**Hub**	**Belt drive**	**Hub**	**Belt drive**	**Hub**
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	**Renukoot (U.P.)**	4.4	4.7	3.8	4.0	3.9	4.1
2	**Hyderabad (Telangana)**	6.2	6.7	5.5	5.9	5.7	6.1
3	**Guwahati (Assam)**	5.3	5.7	4.4	4.8	4.5	4.8
4	**WLTC**	5.3	5.8	4.5	4.9	4.5	4.9
5	**MoRTH**	4.1	4.5	3.6	3.9	3.6	3.9

Table 11.53: Fuel consumption comparison 70 kg (kWh/km) - motor optimized for driving

Sl.No	Drive cycle	IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	**Renukoot (U.P.)**	0.032	0.035	0.028	0.030	0.028	0.030
2	**Hyderabad (Telangana)**	0.044	0.048	0.039	0.043	0.040	0.044
3	**Guwahati (Assam)**	0.033	0.035	0.029	0.031	0.030	0.031
4	**WLTC**	0.035	0.038	0.032	0.034	0.032	0.034
5	**MoRTH**	0.024	0.024	0.022	0.022	0.023	0.022

Table 11.54: Fuel consumption comparison 70 kg (kWh/km) - motor optimized for acceleration

Sl.No	Drive cycle	IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	**Renukoot (U.P.)**	0.03	0.04	0.03	0.03	0.03	0.03
2	**Hyderabad (Telangana)**	0.04	0.05	0.04	0.04	0.04	0.04
3	**Guwahati (Assam)**	0.04	0.04	0.03	0.04	0.03	0.04
4	**WLTC**	0.04	0.04	0.04	0.04	0.04	0.04
5	**MoRTH**	0.03	0.03	0.03	0.03	0.03	0.03

the customer could either buy a cheaper product because of reduced battery size, or they can enjoy a longer range if the battery is kept the same.

Similarly, the same can be inferred for 70 kg payload for one rider. Apart from the earlier discussed point about less fuel consumption for normal driving, the other reason is our second victim, the environment. Emissions are directly proportional to fuel consumption. So, the motor optimized for acceleration is also emitting much more.

11.2.7 Efficiency maps

Now about the efficiency maps for the three different types of motors taken for this analysis, IM, PMSM and SynRel as shown in the figure 11.10

The operating points fall in higher efficiency regions for smaller motors, while there are fewer such occurrences for a larger motor. Here smaller motor will correspond to normal driving conditions used for the optimization of motor, and a larger motor rating will correspond to optimization for acceleration.

Table 11.55: Fuel consumption comparison 70 kg (kWh/100km) - motor optimized for driving

Sl.No	Drive cycle	IM		PM		SynRel	
		Belt drive	Hub	Belt drive	Hub	Belt drive	Hub
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	**Renukoot (U.P.)**	3.2	3.5	2.8	3.0	2.8	3.0
2	**Hyderabad (Telangana)**	4.4	4.8	3.9	4.3	4.0	4.4
3	**Guwahati (Assam)**	3.3	3.5	2.9	3.1	3.0	3.1
4	**WLTC**	3.5	3.8	3.2	3.4	3.2	3.4
5	**MoRTH**	2.4	2.4	2.2	2.2	2.3	2.2

Table 11.56: Fuel consumption comparison 70 kg (kWh/100km) - motor optimized for acceleration

Sl.No	**Drive cycle**	**IM**		**PM**		**SynRel**	
		Belt drive	**Hub**	**Belt drive**	**Hub**	**Belt drive**	**Hub**
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	**Renukoot (U.P.)**	3.3	3.6	2.8	3.0	2.9	3.1
2	**Hyderabad (Telangana)**	4.4	4.9	3.9	4.3	4.0	4.4
3	**Guwahati (Assam)**	3.9	4.3	3.3	3.6	3.4	3.6
4	**WLTC**	4.1	4.5	3.5	3.8	3.6	3.9
5	**MoRTH**	3.0	3.1	2.6	2.7	2.6	2.7

11.3 CVT analysis – commute scooter – Honda Activa

The constant gear ratio analysis was discussed upto this point. Now we will analyse rule-based CVT (discussed in chapter-9) on Honda Activa. All the analysis done in this section is done for a 150 kg payload.

11.3.1 Acceleration performance - Hyderabad drive cycle

For motor optimized for driving:

Table 11.57: Acceleration performance – motor optimized for driving

Acceleration performance	
Speed [km/h]	Time [s]
0-40	4.3
0-60	7.8
0-80	14.6

For motor optimized for acceleration:

Table 11.58: Acceleration performance – Motor optimized for acceleration

Acceleration performance	
Speed [km/h]	Time [s]
0-40	4.07
0-60	7.2
0-80	13.5

11.3.2 Efficiency map comparison

The following figures 11.11 depict the variations between efficiency maps of constant gear ratio case and efficiency maps of rule-based CVT case for Honda Activa with Guwahati drive cycle.

The operating points in pink that we had in the constant gear ratio case can be moved to a higher efficiency region by implementing intelligently controlled CVT, which is the case in the following efficiency maps.

11.3.3 Efficiency improvement

We calculated the weighted mean efficiencies with fixed gear ratio and rule-based CVT from the efficiency map analysis.

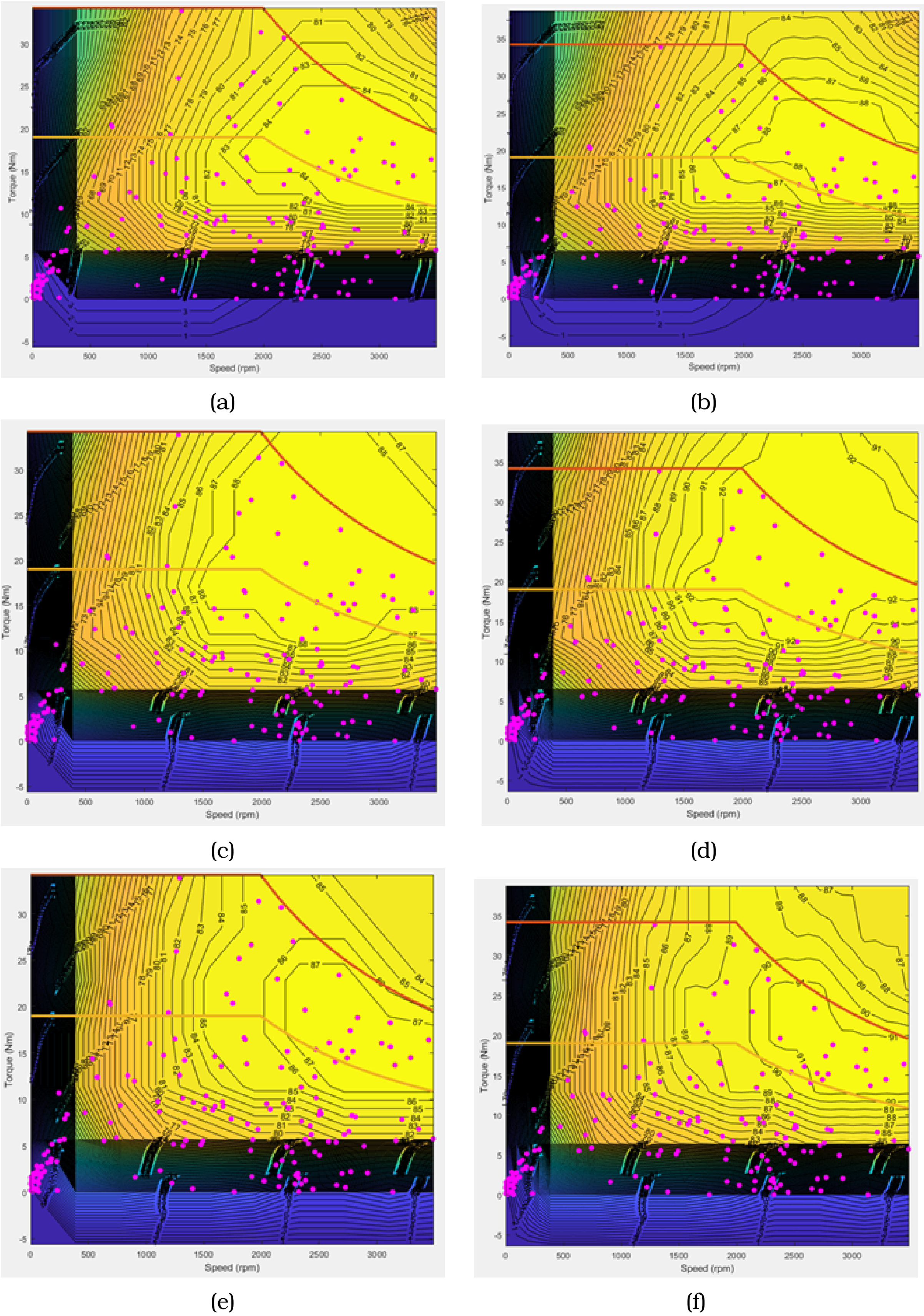
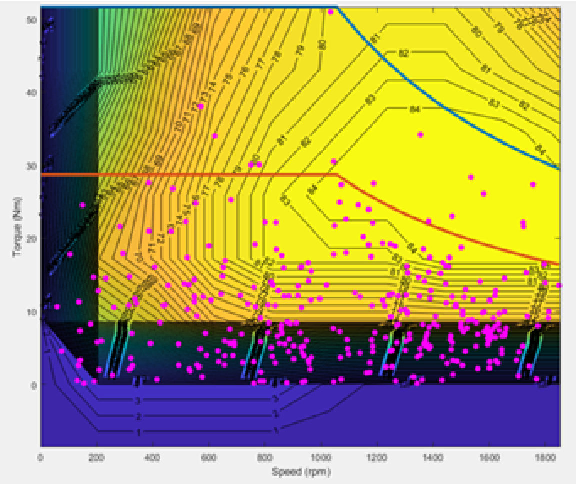
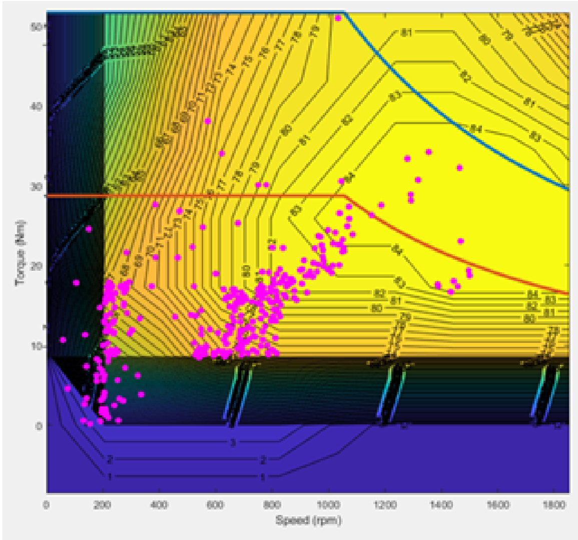


Figure 11.10: Motor optimized for (a) driving IM (b) acceleration IM (c) driving PMSM (d) acceleration PMSM (e) driving SynRel (f) acceleration SynRel

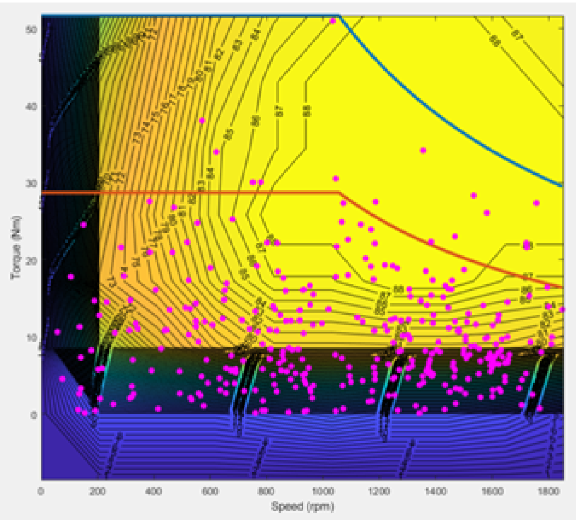
Before going forward, let's understand the meaning of weighted mean efficiency here. An operating point will lie in some regions of efficiency. We will



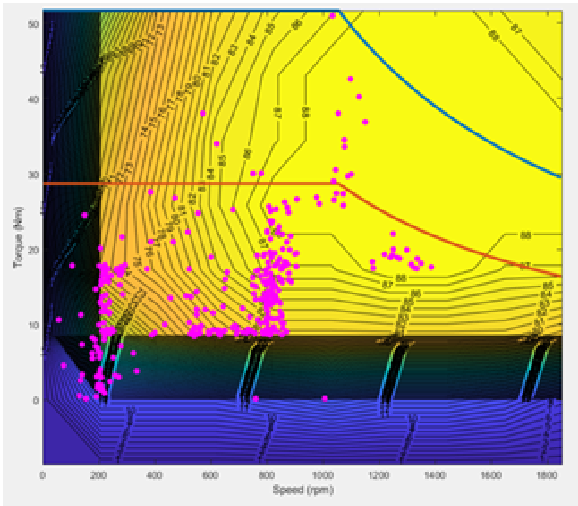
(a)



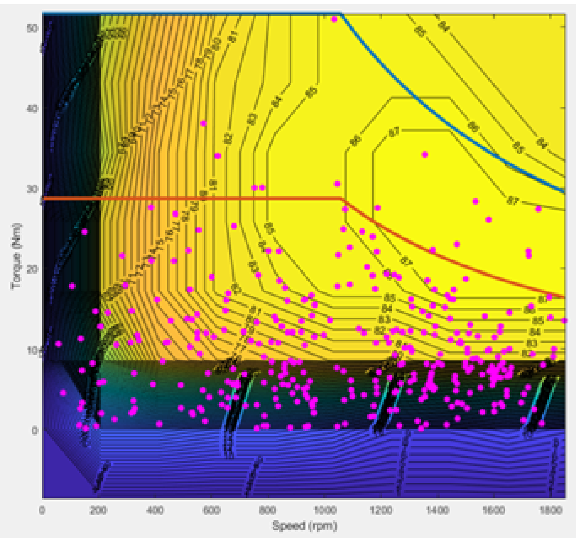
(b)



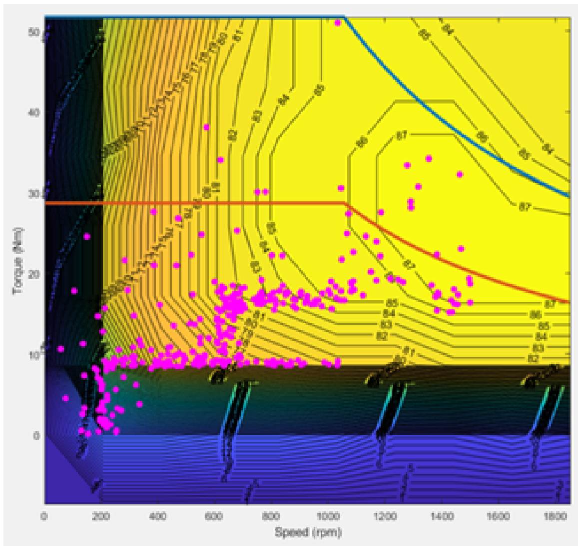
(c)



(d)



(e)



(f)

Figure 11.11: Guwahati drive cycle (a) Constant gear ratio of 2.4 - IM (b) Rule Based CVT - IM (c) Constant gear ratio of 2.4 - PMSM (d) Rule based CVT - PMSM (e) Constant gear ratio of 2.4 - SynRel (f) Rule based CVT - SynRel

add all such efficiencies for all the operating points, and then we will divide the sum with the total number of operating points, to get the weighted mean efficiency of that particular case.

Table 11.59: Weighted mean efficiencies – motor optimized for acceleration

Sl.No	Drive cycle	Constant gear ratio - 2.4				Rule based CVT		
		IM	PM	SynRel		IM	PM	SynRel
		%	%	%		%	%	%
1	**Renukoot (U.P)**	59.8	66.9	65.3		72.2	77.1	75.2
2	**Hyderabad (Telangana)**	51.6	57.4	56.0		59.8	64.2	62.6
3	**Guwahati**	48.8	56.4	55.6		65.7	70.6	68.9
4	**WLTC**	46.3	53.4	53.1		59.8	64.5	63.2
5	**MoRTH**	60.7	67.7	67.2		73.2	78.1	75.5

With the proposed Rule-based CVT, a considerable improvement in the weighted mean efficiencies of the motors can be observed. A higher improvement in efficiency is observed in Guwahati drive cycle (around 20-25%).

Table 11.60: Improvement in efficiencies – motor optimized for acceleration

Sl.No	Drive cycle	IM	PM	SynRel
		%	%	%
1	**Renukoot (U.P)**	17.2	13.3	13.1
2	**Hyderabad (Telangana)**	13.7	10.6	10.6
3	**Guwahati**	25.7	20.1	19.3
4	**WLTC**	22.6	17.2	16.0
5	**MoRTH**	17.1	13.4	11.1

Similarly, the same analysis can be done for the case where the motor is optimized for driving, as shown in the following figure.

Table 11.61: Weighted mean efficiencies – motor optimized for driving

Sl.No	Drive cycle	Fixed gear ratio - 2.4				Rule based CVT		
		IM	PM	SynRel		IM	PM	SynRel
		%	%	%		%	%	%
1	**Renukoot (U.P)**	60.8	67.8	66.2		72.7	77.6	75.7
2	**Hyderabad (Telangana)**	52.2	58.0	56.6		60.1	64.5	62.9
3	**Guwahati**	57.0	63.9	63.0		69.2	74.2	72.3
4	**WLTC**	64.0	69.9	68.5		69.1	74.0	72.0
5	**MoRTH**	77.7	83.1	81.6		79.9	85.1	83.0

And similarly, the same improvement in weighted mean efficiencies of the operating motors can be observed in the driving optimized case. A higher improvement in efficiency is observed in Guwahati drive cycle (around 13-18%)

Table 11.62: Improvement in efficiencies – Motor optimized for driving

Sl.No	Drive cycle	IM	PM	SynRel
		%	%	%
1	**Renukoot (U.P)**	16.4	12.7	12.5
2	**Hyderabad (Telangana)**	13.1	10.1	10.1
3	**Guwahati**	17.7	13.9	12.9
4	**WLTC**	7.3	5.5	4.8
5	**MoRTH**	2.8	2.3	1.6

11.3.4 Motor optimized for acceleration

11.3.4.1 Fuel consumption analysis

As can be seen in the fuel consumption tables, the Renukoot drive cycle consumes the least fuel, followed by MoRTH, then Guwahati, then WLTC and finally Hyderabad cycles. Comparing the types of motors, PMSM is slightly more efficient than SynRel motor and then induction motor.

Table 11.63: Fuel consumption (kWh/km) – motor optimized for acceleration

Sl.No	Drive cycle	Constant gear ratio - CVT				Rule based CVT		
		IM	PM	SynRel		IM	PM	SynRel
		kWh/km	kWh/km	kWh/km		kWh/km	kWh/km	kWh/km
1	**Renukoot (U.P)**	0.038	0.033	0.034		0.034	0.032	0.032
2	**Hyderabad (Telangana)**	0.061	0.053	0.055		0.055	0.052	0.053
3	**Guwahati**	0.052	0.044	0.044		0.039	0.036	0.037
4	**WLTC**	0.053	0.044	0.045		0.039	0.037	0.038
5	**MoRTH**	0.041	0.036	0.036		0.032	0.030	0.031

Table 11.64: Fuel Consumption (kWh/100 km) – Motor optimized for acceleration

Sl.No	Drive Cycle	Constant Gear Ratio - CVT				Rule Based CVT		
		IM	PM	SynRel		IM	PM	SynRel
		kWh/ 100km	kWh/ 100km	kWh/ 100km		kWh/ 100km	kWh/ 100km	kWh/ 100km
1	**Renukoot (U.P)**	3.8	3.3	3.4		3.4	3.2	3.2
2	**Hyderabad (Telangana)**	6.1	5.3	5.5		5.5	5.2	5.3
3	**Guwahati**	5.2	4.4	4.4		3.9	3.6	3.7
4	**WLTC**	5.3	4.4	4.5		3.9	3.7	3.8
5	**MoRTH**	4.1	3.6	3.6		3.2	3.0	3.1

11.3.4.2 Reduction in fuel consumption

With improved efficiency, the fuel consumption would be comparatively low, resulting in better mileage and reduced emissions.

As seen in the table below, the Guwahati drive cycle experiences the maximum reduction in Fuel Consumption of around 17-25% in acceleration optimized case for the proposed rule based CVT mode. Whereas, Hyderabad drive cycle, due to its dynamic behaviour, has the minimum reduction in Fuel consumption of around 2-8% in acceleration optimized case for proposed rule-based CVT mode.

Induction motor sees the maximum reduction in fuel consumption, followed by the PMSM motor, with SynRel having the least decline.

Table 11.65: Fuel consumption reduction – motor optimized for acceleration

Sl.No	Drive Cycle	Reduction in Fuel Consumption		
		IM	PM	SynRel
		%	%	%
1	**Renukoot (U.P)**	11.1	5.5	5.3
2	**Hyderabad (Telangana)**	8.7	2.8	2.7
3	**Guwahati**	26.2	18.0	17.4
4	**WLTC**	25.3	17.4	16.0
5	**MoRTH**	21.4	15.6	12.9

11.3.4.3 Power generation required

This section looks at the energy required to be generated at the power plant, which is then delivered to our car by transmissions and distribution networks and hence used to charge the battery. Each part of this journey has its own efficiency. So, every km our vehicle drives may have used 0.03 to 0.06 kWh/km, from earlier analysis, because of the inefficiencies, this energy will be much more upstream.

The same can be seen from our analysis, the below table, when compared to the fuel consumption table, has higher values of kWh/km.

Table 11.66: Energy needed to be generated at the power plant– motor optimized for acceleration

Sl.No	Drive cycle	Constant gear ratio - 2.4				Rule based CVT		
		IM	PM	SynRel		IM	PM	SynRel
		kWh/km	kWh/km	kWh/km		kWh/km	kWh/km	kWh/km
1	**Renukoot (U.P)**	0.048	0.042	0.043		0.042	0.040	0.041
2	**Hyderabad (Telangana)**	0.076	0.067	0.069		0.070	0.065	0.067
3	**Guwahati**	0.066	0.055	0.056		0.048	0.045	0.046
4	**WLTC**	0.066	0.056	0.057		0.050	0.046	0.048
5	**MoRTH**	0.051	0.045	0.045		0.040	0.038	0.039

11.3.4.4 Emission Analysis

For the energy per km in the above figure, assuming that all the powerplants available are coal-based, the following table discusses emissions for all the drive cycles. As can be seen, the higher the energy consumption was in the previous table, the higher the emissions we get here.

11.3.5 Motor optimized for driving

11.3.5.1 Fuel consumption analysis

As can be seen in the fuel consumption tables, the MoRTH drive cycle is consuming the least fuel, followed by Renukoot, then Guwahati, then WLTC

Table 11.67: Emissions – motor optimized for acceleration

S.No.	Drive cycle	Fixed gear ratio = 2.4			Rule based CVT		
		IM	PM	SynRel	IM	PM	SynRel
		g/km	g/km	g/km	g/km	g/km	g/km
1	Renukoot (U.P.)	31.5	27.9	28.5	28.0	26.3	27.0
2	Hyderabad (Telangana)	50.5	44.4	45.5	46.1	43.2	44.3
3	Guwahati (Assam)	43.5	36.36	36.9	32.1	29.8	30.5
4	WLTC	43.9	37.0	37.4	32.8	30.5	31.4
5	MoRTH	33.9	29.6	29.7	26.6	25.0	25.9

and finally Hyderabad cycles. Comparing the types of motors, PMSM is the most efficient, then comes the SynRel motor and Induction motor, which consumes the most fuel.

Table 11.68: Fuel consumption (kWh/km) – motor optimized for driving

S.No.	Drive cycle	Fixed gear ratio = 2.4			Rule based CVT		
		IM	PM	SynRel	IM	PM	SynRel
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot (U.P.)	0.037	0.033	0.034	0.033	0.031	0.032
2	Hyderabad (Telangana)	0.059	0.052	0.054	0.055	0.052	0.053
3	Guwahati (Assam)	0.044	0.039	0.039	0.036	0.034	0.035
4	WLTC	0.053	0.044	0.045	0.044	0.040	0.040
5	MoRTH	0.031	0.029	0.030	0.030	0.028	0.029

Table 11.69: Fuel consumption (kWh/100 km) – motor optimized for driving

S.No.	Drive cycle	Fixed gear ratio = 2.4			Rule based CVT		
		IM	PM	SynRel	IM	PM	SynRel
		kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km	kWh/ 100km
1	Renukoot (U.P.)	3.7	3.3	3.4	3.3	3.1	3.2
2	Hyderabad (Telangana)	5.9	5.2	5.4	5.5	5.2	5.3
3	Guwahati (Assam)	4.4	3.9	3.9	3.6	3.4	3.5
4	WLTC	5.3	4.4	4.5	4.4	4.0	4.0
5	MoRTH	3.1	2.9	3.0	3.0	2.8	2.9

11.3.5.2 Reduction in fuel consumption

With improved efficiency, the fuel consumption would be comparatively low, resulting in better mileage and reduced emissions.

As seen in the table below, the Guwahati drive cycle experiences the maximum reduction in fuel consumption of around 11-18% in driving optimized case for the proposed rule based CVT mode. Due to its dynamic behaviour, the Hyderabad drive cycle has a minimum reduction in Fuel consumption of around 1-7% in driving optimized case for proposed rule-based CVT mode.

Induction motor sees the maximum reduction in fuel consumption, followed by PMSM with SynRel having the least reduction. With the exception of the WLTC drive cycle, where SynRel motor sees slightly more reduction than PMSM.

Table 11.70: Fuel consumption reduction – motor optimized for driving

S.No.	Drive Cycle	Reduction in fuel consumption		
		IM	PM	SynRel
		%	%	%
1	Renukoot (U.P.)	9.8	4.8	4.5
2	Hyderabad (Telangana)	6.9	1.7	1.5
3	Guwahati (Assam)	17.9	12.3	11.1
4	WLTC	16.1	10.0	10.1
5	MoRTH	2.5	2.2	1.8

11.3.5.3 Power generation required

In this section, we look at the energy required to be generated at the power plant, which is delivered to the battery eventually, and in the process, we see a lot of inefficiencies. Because of this, the energy generated upstream is more than the energy delivered to the battery.

The same can be seen from our analysis, table 11.71, when compared to the fuel consumption table 11.69, has higher values of kWh/km.

Table 11.71: Energy needed to be generated at the power plant– motor optimized for driving

S.No.	Drive cycle	Fixed gear ratio = 2.4			Rule based CVT		
		IM	PM	SynRel	IM	PM	SynRel
		kWh/km	kWh/km	kWh/km	kWh/km	kWh/km	kWh/km
1	Renukoot(U.P.)	0.047	0.042	0.043	0.042	0.040	0.041
2	Hyderabad(Telangana)	0.074	0.066	0.068	0.069	0.065	0.067
3	Guwahati(Assam)	0.055	0.049	0.049	0.045	0.043	0.044
4	WLTC	0.066	0.056	0.057	0.056	0.050	0.051
5	MoRTH	0.039	0.037	0.037	0.038	0.036	0.037

11.3.5.4 Emission analysis

For the energy per km in the above table 11.71, assuming that all the power plants available are coal-based, the table 11.72 discusses emissions for all the drive cycles. As can be seen, the higher the energy consumption was in the previous table, higher the emissions we get here.

Table 11.72: Emissions – motor optimized for driving

S.No.	Drive Cycle	Fixed gear ratio = 2.4			Rule based CVT		
		IM	PM	SynRel	IM	PM	SynRel
		g/km	g/km	g/km	g/km	g/km	g/km
1	Renukoot (U.P.)	30.9	27.5	28.1	27.9	26.2	26.9
2	Hyderabad (Telangana)	49.2	43.7	44.7	45.9	42.9	44.0
3	Guwahati (Assam)	36.6	32.1	32.7	30.0	28.2	29.0
4	WLTC	43.9	37.0	37.4	36.8	33.3	33.7
5	MoRTH	25.6	24.1	24.6	25.0	23.6	24.2

11.4 Some notes on MoRTH

One thing to notice here is the MoRTH drive cycle graph below:

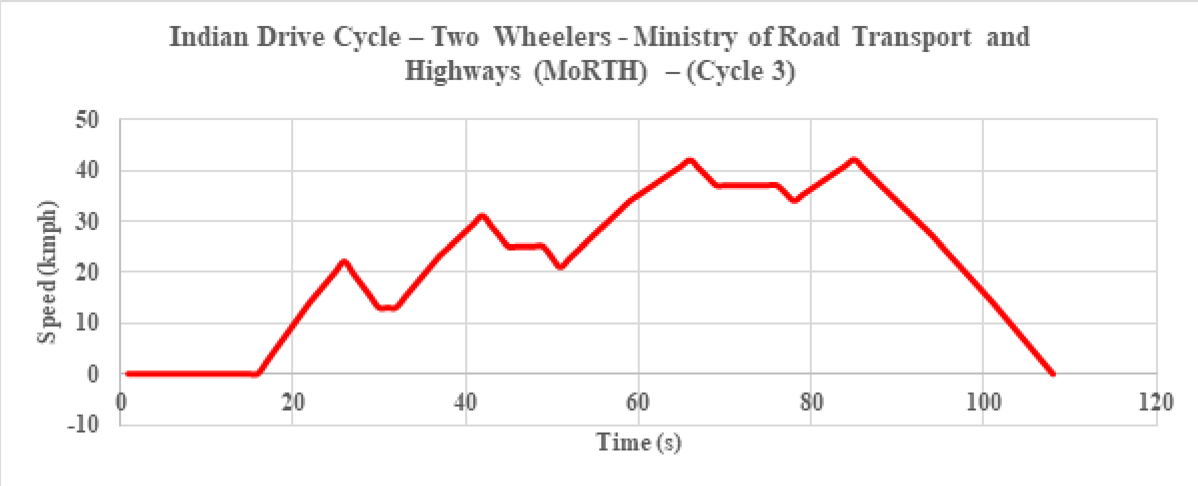


Figure 11.12: Ministry of Road Transport and Highways (MoRTH) drive cycle

This is a concise drive cycle, only 108 seconds when others are all about 230+ seconds. The other big issue here is that this drive cycle has a lot of straight lines. Also, it assumes constant acceleration for long durations. This is not how a normal person drives their vehicle. Anyone would find it hard to maintain a specific acceleration for these durations. So, it can be said that this is a bit of an unrealistic drive cycle. Actual driving cycle results in higher fuel consumption because in reality, we have to consider all kinds of dynamics, and testing on a chassis dynamometer in the testing phase doesn't consider all the actual parameters as we did in real world.

11.5 Environmental impact

Now, one more thing that has to be addressed is that a higher acceleration case requires a higher rated motor. Say the difference is very small between these ratings, say following. The environmental impact of making these motors will be discussed.

1. For the acceleration case, we need a 9 kW peak and 6 kW rated power motor.

    - Total energy consumption: 72000 MJ
    - Water used: 48000 L
    - Greenhouse gases emitted: 30000 kg of CO2 eq.
    - Acidification emissions: 150 kg of SO2 eq.

2. For normal driving case we need a motor of 7 kW peak power and 4.5 kW rated power.

    - Total energy consumption: 54000 MJ
    - Water used: 36000 L

- Greenhouse gases emitted: 22500 kg of CO2 eq.
- Acidification emissions: 112 kg of SO2 eq.

Hence there is a big difference in the environmental impact of these motors. And in reality, the difference between the motor ratings is going to be more.

So, all in all, optimization for acceleration leads to environmental impact far greater than for driving conditions, during the manufacturing and also when on the road.

11.6 Regenerative braking

Regenerative braking is an energy recovery mechanism that slows down a moving vehicle by converting its kinetic energy into a form that can be either used immediately or stored until needed. In this mechanism, the electric traction motor uses the vehicle's momentum to recover energy that would otherwise be lost to the brake discs as heat.

For the analysis in this document, during the deceleration phase, the total force acting on the body is taken into account to proceed for regenerative braking energy calculation.

Ftotal = Faerodrynamic drag + Fdeceleration + Frolling

The negative torque operating points corresponding to that force at the motor end are then projected onto the efficiency map of the respective drive-train, as shown in the figure 11.13.

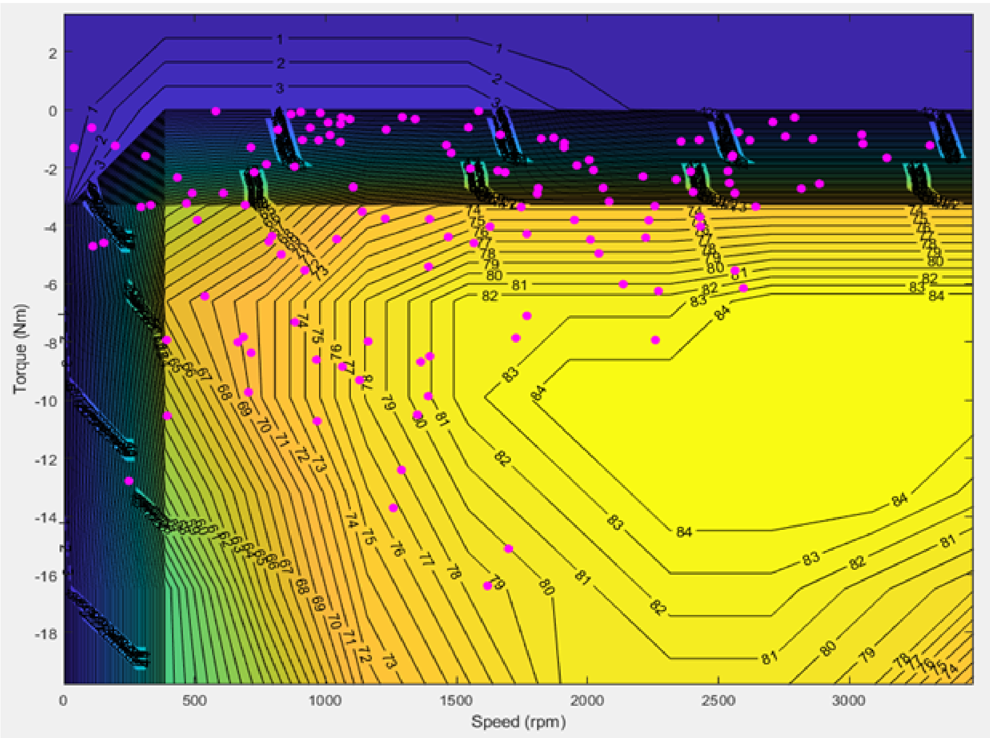


Figure 11.13: Efficiency map of drive train with negative torque operating points projected in pink

Table 11.73: Recuperable braking energy – 150 kg payload

Sl.No	Drive cycle	Recuperable braking energy						Regenerative braking system efficiency
		Ideal regenerative system			Practical regnerative system			
		kWh	kWh/km	kWh/ 100km	kWh	kWh/km	kWh/ 100km	%
1	**Renukoot (U.P)**	0.016	0.012	1.18	0.011	0.008	0.82	68.9
2	**Hyderabad (Telangana)**	0.053	0.019	1.93	0.037	0.013	1.34	69.7
3	**Guwahati**	0.030	0.008	0.81	0.020	0.006	0.55	68.7
4	**WLTC**	0.048	0.004	0.44	0.031	0.003	0.28	63.3
5	**MoRTH**	0.005	0.008	0.77	0.003	0.005	0.46	59.6

Table 11.74: Fuel consumption and battery rating required – with and without regenerative braking – 150 kg payload

Sl.No	Drive Cycle	Without regenerative braking		With regenerative braking		Percentage Reduction
		Fuel consumption	Battery rating	Fuel consumption	Battery rating	
		kWh/km	kWh/100 km	kWh/km	kWh/100 km	%
1	**Renukoot (U.P)**	0.044	4.4	0.036	3.6	18.4
2	**Hyderabad (Telangana)**	0.062	6.2	0.049	4.9	21.6
3	**Guwahati**	0.053	5.3	0.047	4.7	10.5
4	**WLTC**	0.053	5.3	0.050	5.0	5.3
5	**MoRTH**	0.041	4.1	0.036	3.6	11.2

Total braking energy (Ebr) generated is then calculated for the particular drive cycle, considering both efficiencies of the total drive-train and battery columbic efficiency.

11.6.1 Regenerative braking - fixed gear ratio vehicle

This section discusses about the result of incorporating regenerative braking in a vehicle with a fixed gear ratio. Honda Activa with gear ratio 4.5 is considered for this analysis. The table below shows the energy available for us to recharge our battery for the case where the payload is 150 kg. Here, two cases are discussed: an ideal regenerative system and a practical regenerative system.

A regenerative system with a 100% efficient drive-train and battery pack unit would result in an ideal regenerative braking system resulting in a very competent regeneration, as shown.

However, in general, every drive train (motor-inverter) system would have its efficiency along with columbic efficiency of the Battery Pack unit. Considering respective efficiency maps of the drive train and efficiency of the battery unit, the regeneration energy would be as shown in the practical system column.

With this much energy available to us, the fuel consumption and battery rating, with or without the regenerative braking, will differ, as shown in the following table. As can be seen from the data, both the fuel consumption and the battery rating are much lower with regenerative braking turned on. The percentage reduction is written in the final column.

Table 11.75: Recuperable braking energy – after neglecting lower power levels - 150 kg payload

Sl.No	Drive cycle	neglecting <5% energies			neglecting <10% energies		
		kWh	kWh/km	kWh/ 100km	kWh	kWh/km	kWh/ 100km
1	**Renukoot (U.P)**	0.010	0.008	0.75	0.008	0.006	0.61
2	**Hyderabad (Telangana)**	0.035	0.013	1.27	0.032	0.012	1.15
3	**Guwahati**	0.019	0.005	0.51	0.015	0.004	0.41
4	**WLTC**	0.026	0.002	0.24	0.0194	0.002	0.18
5	**MoRTH**	0.002	0.004	0.36	0.000	0.001	0.07

Table 11.76: Fuel consumption and battery rating required – after neglecting lower power levels - 150 kg payload

		neglecting <5% energies			neglecting <10% energies		
Sl.No	Drive cycle	Fuel consumption	Battery rating	Percentage reduction	Fuel consumption	Battery rating	Percentage reduction
		kWh/ km	kWh/ 100 km	%	kWh/ km	kWh/ 100 km	%
1	**Renukoot (U.P)**	0.037	3.7	17.0	0.038	3.8	13.7
2	**Hyderabad (Telangana)**	0.050	5.0	20.4	0.051	5.1	18.5
3	**Guwahati**	0.048	4.8	9.6	0.049	4.9	7.8
4	**WLTC**	0.051	5.1	4.5	0.051	5.1	3.3
5	**MoRTH**	0.037	3.7	8.7	0.040	4.0	1.6

Recuperating energy from operating braking points having power levels less than 5% or 10% of the battery optimal power rating at 1-C rate is challenging. The recuperable energy is as shown in the following table by neglecting such lower energy operating points.

Similarly, for 70 kg of payload, the same analysis was done. And the results are the following.

Note: The highlighted value of 0.0003 in table 11.79 was obtained by neglecting only 9 percent of lower power levels.

11.6.2 Regenerative braking with CVT

This section discusses the result of incorporating regenerative braking with Continuously Variable Transmission (CVT) in a vehicle. Honda Activa is considered for this analysis. Table 11.81 shows the energy available for us to recharge our battery for the case where the payload is 150 kg. Here, two cases are discussed: an ideal regenerative system and a practical regenerative sys-

Table 11.77: Recuperable braking energy – 70 kg payload

Sl.No	Drive cycle	Ideal regenerative system			Practical regenerative system			Efficiency
		kWh	kWh/ km	kWh/ 100km	kWh	kWh/ km	kWh/ 100km	%
1	**Renukoot (U.P)**	0.011	0.008	0.78	0.008	0.006	0.57	73.4
2	**Hyderabad (Telangana)**	0.035	0.013	1.25	0.024	0.009	0.87	69.1
3	**Guwahati**	0.019	0.005	0.51	0.013	0.003	0.34	67.3
4	**WLTC**	0.029	0.003	0.27	0.017	0.002	0.15	58.5
5	**MoRTH**	0.003	0.005	0.46	0.002	0.003	0.28	60.1

Table 11.78: Fuel consumption and battery rating required – with and without regenerative braking – 70 kg payload

Sl.No	Drive cycle	Without Regenrative braking		With Regenerative braking		Percentage reduction
		Fuel consumption	Battery rating	Fuel consumption	Battery rating	
		kWh/km	kWh/100 km	kWh/km	kWh/100 km	%
1	**Renukoot (U.P)**	0.033	3.3	0.027	2.7	17.4
2	**Hyderabad (Telangana)**	0.044	4.4	0.036	3.6	19.5
3	**Guwahati**	0.039	3.9	0.036	3.6	8.7
4	**WLTC**	0.041	4.1	0.040	4.0	3.8
5	**MoRTH**	0.030	3.0	0.027	2.7	9.3

Table 11.79: Recuperable braking energy – After neglecting lower power levels - 70 kg payload

Sl.No	Drive cycle	Neglecting <5% energies			Neglecting <10% energies		
		kWh	kWh/km	kWh/100km	kWh	kWh/km	kWh/100km
1	**Renukoot (U.P)**	0.007	0.005	0.52	0.005	0.004	0.39
2	**Hyderabad (Telangana)**	0.023	0.008	0.82	0.020	0.007	0.72
3	**Guwahati**	0.011	0.003	0.31	0.009	0.002	0.23
4	**WLTC**	0.014	0.001	0.12	0.008	0.001	0.07
5	**MoRTH**	0.001	0.002	0.19	0.0003	0.0004	0.04

Table 11.80: Fuel consumption and battery rating required – after neglecting lower power levels – 70 kg payload

Sl.No	Drive cycle	Neglecting <5% energies			Neglecting <10% energies		
		Fuel consumption	Battery rating	Percentage reduction	Fuel consumption	Battery rating	Percentage reduction
		kWh/km	kWh/100 km	%	kWh/km	kWh/100 km	%
1	**Renukoot (U.P)**	0.028	2.8	15.9	0.029	2.9	11.9
2	**Hyderabad (Telangana)**	0.036	3.6	18.4	0.037	3.7	16.2
3	**Guwahati**	0.036	3.6	7.8	0.037	3.7	5.9
4	**WLTC**	0.040	4.0	3.0	0.040	4.0	1.7
5	**MoRTH**	0.028	2.8	6.5	0.029	2.9	1.5

tem.

A regenerative system with a 100% efficient drive-train and battery pack unit would result in an ideal regenerative braking system resulting in a very competent regeneration, as shown.

However, in general, every drive train (motor-inverter) system would have its own efficiency along with columbic efficiency of the battery pack unit. Considering respective efficiency maps of the drive train and efficiency of the battery unit, the regeneration energy would be as shown in the practical system column.

Table 11.81: Recuperable braking energy

Sl.No	Drive Cycle	Ideal Regenerative System			Practical Regenerative System			Regenerative Braking System Efficiency
		kWh	kWh/ km	kWh/ 100km	kWh	kWh/ km	kWh/ 100km	%
1	**Renukoot (U.P)**	0.016	0.012	1.18	0.013	0.009	0.93	78.4
2	**Hyderabad (Telangana)**	0.053	0.019	1.93	0.041	0.015	1.50	77.7
3	**Guwahati**	0.030	0.008	0.81	0.023	0.006	0.62	76.8
4	**WLTC**	0.048	0.004	0.44	0.037	0.003	0.33	75.5
5	**MoRTH**	0.005	0.008	0.77	0.004	0.006	0.63	81.5

With this much energy available to us, the fuel consumption and battery rating, with or without the regenerative braking, will differ, as shown in the following tables. As can be seen from the data, both the fuel consumption and the battery rating are much lower with regenerative braking turned on.

Table 11.82: Fuel consumption and the corresponding battery rating required – without regenerative braking

Sl.No	Drive Cycle	Without Regenrative Braking	
		Fuel Consumption	Battery Rating
		kWh/ km	kWh/ 100 km
1	**Renukoot (U.P)**	0.033	3.3
2	**Telangana (Hyderabad)**	0.055	5.5
3	**Guwahati**	0.036	3.6
4	**WLTC**	0.044	4.4
5	**MoRTH**	0.030	3.0

And the percentage reduction in fuel consumption that we can observe from the tables 11.82 and 11.83 is given in the table 11.84

Recuperating energy from operating braking points having power levels less than 5% or 10% of the battery optimal power rating at 1-C rate is challenging. The recuperable energy is as shown in the table 11.85 by neglecting such lower energy operating points.

As the recuperable energy has reduced now, the fuel consumption and battery ratings for all the drive cycles will increase a bit, compared to earlier fuel

Table 11.83: Fuel consumption and the corresponding battery rating required – with regenerative braking

		With Regenerative Braking	
Sl.No	**Drive Cycle**	**Fuel Consumption**	**Battery Rating**
		kWh/ km	kWh/ 100 km
1	**Renukoot (U.P)**	0.024	2.4
2	**Telangana (Hyderabad)**	0.040	4.0
3	**Guwahati**	0.030	3.0
4	**WLTC**	0.041	4.1
5	**MoRTH**	0.024	2.4

Table 11.84: Percentage reduction in fuel consumption, with the implementation of regenerative braking

Sl.No	**Drive Cycle**	**Percentage Reduction**
		%
1	**Renukoot (U.P)**	27.8
2	**Telangana (Hyderabad)**	27.2
3	**Guwahati**	17.2
4	**WLTC**	7.5
5	**MoRTH**	20.9

Table 11.85: Recuperable braking energy – after neglecting lower power levels

		Recuperable Braking Energy					
Sl.No	**Drive Cycle**	**Neglecting <5% Energies**			**Neglecting <10% Energies**		
		kWh	kWh/ km	kWh/ 100km	kWh	kWh/ km	kWh/ 100km
1	**Renukoot (U.P)**	0.012	0.009	0.89	0.011	0.008	0.78
2	**Telangana (Hyderabad)**	0.039	0.014	1.42	0.036	0.013	1.30
3	**Guwahati**	0.022	0.006	0.59	0.020	0.005	0.53
4	**WLTC**	0.032	0.003	0.29	0.027	0.002	0.25
5	**MoRTH**	0.004	0.006	0.61	0.0034	0.0051	0.51

consumption data where we had not neglected any energy, as shown in table 11.86.

Table 11.86: Fuel consumption and battery rating required – after neglecting lower power levels

		Neglecting <5% Energies			Neglecting <10% Energies		
Sl.No	**Drive Cycle**	**Fuel Consumption**	**Battery Rating**	**Percentage Reduction**	**Fuel Consumption**	**Battery Rating**	**Percentage Reduction**
		kWh/ km	kWh/ 100 km	%	kWh/ km	kWh/ 100 km	%
1	**Renukoot (U.P)**	0.025	2.5	26.7	0.026	2.6	23.4
2	**Telangana (Hyderabad)**	0.041	4.1	25.8	0.042	4.2	23.5
3	**Guwahati**	0.030	3.0	16.4	0.031	3.1	14.7
4	**WLTC**	0.041	4.1	6.6	0.042	4.2	5.6
5	**MoRTH**	0.024	2.4	20.4	0.025	2.5	17.1

Now that we have discussed our findings for the cases of implementing regenerating braking with a constant gear ratio and with an intelligently controlled CVT let's compare these two cases.

Table 11.87 shows that an intelligently controlled CVT ratio has a higher regenerative braking efficiency than a vehicle with a constant gear ratio. Also, Hyderabad and Renukoot drive cycles provide the maximum opportunities for regeneration with 0.015 kWh/km and 0.009 kWh/km, respectively.

Table 11.87: Recuperable braking energy – Fixed gear ratio vs. rule based CVT

Sl.No	Drive cycle	Recuperable braking energy						Improvement in regeneration
		Fixed gear ratio - 2.4			Rule based CVT			
		kWh	kWh/ km	kWh/ 100km	kWh	kWh/ km	kWh/ 100km	%
1	**Renukoot (U.P)**	0.011	0.008	0.82	0.013	0.009	0.93	13.9
2	**Telangana (Hyderabad)**	0.037	0.013	1.34	0.041	0.015	1.50	11.5
3	**Guwahati**	0.020	0.006	0.55	0.023	0.006	0.62	11.8
4	**WLTC**	0.031	0.003	0.28	0.037	0.003	0.33	19.3
5	**MoRTH**	0.003	0.005	0.46	0.004	0.006	0.63	36.7

Now compare the fuel consumption data that we estimated for both cases above. With regenerative braking system implemented in both, we found that, compared to constant gear ratio controlled vehicle, a rule-based CVT method can significantly reduce fuel consumption and thereby provide better mileage and lesser emissions. For the same drive cycle, lesser battery ratings suffice for a rule-based CVT transmission mode. Table 11.88 shows the reduction in fuel consumption and battery ratings for a rule based CVT vehicle.

Table 11.88: Fuel consumption and required battery ratings – constant gear ratio vs. rule based CVT

Sl.No	Drive Cycle	Fixed Gear Ratio - 2.4		Rule based CVT		
		Fuel Consumption	Battery Rating	Fuel Consumption	Battery Rating	Percentage Reduction
		kWh/ km	kWh/ 100 km	kWh/ km	kWh/ 100 km	%
1	**Renukoot (U.P)**	0.036	3.6	0.024	2.4	33.2
2	**Telangana (Hyderabad)**	0.049	4.9	0.040	4.0	18.0
3	**Guwahati**	0.047	4.7	0.030	3.0	36.7
4	**WLTC**	0.050	5.0	0.041	4.1	18.9
5	**MoRTH**	0.036	3.6	0.024	2.4	34.9

For a given drive cycle, the amount of energy that can be recuperable can be enhanced by rule-based CVT method when compared to constant gear ratio controlled vehicle as shown in table 11.89.

Table 11.89: Comparison of recuperable energy limits – Constant gear ratio vs. Rule based CVT

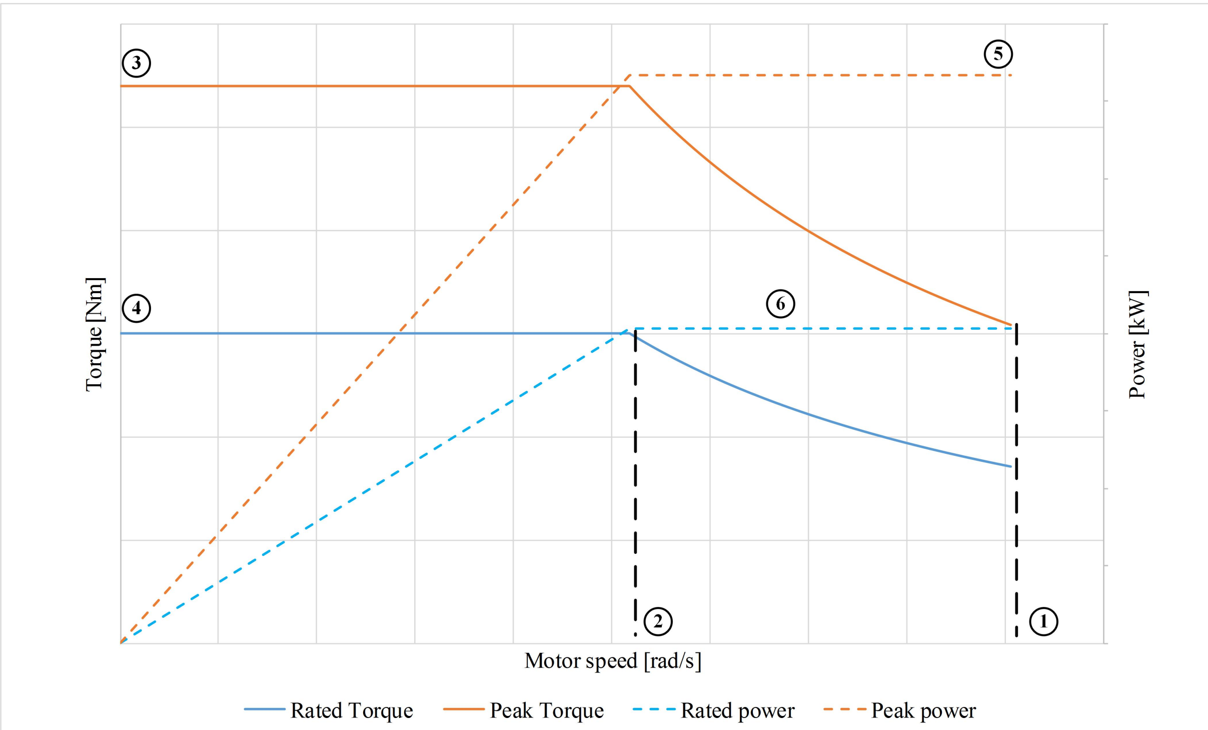
		Recuperable Braking Energy Limit	
Sl.No	Drive Cycle	Fixed Gear Ratio - 2.4	Rule based CVT
		%	%
1	Renukoot (U.P)	68.9	78.4
2	Telangana (Hyderabad)	69.7	77.7
3	Guwahati	68.7	76.8
4	WLTC	63.3	75.5
5	MoRTH	59.6	81.5

12 Conclusion

This report presented a comprehensive drive cycle analysis for drivetrain design for electric two wheelers. Based on emission attributes and optimal fuel consumption, a trade-off between two different modes namely "Optimized for Acceleration performance" and "Optimized for Driving Performance" has been drawn. The design characteristics and specifications requirements were evaluated from the standpoint of drive cycle metrics, emission factors and better mileage performance.

Depending on vehicle type, the optimal drive train parameters can be as shown from table 12.1 to 12.12. For the analysis purpose, a PMSM motor is chosen. An efficiency of 0.8 at peak torque operating point, converter efficiency of 0.9 and battery utilization factor of 0.8 is considered for 150 km range requirement.

Motor output ratings mentioned in tables to are as shown in the figure.



1 Motor maximum speed [rad/s]

2 Motor rated speed [rad/s]

3 Motor peak torque [Nm]

4 Motor rated torque [Nm]

5 Motor peak power[kW]

6 Motor rated power[kW]

Figure 12.1: Motor Characteristics

12.1 Commute Scooter Category

Table 12.1: Motor output ratings - Commute Scooter Category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Motor maximum speed [rad/s]	365.2	365.2
2	Motor base speed [rad/s]	208.7	208.7
3	Peak torque of motor [Nm]	34.2	38.7
4	Rated torque of motor [Nm]	19.0	21.5
5	Rated power of the motor [kW]	4.0	4.5
6	Peak power of the motor [kW]	7.5	8.5

Table 12.2: Battery ratings - Commute Scooter Category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Battery size [kWh]	8.25	8.30
2	Maximum C-rate	1.2	1.4

Table 12.3: Converter ratings - Commute Scooter Category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Nominal Voltage [V]	48 / 60 / 72	48 / 60 / 72
2	Peak Power Rating [kW]	9.0	10.0

12.2 Sports bike category

Table 12.4: Motor output ratings - Sports bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Motor maximum speed [rad/s]	474.8	474.8
2	Motor base speed [rad/s]	271.3	271.3
3	Peak torque of motor [Nm]	27.0	37.9
4	Rated torque of motor [Nm]	15.0	21.0
5	Rated power of the motor [kW]	4.5	6.0
6	Peak power of the motor [kW]	7.5	10.5

Table 12.5: Battery ratings - Sports bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Battery size [kWh]	5.0	6.0
2	Maximum C-rate	2.0	2.5

Table 12.6: Converter ratings - Sports bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Nominal Voltage [V]	48 / 60 / 72	48 / 60 / 72
2	Peak Power Rating [kW]	9.0	12.5

12.3 Mid range bike category

Table 12.7: Motor output ratings - Mid range bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Motor maximum speed [rad/s]	395.8	395.8
2	Motor base speed [rad/s]	247.4	247.4
3	Peak torque of motor [Nm]	32.4	34.7
4	Rated torque of motor [Nm]	18.0	19.3
5	Rated power of the motor [kW]	4.5	4.8
6	Peak power of the motor [kW]	8.0	9.0

Table 12.8: Battery ratings - Mid range bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Battery size [kWh]	8.0	8.2
2	Maximum C-rate	1.4	1.5

Table 12.9: Converter ratings - Mid range bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Nominal Voltage [V]	48 / 60 / 72	48 / 60 / 72
2	Peak Power Rating [kW]	10.0	10.5

12.4 Retro bike category

Table 12.10: Motor output ratings - Retro bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Motor maximum speed [rad/s]	273.1	273.1
2	Motor base speed [rad/s]	156.1	156.1
3	Peak torque of motor [Nm]	59.4	97.2
4	Rated torque of motor [Nm]	33.0	54.0
5	Rated power of the motor [kW]	5.2	8.4
6	Peak power of the motor [kW]	9.5	15.5

Table 12.11: Battery ratings - Retro bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Battery size [kWh]	8.5	10.0
2	Maximum C-rate	1.5	2.1

Table 12.12: Converter ratings - Retro bike category

S.No	Parameters	Optimized for Driving	Optimized for Acceleration
1	Nominal Voltage [V]	48 / 60 / 72	48 / 60 / 72
2	Peak Power Rating [kW]	11.0	18.5