Chapter 4

Road load model analysis

4.1. Introduction

The escalating fuel crisis, growing environmental awareness, and adverse impacts of climate change have created opportunities for the advancement of eco-friendly automobiles that can effectively reduce carbon emissions [1]. Consequently, there has been a rapid advancement in the creation of vehicle technology that is free from pollution in order to meet these global demands. The implementation of electric powertrains of an electric vehicle (EV) introduces novel variations and opportunities, hence enabling research to explore multiple new avenues. Nevertheless, range anxiety is identified as a significant impediment to the widespread acceptance of electric vehicles [2,3]. Accurate range prediction and reduction of range anxiety are important issues that need to be addressed for widespread use of EVs. These issues can be significantly reduced by using the concept of an eco-routing navigation system (ERNS) [4]. Research on these systems is still in the development phase as it is a comparatively new topic. It uses the Global Positioning System (GPS) and determines the least energy-consuming route between a source-destination pair during a trip [5]. Energy usage estimation and, hence, its minimisation can aid in solving the aforementioned issues of limited driving range and range anxiety in electric vehicles. Studies have proved that a vehicle in motion is affected by various factors which are dynamic in nature. These factors in turn influence the energy consumption of the vehicle, which is the determining factor for the driving range. The development of a navigation system should therefore take into account all the major factors which influence energy usage in an electric vehicle (EV). The road on which the EV is manoeuvring plays a cardinal role in the energy estimation procedure. There are various models on which energy consumption estimation can be based [6]. This work mainly emphasises the role of road load in the energy usage of an EV as well as in eco-routing navigation systems. An EV power consumption mathematical model has been simulated and analysed, wherein road load has been considered for the evaluation of power consumption during a trip. There are various constraints which affect the road load when an EV is traversing. The rolling resistance is an important factor affecting the motion of a vehicle and thereby its energy consumption [7]. In traditional Internal Combustion Engine Vehicles (ICEVs), a 30% increase in rolling resistance is reported to consume around 3 to 5% of extra fuel [8]. The effect of rolling resistance on various road types and road grades has not been reported yet. Cross-wind effects occur when a vehicle is moving at higher speeds on a windy day. The aforementioned action will lead to a rise in aerodynamic drag, a crucial factor in the energy consumption of an electric vehicle [9]. The incorporation of cross-wind effects remains absent in most prevailing models. It is obvious that alterations in elevation have a discernible impact on the power consumption and braking performance of electric vehicles (EVs). The duration of an EV journey to a specific location is influenced by the distance and speed restrictions of the route being traversed. Other elements, such as real-time traffic information, weather conditions, and location-specific features, also have an impact on energy use. Nevertheless, the methods documented in the literature mostly cater to Internal Combustion Engine Vehicles (ICEV). The ERNS systems predominantly rely on speed profiles and real-time traffic data pertaining to the vehicle [10]. It has been reported that in order to develop the most efficient navigation system, several factors are required, all of which are not taken into account for evaluation. Vaz et al. developed a novel method that determines the optimal drive speed for the driver by employing a multi-objective optimisation strategy at several trip speeds [11]. However, their strategy does not include road surface condition information. The method presented in [12–14] uses a battery state of charge estimation model to determine the vehicle range. Despite their advantages, these methods are not sufficient because of the lack of proper information about battery energy management inside the vehicle. Rami et al. proposed a model that covers temperature loss, auxiliary loads, and traffic information to determine the energy consumption of the vehicle [15]. Their results were found satisfactory, with considerably less error compared with the actual data. However, their approach does not include road behaviour and its effect on energy consumption. The existing literature focuses on individual factors and does not contain strategies that include comprehensive vehicle dynamics and road-dependent factors. This chapter presents a road load model wherein a road surface approximation technique has been incorporated to measure the tractive effort of an EV while traversing a specific route containing various crests and dips. The roadgrade which is often neglected in most models have been emphasised here. Grade information has been obtained through digital elevation mapping sources which has further been used to estimate energy usage of EVs.

4.2. Theory

4.2.1. Fundamentals of Road Load

Road load refers to the force experienced by a vehicle while it is travelling at a consistent velocity on a flat and even road surface [16]. The term can also be delineated as the counteractive force that impedes the progressive movement of a vehicle, ascertained by conventional techniques such as the coast-down method. The coast-down approach involves subjecting the vehicle to a high level of acceleration on a flat and straight road, followed by allowing the car to coast in neutral until it naturally decelerates to a low speed. The deceleration phase can be utilised to ascertain a theoretical framework for the factors that contribute to the vehicle's loss of energy. Based on the theory of force equilibrium, the forces exerted on an electric vehicle (EV) in the longitudinal direction consist of five constituent elements, namely aerodynamic drag, rolling resistance, uphill driving force, inertial force, and traction force [17]. The initial four actions synergistically contribute to the generation of the traction force, which predominantly serves as the propulsive force responsible for driving the vehicle forward, subsequently delivered to the wheels [18]. The aerodynamic drag of an EV is influenced by factors such as its size, shape, and level of streamlining. Additionally, it is observed that the aerodynamic drag increases according to the square of the vehicle's velocity relative to the surrounding air. The magnitude of rolling resistance is primarily influenced by the characteristics of the terrain, the type of tyres employed, the mass of the vehicle, and to a lesser degree, the velocity of the vehicle. The uphill force can be determined by considering the incline of the hill and the gravitational force acting on the vehicle. This force is responsible for raising the vehicle from the lower point to the higher point on the hill. The magnitude of the inertia force experienced by an automobile is contingent upon both the mass of the car and the magnitude of its acceleration. The process of estimating energy consumption involves performing tractive effort calculations, which can be derived from the tractive force. The assessment of tractive effort plays a crucial role in the creation of an eco-routing system designed to identify environmentally friendly routes.

4.2.2. Tractive effort analysis

Tractive effort refers to the force exerted by the wheels in order to overcome resistance and facilitate forward propulsion. In the field of automotive engineering, the tractive force is typically greater than the rolling resistance due to many factors. Tractive effort is commonly classified into three distinct categories according to varying operational circumstances. They are the tractive effort, continuous tractive effort, and maximum tractive effort [19]. The initial tractive effort refers to the force produced by an electric vehicle when it is in a stationary state. Nevertheless, this force holds greater significance within the realm of railways as it establishes the upper limit for the weight of a train that may be set into motion by a locomotive. The maximum tractive effort is commonly defined as the highest level of tractive power that, without exception, appears not to jeopardise the safety of the vehicle. In a majority of cases, the maximum tractive effort is typically achieved at a low velocity and may be equivalent to the initial tractive effort. In contrast to the greater tractive effort, which is subject to a time constraint and necessitates overcoming the risk of power transmission system overheating, continuous tractive effort refers to a force that may be sustained indefinitely. The force required to propel the electric vehicle is transferred through the drive wheels. The calculation of torque exerted on the wheels can be derived by multiplying the applied force with the radius of the tyre. In the given hypothetical situation, if an electric vehicle (EV) experiences no slippage between its rear tyres and the flat road surface, the tractive effort (TE) or wheel force exerted by the rear wheels can be determined by dividing the torque at the driven wheels (τ_w) by the rolling radius (R_w) or effective radius of the wheel [20]. The mathematical representation of this can be expressed as follows:

$$TE = \frac{\tau_w}{R_w} \tag{1}$$

When the tractive effort is equal to the tractive resistance, an electric vehicle can either be stationary or travelling at a constant rate. An EV achieves acceleration by surpassing the opposing forces until the tractive effort is once again balanced with the tractive resistance. In every circumstance, if the tractive resistance surpasses the tractive effort, an EV will experience deceleration and ultimately come to a halt, unless the tractive effort is augmented or the resistance is diminished [21]. This effort can be expressed quantitatively as the force necessary to counteract the opposing tractive force. Figure 4.1 depicts an algorithmic depiction illustrating the tractive force as the accumulation of many other forces.

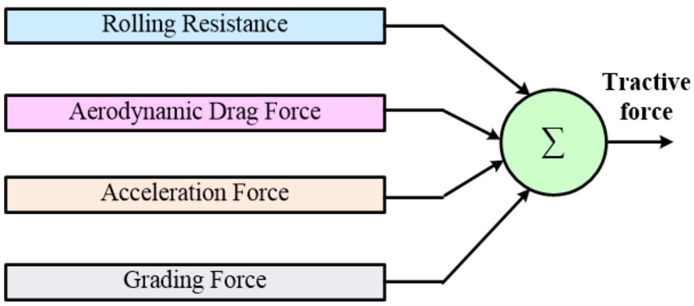

Fig.4.1 The tractive force produced under the tyres of an electric vehicle

4.2.2.1. Forward vehicle dynamics

This section presents the dynamics of an electric vehicle when it is traversing in a straight-forward motion. In forward dynamics analysis, the EV is usually considered an ideal rigid body. The load variation under the tyres is examined . This study of variation helps in the determination of the operating range and limits of various vehicle parameters like acceleration, velocity, tyre pressure, and road grade [21]. Losses caused by air friction are generally ignored. This evaluation involves the extraction of normal force acting on the wheels of an EV under different operating circumstances. The evaluation and expressions shown are in accordance with the test EV prototype that has been developed. The test prototype is an independent rear-wheel-driven battery electric vehicle with a kerb weight of 120 kg, a track width of 103cm, a wheelbase of 145cm and a wheel diameter of 42cm. When the EV is in standby position on a smooth road, the normal forces acting on each of the wheels of the EV can be obtained. Fig. 4.2 is a pictorial representation of an EV, depicting the track width and the wheelbase along with the geometrical centre of the vehicle. Here, a_1 and a_2 sum up to form the total wheelbase of the vehicle, and similarly, b_1 and b_2 can be combined to obtain the trackwidth. The centre is indicated as C in the figure. F_{fr}, F_{fl}, F_{rr} and F_{rl} depict the force on the front right , front left , rear right, and rear left wheels, respectively.

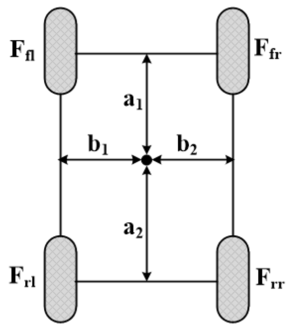

Fig.4.2 The trackwidth and wheelbase of an electric vehicle

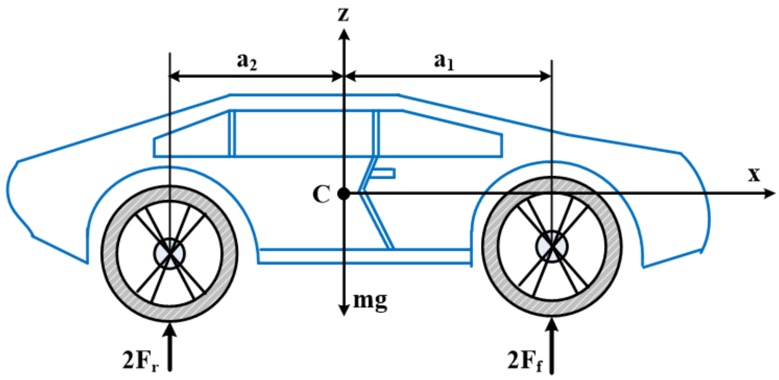

Fig.4.3 Forces acting on a car parked on a smooth levelled road

The car parked on a smooth levelled road has normal forces F_f and F_r acting under its wheels. This has been illustrated in Fig.4.3. The figure shows the forces as $2F_f$ and $2F_r$. This is because forces on both the rear as well as the front wheels have been shown together. The forces $2F_f$ and $2F_r$ are in the z-axis and therefore are interchangeable as $2F_{z1}$ ans $2F_{z2}$ respectively. Following planar static equilibrium equations, the normal forces is denoted as [21]

$$\sum F_z = 0 \tag{2}$$

Applying the laws of equilibrium,

$$2F_{z1} + 2F_{z2} - mg = 0 \tag{3}$$

$$-2F_{z1}a_1 + 2F_{z2}a_2 = 0 \tag{4}$$

Solving euations (iii) and (iv), the reaction forces under the front and the rear wheels can therefore be expressed as

$$F_{z1} = F_f = \frac{1}{2} mg \frac{a_2}{l} \qquad \text{(front wheel)} \qquad (5)$$

$$F_{z2} = F_r = \frac{1}{2} mg \frac{a_1}{l} \qquad \text{(rear wheel)} \qquad (6)$$

Where $l = a_1 + a_2$

If the trackwidth measurements as shown in Fig.4.2 are also taken into consideration, wherein it is assumed that b_1 is equal to b_2 and combines to form b, the above equations (5) and (6) can be re-written as [21]

$$F_{z1} = F_{fl} = \frac{1}{2} mg \frac{a_2}{l} \frac{b_2}{b} \text{ for front left wheel} \qquad (7)$$

$$F_{z2} = F_{rl} = \frac{1}{2} mg \frac{a_1}{l} \frac{b_2}{b} \text{ for rear left wheel} \qquad (8)$$

$$F_{z1} = F_{fr} = \frac{1}{2} mg \frac{a_2}{l} \frac{b_1}{b} \text{ for front right wheel} \qquad (9)$$

and

$$F_{z2} = F_{rr} = \frac{1}{2} mg \frac{a_1}{l} \frac{b_1}{b} \text{ for rear right wheel} \qquad (10)$$

4.2.2.1.1. *Electric vehicle accelerating on level road*

The forward dynamics of an EV change when it starts accelerating. Few other forces come into action when an EV is traversing a level road.A vehicle is undergoing acceleration while travelling on a level roadway. The force exerted on each tyre can be decomposed into two components: a normal force and a longitudinal force. The equations governing the motion of the accelerating automobile are derived from Newton's equation in the x-direction, together with two static equilibrium equations. It is postulated that the vehicle possesses an acceleration, a. Fig. 4.4 illustrates the acceleration of an electric vehicle (EV) on a flat road surface.

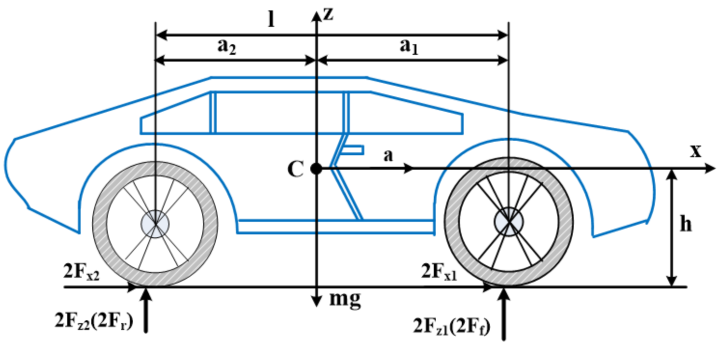

Fig.4.4 Vehicle accelerating on a smooth levelled road

So, $$\sum F_x = mg \text{ , } \sum F_z = 0 \qquad (11)$$

The eequations of motions can be expanded to obtain the values of F_{x1}, F_{x2} ,F_{z1} and F_{z2}.

$$2F_{x1} + 2F_{x2} = ma \qquad (12)$$

$$2F_{z1} + 2F_{z2} = mg \qquad (13)$$

$$-2F_{z1}a_1 + 2F_{z2}a_2 - 2F_{x1}h - 2F_{x2}h = 0 \qquad (14)$$

Here, F_{x1} and F_{x2} are the longitudinal forces produced in the x direction, or the moving direction of the vehicle; *a* is the acceleration of the EV, g is acceleration due to gravity in m/sec2; and *h* is the height from the ground to the centre of the EV. The above equations can be used to obtain the solutions for the normal forces. The expressions for each of these normal forces comprise a static and a dynamic part. The dynamic part has a greater role when the EV is accelerating. The weight distribution in relation to horizontal acceleration is indicated and is contingent upon the vertical position of the centre of mass [22]. In the context of a rear wheel driven vehicle, when the EV experiences positive acceleration, the vertical force acting on the front wheels is lower than the static load, while the vertical force acting on the rear wheels is higher than the static load. Hence, it is apparent that in the context of a rear-wheel-drive automobile, the propulsive force necessary for acceleration is only generated by the rear wheels. The expressions for the solutions of F_{z1} and F_{z2} can be formulated as.

$$F_{z1} = F_f = F_{z1_{static}} + F_{z1_{dynamic}} = \frac{1}{2}mg\frac{a_2}{l} - \frac{1}{2}mg\frac{h}{l}\frac{a}{g} \quad (15)$$

$$F_{z2} = F_r = F_{z1_{static}} + F_{z1_{dynamic}} = \frac{1}{2}mg\frac{a_1}{l} + \frac{1}{2}mg\frac{h}{l}\frac{a}{g} \quad (16)$$

The relationship between the maximum acceleration of a car and the friction under its tyres is stated to be proportional [22]. There is a prevailing assumption in the field that the friction coefficients of the front and rear tyres are equivalent, and that all tyres attain their maximal tractive capabilities simultaneously.

4.2.2.1.2. Electric vehicle accelerating on uneven inclined road

The tractive effort of an EV exhibits an increase during the acceleration phase on an inclined route. This phenomenon can be attributed to the increased magnitude of the force necessary to counteract the usual forces acting on the wheels. The observed rise in the metric can be attributed to the incline of the road, commonly referred to as road gradient that the electric vehicle encounters when ascending. The vehicle is subject to Newton's laws of motion, and similar equations can be derived.

$$2F_{x1} + 2F_{x2} - mgSin\emptyset = ma \quad (17)$$

$$2F_{z1} + 2F_{z2} - mgCos\emptyset = 0 \quad (18)$$

$$2F_{z1}a_1 - 2F_{z2}a_2 + 2F_{x1}h + 2F_{x2}h = 0 \quad (19)$$

Where $\emptyset$ is the slope angle , h is the height of mass centre, F_{z1} and F_{z2} are the normal forces in the z direction and F_{x1} and F_{x2} are the forces in the forward direction. The forces acting on an EV when it encounters a crest or a dip, while travelling through an inclined road has been shown in Fig.4.5. The above equations can be solved to obtain the normal forces acting on the wheels when travelling through a level inclined road.

$$F_{z1} = F_f = F_{z1_{static}} + F_{z1_{dynamic}} = \frac{1}{2}mg\left(\frac{a_2}{l}Cos\emptyset - \frac{h}{l}Sin\emptyset\right) - \frac{1}{2}ma\frac{h}{l} \quad (20)$$

$$F_{z2} = F_r = F_{z1_{static}} + F_{z1_{dynamic}} = \frac{1}{2}mg\left(\frac{a_2}{l}Cos\emptyset + \frac{h}{l}Sin\emptyset\right) + \frac{1}{2}ma\frac{h}{l} \quad (21)$$

When equations (17) and (19) are evaluated with the assumption that the force F_{x2} is negligible, it becomes evident that the normal reaction forces acting on each wheel are nearly equal. Therefore, it can be asserted that the propulsion of the vehicle has minimal impact on the normal forces when the electric vehicle is operated in a linear trajectory with small rates of acceleration. The impacts of front-wheel, rear-wheel, or all-wheel drive vehicles become evident in many scenarios, such as maneuvering, navigating slippery roads, or when there is a need for maximum acceleration [22].

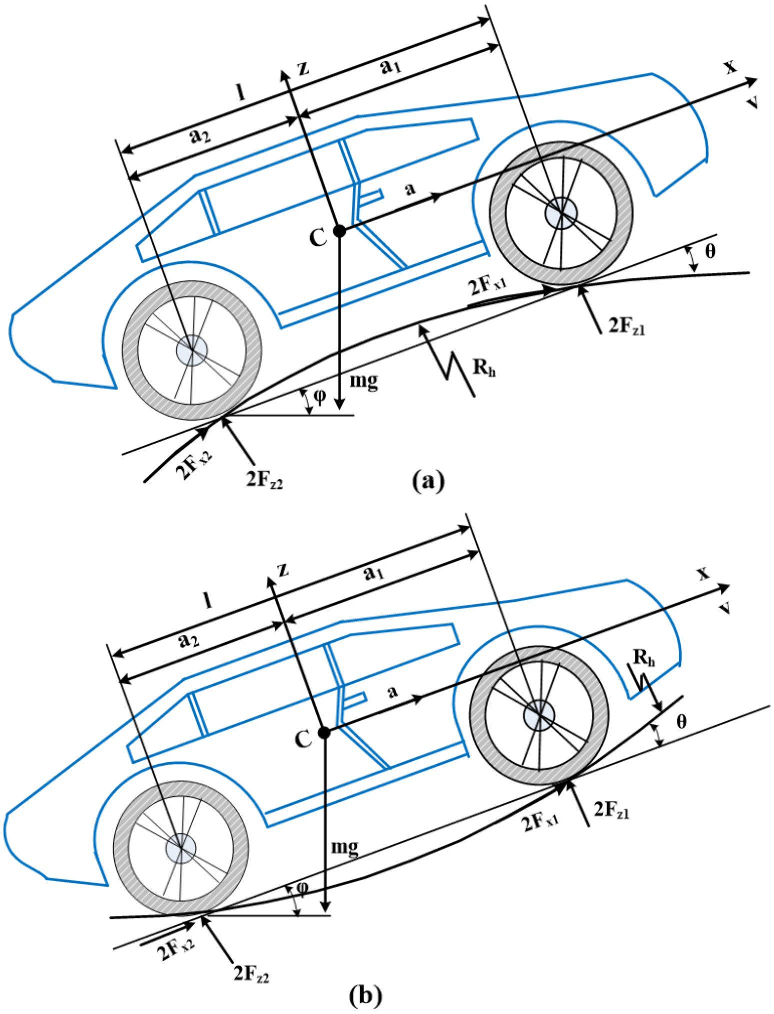

Fig.4.5 (a) An EV travelling through a crest and (b) An EV travelling through a dip

This research work focuses more on the concept of road grade or gradient present in the road and its influence on the energy consumption of EVs. It is because it has been observed that road grade is a factor that is ignored in most models for EVs but contributes generously to the rise in energy usage in EVs. Road grade is present in various degrees on almost all roads. Though the road may seem flat to the eyes, a minute degree of grade can affect energy usage. Most Indian roads also have curves on them, which may either be inward or outward. These curvatures change the normal forces acting under the wheels. A convex rise on an inclined road is called acrest, whereas a low area is known as a dip. The normal force acting on the wheels of a vehicle in a cresting motion is lower compared to the force exerted on a level, inclined road with an equivalent slope. This difference arises due to the presence of the centrifugal force, mv^2/Rh, which is created in the z-direction when the road has a radius of curvature ,R_h.These forces are reversed when the vehicles encounter a crest area where the forces are greater than those on a flat, inclined road. A vehicle traversing on a crest has been illustrated in Fig. 4.5(a), and the same vehicle when in motion through a dip has been shown in Fig. 4.5(b). The equations for traction and normal forces when on a crest as per Newton's equations, can be obtained as

$$2F_{x1}Cos\theta + 2F_{x2}Cos\theta - mgSin\emptyset = ma \tag{22}$$

$$-2F_{z1}Cos\theta - 2F_{z2}Cos\theta + mgCos\emptyset = m\frac{v^2}{R_h} \tag{23}$$

$$2F_{z1}a_1Cos\theta - 2F_{z2}a_2Cos\theta + 2F_{x1}hCos\theta + 2F_{x2}hCos\theta + 2F_{z1}a_1Sin\theta - 2F_{z2}a_2Sin\theta - 2F_{x1}hSin\theta - 2F_{x2}hSin\theta = 0 \tag{24}$$

Given the premise that the wheel base of the EV is significantly less than the radius of curvature, it is possible to derive the equations for the normal force exerted on the wheels.

$$F_{z1} = F_f = \frac{1}{2}mg\left(\frac{a_2}{l}Cos\emptyset + \frac{h}{l}Sin\emptyset\right) - \frac{1}{2}ma\frac{h}{l} - \frac{1}{2}m\frac{v^2}{R_h}\frac{a_2}{l} \tag{25}$$

$$F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}Cos\emptyset - \frac{h}{l}Sin\emptyset\right) + \frac{1}{2}ma\frac{h}{l} - \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l} \tag{26}$$

$$F_{x1} + F_{x2} = \frac{1}{2}m(a + gSin\emptyset) \tag{27}$$

The set laws are applicable while the EV is travelling through a dip on the road. Solving the equations in a similar procedure and assuming $\theta \ll$

1, provides the following results for the normal and the tangential forces under the wheels:

$$F_{z1} = F_f = \frac{1}{2}mg\left(\frac{a_2}{l}Cos\emptyset + \frac{h}{l}Sin\emptyset\right) - \frac{1}{2}ma\frac{h}{l} + \frac{1}{2}m\frac{v^2}{R_h}\frac{a_2}{l} \quad (28)$$

$$F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}Cos\emptyset - \frac{h}{l}Sin\emptyset\right) + \frac{1}{2}ma\frac{h}{l} + \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l} \quad (29)$$

$$F_{x1} + F_{x2} = \frac{1}{2}m(a + gSin\emptyset) \quad (30)$$

In all of the equations expressed above, F_{z1} and F_{z2} refer to the normal forces under the front and the rar tyres respectively whereas F_{x1} and F_{x2} is the tangential force in the moving or x-direction of the vehicle.

4.3. Proposed Method

Road load is an important factor in estimating energy consumption for eco-routing systems. Although there are numerous methods for calculating energy in electric vehicles, this work focuses on and is confined to utilising a road load model to demonstrate an energy efficient path throughout a trip. This road load estimation model can be effectively used in electric vehicle eco-routing navigation systems. The proposed method aids in estimating the energy demand over a particular driving route using road surface profiles. It comprises of road elevation information gathered from available digital elevation mapping (DEM) sources for the route. Estimation of the road model for a specialised drive trip involves a piecewise linear approximation technique. The study offers a basic and low-cost feature that can aid in the creation of an eco-routing navigation system for proper prediction of the vehicle's least energy-consuming route. The power consumption is calculated using three-dimensional vehicle dynamics across a path with inherent dips and crests. The tractive effort of a vehicle can be determined using this model, which can be used to estimate energy consumption in EVs. All essential simulations are run in the Matlab-Simulink environment, and results have been discussed. The reported findings show the efficacy of the proposed model in improving the applicability of the eco-routing navigation system. It has already been discussed that road load is the force experienced by a vehicle while traversing at a consistent speed over a smooth, flat road surface from sources such as tyre rolling resistance, driveline losses, and aerodynamic drag [7]. A pure battery EV chassis has been considered for the drive force analysis, which is propelled by two rear wheel traction motors resembling a commercial distributed drivetrain. The principle of vehicle dynamics is then applied in the simulation model. A few assumptions and design considerations have been adopted in the simulation model. The EV is assumed to have a wheelbase of 200 cm, a track width of 150cm, a tyre radius of 33 cm, and a kerb weight of 150kg. Standard values for the co-efficient of aerodynamic drag as well as rolling resistance have been used in the simulations.

The road load model is dependent on a variety of factors. It has already been mentioned that the force on the wheels and also the energy consumption are highly dependent on factors like road grade and speed of the vehicle. Other factors, including the coefficient of drag, vehicle mass, and vehicle frontal area, also affect energy consumption in a less important way .The air density ρ varies with the weather condition, and the rolling resistance coefficient f_r is determined by the weather and road conditions. Hence, it can be observed that these two metrics exhibit variations under diverse driving situations. To realise a low-carbon society, electric vehicles are gathering more momentum. Energy consumption estimation could hence solve driving range issues in EVs. The road load model considers the following prime factors of vehicle dynamics.

i. Speed and acceleration of the EV
ii. Aerodynamic drag, rolling resistance and other frictional forces
iii. Road grade
iv. Crests and dips on the road
v. Vehicle weight

4.4. Road Surface Estimation

This road load model analysis involves the estimation of the road surface as a design consideration. The impact of road surface on the energy consumption of an Ev when in motion has been studied. The factor of road grade has been emphasised here. It has been seen that visibly smooth and flat roads contain some degree of road grade, which majorly affects the energy usage and efficiency of an EV. Most Indian roads have curvatures, which have been classified as crests and dips in this model. When an EV encounters a crest while traversing a path, the centre of gravity shifts towards the rear, and therefore the normal force on the wheels of the rear tyres becomes higher than that of the forward tyres. The reverse occurs when it encounters a dip in the road. In this work, a section of road has been identified for which the road gradient has been obtained using digital elevation mapping sources.

4.4.1. Road gradient measurement

Road gradient can also be referred to as road grade. It is the slope present on a road and is therefore usually measured in degrees. The grade angle can be determined from elevation information for a particular location. The platform of Google Maps has been used. Using the map, the latitudes, longitudes and elevation of different points along a specified route has been obtained. These results have then been processed into Excel files, and sampled at specific intervals to obtain information of road grade of the test patch. The obtained information have then been directly integrated into MATLAB for modelling purposes. The elevation data along a route can be plotted as below. The elevation data from Google has been used to find the road grade along a route.

$$\tan\theta = h/L \tag{31}$$

$$\theta = tan^{-1}\left(\frac{h}{L}\right) \tag{32}$$

where h refers to the elevation height of a particular point and L is the wheel base of the electric vehicle . The value obtained is then used for obtaining the force at the wheels of the EV. The elevation points have been taken at such instances that the distance between any two points is equal to the wheel base of the vehicle. In such cases, accurate modelling of the road can be done.The effective grade present at a particular point on the route is then calculated as

$$\theta_{eff} = tan^{-1}\left(\frac{h_2-h_1}{L}\right) \tag{33}$$

where h_2-h_1 signifies the average elevation at a point which is obtained by correlating it with its previous value.

4.4.2. Sampling of road patch

In this section a road surface grade estimation model has been discussed relying on a geometrical approximation model with the help of Digital Elevation Mapping

(DEM) data. Grading resistance takes into account the weight of the vehicle on various dips and crests of a road surface. The component of the vehicle weight during an upward and downward slope can be determined using equation (34). Here θ is the grade (slope) angle of the road,

$$F_{grade} = Mg\ Sin\theta \tag{34}$$

A piecewise linear approximation method is used over a particular road surface to precisely estimate the entyre road terrain. This has been accomplished by continuously evaluating the successive road elevation data obtained from DEM along a predefined road trajectory. A suitable distance *d* is chosen in the interval of every successive piecewise calculation. The distance sample *d* has been considered at every wheel base length *l* of the entyre road trajectory by satisfying the equality or inequality relation expressed in (35) where n refers to the number of samples and e_n elevation data of n^{th} sample.

$$\theta = tan^{-1}\left[\frac{e_n - e_{n-1}}{d}\right], d \leq l \tag{35}$$

Fig. 4.6 demonstrates the method of approximation of the terrain based on elevation data. In this study, elevation data is collected for each sampled point relative to a reference level. In our experiment, the reference level is defined as the ground level of the experimental setup. This has been achieved by substituting the difference between ground level and sea level from the available raw data obtained from DEM. Joining the sampled points with line segments gives the approximated road terrain, which is represented by the red line in Fig. 4.7. The accuracy of the model can be increased by decreasing the value of *d*. However, in our case, the value of *d* is restricted by the wheel base length *l*. Moreover, assuming a vehicle chassis with a smaller *l* can give more accurate results. Despite the absence of steep slopes over an urban or semi-urban road, our analysis shows a significant change in the power requirement of the vehicle. This has been explained in the subsequent section.

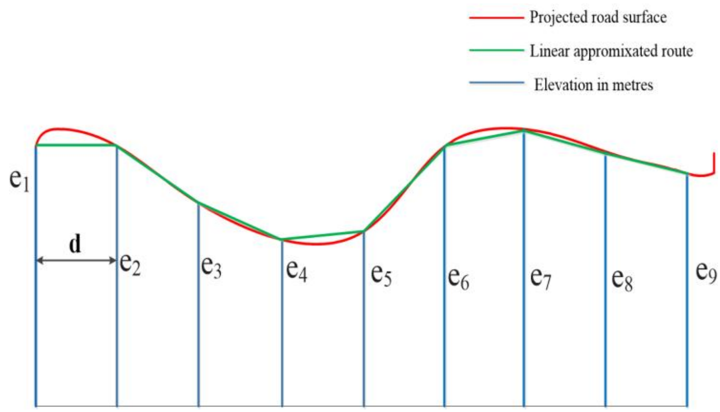

Fig.4.6 Illustration of the road model

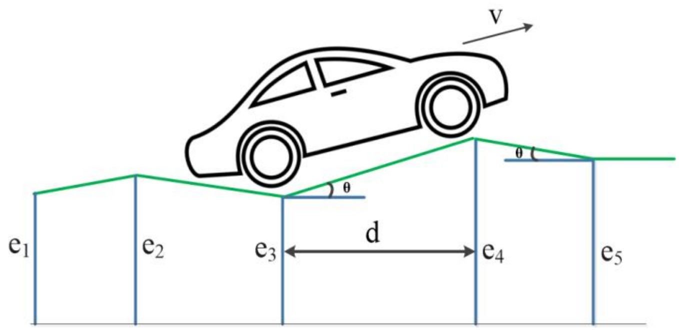

Fig.4.7 Illustration of the different angles on which the vehicle energy demand depends.

4.5. Calculations involved

The force experienced on each of its wheel by an EV varies with the route its traverses.The force required includes various factors like the surface of the road, road grade, the weight of the vehicle, the speed the vehicle is traversing with among others. The following model equations help find the tractive effort baaed on road load or road information data [22, 23]. The tractive effort of the vehicle is a combination of all these forces. It can be mathematically expressed as

$$F_{total} = \sum(F_r, F_{grade}, F_{drag}, F_a) \quad (36)$$

Here, F_r is the rolling resistance force, F_{grade} represents the road grade related force, F_{drag} is the aerodynamic drag force and F_a indicates the acceleration force. Fig. 4.8 illustrates the different forces acting on a vehicle on an inclined road.

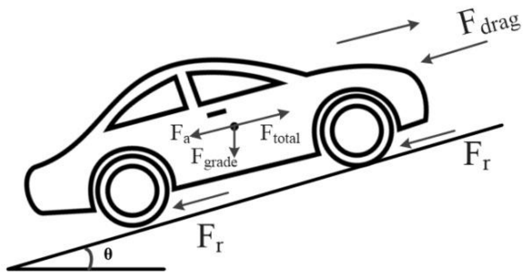

Fig.4.8 Forces experienced by the vehicle during acceleration over an inclined road

The rolling resistance force depends on pressure and type of the tyre and the driven road surface which can be expressed by equation(37).

$$F_r = M * g * \mu \tag{37}$$

where µ is the co-efficient of rolling resistance that varies with the wheel-road contact surface.The grade resistance force, F_{grade} depend entyrely on the road grade angle of the surface which can be given by (38)

$$F_{grade} = M * g * Sin\theta \tag{38}$$

The force necessary to overcome the resistance through air is called drag-force which constitutes of aerodynamic drag force experienced by the vehicle. This force can be represented as

$$F_{drag} = \frac{1}{2}\rho_a C_d A_{frontal} (v \pm v_{wind})^2 \tag{39}$$

where ρ_a is the air mass density, C_d represents aerodynamic drag coefficient, $A_{frontal}$ indicates the frontal area of the vehicle, v is the vehicle speed and V_{wind} is the wind speed .The acceleration force F_a can be expressed by (40), where M is vehicle mass, V_{max} indicates maximum velocity and t_a represents time required achieving maximum speed of the vehicle.

$$F_a = M * \frac{V_{max}}{t_a} \tag{40}$$

The total force acting on the vehicle using (37) to (40) can be summarized in (41) as

$$F_{total} = \sum \left\{ M * \{\frac{V_{max}}{t_a}, g(\mu + \theta)\}, \frac{1}{2} \rho_a C_d A_{frontal} \, (v \pm v_{wind})^2 \right\} \quad (41)$$

The power required to move the vehicle at a specific velocity v can be calculated by using the following equation

$$P = v * F_{total} \quad (42)$$

It is obvious that the power calculation in (42) depends on several dependent factors such as rolling friction coefficient, aerodynamic drag coefficient, road grade angle and mechanics of the vehicle. Out of all the factors, the road grade is seen as a predominant factor which is responsible for significant power consumption of a motor driven vehicle. Consequently, the determination of the vehicle's energy usage is contingent upon the availability of accurate road surface data. Therefore, the accurate estimate of range computation remains incomplete unless the constant impact of road slope is considered. Hence, this study aims to construct a straightforward and efficient road surface estimation algorithm utilising authentic road elevation data for a specific driving excursion. The implementation of an eco-routing navigation system (ERNS) enhances its overall efficacy. Fig. 4.9 illustrates the various constituents of force exerted on an electric vehicle (EV) during its ascent on an incline.The fundamental equations governing the force exerted on the front wheel of a vehicle when it is stationary on an incline are represented as:

$$aF_f + mgSin\theta.h = mgCos\theta.h$$

$$\therefore 2F_f = mgCos\theta \left(\frac{a_1}{a}\right) - mgSin\theta \left(\frac{h}{a}\right) \quad (43)$$

Where a is the total wheel base of the EV, θ is the grade angle present and h is the height of the vehicle. A factor of two has been added to the force because it comprises of the force under both the front wheels. Similarly, force on the rear wheel is denoted as:

$$aF_r - mgSin\theta.h = mgCos\theta.h$$

$$\therefore 2F_r = mgCos\theta \left(\frac{a_2}{a}\right) + mgSin\theta \left(\frac{h}{a}\right) \quad (44)$$

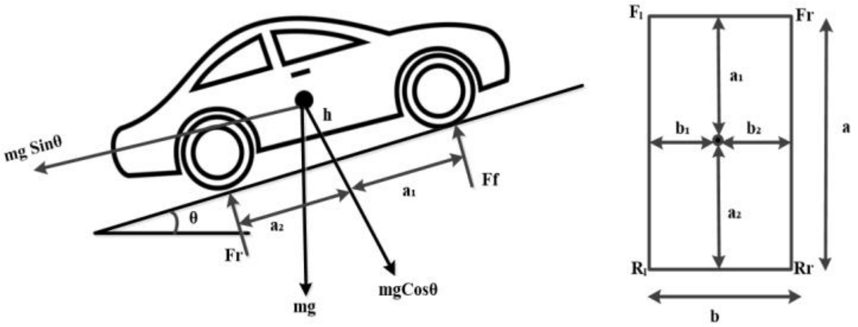

Fig.4.9 Direction of different force components acting on a vehicle

Inclusion of the trackwidth measurements lead to another component being added to the force.Considering all the four wheels of a rear wheel driven electric vehicle, the force on the wheels of an EV when the vehicle is travelling uphill is given by:

$$F_{Fl} = mgCos\theta\left(\frac{a_1}{a}\right)\left(\frac{b_2}{b}\right) - mgSin\theta\left(\frac{h}{a}\right) \quad (45) \quad \text{(Front left wheel)}$$

$$F_{Fr} = mgCos\theta\left(\frac{a_1}{a}\right)\left(\frac{b_1}{b}\right) - mgSin\theta\left(\frac{h}{a}\right) \quad (46) \quad \text{(Front right wheel)}$$

$$F_{Rl} = mgCos\theta\left(\frac{a_2}{a}\right)\left(\frac{b_2}{b}\right) + mgSin\theta\left(\frac{h}{a}\right) \quad (47) \quad \text{(Rear left wheel)}$$

$$F_{Rr} = mgCos\theta\left(\frac{a_2}{a}\right)\left(\frac{b_1}{b}\right) + mgSin\theta\left(\frac{h}{a}\right) \quad (48) \quad \text{(Rear right wheel)}$$

Here, θ is the road grade angle, whose effect comes into consideration when the vehicle is travelling uphill or downhill. On a level road, the road grade is absent and hence θ equals zero. Also, a is the total wheel base of the EV whereas b refers to the track width of the vehicle. From the aforementioned analysis, it has been seen that both the grading resistance and the rolling resistance are dependent on the normal force acting on each driving wheel. The effect of road grade on the normal force can be defined by the three-dimensional vehicle dynamics at the dip and crest of the road surface. Equation (11) and (12) explains the normal force acting on the rear wheel when the vehicle experiences a crest as well as a dip during the drive trip [12]. Since the EV which is taken as the base model for the simulation, is considered a rear wheel driven vehicle, more focus has been given for estimation of the normal force under the wheels of the rear tyres. Due to the curvatures present in the road, a value for the radius of curvature of the road has also been assumed in the simulations. The force under the wheels is a measure of the tractive effort, which has then been used to calculate the instantaneous power of the vehicle during a specified trip.

$$F_{rear\_left\_crest} = F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}\frac{b_2}{b}Cos\theta - \frac{h}{l}Sin\theta\right) + \frac{1}{2}ma\frac{h}{l} - \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l}\frac{b_2}{b} \tag{49}$$

$$F_{rear\_right\_crest} = F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}\frac{b_1}{b}Cos\theta - \frac{h}{l}Sin\theta\right) + \frac{1}{2}ma\frac{h}{l} - \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l}\frac{b_1}{b} \tag{50}$$

$$F_{rear\_left\_dip} = F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}\frac{b_2}{b}Cos\theta - \frac{h}{l}Sin\theta\right) + \frac{1}{2}ma\frac{h}{l} + \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l}\frac{b_2}{b} \tag{51}$$

$$F_{rear\_right\_dip} = F_{z2} = F_r = \frac{1}{2}mg\left(\frac{a_1}{l}\frac{b_1}{b}Cos\theta - \frac{h}{l}Sin\theta\right) + \frac{1}{2}ma\frac{h}{l} + \frac{1}{2}m\frac{v^2}{R_h}\frac{a_1}{l}\frac{b_1}{b} \tag{52}$$

4.6. Results and discussion

The road load model and surface grade estimation are examined in a Matlab-Simulink environment with the necessary constraints and with the proposed vehicle geometry. The DEM source data considered for the analysis covers a specific route, as shown in Fig. 4.10. A route of length around 500 m in length has been chosen as the test route. Although flat to the eye, the elevation data proves that there is a slight amount of varying gradient in the road, and the slope factor cannot be ignored while calculating the energy consumption. After acquiring the data from digital sources, it has been processed to obtain sample points at an interval of approximately 2 metres, which is equivalent to the wheelbase of the EV. This sampling helps in the linear approximation technique, as the vehicle can be considered to be on a linear length of road at any instant of time. At every instant, the road gradient is analysed and classified as a zero gradient, a positive gradient, or a negative gradient. A positive grade involves formulations for an EV travelling through an uphill crest, whereas a negative slope includes equations for an EV traversing through a dip on an uphill path. The variation of elevation data collected for the designated path has been shown in Fig. 4.11. It depicts the sea level elevation data. It can be observed that the points are not in a straight line, thereby hinting at the presence of grade in that section of road. The highest point is around 74.5 metres, and the lowest is 72 metres. To obtain the ground level elevation data, the altitude of Tezpur has been subtracted, which is around 48 metres.

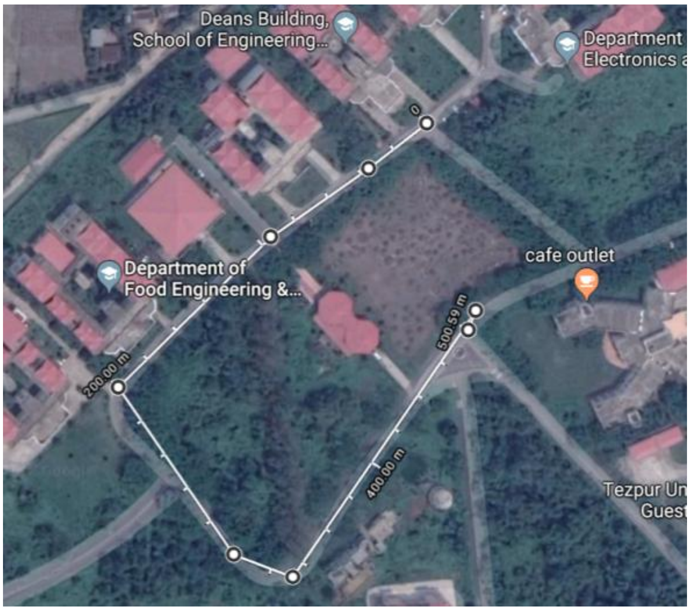

Fig.4.10 Bird eye view of the selected route taken from Google maps[24]

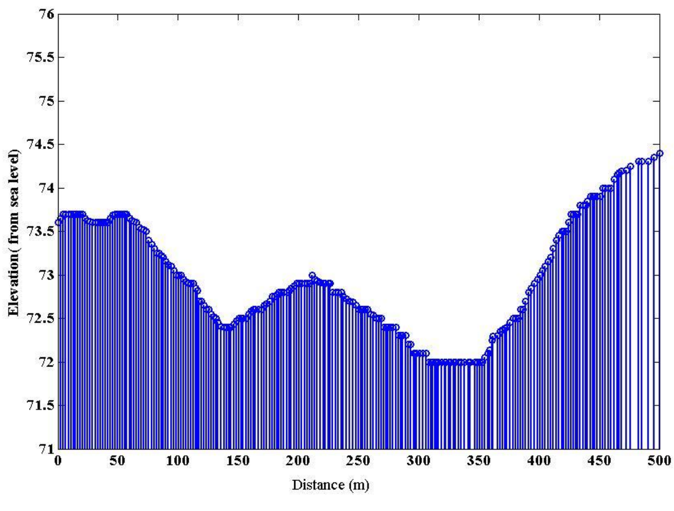

Fig.4.11 Elevation data (from sea level) obtained from DEM sources

Literature has shown that the range of an electric vehicle decreases exponentially with even a slight degree of increase in the grade angle. This has been showcased in Fig. 4.12. The figure shows that if an EV traversing on a flat road with a zero grade angle at a constant speed has a range of 80 km, an increase in the slope of the road causes its range to decline almost exponentially. A slope of around 2 degrees reduces the range of the vehicle to approximately 45 km. This has been experimented with by simulating a similar basic EV model in Simulink, which uses the aforementioned chassis geometry as well as road grade information.

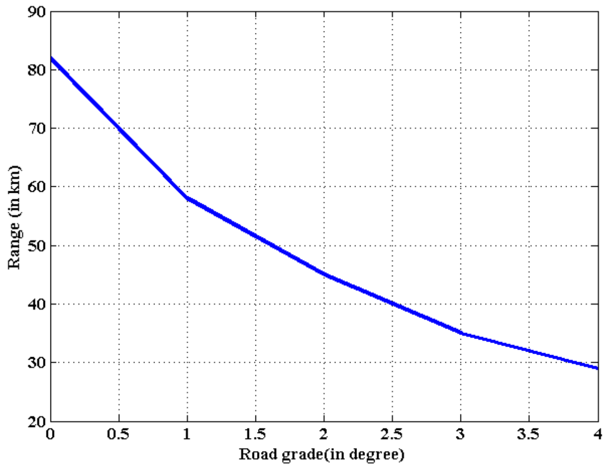

Fig.4. 12 Variation of road grade with respect to range of an EV

The variation of grade angle along the test range was simulated using equation (30) and displayed in Fig. 4.13 with various dips and crests encountered by the vehicle along its route. This depicts the modelled road for the selected test range. With the help of the estimated road model, the total driving force experienced by each wheel has been calculated. Fig. 4.14 depicts the driving force acting on one rear wheel of the proposed EV model. Since the EV model geometry is considered independent rear-wheel drive, the normal force acting on both wheels will be almost similar. Several assumptions have been accepted in order to simplify the calculation and improve the real-time performance of the proposed simulation model. To begin with, it is well acknowledged that the drive motors exhibit almost identical torque-speed characteristics. Furthermore, it has been postulated that the drive line components of an automobile, including motors, batteries, and control circuits, are distributed in a manner that ensures the centre of gravity is symmetrically positioned with respect to the longitudinal and lateral centre planes of the vehicle. Subsequently, on a typical urban driving condition over a fair concrete road surface, the rolling resistance and coefficient of drag are constant over the stretch of test road.

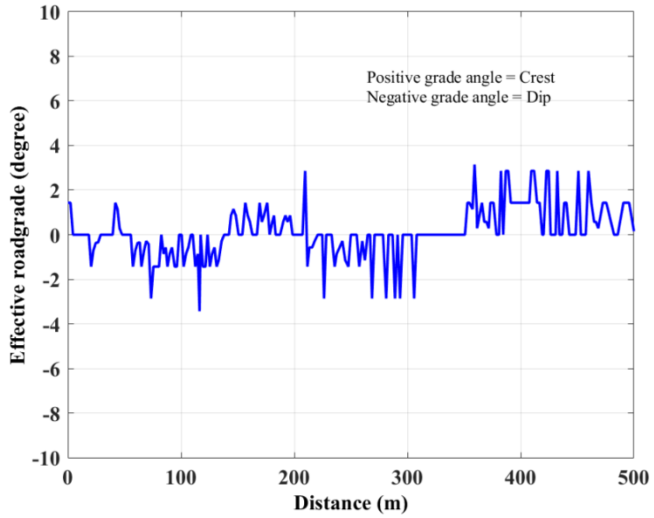

Fig.4.13 Variation of road grade angle along a specified path (test route)

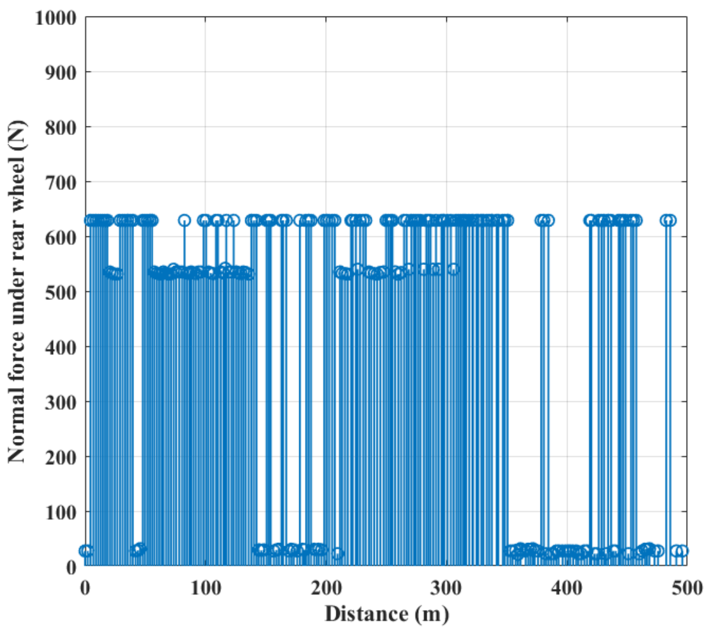

Fig.4.14 Force acting under one of the rear wheels at specified instances along a trip

The normal force under the front wheels along the test route has also been illustrated in Fig. 4.15. It can be clearly seen that the maximum force on one of the wheels is around 600 N.The instantaneous can be seen to be changing every instant. The variation in change in force during the test run is in accordance with the road grade along the test road patch. The force on the front wheels is less than that on the rear wheels because of vehicle geometry considerations. When the EV encounters a crest, the force on the rear wheel is greater than that on the front wheels. A comparison of the normal force under the front and rear tyres has been depicted in Fig.4.16. It can be observed that the forces under the tyres are almost opposite each other. This is because the road has been considered to have a gradient. The uphill causes an increase in the force under the rear wheel while it decreases under the front wheel.

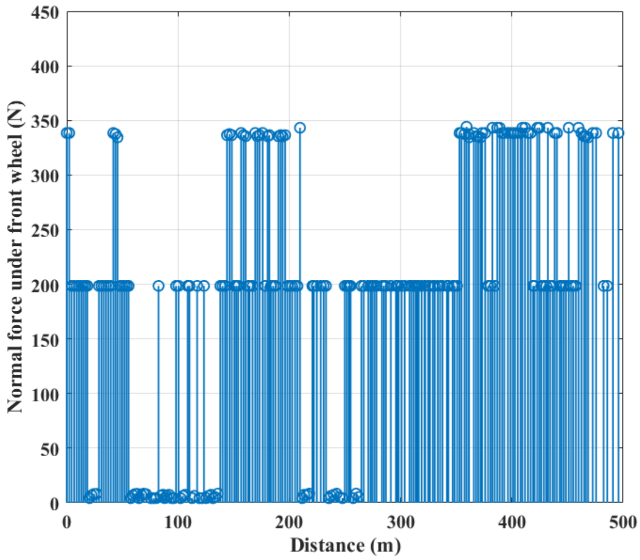

Fig.4.15 Normal force acting under one of the front wheels at specified instances along a trip

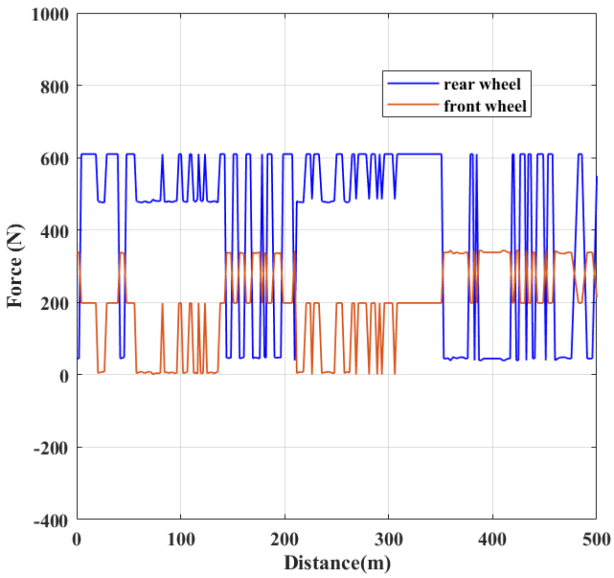

Fig.4.16 Comparison of force acting under the front as well as rear wheel

The instantaneous power requirement of the EV during the selected route is shown in Fig. 4.17. It can be observed that the 150kg EV requires an average of around 6 kW of power to complete the test route. This power can eventually be used to calculate the energy consumption of an electric vehicle and its driving range. There are various other modifications and experiments that can be done to the model. Vehicle speed has been considered a parameter in the simulation of this model. The driving cycle, which is a function of speed and time, has been analysed. There are three common driving cycles that have been discussed: the US cycle,the European cycle, and the Delhi bus drive cycle. Figures 4.18 and Fig. 4.19 have been based on the force output at the wheels when different drive cycles are used.

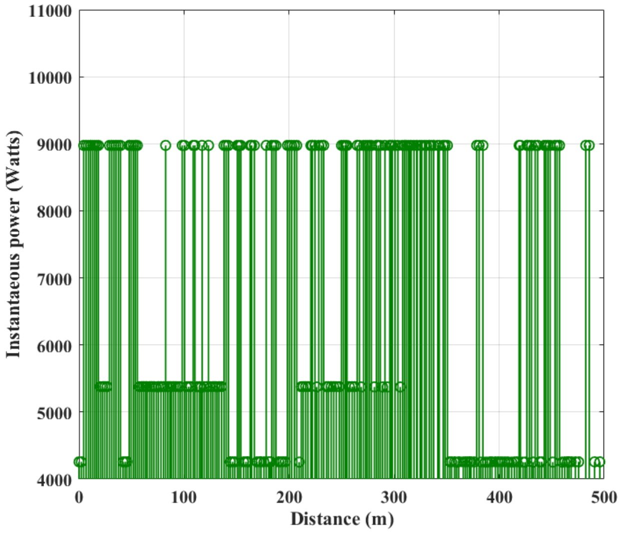

Fig.4.17 The power required by the vehicle during the test trip

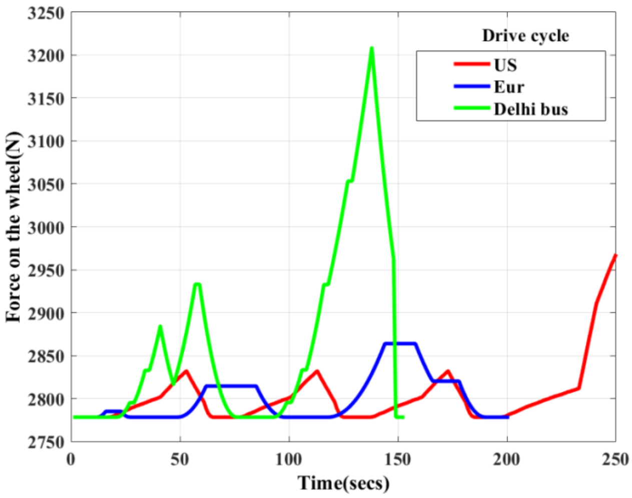

Fig.4.18 Force under the wheels when different driving cycles are used

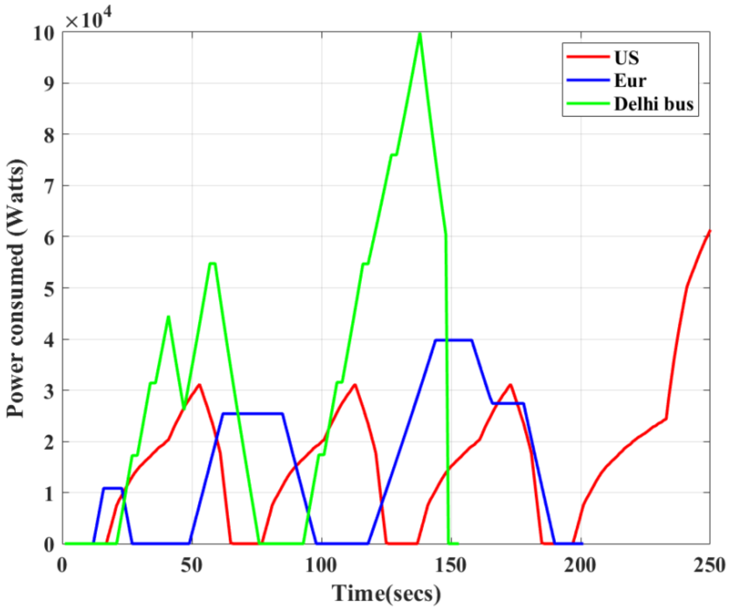

Fig.4.19 Power requirement when different driving cycles are used

It can be seen from Fig.4.18 that speed is a major factor which affects energy consumption in EVs. The simulations for different drive cycles are performed by varying only the speed and keeping the rest of the factors constant. A constant roadgrade factor has been assumed for these simulations. The three driving cycles have varying impacts on the normal force under the wheels and the tractive effort of the vehicle. The Delhi bus cycle has the highest speed and therefore the maximum energy consumption. For instance, using that cycle, the peak force under the wheels shoots to around 3000 N at a specific instant, though the average force is lower. The power consumption, as shown in Fig. 4.19 is also seen to be higher in the Delhi bus cycles as compared to the other driving cycles.

4.7. Conclusion

A comprehensive road load model is can be considered to be for the precise energy consumption estimation in an EV. There are various factors responsible for the energy consumed during a trip which have been identified and used in this model. This work presents an analysis of the road load model which is a prime constituent when developing eco-routing navigation systems for EV. The actual road grade angles of a selected route were obtained from the DEM source data. Accordingly, a road surface estimation model was proposed. The model helps determine the traction effort as well as the normal force required under each wheel. The effects of a few factors like speed and road grade have been studied. The simulation results also validate the importance of grade angle for determining vehicle energy demand. The model developed incorporates elevation data based on Google elevation advanced programming system and other factors from standard sources. The reliability of these data is untested, and hence the effectiveness of this model has been validated by the physical collection of data discussed in later chapters. Thus, it can be concluded that consideration of grade angle must be an integral part of any road model necessary for the development of a competent eco routing system. It can be concluded that consideration of road surface behaviour must be an integral part of any road load model for an effective eco-routing navigation system. This model has been further used on a test electric vehicle for energy demand estimation as well as the determination of an eco-route.

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