An experimental study on effect of rolling resistance of different types of road surfaces on energy consumption in two wheelers and its emission characteristics

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Declaration of originality and compliance of academic ethics

I, Avirup Naskar, hereby declare that this thesis contains original research work done by me as a part of my Master of Technology in Energy Science and Technology course during academic session 2021-2022.

All information and data in this document have been obtained and presented according to academic rules and all ethical conduct.

I also declare that I have cited and referred to all material and results that are not original to this thesis work.

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To whom it may concern

This is to certify that Avirup Naskar, bearing registration number 119527 of 2012-2013, examination roll number M4ENR22014, a bonafide student of School of Energy Studies, Jadavpur University has done a thesis under my supervision, titled "An experimental study on effect of rolling resistance of different types of road surfaces on energy consumption in two wheelers and its emission characteristics". The thesis is approved for submission towards partial fulfillment of the requirements for the degree of Master of Technology in Energy Science and Technology, Jadavpur University for the session 2021-22.

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The thesis is hereby approved as a creditable study of an interdisciplinary subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve this thesis only for the purpose for which it is submitted.

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Contents

List of figures

List of tables

Abstract

Rolling resistance is the force acting on a vehicle over a full journey. It is generated by the hysteresis of tires and pavement. A characteristic of a deformable material such that the energy of deformation is greater than the energy of recovery. The rubber compound in a tire exhibits hysteresis. As the tire rotates under the weight of the vehicle, it experiences repeated cycles ofdeformation and recovery, and it dissipates the hysteresis energy loss as heat. Hysteresis is the main cause of energy loss associated with rolling resistance and is attributed to the viscoelastic characteristics of the rubber. Materials that have a large hysteresis effect, such as rubber, which bounce back slowly, exhibit more rolling resistance than materials with a small hysteresis effect that bounce back more quickly and more completely, i.e., steel or silica. This study investigates how much energy is saved if we change the road surface type and what number of pollutants emit from vehicles over different types of pavements. Hard and smooth surfaces produce lower rolling resistance than soft and rough surfaces. Rolling resistance is affected by both tire and ambient temperature. Rolling resistance coefficient (RRC) is one of the basic resistance parameters when moving objects are being considered. In case of objects not equipped with a motor-driven wheels and suspension system, mobile machinery chopper, shelving and warehouse trucks all resistances are overcome by the muscle strength of the operator. Research is carried out to limit this phenomenon, however, there is a lack of methods for measuring this parameter in the real operating conditions of devices with a wheels and suspension system without a drive unit. Rolling resistance results from the energy dissipated by a tire rolling on a road surface. Accurate estimation of rolling resistance is important from an economical and environmental point of view considering theimpact on vehicle fuel consumption. Until now, environmental assessment only focused on construction and maintenance works whereas recent studies showed that use phase can represent up to 90% of the global energy demand of a road project. Thus, it is possible to diminish the environmental impact of a road project by changing the pavement surface characteristics with a boundary condition related to friction and safety. For on-road two-wheeler vehicle, this investigation had been done and the results shows how much concrete roads are fuel and cost efficient but we cannot use it for long run as it requires more rehabilitation time, and cost. This study aims to find an optimal solution for this type of problem which includes fuel consumption and emission parameters.

Chapter 1: Introduction

Transportation paves the way for developing an area or region. Road transport is one of the most major sections for nation building and country's economic progress. The demand for infrastructure augmentation increases with the region's pursuit of development goals. With the increase in economic activities, the dependence of fossil fuel-based energy sources and consequent greenhouse gas (GHG) emissions have increased rapidly in recent times.

Energy consumption also varies with the modes of transport and the public transport system has the least average energy consumption per passenger kilometer [1]. The urban population of India, which constitutes 28% of the total, is predominantly dependent on road transport. Around 80% of passenger and 60% of freight movement depend on road transport (MoF, 2000). Traffic composition of six mega cities of India (Delhi, Mumbai, Bangalore, Hyderabad, Chennai and Kolkata) shows that there is significant shift from the share of slow-moving vehicles to fast moving vehicles and public transport to private transport [1]. Among different types of motor vehicles, the percentage of two wheelers has shown rapid growth (doubling in every 5 years) and it constitutes 70% of total motor vehicles of India (MoSRTH, 2004). Total number of road vehicles in India as per the latest available statistics (March, 2004) were 72.7 million (MoSRTH, 2007a). Indian railways have an important role for long journey movement of both people and freight. In the last ten years, there has been a sharp increase in the number of passenger and goods movement and consequent fuel consumption. Current energy consumption in railways is around 5.1% of total transport energy with about 77.5% from diesel and balance is through electricity [1]. During 2004–2005, Indian civil aviation accounted for more than 24% increase in the number of international and domestic flights, with a consequent increase of aviation fuel from 0.98 million tons (MT) (1976–1977) to 6.2 MT in 2005–2006. Shipping sector has aided in the movement of about 18 MT of cargo [1]. Road transport has been a major consumer of liquid fuel mainly in the form of diesel, petrol, and gas. The indigenous production of crude oil being insufficient to meet the demand, the country has to import about 80% (ToI, 31.1.2011) of its total consumption. GoI subsidizes (Rs. 43580 crores as per the Union Budget and Economics of the Ministry of Finance, 2012–2013) petroleum products to alleviate the suffering of the common man. To worsen the matter, consumption of liquid fuel in the transport sector has been increasing rapidly along with increase in population and industrialization. The continuous increase in the price of fuel, gradually depleting sources of natural reserves and increasing pollution level have added to the concerns of the country. If the use of conventional liquid fuel in the passenger road transport sector can be reduced or substituted by a nonconventional energy source, then a considerable amount of foreign exchange can be saved, making a positive impact[2]. Economic growth is marked by an inevitable increase in transportation activities of any region. In India, the road share of passenger mobility increased from 35% in 1950-1951 to 87% in 2000-2001.

Road transport sector has been a major consumer of fossil fuel in the form of liquid petroleum and gas and the majority of this energy demand needs to be imported. The economic growth in India has been marked by the preference of privatized and paratransit mode of transport by the passengers, the mobility share of which increased from 16.2% in 1990-1991 to 21.2% in 2000-2001, respectively, whereas the share of both buses and railways declined during this period [3]. The major increase in the per capita mobility in road transportation has been observed in case of auto-rickshaws by 130%. Among the private and paratransit modes of passenger transportation, the three-wheeled vehicles play the most important role in ferrying passengers. This sector consists of both motorized and non-motorized modes. The motorized forms consist of vehicles that are either powered by IC (internal combustion) engines or by electric motors. The volume of traffic on roads increases at the rate of 12% per annum. Capacity augmentation and improvement in the level of service is normally achieved by widening existing roads [4].

The total length of National Highways is about 55000 km out of which 66% comprises two-lane facilities with varying lane widths. The national and state highways together account for about 10% of the total road length but carry 70% of the road traffic. One third of this length is still two-lanes wide. The lane width varies from 2.75 m to more than 5 m. However, due to the growing use of automobiles and its many externalities, the analysis of mixed traffic has always attracted the attention of researchers from all over the world [5].

Prediction and knowledge of capacity are fundamental in the design, planning, operation, and layout of road sections. Among other things, these provide the basis for determining the lane width and number of lanes to be provided at any point in a road network with respect to the volume and composition of traffic. They are valuable tools for the evaluation of the investments needed for future road construction and improvements, and for determining priorities between the competing projects. Apart from other parameters, capacity is greatly influenced by roadway and driver conditions. The effect of lane width or total width of the carriageway as the lane concept is not strictly followed in India and vehicles tend to move abreast. The term carriageway or roadway is used in India for the total width of paved surface of a road excluding its shoulders on the capacity of a two-lane road under mixed traffic conditions [4-5]. Since its beginning over 100 years ago, to present day, on-road transport contributions to GHG emissions have been steadily rising, such that today these emissions, along with diminishing air quality, represent a serious problem not only for the largest cities but for the global environment [6]. The transport sector is responsible for emitting 7737.8 million tons of carbon dioxide equivalent (CO_{2eq}). 24% of GHG worldwide emissions, of which 5792 million tons comes from on-road transport (IEA, 2017). This problem is caused by strong dependence on cars in the largest cities and the historical absence of sustainable mobility proposals. Some measures have been taken since the Kyoto Protocol agreement (1992), which were intensely reinforced during the Paris Climate Conference (2015), to reduce emissions. However, the demand for transport has continued to grow for the principal reason that more passengers and freight loads are traveling because of population growth, production and consumption [8]. The growth of consumption in commodities and services has increased a set of activities related to progress and social welfare that play a major role in the metabolism of cities. Control and reduction of emissions in the housing, transport and logistics sectors [10] must be prioritized by policymakers to coordinate all these activities to reduce energy consumption at the minimum cost [29]. The aim is to minimize effects on climate change, air pollution and traffic congestion [15,13,19] without sacrificing drivability or pedestrian protection. This is not easy, because progressive world population growth (in 2015 the population was 7.35 billion and will be 9.157 by 2040), can be quickly translated to mean higher energy requirements for sustaining enhanced living standards [16,18].

1.1 Rolling Resistance

As the costs of energy resources continue to rise due to increases in demand, and the public is becoming more environmentally conscientious, and the interest in improving vehicle fuel economy has increased. While numerous factors i.e., vehicle aerodynamics and engine efficiency influence overall energy efficiency, one mechanism that dissipates energy inefficiently is in the contact between the tire and the pavement. This loss is often quantified by the rolling resistance, and it is also affected by the properties of the road pavement. The main objective of this work was to objectively investigate the influence of different pavement type (i.e., mastic asphalt, bituminous and concrete) on the rolling resistance of vehicle tires by reviewing existing literature.

Rolling resistance is the force required to keep an object such as a wheel or tire moving. At a constant speed, the rolling resistance force is equal to the traction force between the road and tire. The torque turning the tire then balances with the moment or torque created by the traction force. Forces contributing to the rolling resistance include friction losses at the rolling interface due to slip, friction in the bearings (internal), aerodynamic drag (there is not universal consensus that this should be considered part of rolling resistance), and hysteretic losses due to deformation of the rubber. An ideal rigid cylinder or wheel rolling with no slip against a perfectly smooth, level and rigid surface would have no rolling resistance. It is neither equivalent nor proportional to the friction between the tire and the road. Rather, rolling resistance is due primarily to hysteretic losses from deformations induced on the wheel or tire by the pavement. The hysteretic losses are due to the fluctuating stresses and strains induced in the tire during rolling as the tread comes in and out of contact. Some losses can occur due to deformation of pavement surfaces but are generally negligible except for unbound roadway surfaces. Rolling resistance is sometimes referred to as rolling friction, but this is not the same physical mechanism as sliding or solid against solid friction. The rolling resistance coefficient (RRC) is determined by dividing rolling resistance force by normal load (the force perpendicular to the surface on which the tire is rolling). The force is also known as rolling friction or rolling drag. It is mainly caused by nonelastic effects; that is, not all the energy needed for deformation (or movement) of the wheel, roadbed, etc. is recovered when the pressure is removed. Two forms of this are hysteresis losses, and permanent (plastic) deformation of the object or the surface (e.g., soil). Another cause of rolling resistance lies in the slippage between the wheel and the surface, which dissipates energy. Only the last of these effects involve friction, therefore the name rolling friction is to an extent a misnomer. In the broader sense, specific rolling resistance (for vehicles) is the force per unit vehicle weight required to move the vehicle on level ground at a constant slow speed where aerodynamic drag (air resistance) is insignificant and also where there are no traction (motor) forces or brakes applied. In other words, the vehicle would be coasting if it were not for the force to maintain constant speed. Dependency between RRC and temperature can be found, i.e., RRC values were reduced if the tire had a higher temperature.

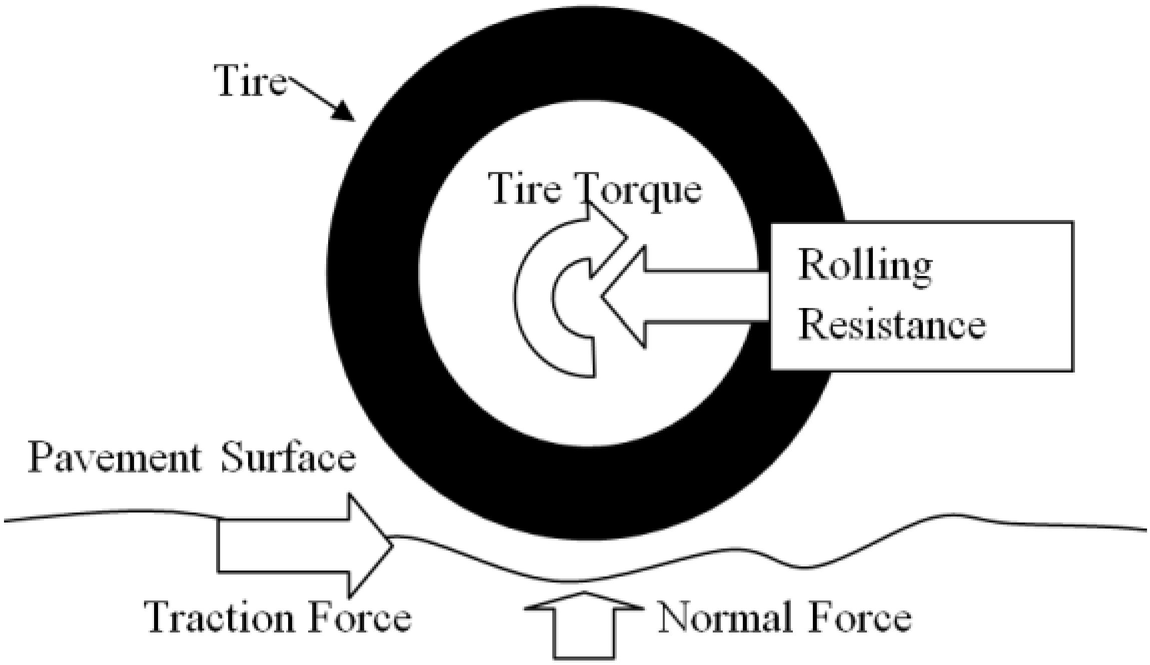

Figure 1: Schematic diagram of the forces affecting on a tire interacting with road

Factors that affect the rolling resistance include air drag, properties and material composition of the wheel or tire, the tire's geometry, the road material composition, and the roughness of both the tire and the road. Most research on rolling resistance tends to explore these factors independently, which diminishes the understanding of the relative magnitudes of the effects associated with each factor. Rolling resistance studies are affected by other experimental variables such as air temperature, vehicle speed, and tire-inflation pressure. The hysteresis phenomena can be observed when a rubber compound undergoes repeated strain. A rolling tire deforms when it contacts the pavement surface and recovers when it leaves the contact area.

Road surface texture, stiffness and temperature need to be considered in the rolling resistance calculation or simulation as they have a quantifiable influence on rolling resistance. A characteristic of a deformable material i.e., the energy of deformation is greater than the energy of recovery. The rubber compound in a tire exhibits hysteresis. As the tire rotates under the weight of the vehicle, it experiences repeated cycles of deformation and recovery, and it dissipates the hysteresis energy loss as heat. Hysteresis is the main cause of energy loss associated with rolling resistance and is attributed to the visco-elastic characteristics of the rubber. If two equal cylinders are pressed together then the contact surface is flat. In the absence of surface friction, contact stresses are normal (i.e., perpendicular) to the contact surface. Consider a particle that enters the contact area at the right side, travels through the contact patch and leaves at the left side. Initially its vertical deformation is increasing, which is resisted by the hysteresis effect. Therefore, an additional pressure is generated to avoid interpenetration of the two surfaces. Later, its vertical deformation is decreasing. This is again resisted by the hysteresis effect. In this case, this decreases pressure that is needed to keep the two bodies separate. The resulting pressure distribution is asymmetrical and is shifted to the right. The line of action of the (aggregate) vertical no longer passes through the centers of the cylinders. This means that a moment occurs that tends to retard the rolling motion. Materials that have a large hysteresis effect, i.e., rubber, which bounce back slowly, exhibit more rolling resistance than materials with a small hysteresis effect that bounce back more quickly and more completely, i.e. steel or silica. Low rolling resistance tires typically incorporate silica in place of carbon black in their tread compounds to reduce low-frequency hysteresis without affecting traction. Like the fuel consumption, rolling resistance also has a significant relationship with velocity. Rolling resistance is affected by both tire and ambient temperature. The temperature of the tyre will be presented first then followed up by ambient temperature. Since a warmed tire becomes soft and thus, less energy is needed to deform the tire, which means less energy is consumed in the rolling process. There would also be reduced stress concentration at tyre-pavement contacts and therefore less pavement deformation. Rolling resistance varies between different pavement surfaces. Hard and smooth surfaces produce lower rolling resistance than soft and rough surfaces. The materials and surface characteristics also affect the rolling resistance.

As the frictional characteristics of a pavement surface are influenced by pavement texture (Thom, 2008), pavement texture influences rolling resistance as well. Descornet (1990) stated a linear relationship between rolling resistance coefficient and texture depth by measuring a reference tire of a trailer. Rolling resistance coefficient increases by 0.002 as the depth of road texture increases by 1mm. Other minor factors affecting rolling resistance are wheel radius, vehicle forward speed, surface adhesion, micro relative sliding etc. The replacement of some carbon black with higher-priced silica–silage is one common way of reducing rolling resistance. Rolling resistance in tires is related to the flex of sidewalls and the contact area of the tire. Lower pressure in tires results in more flexing of sidewalls and higher rolling resistance. This energy conversion in the sidewalls increases resistance and can also lead to overheating. With both solid and pneumatic tires, rolling resistance has been found to decrease as temperature increases (within a range of temperatures: i.e., there is an upper limit to this effect). For a rise in temperature from 30°C to 70°C the rolling resistance decreased by 20-25%. In tires, tread thickness and shape has much to do with rolling resistance. The thicker and more contoured the tread, the higher the rolling resistance.

Chapter 2: Literature review

The purpose of the literature review presented here is twofold: first, this provides evidence of a knowledge gap that justifies the need for this work; and second, it also provides support for the methodology used in the study and is a source of information for comparison, triangulation and referencing. Given the above purpose, we use the literature to show the limitations of existing studies by focusing mainly on studies that relied on transport energy simulation and emission strategies. In India, the total number of registered motor vehicles was 141.8 million by the end of the fiscal year 2010–2011 (Road Transport Year Book 2012). There has been a steady rise in the number of registered motor vehicles at a CAGR (Compound Annual Growth Rate) of 9.9 % for the period 2001–2011. Among the total vehicle population, personalized mode (constituting mainly two wheelers and cars) accounted for more than 80% of the motor vehicle population in the country compared to their share of over 60% in 1951. Preponderance of two-wheelers (72 %) can clearly be observed and is followed by 13.6% of passenger vehicles (including jeeps and taxis). A heterogeneous category which includes three-wheelers [Light Motor Vehicle (LMV)], trailers, tractors, etc., had a share of 9.2%. But unlike the personalized mode, the share of buses in total registered vehicles declined from 11.1% in 1951 to 1.1% in 2011 (Road Transport Year Book 2012). Also, the share of goods vehicles at 5% has shrunk since 1951. This decline in the number of public transports has reflected slow growth of buses in the vehicle population. It has been observed that the contribution of the road transport sector in GDP has reached 4.7 % in 2010–2011, surpassing the previous share of 3.9% as in 2001–2002. The increase in economic activities of the country leads to the increase in the number of transports in restricted areas of metropolitan cities. For example, the share of road vehicles in Kolkata city was about 34 % of that of the total number of registered motor vehicles in the state of West Bengal [1]. Transport sector has been contributing 22% of the total CO_2 emissions worldwide [2]. Thus, there is an urgent requirement for technological advancement to address both the issues of conventional fuel consumption and pollution emission. An efficient way for improvement of fuel consumption by conventional vehicles is to set proper fuel economy standards that should be maintained by the manufacturers before the market penetration of the vehicles [2]. The study has shown that by improving the fuel economy standards for the vehicles in Iran the expected saving of fuel for a span of 5 years was about 3.81 billion liters. Again, the estimated emission reduction was around 7.35 million tons, 2.54, and 1.2 tons for CO2, CO, and NOx, respectively. In case of improving the emission standards, an important role is played by the increase in the number of vehicles. In case of emission standards, the vehicles are manufactured in a way such that they are able to comply with the required standards; however, the importance of the standards is lost within a few years due to the gradual technological advancements and increase in vehicle number [4]. A new standard has to be set after a certain time span. Thus, the use of cleaner energy may help in reducing environmental pollution and also address the issue of checking the use of fossil fuels. Transport sector, in all developing countries, is important, demanding the concentration to be upon energy efficient technologies, such as battery electric vehicles (BEV), alternative fuels, energy efficient designs etc. [2]. The incorporation of BEV in the transport system powered by conventional grid has been suggested by the authors as an alternative to address the pollution reduction issue and is also economically acceptable [4]. The study has shown that for the GHG mitigation program the introduction of BEVs powered by the existing grid has the lowest economic costs whereas the life cycle GHG emission can be reduced by 37% if a system of solar energy powered BEV models is adopted. In [2], the passenger road transport system in Kolkata has been taken into consideration i.e., public transport consisting buses, taxis, and auto-rickshaws (LMV 3 wheelers). By the end of March, 2009, the number of registered buses and taxis plying on the streets of Kolkata has been 6938 and 32826 (Road Transport Year Book 2011), respectively. But in the two-year term, it was observed that, by March end, 2011, the numbers have decreased to 4249 and 30840, respectively. The primary reason behind the decrease in the number of buses and taxis has been the cancellation of vehicles having registrations prior to 1993 (Road Transport Year Book 2012) as per the law enforced by the Government. But the number of buses is likely to increase, as the state Government and private bus owners get through a stalemate over the issue of an increase in bus fare. This demand of hike in fare structure is due to the increase in the price of diesel and also the cost of vehicles and its spare parts. No. of registered auto-rickshaws in the city was 26959 by the month of May, 2012 [2]. Measurement and quantification of GHG from the transport sector is essential for a very fast developing economy like India, in order to design and implement suitable technologies and policies with appropriate mitigation measures. Authors have computed GHG emission per unit area in metro cities by quantifying emission and emission factors [1]. The proposed electric vehicle infrastructure model has potential to check the issues of increasing petroleum-based fuel consumption and pollutants emission. Thus, this model has been considered for other metropolitan cities as well for calculating the electrical energy requirement and the possible environmental impact. The fuel consumption and travel pattern for the vehicles have been considered to be the same as that of the case study. It can be observed from results that by replacing conventional road transport vehicles by BEV, air quality can be improved throughout the country. Such models, if implemented globally, may address the present issue of maintaining air quality as well as reducing the use of fossil fuels. Authors have shown that the electric vehicle infrastructure may be implemented along with the conventional road transport system and it has the potential to be beneficial from both economic and environmental aspects. The study on the conditions of Kolkata has shown that this system can be implemented at a national level. The reduction in the amount of diesel and LPG consumption per day by replacing 2% of the present passenger road transportation mode shows the feasibility of implementing parallel electric vehicle infrastructure. There is a major reduction in emission of pollutants from the transport sector if we can come down in favor of this alternative. The calculations involving some of the major metropolitans in India have clearly reviewed the importance of technological advancement required in the transport sector, to check the fuel economy of the country as well as meeting the pollution standards. Due to the rising competition in the international market, there has been a gradual decline in the price of solar modules. This may certainly reduce the cost of generation of electricity bringing down the operating cost for running the alternate system. However, there has to be a valuable initiative from the side of the Government. This system has the benefits of: (i) reducing the consumption of conventional energy sources, (ii) commercializing the use of renewable energy in a larger context, (iii) reducing the ever-increasing problem of environmental pollution, (iv) reducing the financial burden by checking the quantity of crude oil imports, and (v) earning financial benefits through carbon trading [2]. Chennai, Bangalore, Kolkata, Delhi and Hyderabad are the five major metropolitan cities of India with a large number of industries and play a vital role in the Indian economy. In the case of Mumbai, GDP has increased from 90.2 to 149.9 billion Rs. During 1997–2005, the human population has increased from 10.8 to 11.9 million [1]. These increases have also increased the total passenger travel demand from 32 to 61 billion passenger km. Similar situation prevails in other major metropolitan cities in India. With the increase in economic activities the number of transports is increasing in restricted areas of metropolitan cities. It increases the transportation emission load of Indian cities. The introduction of vehicles with stricter emission control may decrease the overall emissions, but the vehicle population growth rate might neutralize that impact in overall emissions [1]. Number of vehicles in important Indian cities is 40 million, with a share of 38% of the total vehicles of India. Chennai, Bangalore, Kolkata, Delhi and Mumbai with 30.2 million vehicles constitute 61.1% of the total vehicles of important Indian cities and 14% of total vehicles of India [1]. One of the main contributors of emissions in Indian transport is from the road sector. Encouraging the use of efficient public transport in place of private transport will help to reduce the number of vehicles. Introduction of more efficient vehicles and fuels, such as CNG or battery-operated vehicles, will reduce emissions. Various urban policies such as metro railway, transport management and emission control practices will further curtail transport emissions. In India, the number of vehicles and their consequent emissions were different for each state or UT. Therefore, decentralized emission inventories were prepared for the road transport sector in order to design and implement suitable technologies and policies for appropriate GHG mitigation measures. First time an attempt has been made to calculate decentralized or state-wise road transport emission of India, using a number of different categories of vehicles and region-specific mass emission factors and a country level emission were calculated for shipping, railways and aviation, using different types of fuel consumption [1]. The total CO2 emission for Indian transport was 258.10 Tg in 2003–2004. Among all types of transport, road and aviation were the first and second major contributors of air pollution. The road transport sector has contributed 94.5% and 53.3% of total transport emission of CO2 and CO. Aviation has contributed 2.9% and 45.1% of CO2 and CO of total transport emission. Shipping is the most environmentally friendly mode of transport. It has contributed only 0.6% of CO2 emission, while railways have contributed 2.0% and 1.2% of CO2 and CO of total transport emission [2]. The three-wheeled vehicles have an important role in the public transport sector in West Bengal. In [3], the performance of e-rickshaws was studied and compared to other forms of three-wheeled public transport vehicles to check the merits. Due to the use of petroleum-based fuels in the other form of vehicles, there remained the issue of environmental impact due to the public transportation system. In West Bengal, majority of the power supplied to the grid has been based on coal fired thermal power plants. Thus, the charging of the battery for e-rickshaws involves the emission of pollutants at the power plants. The survey has been extended for different types of public road transport vehicles like auto-rickshaws, buses, and AC (air conditioned) buses, for comparison of energy consumption patterns. In passenger transportation, the auto-rickshaws have been mostly utilized for both medium and short distance commutes. Taking into account the driving pattern and technical characteristics, auto-rickshaws have been a good option for vehicle electrification [3]. The average fuel consumption of the auto-rickshaws was found to be around 8.04 liters/day of auto LPG for the scenario of Kolkata [3]. Again, parallel running of both auto-rickshaws and e-rickshaws by replacing a certain percentage of the former by e-rickshaws showed the economic and environmental benefits [3]. But e-rickshaws have already emerged in the road transport sector in West Bengal. The average specific energy consumption of the e-rickshaws has been calculated to be around 53.76 kJ/passenger-km. But the traveling pattern of the auto-rickshaws which shows the maximum speed and acceleration [3], discards the e-rickshaw as the exact counterpart of the auto-rickshaws. The maximum speed condition of the e-rickshaws hinders the pathway of their implementation as a replacement for the auto-rickshaws. Compared to all the forms of motorized three-wheeled vehicles, the e-rickshaws were found to be the most energy efficient among all, and can be considered for exact replacement of the mechanized van-rickshaws from which the e-rickshaws were technically superior. Thus, the e-rickshaws could not be considered as a zero-emission vehicle as the charging relates to the CO_2 emission at the thermal power stations. Coal-fired thermal power stations in India have been reported to emit 1.281 kg of CO_2 per unit of electricity generated [3]. Again, CO_2 emission considering full combustion of LPG (propane base) has been 1.53 kg/liter [5]. Considering combustion of diesel for the two types of three-wheelers the CO_2 emission rate has been considered at 2.71 kg/liter [4]. Thus, the specific CO_2 emission of the motorized three-wheelers for passenger transportation has been calculated and results show that the e-rickshaw has been more efficient than that of the other motorized versions of three-wheelers, whereas the specific CO_2 emission is higher than that of the mechanized van-rickshaws. The present technology of the e-rickshaw needs enhancement for compatibility with the present-day traffic. The designing of the vehicles requires maintaining safety standards for the passengers, thus requiring proper inspection of these vehicles by the right authorities. The number of these e-rickshaws operating in the different regions needs proper regularization and eradication of vehicular conflicts by proper route management between passenger vehicles. E-rickshaws have the potential to reduce the fuel oil consumption for passenger transportation which may lead to both economic and environmental benefits [3]. The effect of lane width is more prominent under mixed traffic conditions when vehicles do not follow one another and tend to move abreast. The study [5] has shown the effect of lane width on the PCU for different categories of vehicles and thereby on the capacity of a two-lane road. It is found that the PCU for a vehicle type increases with increasing lane width. The effect of lane width on the PCU is apparently linear; the slope of linearity depends on the type of vehicle. The capacity of a 7.2 m wide road is estimated to be 2818 PCU/h which is slightly larger than the value specified in [4], but much lower than the value of 3200 PCU/h suggested in [6]. This is attributed to the nature of mixed traffic and the regulatory system on Indian roads. The second-degree equation developed between the capacity and the total width of the carriageway was used to derive the adjustment factors for capacity on substandard lane width [5]. These adjustment factors are lower than those given in [4]. This indicates that the negative effect of mixed traffic is more pronounced on narrow lanes. These results illustrate the importance of widening a lane in congested areas. The first 0.3 m of lane widening from 3.0 to 3.3 m, corresponds to an increase in capacity of about 14% while 0.6 m of lane widening from 3.0 to 3.6 m results in a 24% increase in capacity [5]. The study [11] has yielded updated relationships for time related and distance related congestion factor equations representing time and fuel cost respectively. There have only been some isolated attempts in Canada to measure cost of congestion in specific urban areas which included three main components: delay costs (time wasted under congested conditions), vehicle operational cost (fuel wasted) and an imputed cost for excessive pollution cost due to traffic congestion for passenger vehicles, trucks and city buses [10]. The assessment of congestion costs in this study is mainly based on the estimated amount of time loss of road users due to congested traffic conditions corresponding to HCM levels of-service D, E or F [6]. Congestion study conducted in Australia dealt with the eight Australian capital cities by comparing the business-as-usual scenario with the horizon year projections in 2020 by assessing social costs of congestion for the various Australian metropolitan traffic [7]. The congestion study conducted in London was aimed at the estimation of the economic cost of congestion. It was inferred from study [8] that at very low levels of traffic volume, called ‘free flow’, changes in the number of vehicles would have little effect. But as traffic volume increases, even very small increases or reductions in traffic would have a disproportionately large effect on speed [6]. The approach adopted in the Auckland study [7] was based on modeling of acceleration noise defined as the standard deviation of the accelerations. During periods of high traffic congestion there is a greater variability in speed resulting in higher acceleration noise levels[9]. Once the acceleration noise level is estimated, the impact on fuel consumption and vehicle emissions is determined. The [10] study on congestion cost evaluation emphasized accounting for additional costs incurred due to unreliability as well as loss of mobility and excess emission costs in addition to the direct costs, including loss of time and excess fuel costs accrued to vehicle users [11]. Eventually, the principal categories of congestion cost considered in this study are travel time cost, unreliability cost, VOC, mobility cost and emission cost [8]. It is well understood that the travel time cost plays a significant role in economic analysis in addition to the other VOC components. Hence a rational approach has been adopted to evaluate the time related congestion cost separately for passenger and goods vehicles. The travel time cost for passenger vehicles is obtained by multiplying the travel time per km with the value of time of passengers and average occupancy of the vehicles [6]. At the same time, the travel time cost for goods vehicles is obtained by multiplying the travel time per km with the commodity holding cost of the vehicle. Adopting the above analogy, a linear relationship has been established between travel time costs per km and flow for different road sections [7]. The typical parabolic shape curves have been developed between the fuel consumption and journey speed of the petrol driven small cars, diesel driven big cars, two wheelers and two axle trucks. These fuel consumption curves are compared with the updated steady state condition equations recently developed. From this, the optimum speed for petrol driven small cars, diesel driven big cars, two wheelers and two axle trucks are 58 km/h, 62 km/h, 60 km/h and 74 km/h respectively. The fuel consumption under steady and congested conditions would be the same for speeds in excess of 55 kmph and above in the case of small cars, 60 kmph and above in the case of big cars and two axle trucks, and 45 kmph and above for two wheelers [11]. Suitable relationships were developed between Time Related Congestion Factors and V/C ratio for cars, two wheelers, buses, LCVs, HCVs and MCVs. The congestion factors increase with increase in traffic flow in this case [10]. Typical parabolic curves were developed between the Fuel Related Congestion Factors and Volume-Capacity ratio for petrol driven small cars, diesel driven big cars, two wheelers and two axle trucks. The fuel consumption decreases with increase in V/C ratio till vehicle reaches its optimum speed and increases later on [9]. The congestion equations developed for the assessment of fuel consumption have been validated to check for its accuracy and rationality. This is accomplished by developing a goodness of fit plot between the predicted and observed fuel consumption for different vehicle types. The statistical validity of the above equations can be judged from the high values of R^2, significant t-value, low standard error of the coefficients and low RMSE for all the vehicle types. Finally, the suitability of developed congestion cost equations has been demonstrated by taking a real test section and estimating the effect of congestion on fuel and time cost [8,11]. Hence, it is concluded from [11] study that the developed congestion cost equations can be applied on any carriageway namely four, six and eight lane divided carriageways in order to estimate the loss in fuel and travel time due to congestion. Passenger car unit (PCU) values for a vehicle are not static and vary with traffic volume and composition. Data collected at eight urban arterial roads in India were analyzed to explain the dynamic nature of the PCU factor. All vehicles in the traffic stream were divided into five categories, and simultaneous equations were developed to determine the speed of a vehicle type from information on traffic volume and composition. These equations were used to show the variation in PCU values with traffic volume and composition on a road. The change in PCU values was explained on the basis of the relative interaction of vehicle type in the traffic stream at different volume levels. A proposed range of PCU values for big vehicles was from 1.47 to 1.65 for big cars and for heavy vehicles from 5.51 to 6.54, respectively, when their proportions in the mix remained within an observed range in the field. Similarly, a range of PCU values for motorized three-wheelers of 0.99 to 1.01 and a set of PCU values for motorized two-wheelers of 0.20 to 0.23 were obtained. Accuracy of PCU values estimated through simultaneous equations was checked by comparing the estimated values with those calculated directly from the field data. Statistical testing showed that there was no significant difference between field-estimated and model-predicted PCU values. Further, the speed–volume relationships developed by using two sets of PCU factors yielded the capacity values with a difference of less than 2%; this result indicates the correctness of the methodology in study [12]. Determination of correct PCU values for a vehicle type has always been a challenging task for researchers all over the world. As a result, several methods have been developed in the literature to estimate PCU values for a vehicle in mixed traffic. However, all these methods yield a single set of PCU values to be used for all traffic conditions on a road. The study demonstrates the dynamic nature of the PCU factor on urban arterials. This considers speed and size of the vehicle as prime variables for estimation of PCU factors. Since speed of a vehicle is influenced by both traffic composition and traffic volume on a road, a set of simultaneous equations is developed relating speed with density for categories of individual vehicles [14]. These equations are solved for varying compositions of the traffic stream at fixed values of traffic volume and for varying volume levels at fixed traffic composition. The variation in PCU values for different types of vehicles is demonstrated graphically with traffic volume and traffic composition. It is observed that PCU values for a vehicle increase with the vehicle's own proportion in the traffic stream. This observation is explained on the basis of the relative influence of traffic composition on the speed of a standard vehicle type. An increase in the proportion of a vehicle type will create more heterogeneity in the traffic stream and will result in a larger speed differential between CS and the vehicle type, and hence greater PCU values for the vehicle. The accuracy of the PCU factors derived by using simultaneous equations is shown by collecting field data on one additional section of urban arterial and estimating PCU factors from field data as well as by model PCU values. The two sets of PCU values were found to be quite similar and speed–flow curves developed by using these PCU factors yielded a difference in capacity values of less than 2% [13]. It provides a methodology for estimation of PCU factors from traffic volume data alone. The speed of individual types of vehicles can be estimated from the simultaneous equations developed here. These equations were developed by using the data from eight sections in three major metropolitan cities in India. Traffic composition and volume vary widely on different sections and therefore equations are expected to be quite general in nature and can be used to derive PCUs (or to estimate speed) for different categories of vehicles [13]. However, these equations are only applicable to traffic situations with vehicle categories as observed in these cities. Another contribution of this research is the formulation of dynamic PCU values for different volume and traffic composition. These values can readily be used by field engineers. They will reduce the time and cost of field data collection considerably in situations where speed and volume data are collected manually. Traffic congestion is recognized throughout the world as a growing problem. It is particularly important in Asian countries like India where many cities operate under severely congested traffic conditions on a daily basis due to heterogeneous traffic mix [6]. Congestion is in fact the saturation of road network capacity due to regular or irregular reductions in service quality, exemplified by increased travel times, variation in travel times and interrupted travel. In general, traffic congestion has three principal effects on road users namely increase of travel time required for trips, Vehicle Operating Costs (VOC) and quantum of emissions from vehicles [7]. There are thus strong economic arguments for ameliorating traffic congestion. When the vehicle is moving under congested conditions, it has to undergo many operations like acceleration, deceleration, gear changes, brake applications etc. Maneuvering on congested roads will also result in additional wear and tear of moving parts and tires etc. of the vehicles. Hence, the VOC (fuel cost is the major component) under congested traffic conditions would be higher than those under steady state. Moreover, the travel time increases as the volume increases, adding to the time cost. Therefore, the equations evolved to estimate fuel and time cost under a steady state will yield unrealistic values [8]. In spite of the fact that the fuel and time cost play a major role in road user costs, there has been relatively little research conducted into quantifying the effects of congestion on these components. By measuring the extra fuel and time consumed under congested conditions, the influence of congestion on these components can be quantified. In India, this was attempted for the first time in the study on Updating of Road User Cost Data [8] and subsequently road user costs were further updated [9-10]. These studies covered up to four lane divided carriageways only and moreover, the outcome of the above studies has become rather obsolete as the vehicle technology, roadway capacity augmentation and price has changed the road scenario quite dramatically in recent times. In view of these issues, the formulated objectives of the study are to develop fuel consumption equations for congested traffic conditions; to estimate the travel time cost under varying flow conditions; to develop congestion cost equations for fuel and time cost for different vehicle types considering varying widths of multi-lane divided carriageways [11]. Transport electrification through battery electric vehicle (BEV) power trains is currently regarded as a solution for clean mobility, perfect for metropolitan decarbonization, with high impact and short-term feasibility. However, it is necessary to consider that this technological deployment will constitute only a partial solution for the problem regarding the availability of automotive fuel and its impact on air quality. Suitability of electric power train as a substitute for the Internal Combustion Engine Vehicles (ICEVs) is not under discussion, nor its main environmental potential benefits (no contribution to pollution, no emissions of particles or nitrogen oxides) at a local level, but the generation of electricity to be stored in the batteries pollutes the environment during its production at power plant level. Global Zero-Emissions (ZE) transport solutions go through supplying electricity using renewable energy sources (such as wind, solar, geothermal), together with a change in social habits. The use of electric vehicles and its influence in greenhouse gas emissions (GHG) inventories is analyzed. Calculation of the GHG emissions associated with the use of BEVs is put under question, and a new approach for assessing realistic GHG emissions at power plant level puts in evidence the inaccuracy of the existing methods [14]. A city can be considered itself as a big company, and it is possible to adapt the same principles as in a company in order to assess its carbon footprint. In view of this, it is essential to accurately measure the different carbon footprints of the activities of the city, especially of those generating greenhouse gas emissions that occur outside of administered territory. The situation is complex for cities, as they are sites of many inflows and out-flows of people, goods and services. It represents the global standard procedure for how to measure, manage, and report greenhouse gas emissions that occur inside, as well as outside, the city boundary. GPC distinguishes three categories based on where the activities occur, aiming to differentiate emissions occurring physically within or outside the city boundaries: **Scope 1.** Direct emissions. This scope covers all GHGs that are directly emitted within the territory: stationary combustion of fossil fuels (e.g., natural gas, fuel oil, propane, etc.) for comfort heating or other industrial applications, emissions from the combustion of fossil fuels burned in vehicles or other types of passengers or goods transport, as well as emissions released during manufacturing processes in specific industrial sectors. **Scope 2.** Indirect emissions which result as a consequence of activities of the territory such as emissions due to the generation of electricity, district heating, steam and cooling. **Scope 3.** Includes a number of different sources of GHG including employee commuting, logistics, production of purchased goods and several more. These three scopes help to group emissions trying to avoid double counting. It is also important to categorize greenhouse gas emissions into those that could be under control (Scope 1) versus those that exercise significant influence (Scope 3). One of the recurrent double counting problems is related with electricity generation location and emissions [15]: a power plant which is located on the territory of a city produces electricity and, obviously, direct emissions; but this electricity generated is exported to other cities that use it. GHG emissions caused by the power plant would be taken into account where it is located (Scope 1). Other cities (those that receive and use this electricity) would include GHGs caused by the power generation as indirect emissions (Scope 2) in their inventories. Therefore, there would be a problem of double counting [16]. This problem will assume greater importance in the near future, when electric power trains will be consolidated as the substitutes for internal combustion engines as a natural consequence to the unstoppable growth of air pollution caused by the burn of fossil fuels. Because, despite all the barriers (range, infrastructure, prize, recharge time) against the consumer adoption [17], the European Environment Agency (EEA) has estimated that electric vehicles could assume in 2030 between 4% and 5% of total electricity consumption and up to 9.5% in 2050, according to new projections released (50% of the fleet to be electric by 2030 and 80% in 2050) (EAA 2016). These electric vehicles do not burn fossil fuels and they are clean at local level (Scope 1). Nevertheless, these vehicles may require to fill their batteries with electricity, therefore, there exist GHG emissions caused by electricity generation that must be taken into account, and these emissions will move from Scope 1 to Scope 2 in the city inventory. Additionally, working and leisure activities are increasingly concentrated in big cities due to urban sprawl, that is moving citizens to live in smaller but progressively denser towns, close to big cities. Therefore, new and uncertain accounting problems arise. One of these problems is that owners of battery electric vehicles could live in a city A, work in a city B, use the BEV to drive from A to B (commute) and charge the batteries mainly in A or occasionally in B, but nevertheless the electricity needed to fill the batteries could be generated in a power plant located at a third and different place C. This fact makes the situation even more difficult to analyze, because there exist a higher and more uncertain number of variables. Despite this important problem of accounting, another, even with major importance in that scenario and which requires urgent and sustained attention, exists: the methodology used to calculate those emissions. In this scenario, the methodology selected to calculate the emissions of using electric vehicles becomes a key point, as it represents the basis to build trustable inventories and avoid repeating the same errors committed in the past [20]. Measures needed to curb GHG emissions have focused on improving the Internal Combustion (IC) power trains [28], or introducing mitigation techniques [21] which can substantially reduce the risks associated with human-induced global warming [22]. Other measures have included emphatic restrictions for heavy polluters and privileged access for low-emitting vehicles in sensitive areas. Both of them not only reduced the number of vehicles, but also promoted zero emission mobility through tax exemptions or subsidizing the purchase of alternative vehicles and fuels at the expense of traditional fossil fuels. The government, through schemes, has set aside 20 million euros for grants for the purchase of electric and gas-fueled cars (IDAE, 2018). This new framework has been the starting point for promoting the Battery Electric Vehicle (BEV) as the greatest contributor to GHG and air pollution abatement [26]. Consequently, if the electric transport is the new mobility paradigm, it is absolutely necessary to consider, not only well-known BEV market barriers [27] including range anxiety phenomenon, but also developing of tools to analyze and improve how the vehicle is driven, because this is one of the most influential factors for vehicle energy consumption. It is true that although performance of the vehicle will mainly depend on driver behavior [25,24] and traffic congestion [23,27], cities still impose a set of constraints beyond driver control such as pedestrian crossings, traffic lights, speed limits, roundabouts, and bus stops [21,22,25,28]. These constraints can affect the number of starts and stops and vehicle speed. This inevitably creates uncertainty about the proportion of fuel consumption while driving that depends on driver decisions. With internal combustion vehicles this uncertainty represents a significant instantaneous environmental problem of greenhouse gas emissions and air quality, but for battery electric vehicles the problem is worse, since it combines the environmental aspect (often neglected) with the lack of confidence in electric transport [26]. City-conditioned driving directly impacts travel itinerary choices with the aim of minimizing energy consumption, environmental impacts (eco-driving and eco-routing) or travel times. However, authors of [24] have published results of a questionnaire-based study showing that, at driver decision-making level, routes with fewer traffic lights were preferred even if probability of having to stop at those lights were high and waiting times at red lights were long. This individual preference could sometimes cause non-optimal route choices from an environmental perspective. To reduce fuel consumption and emissions, tactical decisions like urban planning or traffic regulations as well as operational decisions like driving behavior must be considered [27] at the public administration level of decision making. The traffic data collection necessary to propose appropriated travel itineraries for minimizing fuel consumption and associated environmental impacts [22] must consider speed, geographic data, travel times and fuel consumption, among others. Therefore, the author's achievement for this work is to establish a simplified method for visualizing the influence of city constraints (urbanism, laws, traffic regulation elements) on the energy consumption and consequent GHG emissions of a BEV on a given route [31]. The main contribution of this work is the methodology developed to build a speed cycle for a concrete route, where the influence of human behavior is minimized, in such a way that the vehicle specifically obeys to road constraints, passenger safety, comfort and city regulations. This could be a useful tool for urban planners to improve understanding of the influence of traffic control infrastructure and other regulations on energy consumption and GHG emissions [30].

Table 2.1: Summary of various papers addressing effects of road on rolling resistance [32]

Experimental or Theoretical Methodology	Most Influential Texture Scale	Change in Resistance (RR) or Fuel Consumption (FC) from Roughness	Rolling Resistance (RR) and Fuel Consumption (FC) Relation	Other Losses	Other Important Factors
Analysis of previous experimental work	--	Roughness influences FC by up to 10%; no difference between asphalt and concrete	10% change in RR accounts for a 3-4% change in FC	Drag and driveline	--
Experimental coast down method	--	Both constant and speed-related RR coefficients affected by roughness for cars; only the constant RR coefficient affected by roughness for trucks	Lower RR results in lower FC	Drag and gradient	--
Used both coast-down and steady state torque tests	--	24% difference between smooth and rough surfaces	--	Drag and gradient	--
Theoretical	--	--	Can effect FC by up to 30%	--	Contact pressure between road and tire
Hydraulic bench test, hub sensor on track, fuel consumption on road	Short wavelength roughness (1-2 m)	Up to 50% increase in RR from 1.5 mm increase in roughness	Lower RR results in better FC improvements up to 6%	Shocks	Road alignment
Experimental dynamometer and track	--	5.3% increase in the laboratory test and 8% difference in the road test	--	--	Road noise increases with roughness
Towed trailer method	Mega-texture	Surface condition can affect RR by 47%	Max. fuel savings of 9%	--	Temperature and velocity
Theoretical	Roughness, macro and mega-texture.	Equations provided. For trucks the RR could increase by as much as 50% due to roughness	FC effected by RR up to 7%	Road gradient	Tire load and temperature
Experimental coast-down method and fuel consumption	--	Increasing IRI from 60 to 120 resulted in 1.8% increase in RR at 30 mph and 6% at 55 mph	Factor 0f 0.18 (i.e., 22% RR increase = 4% FC increase)	Stiffness	Lack of data for load, tire type, vehicle type, etc.
An experiment determined the rolling resistance of four different surfaces	Macro-texture and evenness	Smoother road results in lower RR	RR must be reduced by 6-7% to reduce FC by 1%	--	Surface texture, softness or loose material

Table 2.2: Summary of different papers addressing effects of road on rolling resistance [32]

Experimental or Theoretical Methodology	**Most Influential Texture Scale**	**Change in Resistance (RR) or Fuel Consumption (FC) from Roughness**	**Rolling Resistance (RR) and Fuel Consumption (FC) Relation**	**Other Losses**	**Other Important Factors**
Road Tests on the NCAT test track	--	Increased roughness has resulted in higher fuel consumption of test trucks		--	Vehicle wear
Reviewed previous experimental results	Mega-texture	--	--	--	Tire noise
Experimented with a hydraulic bench and on a track	--	Lower roughness results in better FC	--	Shocks	Road alignment
Theoretical	--	10% from poor to good pavement finish	Both improve w/ less roughness	Tire, shocks	Velocity
Experimental using fuel consumption	Mega and macro-texture	10x increase in IRI increases FC by 2 to 16%. 10x increase in megatexture increases FC by 8 to 14%; increase in macrotexture (MPD) from 0.3-3 increases FC by 2 to 21%.	%FC/%RR ratio is 0.25	--	--
Experimental fuel consumption on a track	--	Increasing road roughness increased FC by 4.5%; rehabilitation used to reduce roughness	--	Fatigue failures of vehicles	--
Theoretical	--	Increasing roughness by 26.7% increases RR by 38.7%	--	Tire, shocks	Velocity
Falling weight deflectometer and towed trailer	--	A 0.5 mm increase in mean profile depth results in a 10% increase in RR	--	Road stiffness	--
Experimental, focusing mostly on the tire.	--	Suggests that RR of very soft surfaces (dirt, sand) could be twice that of hard pavements surfaces (concrete, asphalt)	--	--	Tire composition
Tested the responses wrt rolling resistance by changes in velocity, tire type, and size	--	--	--	Drag and shocks	Velocity, tire type, tire pressure, and tire size

So, basically [32] summarizes many references on tire rolling resistance and the effect of pavement. The key parameters of the pavement that affect rolling resistance have been identified. Pavement roughness and texture are very influential characteristics, with large-scale roughness being the most important factor. Further research is needed to optimize pavement texture for rolling resistance without sacrificing friction or safety. Stiffness of the road does not appear to have a significant effect on the rolling resistance or fuel economy of vehicles. Rolling resistance of a tire on concrete or asphalt pavements with the same profile or texture should be practically identical. The literature suggests that improvements in pavement roughness could directly improve fuel efficiency by approximately 2-6%. Of course, tire rolling resistance is also dependent on factors such as tire type, inflation pressure, temperature, weather conditions, speed, and more. Fuel efficiency will, therefore, be influenced by all these factors in addition to other losses not related to tire rolling resistance, i.e., aerodynamic drag, engine friction etc. and also recommends that there is only superficial qualitative understanding of the relationship between pavement properties and rolling resistance. Therefore, additional studies on rolling resistance under controlled conditions while monitoring all the influential parameters are suggested. Several plausible methods for measuring rolling resistance were identified. For further research of the effects of pavement characteristics on rolling resistance, an isolated trailer containing a rolling tire appears to be the best option. The surface profiles of the pavements would be characterized using several different methods, including the traditional IRI method and spectral methods. Different types of tires and inflation pressures could also be investigated on different pavements, as it is believed that stiffer tires will be influenced less by the pavement roughness. Pavement texture, roughness, and stiffness would be measured using the inertial profilers and falling weight deflectometers to fully capture the pavement properties that may affect rolling resistance and fuel economy. Since these pavement measurements are routinely measured on the wide variety of asphalt test pavements on the NCAT Pavement Test Track, it is well suited for rolling resistance experiments. Additional pavements should be included in the experimental plan so that the research includes a complete range of pavement types and surface conditions and these pavements should come from different climatic regions of the country. Rolling resistance is greatly influenced by tire pressure. Underinflated tires can impair the economy of fuel consumption because in the case of most tires lower tire pressure will cause deformities and great absorption of energy through the tire, increased friction between the rim and the tire, as well as the increase of contact surface between the tire and the road. In case of tires underinflated to 1 psi the rolling resistance increases by 1.1%. The relation between the rolling resistance and fuel consumption is dynamic and it depends on various factors including vehicle type, weight, condition of the surface ground and environment etc. The sample of 100 vehicles was chosen and the tire pressures were measured on them (Djordjevic et al., 2007). The results have shown that even 24% of vehicles have had all four tires under inflated, their pressure being more than 7.25 psi lower than nominal and even 70% of vehicles have had at least one tire underinflated by more than 7.25 psi [33].

The Republic of Serbia could save up to 73700 tons of fuel annually, as observed only in case of passenger vehicles (53000 tons by choosing the low rolling resistance tires and 20700 tons by regular tire pressure maintenance) [33]. As tires are tested while within the atmosphere, the measured rolling resistance has two major aspects to its composition. The primary aspect has to do with the flexing/ squirming of the tread/ sidewall material as the tire rotates on the test drum, resulting in resistance due to hysteresis or friction. The secondary aspect has to do with resistance due to rotational aerodynamic drag at the external or internal tire surfaces [34]. When John Boyd Dunlop re-invented the pneumatic tire (1888), the prevailing level of technology had risen considerably and the bicycle craze was in full boom, with the rise of the automobile just beginning. For the next 40 years the pneumatic rubber tire would undergo a rapid development unaided by any scientific understanding of the physical mechanisms involved. Such an understanding would await the development of machines which would allow for the testing of tire behavior in a laboratory environment [35]. The first tire testing machine was possibly the rotating steel drum tire tester of Becker, Fromm, and Maruhn (1930). These German researchers generated tire data as a prerequisite for their investigation of the great automotive problem of the time: steering "shimmy". In this they followed up on the French researcher George Broulheit who had identified the tire characteristic of slip angle in his investigation relating to shimmy. A notable follower in the footsteps of these scientists was R.D. Evans continued the investigation of the physical properties of tires via another drum tire tester [36,37]. Evaluation of the performance potential of an automotive conceptual design demands few initial quantitative estimates of numerous important parameters i.e., vehicle mass properties, frontal and plan areas, aerodynamic drag and lift coefficients, available power and torque, and different tire characteristics i.e., rolling resistance coefficient [38]. [39] suggested a methodology to rectify the seeming deficiency. The methodology presented in [39] could not be rigorously validated without an expenditure of time and effort which was beyond the resources. A limited validation was undertaken which, while not constituting an absolute proof of the methodology's validity, The validation consisted of taking 90 tires for which an empirically obtained C_r value, along with normal load and inflation pressure. This involved a span of wheel sizes 13 to 16 in (330 to 406 mm) for bias, bias-belted, and radial tires over the years (1958-2008). Those tires were then treated as being of unknown origin. Capitalizing the rolling resistance estimating methodology put forth herein, corresponding estimated values were determined; the comparison indicated that the methodology is accurate on average within a range of about ±8% (but with a maximum range of variation of +32%/ -21% due to possible data point outliers); the correlation coefficient between estimated and empirical is a reasonable (0.86). It is only valid for ordinary passenger car tires operating within the tire design range of load and inflation pressure (15-50 psi/ 103-345 kPa) bounds of the rolling resistance coefficients regression analysis [39]. The proposed model of rolling resistance on road pavements is based on the simplification of the tire/pavement adhesion model taking into account all the possible slip rates of a tire on the pavement ranging from 0 to 1. For its adaptation, all the parts related to the slip were removed to leave only the pure rolling as kinematic conditions. The model was tested on a set of surfaces differentiated by their macro-texture and validated by measuring rolling resistance on these surfaces. The results show that the texture contribution to the rolling resistance increased with the macro-texture, which would be due to larger stones that needed to be overcome. In addition, it should be noted that the random distribution and the pointed shape of the summits might cause an inconvenience with respect to rolling resistance [40]. Rolling resistance cannot correlate well with the mean profile depth evaluated in a classical way, as the tire in most cases only partially envelops pavement texture. The conducted experiments showed that experimental estimation of the enveloped mean profile depth (MPD) is possible and that it allows elimination of those texture regions that do not come into contact with the tire. Although the method of making rubber castings is laborious, it allows for a more realistic estimate of the enveloped MPD value, as in a way the tire just feels it. The authors believed that a completely different method of pavement characterization in respect to rolling resistance could also be used, which might take better account of the pavement texture properties that were important for energy loss. The proposed method examines the relationship between the penetration depth of the texture summits and the volume of deformed rubber [41]. Till now, environmental assessment only focused on construction and maintenance works whereas recent studies showed that use phase can represent up to 90% of the global energy demand of a road project. Thus, study of [42] proposes to assess the impact of pavement surface characteristics (evenness with IRI and macro-texture with MPD) on environmental indicators (Energy total demand and Global Warming Potential) by considering both construction and use phase. Two fuel consumption models were selected for this research work. The results showed that more than 90% of energy consumption was due to the use phase when considering 30 years of lifespan. Moreover, an increase of IRI from 1 m/km to 2.5 m/km multiplies by three the annual energy consumption. In the same manner, a decrease of MPD from 1.2 mm to 0.8 mm represented a profit of more than 1.106 MJ/year. Equivalent results were observed on GWP. Thus, it is possible to diminish the environmental impact of a road project by changing the pavement surface characteristics with a boundary condition related to safety and friction. The set values of one wheel load (from about 25 kg to 50 kg) did not affect the value of the rolling resistance coefficient. The results of [43] obtained are convergent with the data available in the literature. This indicates that the method can be used for further tests determining the value of the rolling resistance coefficient of wheeled systems. Further research will be carried out to determine the rolling resistance coefficient when moving on non-standard surfaces used in households and the impact of internal wheelchair driving mechanisms equipped with e.g., a lever drive system or hybrid drive. Due to changes in mechanical properties due to the wear of drive mechanisms and surfaces, research would be carried out on determining the impact of exploitation on the value of the rolling resistance coefficient [44,45]. One should consider how much a wheel sinks into the road as it majorly affects energy losses in tires. It was shown that it might take twice as much effort to ride on a gravel road compared to hard smooth road [46]. A deterministic road roughness model was developed to predict energy losses in both tire and suspension of the vehicle. Using this model, authors could vary different inputs like vehicle speed, tire pressure and road roughness to assess effects of each parameter on rolling resistance and drag force. It determined that roadway roughness increased both rolling and drag losses due to energy dissipation and rolling losses could be more than 20% in addition to aerodynamic losses [47]. Rolling resistance was found to increase with increased texture. Rolling resistance was normalized to the new concrete surface and it was found that there was an 8% difference in rolling resistance between the new concrete surface and the most textured asphalt surface. The polished concrete showed a 12% reduction in rolling resistance over the new concrete surface. An 8% difference was reported; the difference between the average asphalt highway and new concrete was one unit of rolling resistance. 30% differences were reported for hard-surface public roads, asphalt covered with coarse sealcoat. The author recognized the importance of surface texture for wet traction performance and suggested that surface texture consider both rolling resistance and the need for safety during wet traction performance [48]. While the primary intent was to know how tires influenced rolling resistance, the author assessed interaction between tire and road on rolling resistance. There was a 15% difference in the rolling resistance of a tire, when compared with others no significant differences were noted [49]. The author used a coast-down method of experiment to measure the rolling resistance of passenger cars and trucks on eight different surfaces like asphalt, concrete, surface treatment, and unsurfaced etc. He determined that pavement type (asphalt or concrete) had only a small effect on rolling resistance. Both the asphalt and concrete roads had lower rolling resistance values than surface treatments. The roughness had an effect on rolling resistance as smoother roads had lower rolling resistance values [50]. Using the spectral density functions and developed models, the researchers were able to compare the effect of road roughness on rolling resistance. As the roughness of a road increased, the rolling resistance became exponentially greater. If the amount of force required to keep the vehicle moving on a good road in one condition was 300 N. If the same roadway were in a poor condition, 10% more energy (330 N) would be required to keep the car moving. A road in a very poor condition would increase the rolling resistance by 40% (420 N). These models showed that roughness and vehicle speed interact to affect rolling resistance. When a vehicle is traveling at a slower speed, the roughness of the road does not affect rolling resistance as much as if the vehicle were traveling rapidly [51]. The rolling resistance coefficient increases by 0.0021 for each mm of texture. This study concluded that mega texture was the most influential property, but one must also realize that macro-texture was important when disregarding sections that were transversely grooved. The total combination of mega and macro-texture could influence rolling resistance by almost 47%, which could save 9% fuel [52]. If one can assume the vehicle is a rigid body with the mass of the wheel concentrated in center, no slippage occurs between the tire and pavement. If the road is rigid, one can assume the relationship between rolling resistance is linear with vehicle speed. Two typical roads were chosen to model the effects of ride on rolling resistance. Using the model coupled with rolling resistance models, it was shown that rolling resistance increases as roughness increases. An average of 38.7% difference was seen between the rolling resistances of the smoothest and roughest roads in the study. A more common comparison of a good to a rough road would show almost 12% difference in rolling resistance. These values were all modeled at 10 m/s. When vehicle speeds were increased from 10 to 15 m/s, the rolling resistance coefficients increased by 11%, showing that roughness is even more important when a vehicle is traveling at higher speeds [53].

2.1 Scope of improvements in available research / research gap

The strong requirement of environmental sustainability and energy saving in urban transport got, as first result, the appearance of a rainbow of solutions for on-road vehicles, characterized by low or zero emissions. Nowadays hybrid, electric, hydrogen or bio-fuels vehicles are available on the market.

Measuring fuel consumption is the most common way to assess rolling resistance as it includes all plausible factors which influence rolling resistance. Tire rolling resistance surely affects fuel consumption, but as various factors influence energy dissipation experienced by the vehicle, it is very difficult to identify rolling resistance loss in the fuel consumption method. [32]

The emission analysis improved with each study, including age-wise segregation of vehicles on the road and reducing uncertainty in the total road transportation emissions. These studies did not highlight the changes over time in the fleet characteristics i.e., fuel efficiency, annual average distance traveled, fuel and technology share,and also emission standards. Therefore, the present study exhibited a change in characteristics over different roads and examined the impact on vehicle emissions (CO_2, CO, PM, NOx etc.) from these roads at the national and state-level for India in 2022. [33]

So, technically the research question is which type of roadway or carriageway is more environment-friendly and cost-effective while asphalt is cheaper upfront, but in long run concrete roads would prove to be of lower costing and more environmentally friendly.

2.2 Aims and objectives of this study

The aims and objectives of the present study are as follows:

- To find out the effects of different types of road surfaces on the energy consumption of roads vehicles.
- To estimate the Rolling Resistance Coefficient values for different types of road surfaces practiced in India and its effects on fuel consumption of road vehicles taking two-wheelers as a case study.
- To estimate the emission characteristics from the same vehicle plying on different road surfaces.
- To estimate the capital cost and maintenance cost for three different types of road surfaces under study.
- To estimate the energy cost for plying two wheelers in different road surfaces.

Chapter 3: Methodology and Flowchart of the Experimental Research

The experiment was conducted on three different roads at Jadavpur in Kolkata, West Bengal, India.

Here, three types of pavement surfaces were considered for experimentation purposes.

Firstly,

Mastic Asphalt road

Figure 3(a): Mastic asphalt road surface used in the experiment

Figure 3(b): Asphalt Mastic Road surface used in the test

Figure 3(c): Asphalt Mastic Road surface used in test

Figure 3(d): Mastic Asphalt Road surface used in the experiment

Secondly,

Bituminous Asphalt road

Figure 3(e): Bituminous Road surface used in this experiment

Figure 3(f): Bituminous asphalt road surface used in this experiment

Figure 3(g): Bituminous asphalt road surface used in the test

Figure 3(h): Bituminous asphalt road surface used in this experiment

Thirdly,

Cement Concrete road

Figure 3(i): Concrete Road surface used in experiment

Figure 3(j): RCC road surface used in the test

Figure 3(k): Concrete Road surface used in the experiment

Figure 3(l): Concrete cement road surface used in this experiment

These three roads were selected to realistically represent pavement surfaces mainly encountered on two-wheeler motorcycle bike routes. The bumpers were used as obstacles to make provisions for suitable obstructions without harming the tires of the vehicle used in the test. The method to determine the loss of energy due to bumps has been enabled to check effect of a relative anomaly (more than normal unevenness or obstacles such as smaller rocks), within the riding pathway to be quantified (to compare between three situations for the experiment), in a manner that has practical relevance to a rider with a passenger (optional).

Firstly, different parameters like length, breadth, height etc of road stretches and bumpers of different pavement surfaces were measured for the experiment using a lightweight flexible tape which was necessarily desirable. These all were done using FREEMANS TOP-LINE metallic wired measuring tape {top line 50 m (length) :0.016 m (width)} which is a type of tape woven longitudinally from different metal wires to increase and decrease strength and stretch respectively with strong dimensional stability. Graduation marks and numbers (accuracy: +/- 0.005 m) were printed or stamped on the tape. The tape was made of waterproof linen fabric, and coated with a plastic material to reduce the effects of humidity, moisture, and abrasion. It was used in this experiment principally to mark the limits of the distances of the road stretches accurately for detailing and sectioning.

Figure 3(m): Freeman’s top-line metal wired tape used in the experiment

The following two tables have various parameter values of the three different roads used in this test.

Table 3.1: Different parameters measurements of the three types of roads used in test

Road surface material	Mastic Asphalt	Bituminous Asphalt	Cement Concrete
Iteration measurements for length (m)	(i) 291.53 (ii) 291.526 (iii) 291.528	(i) 1532.654 (ii) 1532.656 (iii) 1532.657	(i) 583.632 (ii) 583.631 (iii) 583.631
Iteration measurements for width (m)	(i) 3.555 (ii) 3.554 (iii) 3.556	(i) 3.755 (ii) 3.75 (iii) 3.76	(i) 4.654 (ii) 4.656 (iii) 4.655
Iterations to measure bumper length (m)	(i) 3.525 (ii) 3.525 (iii) 3.525	(i) 3.715 (ii) 3.725 (iii) 3.72	(i) 4.258 (ii) 4.257 (iii) 4.256
Iterations to measure bumper width (m)	(i) 0.345 (ii) 0.345 (iii) 0.345	(i) 0.366 (ii) 0.365 (iii) 0.364	(i) 0.355 (ii) 0.355 (iii) 0.355
Iterations to measure bumper height (m)	(i) 0.045 (ii) 0.045 (iii) 0.045	(i) 0.052 (ii) 0.05 (iii) 0.051	(i) 0.045 (ii) 0.045 (iii) 0.045

Table 3.2: Information about these three roads used in the test

Road material	Mastic Asphalt	Bituminous	Concrete
Location	From Chemical Engineering Department to Girls hostel, Jadavpur University, Jadavpur, Kolkata, WB 700032	1st Road, Survey Park, Santoshpur, Kolkata, WB 700075	Aurobindo Bhawan Electrical Engineering Department juncture to Department of Pharmaceutical Technology, Jadavpur University, Kolkata, WB 700032
Length of Stretch (m)	291.528	1532.656	583.631
Width of Road (m)	3.555	3.75	4.655
Number of Bumpers	3	9	12
Bump Length (m)	3.525	3.72	4.257
Bump Width (m)	0.345	0.365	0.355
Bump Height (m)	0.045	0.05	0.045

Bumpers had important roles in this experiment. As the test was conducted assuming zero congestion, bumps added instantaneous or immediate jerk (d3y/dx3) to the velocity and acceleration profiles over different types of roads. Bumper to bumper distances played one of the key factors for vehicles to take proper action on the Braking System that directly affected velocity and acceleration which had strong correlations with the rolling of the vehicle, resistance forces, fuel consumption and emissions.

The table below consists of bumper-to-bumper distances over different road surfaces.

Table 3.3: Bumper to Bumper distances over various types of roads

Mastic Asphalt	Distances (m)	Bituminous Asphalt	Distances (m)	Cement Concrete	Distances (m)
Chemical Building -- 1st Bumper	78.517	Start point -- 1st Bumper	45.565	Juncture -- 1st Bumper	9.655
1st Bumper -- 2nd Bumper	99.256	1st Bumper -- 2nd Bumper	300.455	1st Bumper -- 2nd Bumper	29.312
2nd bumper -- 3rd bumper	99.557	2nd Bumper -- 3rd bumper	151.816	2nd Bumper -- 3rd bumper	31.236
3rd bumper -- Girls hostel	14.228	3rd bumper -- 4th bumper	301.503	3rd bumper -- 4th bumper	96.128
		4th bumper -- 5th bumper	301.533	4th bumper -- 5th bumper	78.141
		5th bumper -- 6th bumper	150.651	5th bumper -- 6th bumper	24.353
		6th bumper -- 7th bumper	60.465	6th bumper -- 7th bumper	45.737
		7th bumper -- 8th bumper	60.196	7th bumper -- 8th bumper	41.164
		8th bumper -- 9th bumper	100.397	8th bumper -- 9th bumper	53.185
		9th bumper -- end point	60.245	9th bumper -- 10th bumper	54.477
				10th bumper -- 11th Bumper	25.196
				11th bumper -- 12th Bumper	73.475
				12th Bumper -- pharmacy building	21.648

Following three figures represent architectural design of chosen roads for this experiment respectively.

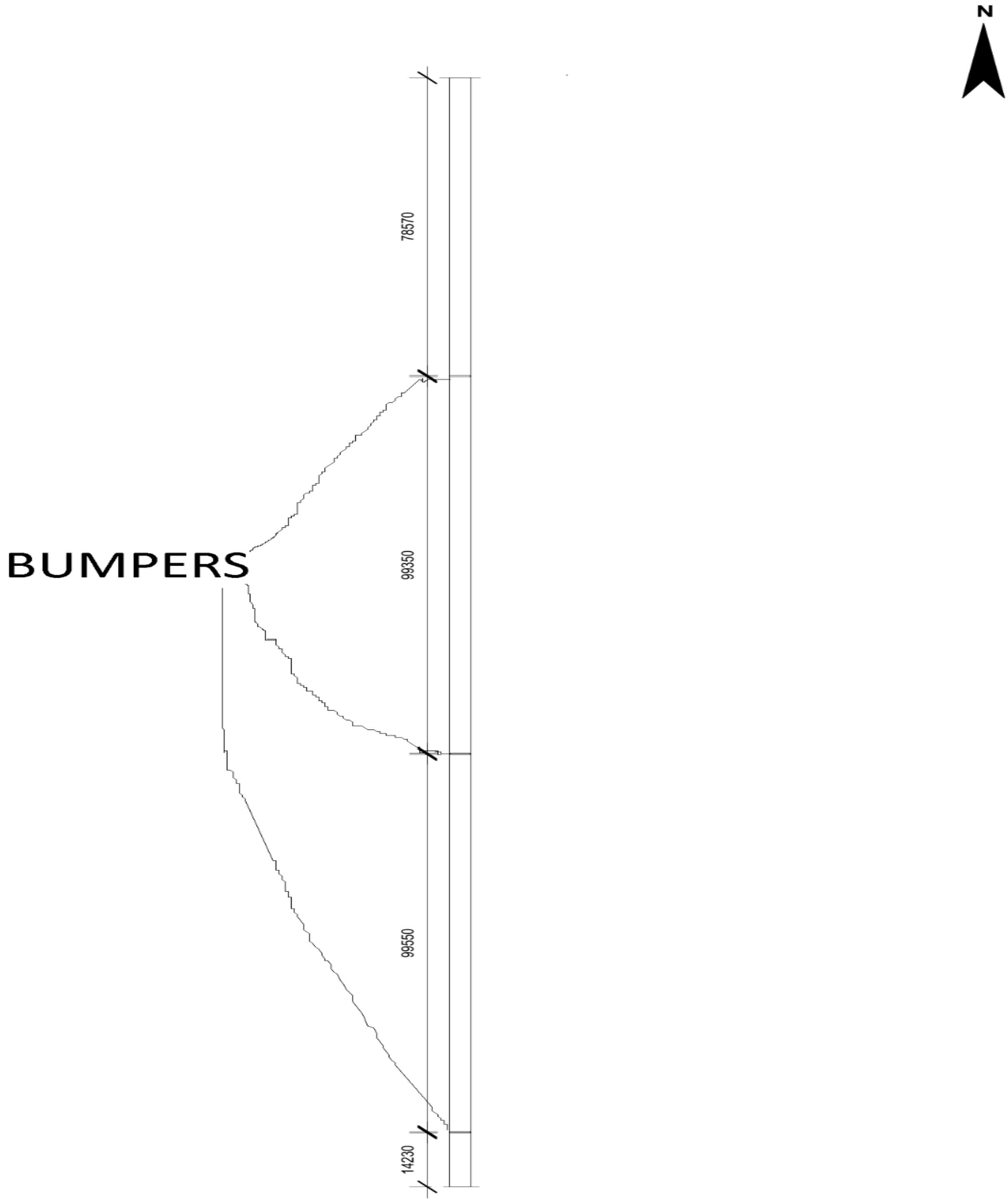

Figure 3(n): Approximate architectural urban road layout design of the chosen mastic asphalt road (scale=1:1000)

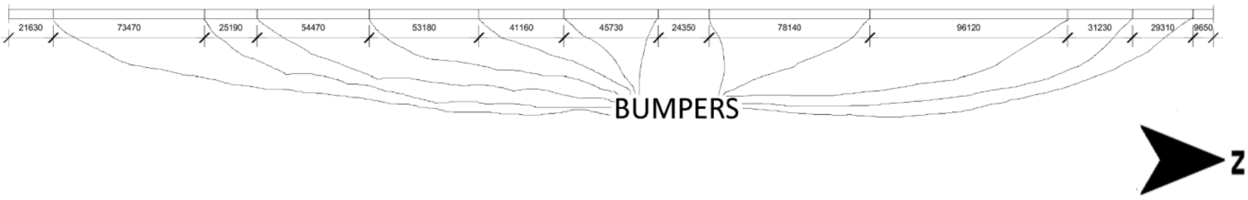

Figure 3(p): Approximate architectural urban road layout design of the chosen concrete cement road (scale=1:1500)

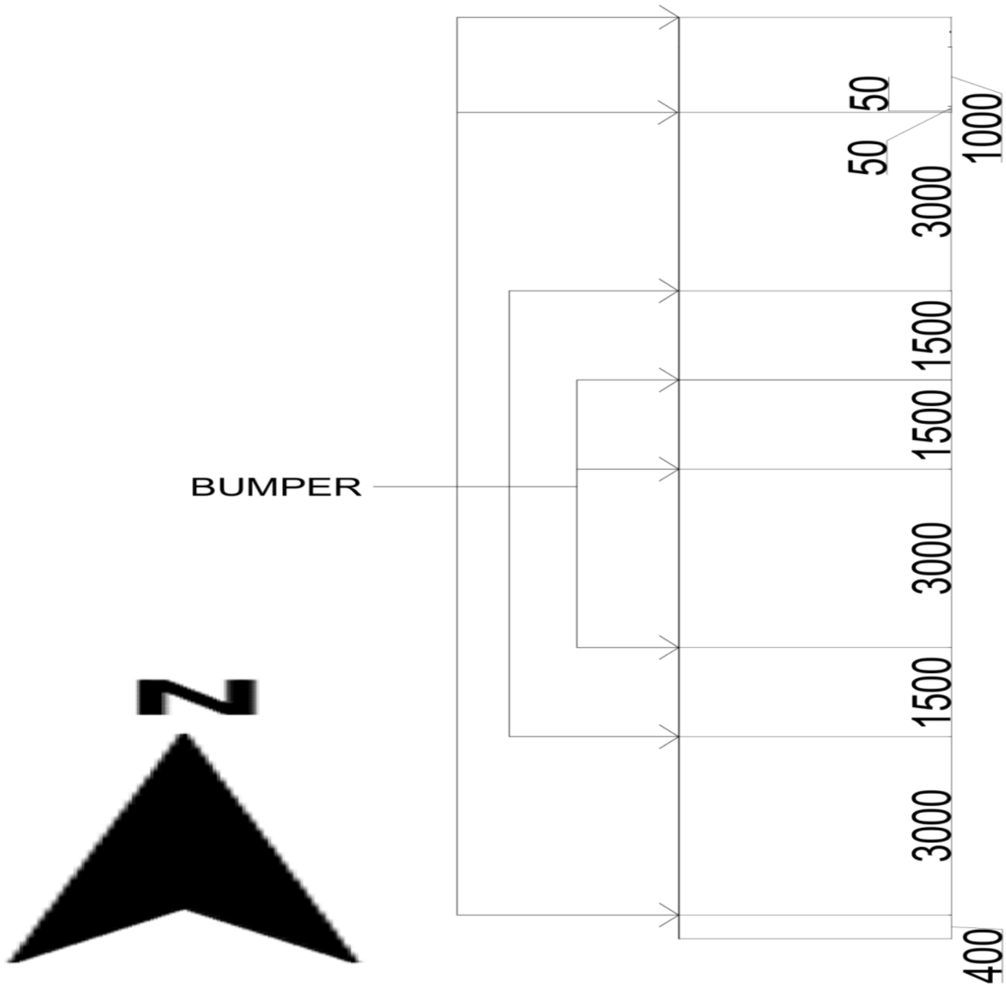

Figure 3(o): Approximate architectural urban road layout design of the chosen bituminous asphalt road (scale=1:2500)

Secondly, a two-liter measuring cylinder (accuracy: +/-20 ml) was taken to inject 1 liter of fuel (petrol) into the fuel tank of the test vehicle to take the measurements of oil exhaustion for estimating the factors in the performance of this bike over different road surfaces.

Figure 3(q): 2 liter measuring cylinder used in the test

The table below exhibits the amount of petrol, feeded before each trip, which depletes completely after the trip for all trials.

Table 3.4: Petrol as fuel for the trials

Iteration	Fuel amount for mastic asphalt road (liter)	Fuel amount for bitumen road (liter)	Fuel amount for concrete road (liter)
1	1.02	1.01	1.02
2	1.02	1.02	1.01
3	1.02	1.01	1.01
4	1.01	1.02	1.02
5	1.02	1.01	1.01
6	1.03	1.01	1.01
7	1.02	1.02	1.01
8	1.01	1.01	1.02
9	1.02	1.01	1.01
10	1.02	1.02	1.01

For this study, a lightweight (148(+/-2.5) kg kerb or wet weight) two-wheeler (BAJAJ PULSAR 150) was used to provide insights regarding influence of rolling resistance parameters on overall fuel consumption for majorly popular different types of pavement surfaces based on materials made by civil engineers in one of the popular urban areas (Jadavpur) of Kolkata, West Bengal, India.

Figure 3(r): Vehicle used for the experiment

Figure 3(s): Motorcycle used for the experiment

A calibrated Global Positioning System (GPS) device (velocity accuracy: ± 0.5 km/h) was used to measure and collect the speed and location of the bike during the tests. The test was performed thirty times (ten times each) using the test vehicle by traveling to and fro roads to determine the average fuel utilization for this motorcycle on different pavement surfaces (not any gravel road) considering one fixed gear (second gear) with vehicle compression ratio- 9.8(+/-0.3):1, same driving behavior, and zero congestion factor.

While measuring, two people were bestriding the vehicle which have salient specifications like 149.5(+/-0.5) cc displacement, 4 Stroke, 2 Valve, air cooled cooling system, twin Spark BS IV compliant DTS-i FI engine, 1 cylinder, maximum power of 14 PS (10.3 kW) @ 8500 rpm, maximum torque of 13.4 Nm @ 6500 rpm, fuel capacity of 15 L, reserve fuel capacity of 3.2 L, fuel injection delivery system, 5 speed manual transmission of chain drive type, full DC Maintenance Free (MF) type battery capacity of 12 V (9 Ah), halogen headlight bulb of 12 V 35/35 W with two pilot lamps with AHO (Auto Headlight On), gearbox with five number of gears, wet multi-plate clutch; and other typical features like analogue tachometer, analogue digital instrument console, single channel ABS (Anti-Lock Braking System), dual piston type caliper, electric start, LED tail light, digital speedometer, digital odometer, digital trip meter, digital fuel gauge, digital twin spark ignition, double cradle chassis type etc. This motorcycle has other necessary attributes like bs4 emission type, width of 0.765 m, length of 2.055 m, height of 1.06 m, ground clearance of 0.165 m, wheelbase of 1.32 m, saddle or seat height of 0.785 m, front brake diameter of 0.26 m, rear brake diameter of 0.23 m, front suspension of telescopic 31 mm conventional fork with anti-friction bush, suspension rear of twin shock nitrox gas-charged mono shocking absorber with canister, front disc and rear drum brakes, bore of 0.057 m, stroke of 0.564 m, tubeless tires Size of front: 80/100-17 46 P| rear: 100/90-17 55 P {here, 46 and 55 represent the Load Index (maximum weight that each tire can carry at full speed) and P indicates the speed rating (maximum speed for each tire at full load 100 and 115 km/l respectively)}, alloy type wheels size of 0.4318 m (17 in), front and rear tire pressures are 25 psi (1.724 bar) and 28 psi (1.931 bar) respectively etc.

The approximate average passenger and driver weights were 71.53 kg and 81.23 kg respectively. So, the total calculated weight of the riders= 152.76 kg; which were weighed using a RORIAN analog display weight machine for humans (Model No- B9820 1) that had a tremendous 130 kg maximum capacity.

Table 3.5: Weight measurements of both driver and passenger

Serial no.	Driver's weight (kg)	Passenger's weight (kg)
1	81.1	71.5
2	81.4	71.3
3	81.2	71.8
MEAN WEIGHT	81.23	71.53

Below figures show the profiles of velocity and acceleration of the test-vehicle over different road surfaces.

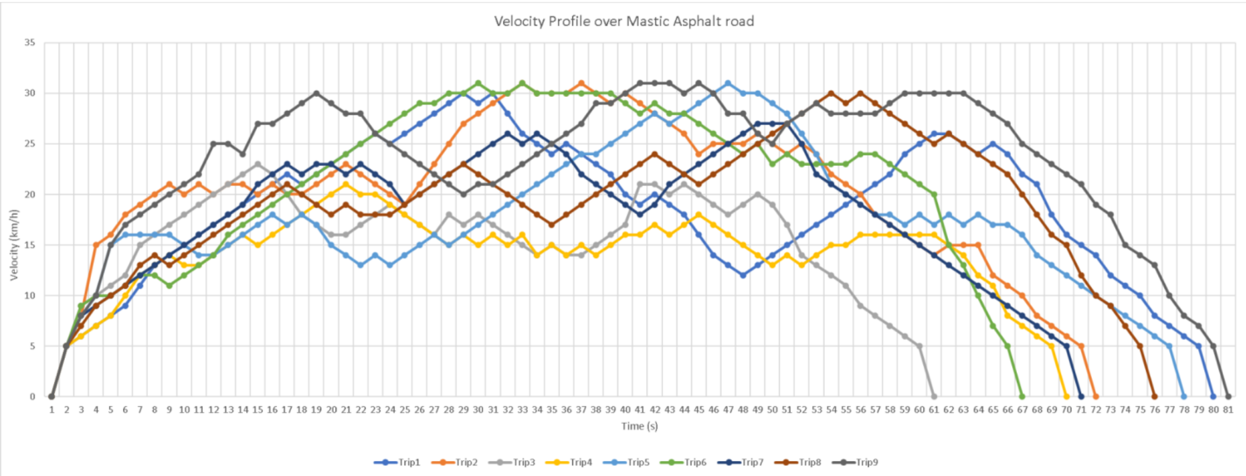

Figure 3(t): Velocity profile over mastic asphalt road

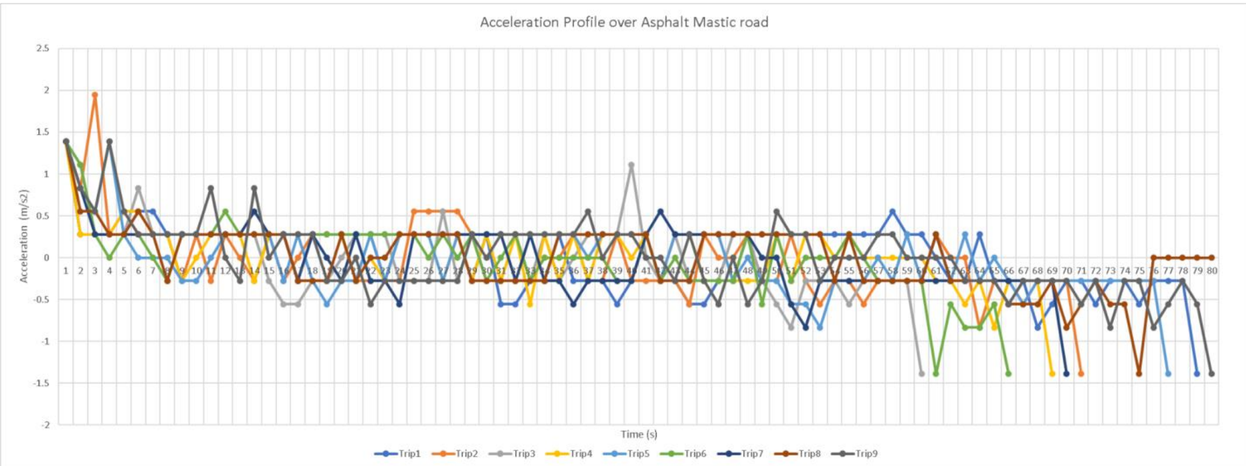

Figure 3(u): Acceleration profile over mastic asphalt road

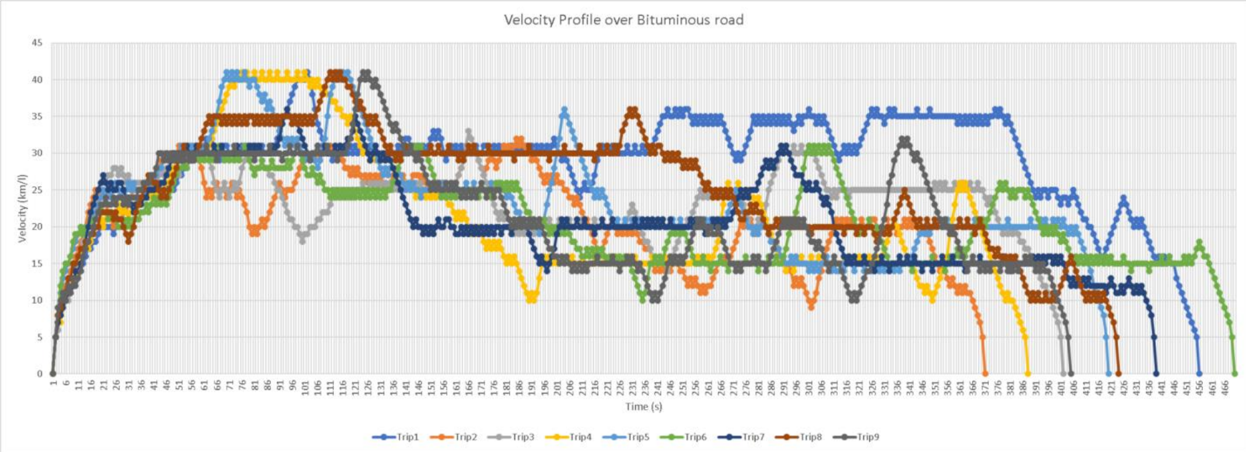

Figure 3(v): Velocity profile over bituminous asphalt road

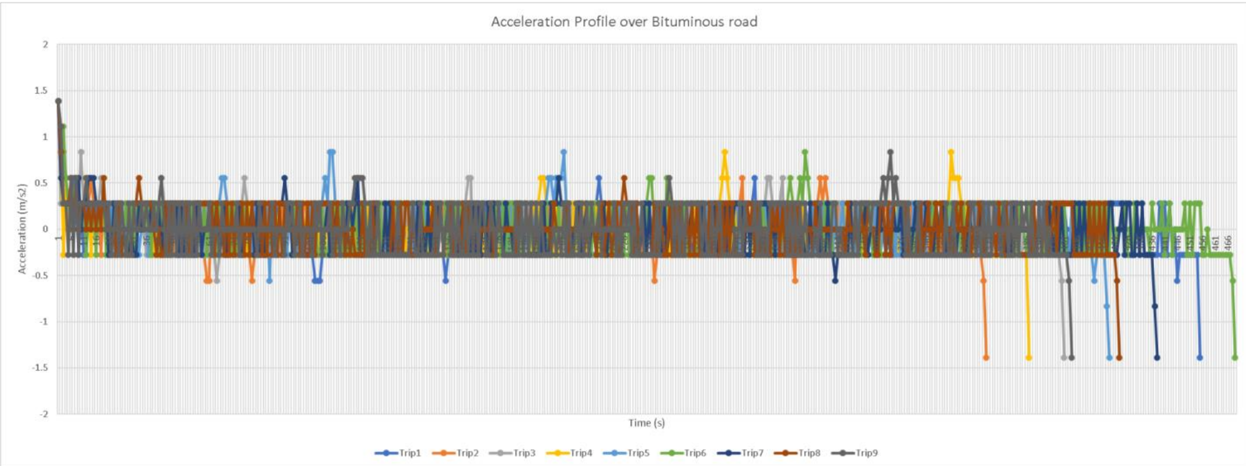

Figure 3(w): Acceleration profile over bituminous asphalt road

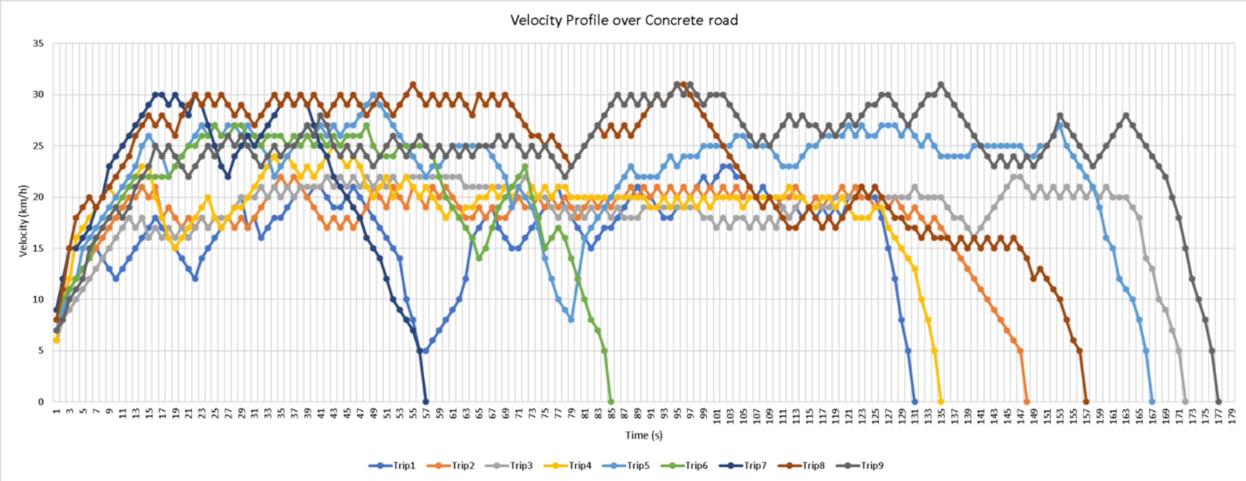

Figure 3(x): Velocity profile over cement concrete road

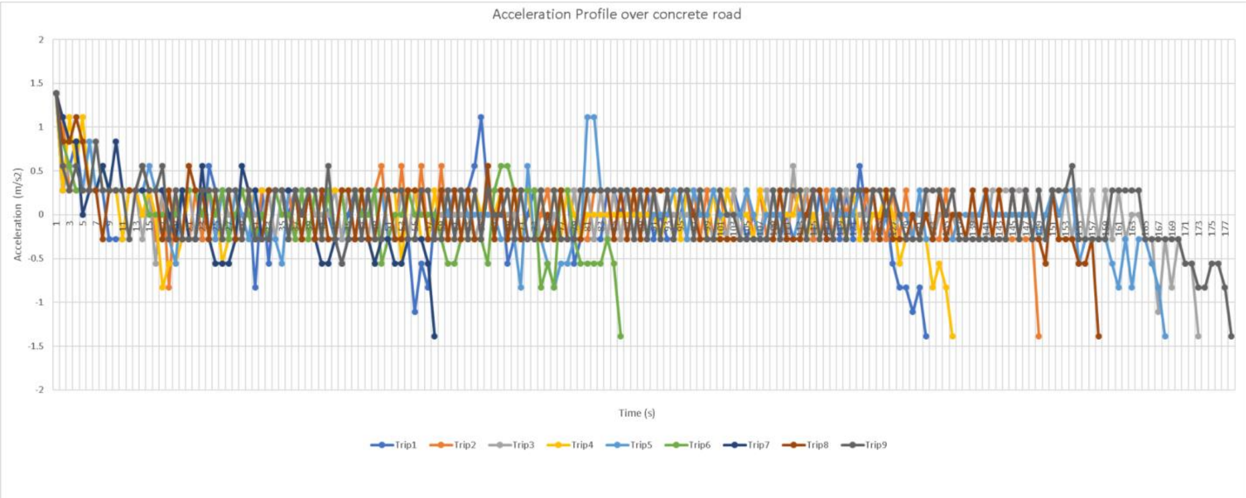

Figure 3(y): Acceleration profile over cement concrete road

Chapter 4: Data Analysis and Results Interpretation

The following table shows the test results.

Table 4.1: Average Distance and Fuel consumption of each type of roads

Road material	Asphalt	Bituminous	Concrete
Maximum speed (km/h)	31	41	31
Average speed (km/h)	18.521	23.01	20.297
No. of Back-and-forth trips	(i) 94 (ii) 96 (iii) 88 (iv) 90 (v) 99 (vi) 101 (vii) 107 (viii) 106 (ix) 92 (x) 94	(i) 17 (ii) 18 (iii) 17 (iv) 17 (v) 19 (vi) 19 (vii) 18 (viii) 19 (ix) 17 (x) 17	(i) 51 (ii) 53 (iii) 49 (iv) 49 (v) 58 (vi) 54 (vii) 55 (viii) 53 (ix) 49 (x) 49
Extra Distance (m) (if any)	(i) 73.704 (ii) 61.851 (iii) 10.817 (iv) 47.329 (v) 35.238 (vi) 18.925 (vii) 16.466 (viii) 96.914 (ix) 9.063 (x) 11.642	(i) 70.394 (ii) 6.961 (iii) 941.729 (iv) 836.357 (v) 236.215 (vi) 125.622 (vii) 496.648 (viii) 433.911 (ix) 467.389 (x) 506.213	(i) 132.479 (ii) 24.232 (iii) 21.223 (iv) 336.824 (v) 19.378 (vi) 153.225 (vii) 7.231 (viii) 8.478 (ix) 3.265 (x) 76.089
Total average distance (km)	(i) 55.237 (ii) 56.334 (iii) 51.372 (iv) 52.751 (v) 57.928 (vi) 58.999 (vii) 62.483 (viii) 62.369 (ix) 53.694 (x) 54.875	(i) 54.268 (ii) 55.389 (iii) 54.997 (iv) 54.674 (v) 58.965 (vi) 58.626 (vii) 56.698 (viii) 59.571 (ix) 53.543 (x) 53.662	(i) 59.685 (ii) 61.857 (iii) 57.028 (iv) 57.589 (v) 67.456 (vi) 63.211 (vii) 64.162 (viii) 61.783 (ix) 57.125 (x) 58.084
Vehicle mileage (km/l)	(i) 55.148 (ii) 56.224 (iii) 51.269 (iv) 52.626 (v) 57.813 (vi) 58.982 (vii) 62.356 (viii) 61.968 (ix) 53.592 (x) 54.391	(i) 54.134 (ii) 54.984 (iii) 54.886 (iv) 54.565 (v) 58.818 (vi) 58.503 (vii) 56.454 (viii) 59.459 (ix) 53.407 (x) 53.562	(i) 59.566 (ii) 61.734 (iii) 56.912 (iv) 57.473 (v) 67.288 (vi) 63.089 (vii) 64.031 (viii) 61.659 (ix) 57.036 (x) 57.967
Mean vehicle mileage (km/l)	56.604	55.877	60.766
SD vehicle mileage (km/l)	3.990145	2.27811	3.482178

From the data, Rolling Resistance Coefficients also known as RRCs (µ) can be evaluated and the table below consists of Rolling resistance constant values for the entire project.

Table 4.2: RRC values of different types of roads

Road surface	Mastic Asphalt	Bituminous	Cement Concrete
RRCs	1. 0.0181 2. 0.0177 3. 0.0194 4. 0.0195 5. 0.0172 6. 0.0169 7. 0.0163 8. 0.0166 9. 0.0185 10. 0.0182	1. 0.0183 2. 0.0178 3. 0.0182 4. 0.0181 5. 0.0169 6. 0.0172 7. 0.0174 8. 0.0168 9. 0.0187 10. 0.0186	1. 0.0167 2. 0.0162 3. 0.0173 4. 0.0172 5. 0.0147 6. 0.0158 7. 0.0154 8. 0.0161 9. 0.0173 10. 0.0169
Mean RRC	0.01784	0.0178	0.01636
SD RRC	0.00111	0.00069	0.00088
Median RRC	0.0179	0.01795	0.01645
Skewness of RRCs	0.178187706	-0.197139397	-0.551609864

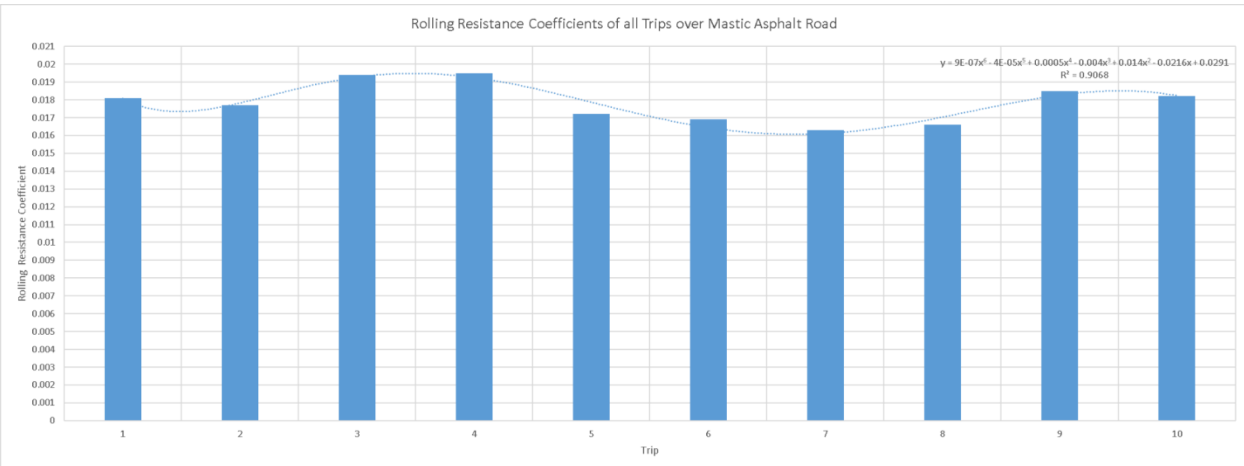

Figure 4(a): RRCs of all trips over mastic asphalt road

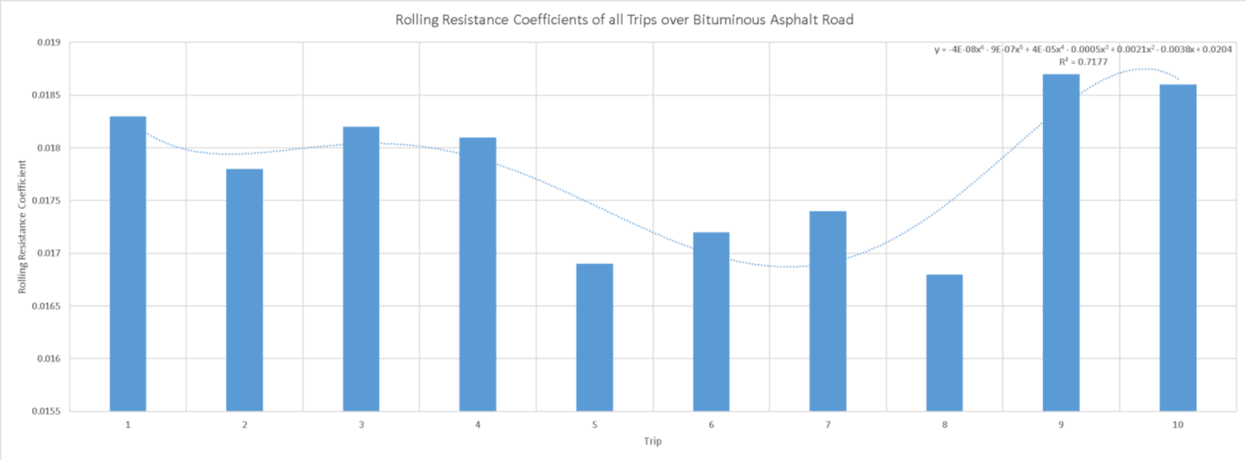

Figure 4(b): RRCs of all trips over bituminous asphalt road

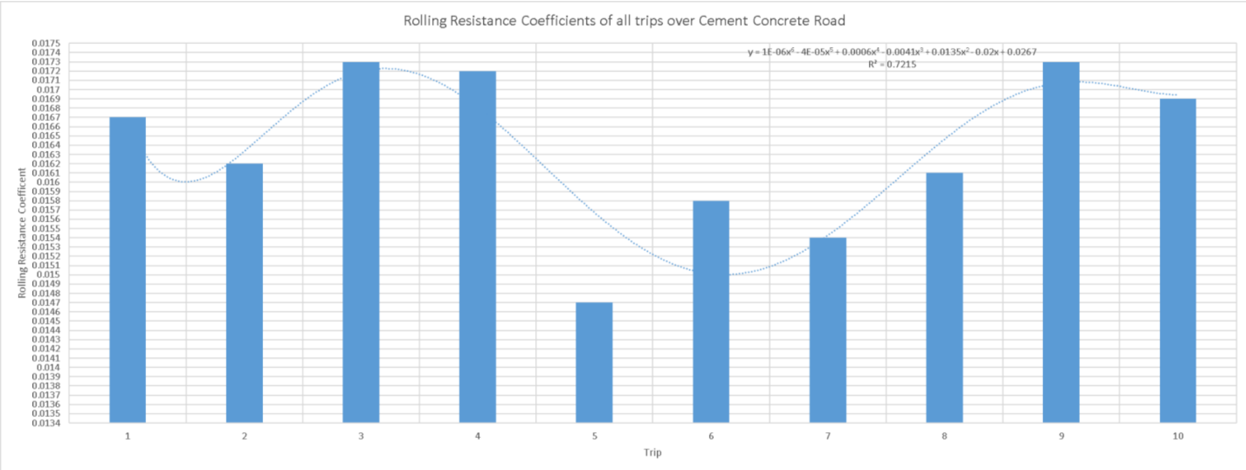

Figure 4(c): RRCs of all trips over cement concrete road

Calculations for different required parameters like (i) Frictional resistance force, (ii) Aerodynamic drag resistance force, (iii) Total resistance force, (iv) total tractive force, (v) wheel torque, (vi) Total transmission ratio etc. were done carefully. This is repeated for all of the trips.

The parameters needed for this experiment are:

i. Total weight on vehicle (M)= Weight of vehicle + Weight of riders= 148+152.76=300.76 kg
ii. Frictional constant of mastic asphalt road with respect to the vehicle tires (µ1)= 0.01784
iii. Frictional constant of asphalt bitumen road with respect to the vehicle tires (µ2)= 0.0178
iv. Frictional constant of cement concrete road with respect to vehicle tires (µ3) = 0.01636
v. Frontal area taken (A)= Overall vehicle height including ground clearance * Overall vehicle width= {(1.06+0.165) *0.765} = 0.9371 m^2
vi. Gravitational acceleration (g)= 9.81 m/s^2

vii. Fixed one gear (2nd gear) with compression ratio= 9.8:1
viii. Air density (þ)= 1.23 kg/m^3
ix. Wheel radius (r_d)= 0.2159 m
x. Coefficient of drag force (c)= 1.8

Rolling resistance force can be calculated by multiplying the total mass of a vehicle including riders with gravitational acceleration and cosine of gradient, which is zero here and the coefficient of friction.

Rolling Resistance Force for Mastic Asphalt Road = M * g * cos0 * µ1
= 300.76 * 9.81 * 1 * 0.01784 N
= 52.636 N

Rolling Resistance Force for Asphalt Bituminous Road = M * g * cos0 * µ2
= 300.76 * 9.81 * 1 * 0.0178 N
= 52.518 N

Rolling Resistance Force for Cement Concrete Road = M * g * cos0 * µ3
= 300.76 * 9.81 * 1 * 0.01636 N
= 48.269 N

Aerodynamic drag force can be measured using the value of air density, frontal area, drag force coefficient and square of velocity.

Aerodynamic force = 0.5 * þ * A * c * v^2
= 0.5 * 1.23 * 0.9371 * 1.8 * v^2
= 1.0373697 * v^2

Therefore,
Total Resistance Force for Mastic Asphalt Road = 52.636 + 1.0373697v^2 N

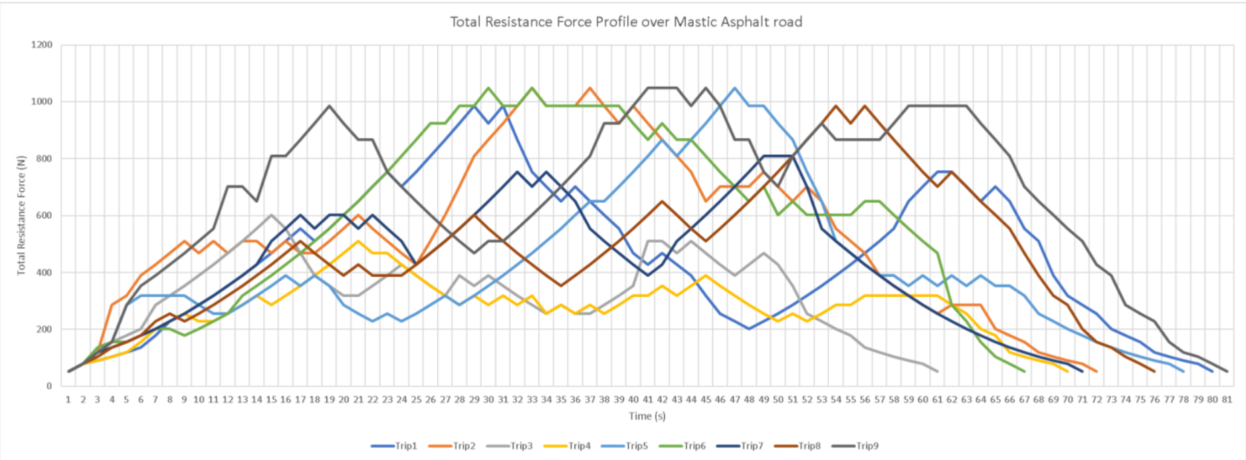

Figure 4(d): Total resistance force profile over mastic asphalt road

Total Resistance Force for Asphalt Bituminous Road = $52.518 + 1.0373697v^2$ N

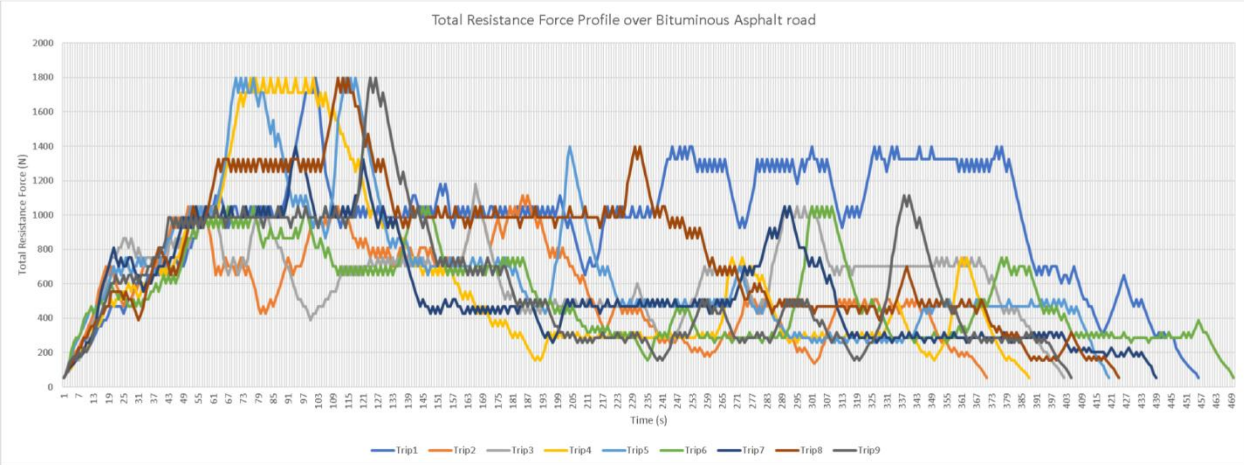

Figure 4(e): Total resistance force profile over bitumen asphalt road

Total Resistance Force for Concrete cement road = $48.269 + 1.0373697v^2$ N

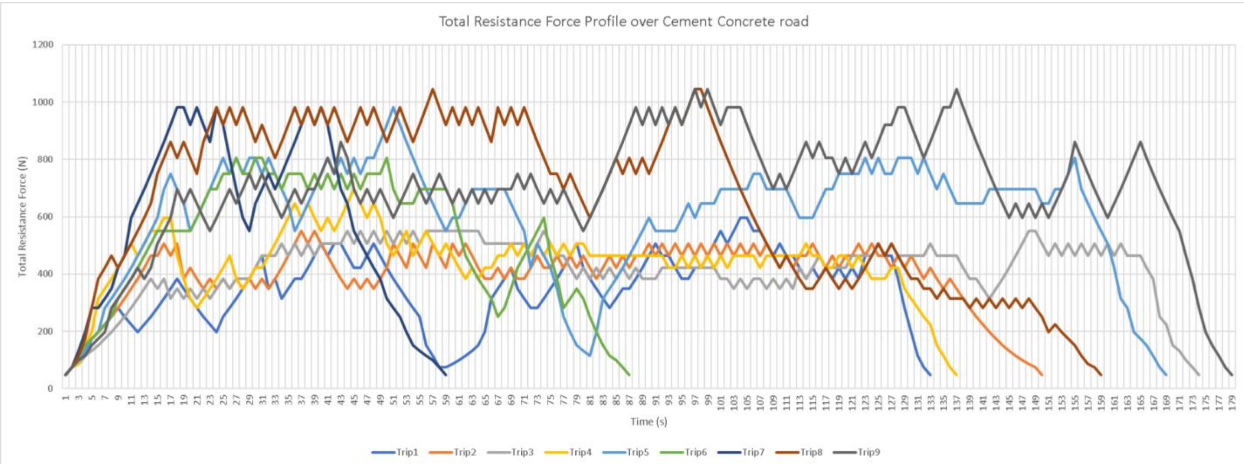

Figure 4(f): Total resistance force profile over concrete cement road

Now, total tractive force can be measured by using total resistance force and acceleration of the vehicle.

Total Tractive Force for Mastic Asphalt Road (F_{t1}) = $52.636 + 1.0373697v^2$ + C̆ *M*acceleration N

Total Tractive Force for Bituminous Road (F_{t2}) = $52.518 + 1.0373697v^2$ + C̆ *M*acceleration N

Total Tractive Force for Concrete Road (F_{t3}) = $48.269 + 1.0373697v^2$ + Ꞇ *M*acceleration N

Here, Ꞇ is Mass Factor that can be calculated by using the formula with gear ratio (ε). The formula is $1.04 + 0.0025*\varepsilon^2$; where ε = 9.8

So, Ꞇ = 1.2801 and as M = 300.76 kg

Then,
Total Tractive Force for Mastic Asphalt Road (F_{t1}) = $52.636 + 1.0373697v^2 + 385$ * acceleration N

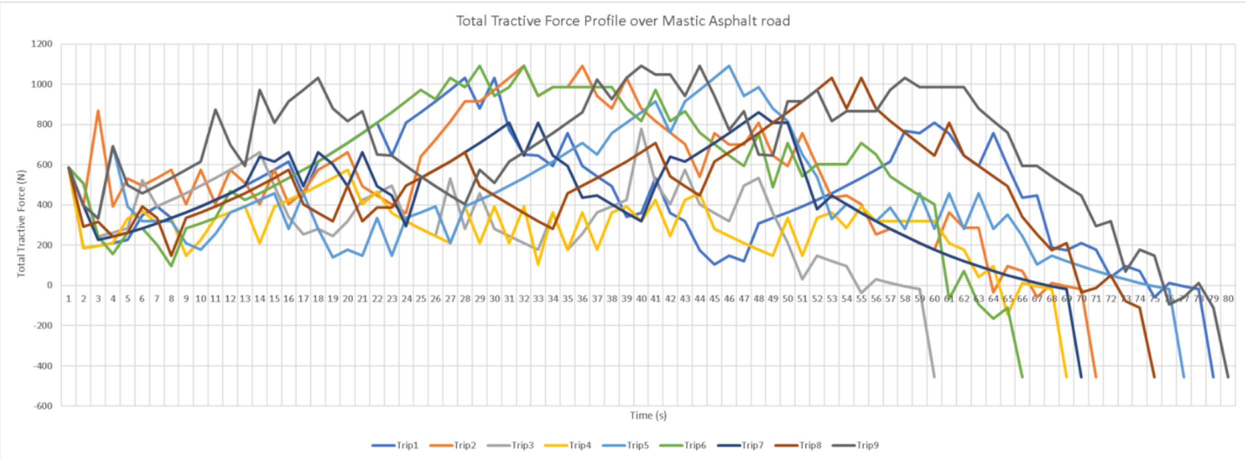

Figure 4(g): Total tractive force profile over mastic asphalt road

Total Tractive Force for Bituminous Road (F_{t2}) = $52.518 + 1.0373697v^2+385$ * acceleration N

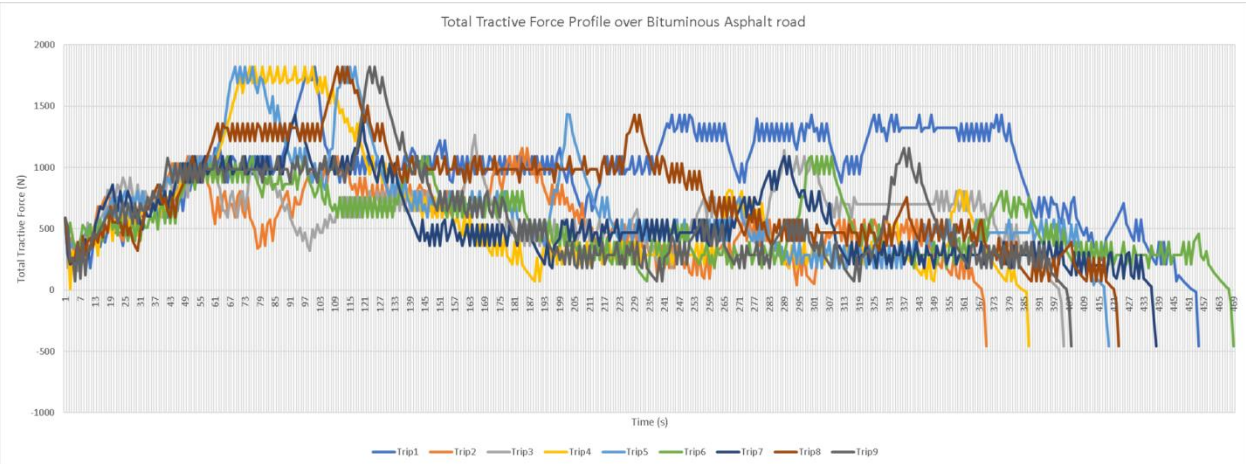

Figure 4(h): Total tractive force profile over bituminous asphalt road

Total Tractive Force for Concrete Road (F_{t3}) = 48.269 + 1.0373697v^2 + 385 * acceleration N

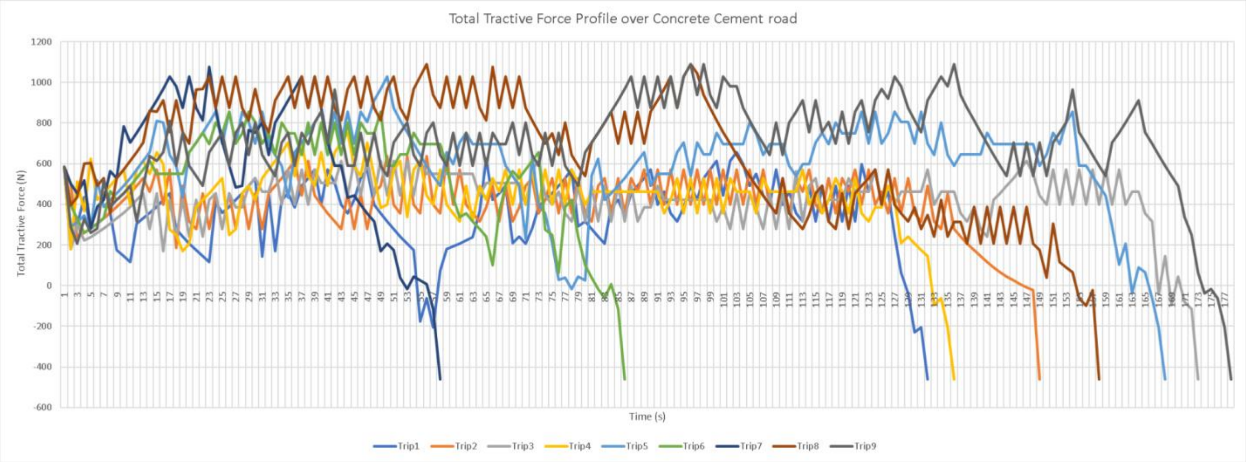

Figure 4(i): Total tractive force profile over cement concrete road

After that, wheel torque can be calculated by tractive force multiplied with wheel radius 0.2159 m.

Wheel Torque (T_{w1}) for Mastic Asphalt Road = $F_{t1} * r_d$ Nm

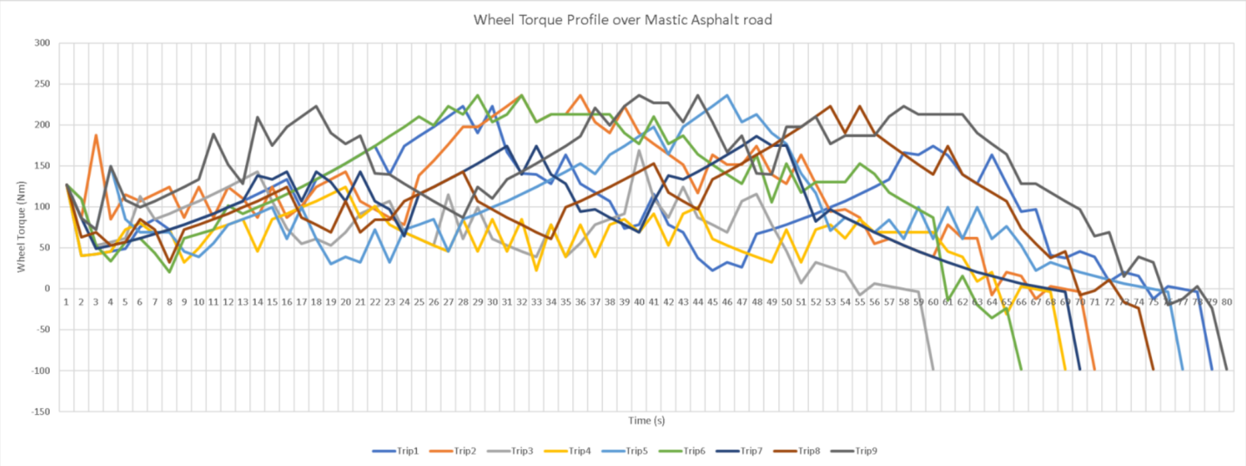

Figure 4(j): Wheel torque profile over mastic asphalt road

Wheel Torque (T_{w2}) for Bituminous Asphalt Road = $F_{t2} * r_d$ Nm

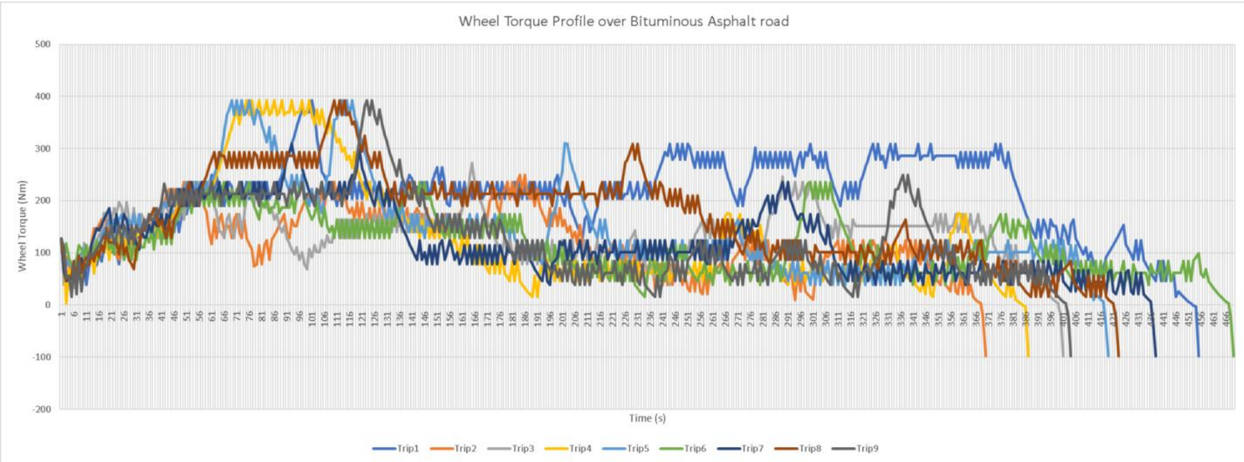

Figure 4(k): Wheel torque profile over bitumen asphalt road

Wheel Torque (T_{w3}) for Cement Concrete Road = $F_{t3} * r_d$ Nm

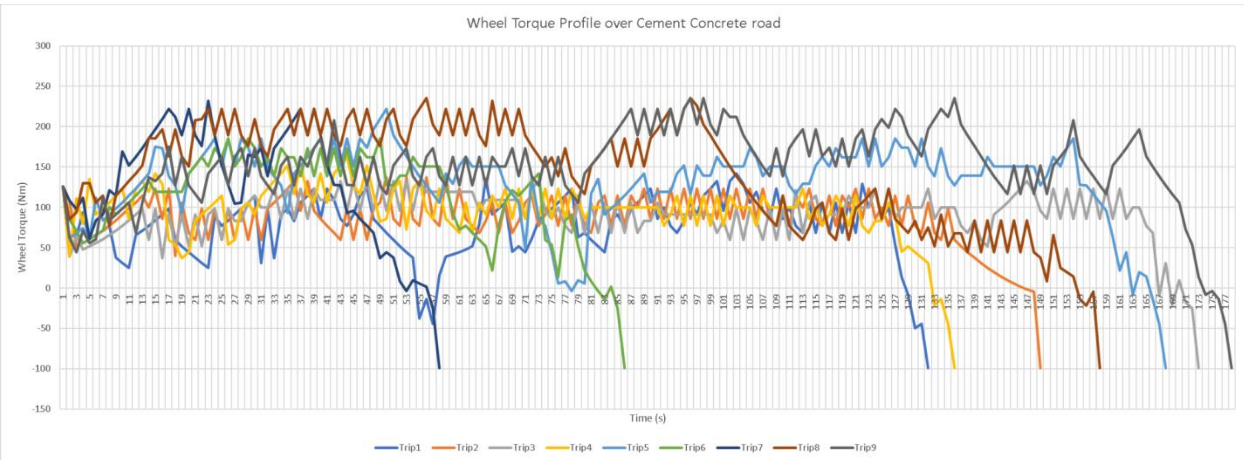

Figure 4(l): Wheel torque profile over concrete cement road

A maximum power of 10.3 kW @ 8500 rpm and maximum torque of 13.4 Nm @ 6500 rpm vehicle, had been taken into account, which purposefully used a fixed (2nd) gear compression ratio of 9.8:1.

Desirable Transmission Ratio over Mastic Asphalt road = $T_{w1}/(13.4*9.8) = T_{w1}/131.32$

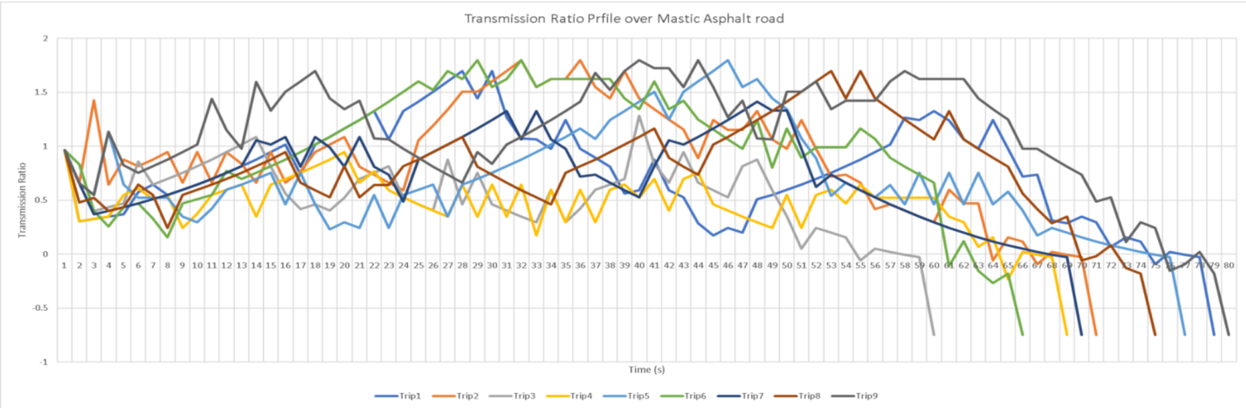

Figure 4(m): Transmission ratio profile over mastic asphalt road

Desirable Transmission Ratio over Bituminous Asphalt road = $T_{w2}/(13.4*9.8) = T_{w2}/131.32$

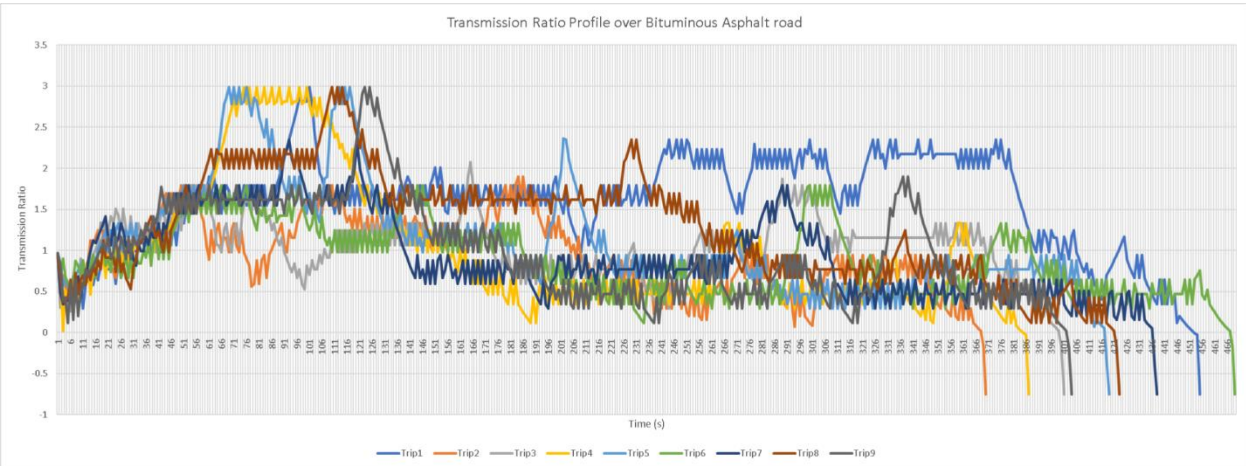

Figure 4(n): Transmission ratio profile over bituminous asphalt road

Desirable Transmission Ratio over Cement Concrete road = $T_{w3}/(13.4*9.8) = T_{w3}/131.32$

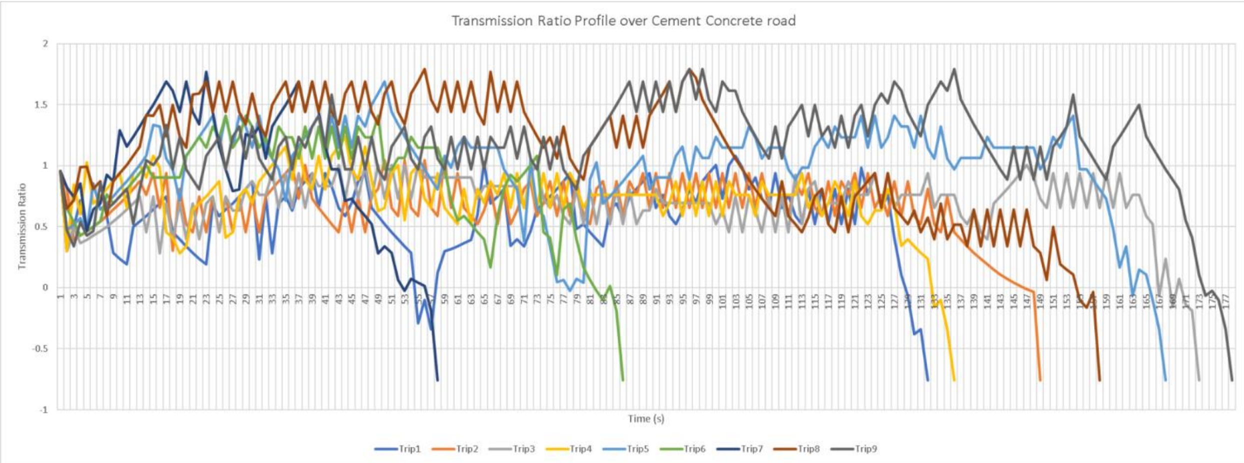

Figure 4(o): Transmission ratio profile over cement concrete road

4.1 Capital Cost Analysis

Mastic and Bituminous Asphalt Roads require more frequent repair and maintenance than cement concrete roads. Concrete Roads require approximately 1/12th of annual maintenance cost of asphalt roads.

Different costs for various types of roads are taken from [65].

Approximate construction cost to make a 1 km length ofmastic asphalt road=Capital cost/ some major amount of initial investment

=[{Road carriage cost (assuming 15 km distance between from stackyard to worksite where experimentation was conducted @ 11.1 Rs./km) + Carriage of materials} +{Loading-unloading cost} + {Materials cost (sand, stone chips, bitumen etc.)} + {Labor cost (assuming 20 unskilled, 15 semiskilled, 10 skilled, 5 highly skilled, and 2 specially trained personnel (1 supervisor 1 engineer) working 6 days to make 1 km road stretch) + Tools and plants cost + Machinery cost etc.} + {Formwork cost (considering 0)} + (Overhead charges) + (Contractor's profit) + (Welfare cess) etc.]

= [{(15*11.1 +77 + 65 +75)/ (3.555*0.05)} + {(169 + 8.4 + 8.4 + 8.4) *1.133/(3.555*0.05)} +[(1430+1234+1564+1914 + 174)/ (3.555*0.05)+{(0.011428*291.528*3.555)+(0.022*298.528*3.555) + (0.02058*291.528*3.555) + (0.0314*291.528*3.555) +(0.00114*291.528*3.555)+ (0.000028*291.528*3.555)}] + {(308*20)+(339*15)+(373*10)+(410*5)+(1165*1)+(1800*1)) *6 + (0.0003*1.4)/ (3.555*0.05) + (0.0003*1.4)/(3.555*0.05)} + 0 + 10% of previous total + 10% of previous total + 1% of total cost]*1000

= [2157.52 + 1237.85 + 35622.78 + 119940.47 + 0 + 0.1*158958.62 + 0.1*174854.48 + 0.01*1923339.97]* 1000

= 1942630 Rs.

Approximate construction cost to make a 1 km length of bituminous asphalt road = Capital cost/ some major amount of initial investment

= [{Road carriage cost (assuming 15 km distance between from stackyard to worksite where experimentation was conducted @ 11.1 Rs. /km) + Carriage of materials} + {Loading-unloading cost} + {Materials cost (sand, stone chips, dust, bitumen etc.)} + {Labor cost (assuming 20 unskilled, 15 semiskilled, 10 skilled, 5 highly skilled, and 2 specially trained personnel (1 supervisor 1 engineer) working 6 days to make 1 km road stretch) + Tools and plants cost + Machinery cost etc.} + {Formwork cost (considering 0)} + (Overhead charges) + (Contractor's profit) + (Welfare cess) etc.]

= [{(15*11.1 + 77 + 65 +75 + 55)/ (3.75*0.1)} + {(169 + 8.42 + 8.4 + 8.45 + 0.58 + 0.104) *1.133/ (3.75*0.1)} + [(1430 + 1234 + 1564 + 1914 + 174 + 1049.7)/ (3.75*0.1) + {(0.011428*1532.656*3.75) + (0.022*1532.656*3.75) + (0.02058*1532.656*3.75) + (0.0314*1532.656*3.75) + (0.00114*1532.656*3.75) + (0.000028*1532.656*3.75) + (0.043*1532.656*3.75)}] + {(308*20)+(339*15)+(373*10)+(410*5)+(1165*1)+(1800*1)) * 6 + (0.0003*1.45)/ (3.75*0.1) + (0.0003*1.42)/ (3.75*0.1) + (0.0006*1.75)/ (3.75*0.1)} + 0 + 10% of previous total + 10% of previous total + 1% of total cost] * 1000

= [1169.33 + 589.02 + 20387.78 + 119940.74 + 0 + 0.1*142086.69 + 0.1*154536.86 + 0.01*202835.74] * 1000

= 2297450 Rs.

Approximate construction cost to make a 1 km length of cement concrete road = Capital cost/ some major amount of initial investment

= [{Road carriage cost (assuming 15 km distance between from stackyard to worksite where experimentation was conducted @ 11.1 Rs. /km) + Carriage of materials} + {Loading-unloading cost} + {Materials cost (sand, stone chips, cement, binding reinforcement bar etc.)} + {Labor cost (assuming 24 unskilled, 18 semiskilled, 12 skilled, 6 highly skilled, and 2 specially trained personnel (1 supervisor 1 engineer) working 7 days to make 1 km road stretch) + Tools and plants cost + Machinery cost etc.} + {Formwork/scaffolding cost} + (Overhead charges) + (Contractor's profit) + (Welfare cess) etc.]

= [{(15*11.1 + 77 + 65 +75 + 56.66)/ (4.655*0.15)} + {(169 + 8.42 + 8.45 + 8.45 + 0.532) *1.133/ (4.655*0.15)} + [(1430 + 1234 + 1564 + 1914 + 6056 + 49730)/ (4.655*0.15) + {(0.9*583.631*4.655) + (0.45*583.631*4.655) + (0.42*583.631*4.655) + (0.01*583.631*4.655) + (0.016*583.631*4.655) + (0.001107*583.631*4.655) + (0.00176*583.631*4.655) + (0.00011*583.631*4.655) +(0.20571*583.631*4.655)}] + {(308*24)+(339*18)+(373*12)+(410*6)+(1165*1)+(1800*1)) * 7 + (0.0003*1.5)/ (4.655*0.15) + (0.0003*1.45)/ (4.655*0.15)} + 3.75% of materials cost + 10% of previous total + 10% of previous total + 1% of total cost] * 1000

= [630.38 + 316.18 + 94136.66 +234536.34 + 3530.14 + 0.1*333129.72 + 0.1*366442.67 + 0.01*370107.14] * 1000

= 4068080 Rs.

4.2 Maintenance Cost Analysis

As asphalt roads does not require regular maintenance, periodical routine checkup has to be done (assuming lifespan of 20 years and regular checkup).

Approximate per 1 scheduled maintenance cost of 1 km stretch of mastic asphalt road = [Restoration of rain cuts + (Maintenance filling with fresh soil for shoulder + Maintenance filling with stripping excess soil for shoulder + {Filling or repairing potholes and patch repairs) + Crack filling + Dusting + Fog seal + Crack prevention courses + Slurry seal + Surface dressing} (cost of materials to be added)+ Repairments of joints + Removal and repair of old joints + Micro surfacing etc.]

=[115/ (3.555*0.05) + (39.1 + 14 + 23.2 + 39.1)/ 0.05 + 0.7 + (0.2 + 1.3 + 3.3 + 1.39 + 5.4)/ 0.05 + 633.2 + 69 + 13/ 0.05] * 1000/ 20

= [646.98 + 2308 + 0.7 + 231.87 +702.22 + 260] * 1000/ 20

= 207491 Rs.

In the case of bituminous roads, they need regular maintenance (assuming lifespan of 10 years).

Approximateper 1 scheduled maintenance cost of 1 km stretch of bituminous asphalt road = [Restoration of rain cuts + (Maintenance filling with fresh soil for shoulder + Maintenance filling with stripping excess soil for shoulder + {Filling or repairing potholes and patch repairs) + Crack filling + Dusting + Fog seal + Crack prevention courses + Slurry seal + Surface dressing} (cost of materials to be added) + Repairments of joints + Removal and repair of old joints + Micro surfacing etc.]

=[115/ (3.75*0.1) + (39.1 + 14 + 23.2 + 39.1)/ 0.1 + 0.7 + (0.2 + 1.3 + 3.3 + 2.2 + 6)/ 0.1 + 633.2 + 69 + 13/ 0.1] *1000 /10

= [306.67 + 1154 + 0.7 + 130 + 702.22 + 130] * 1000/ 10

= 242481 Rs.

As cement concrete roads do not require much maintenance, assuming 40 years lifespan of concrete cement roads.

Approximate per 1 scheduled maintenance cost of 1 km stretch of concrete cement road = [Restoration of rain cuts + (Maintenance filling with fresh soil for shoulder + Maintenance filling with stripping excess soil for shoulder) + (Dusting + Surface dressing) (cost of materials to be added) + Repairment of joints + Removal and repair of old joints + (Micro surfacing + Removal of existing cement concrete coat including full disposal +Guniting concrete surface with cement mortar applied with compressor and epoxy complete +Patching and curing of damaged concrete surface + Applying epoxy mortar over leached, honeycombed and spoiled concrete surface + Removal of defective concrete, cleaning thoroughly and mechanically with compressed air + Applying prepacked cement based mortar at 28 days for replacement of old concrete + epoxy bonding of new concrete to old concrete) + Providing and inserting nipples after drilling holes for grouting +Replacement of expansion joints complete]

= [115/ (4.655*0.15) + (39.1 + 14)/ 0.15 + (0.2 + 5.4)/ 0.15 + 633.2 + 69 + (13 + 180.8 + 608 + 2571 + 482 + 129.7 + 101.2 + 538.9)/ 0.15 +125 + 753.8] * 1000/ 40

= [164.74 + 354 + 37.33 + 633.2 + 63 + 30156 + 125 + 753.8] * 1000/ 40

=576717 Rs.

4.3 Fuel Cost Analysis

For fuel consumption of the vehicle, assuming 6 days a week and 300 days annually, it had to travel daily on an average of 40 km to simplify the work, let it be used for this purpose.

So,
Annual Fuel (petrol) consumption for mastic asphalt road = 40*6*300/56.604 = 1271.9949 liter

Annual Fuel (petrol) consumption for bitumen asphalt road = 40*6*300/55.877 = 1288.5445 liter

Annual Fuel (petrol) consumption for cement concrete road = 40*6*300/60.766 = 1184.8731 liter

Then,
Average Annual Fuel Cost of the vehicle over mastic asphalt road
={(100.36 + 102.15 + 111.35 + 104.67 + 102.42 + 104.67 + 104.67 + 108.05 + 102.47 + 113.235 + 103.96 + 106.39)/ 12} * 1271.9949
=105.3663 * 1271.9949 = 134025.33 Rs.

Average Annual Fuel Cost of the vehicle over bituminous road
= {(100.36 + 102.15 + 111.35 + 104.67 + 102.42 + 104.67 + 104.67 + 108.05 + 102.47 + 113.235 + 103.96 + 106.39)/ 12} * 1288.5445
=105.3663 * 1288.5445 = 135769.17 Rs.

Average Annual Fuel Cost of the vehicle over cement concrete road
= {(100.36 + 102.15 + 111.35 + 104.67 + 102.42 + 104.67 + 104.67 + 108.05 + 102.47 + 113.235 + 103.96 + 106.39)/ 12} * 1184.8731
= 105.3663 * 1184.8731 = 124845.69 Rs.

Table 4.3: Cost comparison over different roads

Road material	Mastic Asphalt	Bituminous Asphalt	Cement Concrete
Capital Cost (Rs.)	1942630	2297450	4068080
Maintenance Cost (Rs.)	207491	242481	576717
Annual Fuel Cost (Rs.)	134025.33	135769.17	124845.69

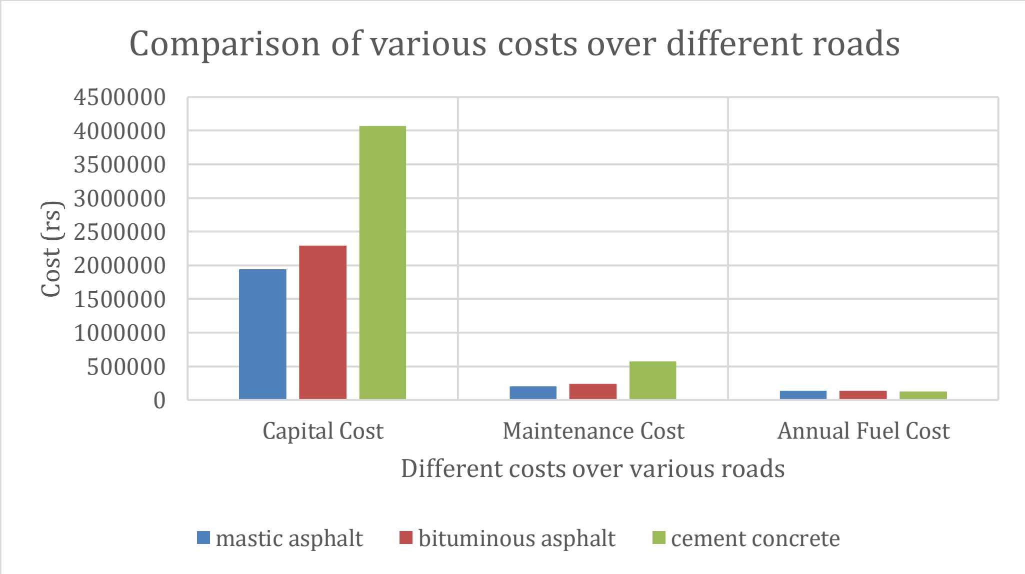

Figure 4(p): Comparison of various costs over different road surfaces

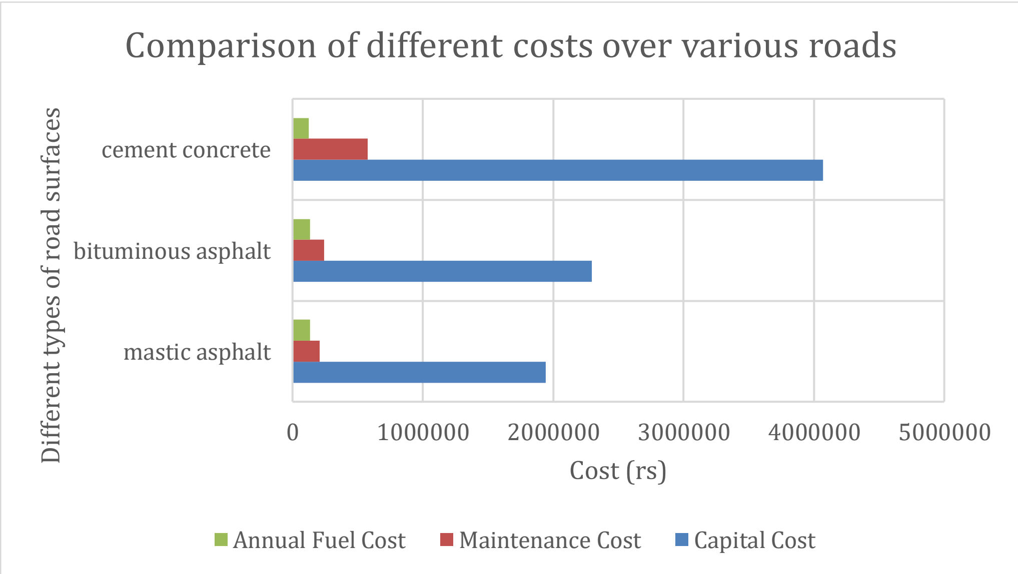

Figure 4(q): Comparison of different costs over various road surfaces

4.4 Emission Calculation

Table 4.4: Emission Factors of pollutants during full burning of petrol for two wheelers (kg/kWh) [58]

CO_2	0.2668
CO	0.00984
NO_x	0.0160258
CH_4	0.00236
SO_2	0.00000726
PM2.5	0.00156
PM10	0.0017

Density of petrol = 0.737 kg/l

Gross calorific value of petrol (GCV) = 12.89 kWh/kg

CO_2 emission during full burning of 1 liter of petrol = 0.2668 * 0.737 * 12.89 = 2.534581 kg

CO emission during full burning of 1 liter of petrol = 0.00984 * 0.737 * 12.89 = 0.0934793 kg

NO_x emission during full burning of 1 liter of petrol = 0.0160258 * 0.737 * 12.89 = 0.15224398 kg

CH_4 emission during full burning of 1 liter of petrol = 0.00236 * 0.737 * 12.89 = 0.0224198 kg

SO_2 emission during full burning of 1 liter of petrol = 0.00000726 * 0.737 * 12.89 = 0.0000689 kg

PM2.5 emission during full burning of 1 liter of petrol = 0.00156 * 0.737 * 12.89 = 0.01481989 kg

PM10 emission during full burning of 1 liter of petrol = 0.0017 * 0.737 * 12.89 = 0.01614988 kg

Table 4.5: Pollutants emissions produced in combustion of 1 liter of Petrol

CO_2 (kg/l)	CO (kg/l)	NO_x (kg/l)	CH_4 (kg/l)	SO_2 (kg/l)	PM2.5 (kg/l)	PM10 (kg/l)
2.53	0.093	0.152	0.022	0.000068	0.0148	0.016

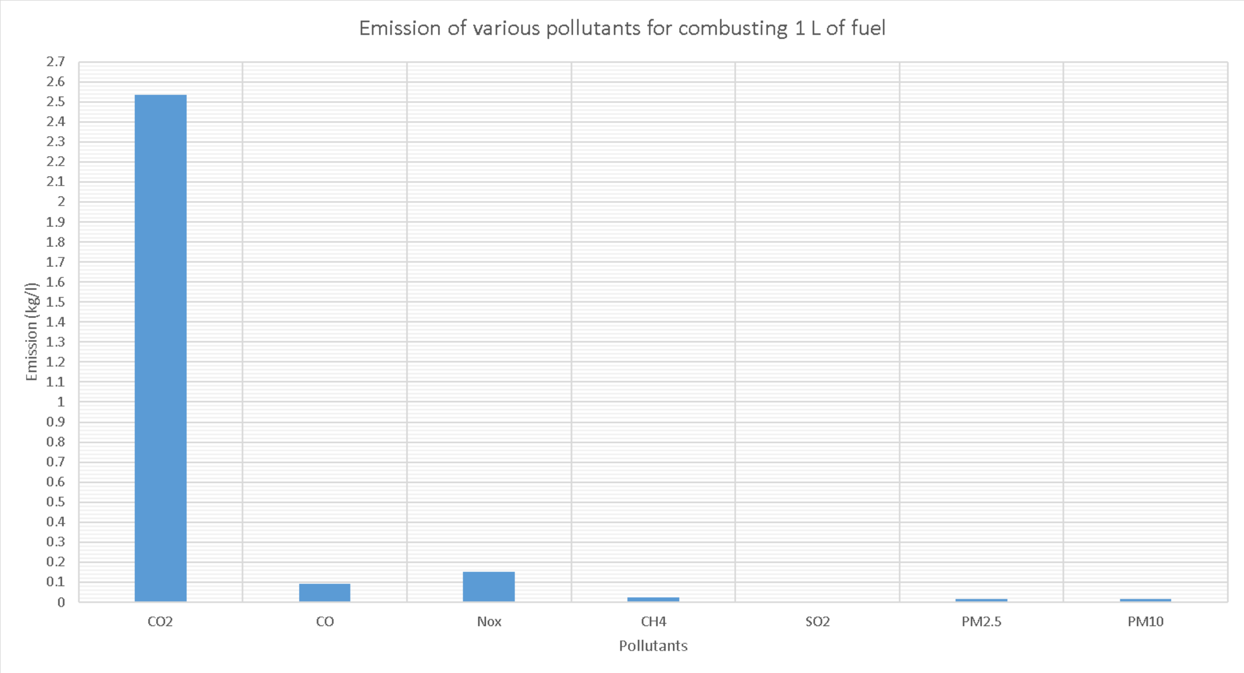

Figure 4(r): Emission comparison of different emission factors for full combustion

Average annual CO_2 emission over mastic asphalt road = 2.534581 * 1271.9949 = 3223.974 kg

Average annual CO_2 emission over bituminous road = 2.534581 * 1288.5445 = 3265.9204 kg

Average annual CO_2 emission over concrete road = 2.534581 * 1184.8731 = 3003.15685 kg

Average annual CO emission over mastic asphalt road = 0.0934793 * 1271.9949 = 118.90519 kg

Average annual CO emission over bituminous road = 0.0934793 * 1288.5445 = 120.4522379 kg

Average annual CO emission over concrete road = 0.0934793 * 1184.8731 = 110.761108 kg

Average annual NO_x emission over mastic asphalt road = 0.15224398 * 1271.9949 = 193.654 kg

Average annual NO_x emission over bituminous road = 0.15224398 * 1288.5445 = 196.173143 kg

Average annual NO_x emission over concrete road = 0.15224398 * 1184.8731 = 180.3897965 kg

Average annual CH_4 emission over mastic asphalt road = 0.0224198 * 1271.9949 = 28.51787 kg

Average annual CH_4 emission over bituminous road = 0.0224198 * 1288.5445 = 28.88890998 kg

Average annual CH_4 emission over concrete road = 0.0224198 * 1184.8731 = 26.56461793 kg

Average annual SO_2 emission over mastic asphalt road = 0.0000689 * 1271.9949 = 0.087641 kg

Average annual SO_2 emission over bituminous road = 0.0000689 * 1288.5445 = 0.088780716 kg

Average annual SO_2 emission over concrete road = 0.0000689 * 1184.8731 = 0.081637756 kg

Average annual $PM_{2.5}$ emission over mastic asphalt road = 0.01481989 * 1271.9949 = 18.85 kg

Average annual $PM_{2.5}$ emission over bituminous road = 0.01481989 * 1288.5445 = 19.09088 kg

Average annual $PM_{2.5}$ emission over concrete road = 0.01481989 * 1184.8731 = 17.5596891 kg

Average annual PM_{10} emission over mastic asphalt road = 0.01614988 * 1271.9949 = 20.543 kg

Average annual PM_{10} emission over bituminous road = 0.01614988 * 1288.5445 = 20.809839 kg

Average annual PM_{10} emission over concrete road = 0.01614988 * 1184.8731 = 19.13555838 kg

Table 4.6: Average Annual Pollutants Emissions over various types of roads

Road Surface	CO2 (kg/l)	CO (kg/l)	NOx (kg/l)	CH4 (kg/l)	SO2 (kg/l)	PM2.5 (kg/l)	PM10 (kg/l)
Mastic	3223.974	118.905	193.654	28.51787	0.087	18.85	20.54
Bituminous	3265.920	120.452	196.173	28.888	0.088	19.09	20.809
Concrete	3003.1568	110.761	180.389	26.564	0.081	17.55	19.135

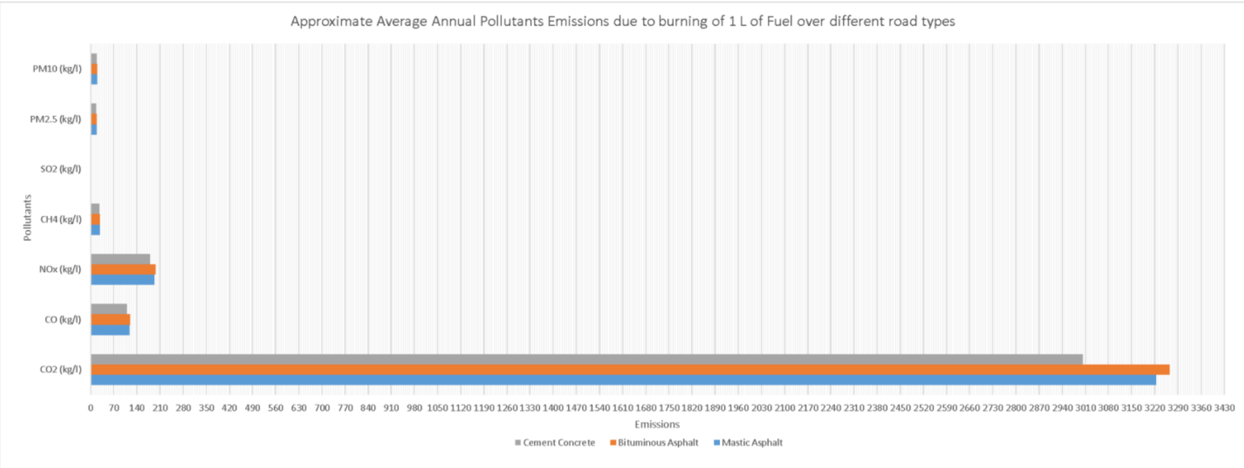

Figure 4(s): Approximate average annual emission parameters over various road surfaces

For emission parameters for the study region Jadavpur, Kolkata, India, the continuous air quality data had been taken from CPCB. And, it had been found that ambient air quality is more or less okayish for this study area. Benzene emission is slightly higher for this region and CO_2 emissions data could not be collected which is one of the disadvantages as it is one of the major emission parameters.

Table 4.7: Some Sample Standard Values for Emission Parameters at Jadavpur

Prescribed Standards		0-60	0-100	0-80	0-80	0-80	0-400	0-80	0-4	0-180	0-5	0-5	0-5	0-5	NA	NA	NA	NA	NA	NA	NA	NA
Exceeding Standards		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Unit		ug/m3	ug/m3	ug/m3	ug/m3	ppb	ug/m3	ug/m3	mg/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	%	m/s	degree	W/m2	mmHg	m/s	•C	ug/m3
From Date	To Date	PM2.5	PM10	NO	NO2	NOx	NH3	SO2	CO	Ozone	Benzene	Toluene	Eth-Benzene	MP-Xylene	RH	WS	WD	SR	BP	VWS	AT	O Xylene
23-05-2022 00:00	23-05-2022 00:15	55.7	103	18.7	20.1	38.7	6.4	6.4	0.76	14.51	7.11	3.6	0.06	0.18	99.09	0.28	268.53	16.73	973.4	0.02	26.56	16.73
23-05-2022 00:15	23-05-2022 00:30	62.7	104	18.7	20.5	39.2	6	6.8	0.73	8.68	7.39	3.77	0.06	0.17	99.1	0.08	40.17	17.74	973.1	0.01	26.47	17.74
23-05-2022 00:30	23-05-2022 00:45	63	104	19.3	19.2	38.4	6.1	6.3	0.8	10.43	6.13	3.3	0.07	0.19	99.1	0.04	151.63	17.38	973.4	0.05	26.57	17.38
23-05-2022 00:45	23-05-2022 01:00	63	104	24.4	19.6	44	6.5	6.2	0.74	8.65	5.56	3.02	0.06	0.19	99.13	0.34	274.7	17.05	973	0.02	26.42	17.05
23-05-2022 01:00	23-05-2022 01:15	63	104	19.8	20.6	40.4	6.3	5.8	0.57	15.68	7.9	3.98	0.06	0.18	99.13	0.16	82.38	16.98	972.9	0.04	26.41	16.98
23-05-2022 01:15	23-05-2022 01:30	56.9	95.6	29.1	22.7	51.8	7.2	6.1	0.61	4.8	7.03	3.62	0.06	0.18	99.11	0.09	303.21	17.01	973.1	0.02	26.45	17.01
23-05-2022 01:30	23-05-2022 01:45	56.5	95.1	21.9	20.1	41.9	6.6	7.5	0.58	9.31	4.47	2.49	0.06	0.18	99.11	0.27	101.08	17.89	973.6	0.02	26.64	17.89
23-05-2022 01:45	23-05-2022 02:00	56.5	95.1	18.8	19.1	37.9	6.3	7.3	0.61	10.09	3.93	2.19	0.06	0.18	99.1	0.13	344.42	17.54	973.7	0.02	26.68	17.54
23-05-2022 02:00	23-05-2022 02:15	56.5	95.1	17.1	18.3	35.4	6.4	7.3	0.42	16.85	7.8	3.77	0.06	0.17	99.09	0.36	108.22	17.94	973.8	0.02	26.71	17.94
23-05-2022 02:15	23-05-2022 02:30	49.6	104	14.4	18.7	33.1	6.1	6.4	0.47	9.95	7.75	3.74	0.06	0.16	99.1	0.2	285.73	16.24	973.6	0.02	26.63	16.24
23-05-2022 02:30	23-05-2022 02:45	49.2	104	14.8	18.3	33.1	6	6.7	0.47	13.56	8.13	3.87	0.06	0.15	99.14	0.41	289.59	16.02	972.5	0.01	26.24	16.02
23-05-2022 02:45	23-05-2022 03:00	49.2	104	14.9	18	32.9	6	6.4	0.44	10.48	7.44	3.56	0.05	0.13	99.15	0.12	62.29	16.5	972	0.02	26.08	16.5
23-05-2022 03:00	23-05-2022 03:15	49.2	104	16	18.5	34.5	6.2	6.1	0.4	9.74	7.86	3.76	0.05	0.14	99.15	0.15	10.16	16.68	972	0.02	26.05	16.68
23-05-2022 03:15	23-05-2022 03:30	47.9	87	19.3	19.5	38.8	6.4	6.2	0.36	8.9	8.4	3.98	0.05	0.14	99.15	0.22	303.48	16.46	971.8	0.02	25.99	16.46
23-05-2022 03:30	23-05-2022 03:45	47.8	86.2	17.1	18.4	35.4	6.2	6	0.42	7.12	8.02	3.85	0.06	0.13	99.15	0.2	47.11	16.92	971.5	0.01	25.88	16.92
23-05-2022 03:45	23-05-2022 04:00	47.8	86.2	16.7	18.4	35.1	6.1	5.6	0.41	6.04	7.56	3.61	0.05	0.11	99.15	0.18	52.18	16.86	971.5	0.02	25.89	16.86
23-05-2022 04:00	23-05-2022 04:15	47.8	86.2	16.3	18	34.3	6.3	5.8	0.37	11.39	9.49	4.38	0.05	0.12	99.15	0.19	94.33	16.65	971.5	0.02	25.88	16.65
23-05-2022 04:15	23-05-2022 04:30	45.6	83	15.9	18.8	34.6	6.3	5.6	0.38	8.56	9.24	4.25	0.05	0.12	99.16	0.25	290.88	16.28	971.1	0.02	25.75	16.28
23-05-2022 04:30	23-05-2022 04:45	45.5	82.9	14.9	18.4	33.3	5.9	6.3	0.34	12.25	8.29	3.8	0.04	0.11	99.15	0.11	4.61	16.9	970.6	0.02	25.56	16.9
23-05-2022 04:45	23-05-2022 05:00	45.5	82.9	19.4	18.4	37.8	6.4	4.9	0.37	8.14	7.35	3.33	0.04	0.09	99.17	0.04	85.78	17.88	970.6	0.02	25.57	17.88
23-05-2022 05:00	23-05-2022 05:15	45.5	82.9	18.5	18.6	37.1	6.4	5.6	0.39	12.37	9.1	4.06	0.04	0.1	99.17	0.08	25.96	23.02	970.4	0.02	25.51	23.02
23-05-2022 05:15	23-05-2022 05:30	45	79.9	21.6	19.2	40.8	6.8	4.9	0.45	5.99	9	4.09	0.04	0.11	99.15	0.11	287.26	30.6	971	0.02	25.7	30.6
23-05-2022 05:30	23-05-2022 05:45	44.9	79.7	22.8	18	40.7	6.6	5.3	0.54	9.33	7.75	3.6	0.04	0.1	99.15	0.13	348.13	39.88	971.9	0.02	26.02	39.88
23-05-2022 05:45	23-05-2022 06:00	44.9	79.7	20.8	18.7	39.4	6.4	4.8	0.39	13.73	6.6	3.05	0.04	0.09	99.12	0.26	19.58	57.35	973.5	0.02	26.59	57.35
23-05-2022 06:00	23-05-2022 06:15	44.9	79.7	16	18.5	34.5	6.2	5.3	0.38	13.55	8.58	3.94	0.04	0.1	99.09	0.35	97.04	75.28	975.4	0.02	27.29	75.28
23-05-2022 06:15	23-05-2022 06:30	48.9	86.4	13.8	17.7	31.6	5.9	5	0.35	12.13	8.1	3.7	0.04	0.1	99.08	0.28	78.95	99.54	976.5	0.02	27.7	99.54
23-05-2022 06:30	23-05-2022 06:45	49.1	86.8	13.1	17.7	30.9	5.8	5	0.38	12.88	7.09	3.2	0.04	0.08	99.07	0.14	51.54	114.9	978	0.02	28.2	114.94
23-05-2022 06:45	23-05-2022 07:00	49.1	86.8	12.1	18	30	5.9	5.5	0.32	18.77	7.68	3.44	0.03	0.08	99.05	0.35	81.6	184.2	979.9	0.02	28.89	184.2
23-05-2022 07:00	23-05-2022 07:15	49.1	86.8	10.7	17.9	28.6	5.7	6.4	0.31	28.54	8.42	3.71	0.04	0.08	99.04	0.65	101.77	153	980.2	0.01	28.99	152.95
23-05-2022 07:15	23-05-2022 07:30	45.8	79.1	8.5	17.9	26.3	5.9	5.7	0.21	26.6	7.64	3.36	0.03	0.08	99.02	0.55	97.68	252.6	981.2	0.01	29.36	252.6
23-05-2022 07:30	23-05-2022 07:45	45.6	78.7	8.7	18.1	26.8	5.6	6.1	0.33	23.42	6.41	2.76	0.03	0.07	99.04	0.74	90.41	138.1	980.6	0.01	29.14	138.13
23-05-2022 07:45	23-05-2022 08:00	45.6	78.7	8.7	17.9	26.6	5.7	6	0.25	32.39	5.38	2.34	0.02	0.06	98.98	0.44	75.84	167.3	982	0.02	29.63	167.33
23-05-2022 08:00	23-05-2022 08:15	45.6	78.7	8.3	17.7	26	5.7	6.1	0.21	35.56	6.64	2.87	0.03	0.06	99.01	0.48	66.89	172.6	981.5	0.01	29.47	172.55
23-05-2022 08:15	23-05-2022 08:30	42	78	7.1	17.5	24.6	5.6	5.7	0.22	30.18	7.24	3.1	0.03	0.06	97.65	0.9	106.32	312.7	983.1	0.02	30.05	312.66
23-05-2022 08:30	23-05-2022 08:45	41.8	78	6.8	17.4	24.2	5.5	6.5	0.17	45.24	5.51	2.41	0.02	0.05	97.07	0.57	83.9	209.1	983	-0.06	30.01	209.08
23-05-2022 08:45	23-05-2022 09:00	41.8	78	6	17.7	23.7	5.7	6.3	0.14	55.92	3.63	1.59	0.02	0.04	88.81	0.47	66.74	185.7	986.3	0.01	31.19	185.74
23-05-2022 09:00	23-05-2022 09:15	41.8	78	5.8	17.7	23.6	5.4	6.2	0.28	41.66	5.23	2.25	0.02	0.04	87.32	0.65	42.2	189	986.9	0.01	31.4	189
23-05-2022 09:15	23-05-2022 09:30	38.5	76.6	6.3	18.2	24.5	5.7	5.7	0.32	40.42	3.2	1.39	0.02	0.01	91.84	1	94.32	225.2	985.5	-0.02	30.89	225.23
23-05-2022 09:30	23-05-2022 09:45	38.3	76.5	6	17.1	23.2	5.7	6.6	0.25	47.68	3.84	1.62	0.01	0.04	84.29	0.54	51.45	230.2	987.7	0.01	31.67	230.2
23-05-2022 09:45	23-05-2022 10:00	38.3	76.5	5.9	16.5	22.4	5.7	6.3	0.25	47.76	4.62	1.94	0.01	0.05	83.35	0.77	98.83	234.8	988.3	-0.02	31.89	234.78
23-05-2022 10:00	23-05-2022 10:15	38.3	76.5	5.4	17.3	22.6	5.5	6.2	0.25	51.12	4.59	1.93	0.01	0.04	82.94	0.73	100.51	179	988	-0.01	31.77	179.02
23-05-2022 10:15	23-05-2022 10:30	40.1	66.7	5.4	17.4	22.8	5.6	6.2	0.26	43.76	4.65	2.02	0.01	0.04	80.16	0.94	97.62	400.6	988.4	0	31.95	400.56
23-05-2022 10:30	23-05-2022 10:45	40.3	66.2	5.2	17.2	22.4	5.5	6.1	0.21	59.31	4.31	2.06	0.02	0.04	76.71	0.98	99.9	662.8	990.1	-0.02	32.54	662.78
23-05-2022 10:45	23-05-2022 11:00	40.3	66.2	5.1	16.9	22	5.5	6.4	0.26	40.23	4.15	1.84	0.02	0.03	76.11	0.31	113.2	291.3	990.5	0	32.69	291.25
23-05-2022 11:00	23-05-2022 11:15	None	None	5.1	17	22.1	5.5	6.3	0.19	66.45	5.12	2.26	0.01	0.04	77.77	0.35	51.16	292.8	989.8	0.01	32.43	292.79
23-05-2022 11:15	23-05-2022 11:30	None	None	5.6	17.4	23.1	5.7	None	0.23	58.88	4.71	2.15	0.01	0.04	78.06	0.45	46.46	156.3	989.8	0.01	32.42	156.3
27-05-2022 17:00	27-05-2022 17:15	61.4	117	13.2	20.4	33.6	10.2	16.7	0.26	70.63	2.56	1.09	0.02	0.03	45.82	1.08	271.49	48.25	995.1	0.01	34.33	48.25
27-05-2022 17:15	27-05-2022 17:30	53.4	116	13.7	20.8	34.4	10	16	0.27	90.82	2.43	1.1	0.02	0.01	47.79	0.54	280.01	42.97	994.7	0.01	34.18	42.97
27-05-2022 17:30	27-05-2022 17:45	53.4	116	14	21.4	35.4	10.1	17.4	0.34	90.38	3.68	1.53	0.02	0.03	52.8	0.56	280.81	34.22	993.7	0	33.81	34.22
27-05-2022 17:45	27-05-2022 18:00	53.4	116	14.3	21.8	36.1	10	17.2	0.41	88.36	1.64	0.9	0.02	0.04	55.3	0.63	281.92	24.44	992.7	0.02	33.45	24.44
27-05-2022 18:00	27-05-2022 18:15	54	112	14.3	23.8	38.1	9.8	17.3	0.38	83.76	0.98	0.86	0.02	0.05	54.81	0.24	282.11	17.66	991.9	0.01	33.18	17.66
27-05-2022 18:15	27-05-2022 18:30	59.3	112	14.8	24.1	38.9	10.1	16.5	0.49	71.38	0.69	0.82	0.03	0.06	59.57	0.28	288.74	14.78	990.5	0.02	32.68	14.78
27-05-2022 18:30	27-05-2022 18:45	59.3	112	15.9	24.9	40.8	10.5	18.3	0.51	61.24	0.53	0.81	0.03	0.08	57.28	0.24	289.65	13.45	989.9	0.02	32.47	13.45
27-05-2022 18:45	27-05-2022 19:00	59.3	112	17.5	26.6	44.1	10.5	17.4	0.54	57.47	0.66	0.87	0.05	0.1	61.32	0.27	287.93	13.98	988.9	0.01	32.1	13.98
27-05-2022 19:00	27-05-2022 19:15	59.2	119	18.3	28.3	46.6	10.6	17.5	0.7	38.94	0.84	0.93	0.05	0.11	59.66	0.27	285.64	15.01	988.6	0.02	31.99	15.01
27-05-2022 19:15	27-05-2022 19:30	58.1	121	42.6	37.1	79.7	12.9	19.2	2.32	7.19	1.01	1.02	0.06	0.13	59.84	0.19	258.9	15.84	988.6	0.02	32	15.84
27-05-2022 19:30	27-05-2022 19:45	58.1	121	114	39.9	154	16.8	20.2	2.82	10.38	0.77	1.04	0.07	0.19	63.83	0.1	252.34	15.86	988.2	0.02	31.85	15.86
27-05-2022 19:45	27-05-2022 20:00	58.1	121	86	37.4	123	14.5	18.9	1.51	9.55	1.22	1.84	0.13	0.48	65.86	0.46	109.88	16.93	987.5	0.01	31.6	16.93
27-05-2022 20:00	27-05-2022 20:15	58.7	129	43.3	33.2	76.5	11.4	25.9	0.77	43.3	1.57	2.72	0.2	0.83	76.69	0.15	304.27	16.43	987.8	0.02	31.71	16.43
27-05-2022 20:15	27-05-2022 20:30	64	131	23.3	28.3	51.6	10.2	34.5	0.64	50.51	1.31	1.82	0.12	0.46	83.98	0.34	110.62	16.89	986.9	0.02	31.41	16.89
27-05-2022 20:30	27-05-2022 20:45	64	131	18.1	26.5	44.6	10.1	37.2	0.64	48.08	0.82	0.91	0.07	0.23	85.67	0.55	109.84	17.25	987.2	0.02	31.51	17.25
27-05-2022 20:45	27-05-2022 21:00	64	131	17.2	25.3	42.4	10.2	40.1	0.63	48.03	0.88	0.7	0.06	0.17	86.42	0.72	109.53	17.29	987.3	0.02	31.52	17.29
27-05-2022 21:00	27-05-2022 21:15	65.1	140	16.4	24.1	40.6	10.2	40.1	0.32	51.9	1.01	0.67	0.06	0.14	87.39	0.6	108.56	16.97	987.1	0.02	31.46	16.97
27-05-2022 21:15	27-05-2022 21:30	74.7	141	16.5	25	41.5	10.1	33.5	0.48	34.99	1.35	0.82	0.05	0.14	90.3	0.53	98.21	16.48	986.5	0.01	31.26	16.48
27-05-2022 21:30	27-05-2022 21:45	74.7	141	18.9	27.1	46	10.2	33.8	0.37	39.88	1.43	0.8	0.05	0.13	97.65	0.47	110.31	15.95	985.9	0.02	31.02	15.95
27-05-2022 21:45	27-05-2022 22:00	74.7	141	16.9	24.4	41.3	10.2	26.1	0.25	44.22	1.32	0.76	0.04	0.14	99.02	0.45	104.94	15.8	985.3	0.02	30.82	15.8
27-05-2022 22:00	27-05-2022 22:15	74.1	138	15.3	22.5	37.8	10.2	20	0.24	54.16	1.2	0.72	0.04	0.14	99.03	0.79	108.87	15.99	984.7	0.02	30.61	15.99
27-05-2022 22:15	27-05-2022 22:30	68.9	138	15	21.9	37	10.3	16.7	0.28	42.64	1.34	0.66	0.03	0.11	99.03	0.96	106.91	16.05	984.3	0	30.47	16.05
27-05-2022 22:30	27-05-2022 22:45	68.9	138	15.2	22.9	38.1	10.2	14	0.21	49.18	1.44	0.65	0.03	0.1	99.01	0.4	104.14	15.69	984	0.02	30.35	15.69
27-05-2022 22:45	27-05-2022 23:00	68.9	138	15.7	24.2	39.9	10.1	12.8	0.2	48.86	2.05	0.87	0.02	0.11	99	0.53	90.6	16.09	983.7	0.01	30.24	16.09
27-05-2022 23:00	27-05-2022 23:15	68.4	128	16	24.7	40.7	10	11.7	0.14	57.62	1.2	0.58	0.02	0.08	98.89	0.71	103.37	16.33	983.7	0.01	30.24	16.33
27-05-2022 23:15	27-05-2022 23:30	64	126	15.6	24.6	40.2	10.2	11.5	0.21	52.2	0.61	0.35	0.02	0.05	98.98	0.36	89.36	16.25	983.5	0.01	30.16	16.25
27-05-2022 23:30	27-05-2022 23:45	64	126	15.6	24.6	40.2	10	11.2	0.22	42.29	0.4	0.25	0.01	0.04	99	0.47	96.93	16.27	983	0.02	29.99	16.27
27-05-2022 23:45	28-05-2022 00:00	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
28-05-2022 00:00	28-05-2022 00:15	63.5	121	16.5	24.4	40.9	10.1	11.3	0.19	50.68	0.59	0.35	0.01	0.05	98.54	1.15	105.44	17.02	983.3	-0.01	30.09	17.02
28-05-2022 00:15	28-05-2022 00:30	60.2	120	15.1	22.7	37.8	9.9	10.6	0.12	48.91	0.54	0.33	0.01	0.04	99.01	1.33	107.03	16.59	983.1	-0.02	30.03	16.59
28-05-2022 00:30	28-05-2022 00:45	60.2	120	14.2	22.9	37.1	9.9	9.6	0.08	56.52	0.54	0.3	0.01	0.04	99.03	0.72	97.74	16.07	982.6	0.01	29.87	16.07
28-05-2022 00:45	28-05-2022 01:00	60.2	120	14.3	23.4	37.7	9.8	8.8	0.08	47.19	0.87	0.41	0.01	0.03	99.04	0.43	100.86	15.64	982.1	0.01	29.66	15.64
28-05-2022 01:00	28-05-2022 01:15	61.1	123	14.8	23.1	37.9	10	8.3	0.19	40.43	1.07	0.5	None	0.03	99.07	0.34	82.72	15.68	981.6	0.01	29.51	15.68
28-05-2022 01:15	28-05-2022 01:30	69.2	123	15.6	23.1	38.7	9.9	8.1	0.22	40.06	0.64	0.34	None	0.03	99.08	0.34	92.82	15.78	981.2	0.02	29.37	15.78
28-05-2022 01:30	28-05-2022 01:45	69.2	123	15.4	22.7	38.1	9.9	8.1	0.2	39.17	0.4	0.23	0.01	0.03	99.08	0.46	92.52	16.04	981.1	0.01	29.33	16.04
28-05-2022 01:45	28-05-2022 02:00	69.2	123	14.9	22.6	37.5	9.9	8.2	0.23	32.13	0.5	0.27	0.01	0.03	99.08	0.33	69.37	16.44	981.1	0.02	29.31	16.44
28-05-2022 02:00	28-05-2022 02:15	68.8	119	14.1	22.7	36.8	9.8	8.3	0.19	36.55	0.82	0.38	0.01	0.03	99.1	0.39	98.49	16.38	980.9	0.02	29.27	16.38
28-05-2022 02:15	28-05-2022 02:30	64.5	118	14.2	21.5	35.6	10.2	7.7	0.22	28.76	1.84	0.73	0.01	0.03	99.1	0.4	86.71	16.53	980.7	0.01	29.17	16.53
28-05-2022 02:30	28-05-2022 02:45	64.5	118	14.5	21.8	36.3	10	7.1	0.2	30.81	2.59	0.99	0.01	0.03	99.1	0.49	99.71	16.4	980.3	0.02	29.05	16.4
28-05-2022 02:45	28-05-2022 03:00	64.5	118	14.2	21.8	36	10.1	7.4	0.2	31.13	2.89	1.13	0.01	0.03	99.1	0.49	84.32	16.69	980.2	0.02	29.02	16.69
28-05-2022 03:00	28-05-2022 03:15	63.8	111	13.9	22.1	36	10	6.7	0.19	34.59	2.54	0.99	0.01	0.03	99.1	0.53	97.32	16.3	980.1	0.01	28.95	16.3
28-05-2022 03:15	28-05-2022 03:30	56.9	110	14	21.6	35.6	9.8	7.1	0.24	25.24	2.75	1.04	0.01	0.03	99.12	0.55	104.22	16.09	979.7	0.01	28.81	16.09
28-05-2022 03:30	28-05-2022 03:45	56.9	110	13.8	21.3	35.1	9.7	6.8	0.21	28.07	3	1.13	0.01	0.03	99.14	0.38	80.73	15.91	979.3	0.02	28.69	15.91
28-05-2022 03:45	28-05-2022 04:00	56.9	110	13.8	20.9	34.7	9.9	6.8	0.2	29.38	3.85	1.42	0.01	0.02	99.14	0.61	104.04	16.15	979.1	0.01	28.61	16.15
28-05-2022 04:00	28-05-2022 04:15	57	107	13.5	21.4	35	9.8	6.9	0.17	37.54	4.5	1.7	0.01	0.01	99.14	0.75	101.92	16.36	979	0.01	28.56	16.36
28-05-2022 04:15	28-05-2022 04:30	57.3	106	14	22	35.9	9.6	6.4	0.14	33.46	4.03	1.52	0.01	0.03	99.13	0.39	99.82	15.96	978.8	0.01	28.5	15.96
28-05-2022 04:30	28-05-2022 04:45	57.3	106	14	21.8	35.8	9.7	6.1	0.15	35.91	3.37	1.31	0.01	0.03	99.16	0.46	97.57	16.57	978.7	0.01	28.45	16.57
28-05-2022 04:45	28-05-2022 05:00	57.3	106	13.4	21.6	35.1	9.7	5.7	0.14	36.65	0.48	0.26	None	0.02	99.18	0.55	76.27	18.25	978.5	0.02	28.41	18.25
28-05-2022 05:00	28-05-2022 05:15	56.6	101	13.8	22	35.8	9.7	6	0.23	34.17	0.49	0.25	None	0.01	99.18	0.62	103.65	23.01	978.5	-0.03	28.38	23.01
28-05-2022 05:15	28-05-2022 05:30	50.3	99.9	13.9	21.3	35.2	9.8	5.8	0.24	31.95	0.58	0.28	None	None	99.17	0.72	105.41	29.24	978.8	-0.01	28.49	29.24
28-05-2022 05:30	28-05-2022 05:45	50.3	99.9	14	21.7	35.6	10	5.9	0.26	36.44	0.5	0.26	None	None	99.12	0.7	95.92	40.72	979.2	0.01	28.64	40.72

Chapter 5: Discussions

Mileage profile could similarly have been derived from the velocity and acceleration profile. As the drivers' behavior and gear was fixed throughout the driving cycle, the vehicle would give lower mileage if the road had inclination or slope. When the vehicle is in full rolling mode, better mileage could be expected. Here, bumper to bumper distances play an important role.

Gravel and earthen roads were not considered for this study as these types of roads were least fuel efficient in terms of vehicular mileage as it needs more resistance force to overcome.

In mastic asphalt roads, stone chips were added to protect the driver due to skid resistance (specially in monsoon season), and also protect the road from unnecessary wear and tear of road surface due to continuous traffic or transport load. It also offered more safety to the riders and increased the roughness and friction, thus braking distance would be decreased. The vehicle would slow down faster and it would stop or reduce velocity early. This type of road needed more bumpers and bumper to bumper distance must be optimal from all aspects.

Mastic asphalt road had 0.2247% and 9.0465% higher Rolling Resistance Coefficients (RRCs) than bituminous asphalt and cement concrete road respectively. Bituminous asphalt road had 8.802% higher RRC than concrete cement road.

The more the RRC, the less the fuel consumption. By combusting 1 liter of fuel, the test vehicle traveled 1.3011% more and 7.3528% less over mastic asphalt road surface than bituminous asphalt and cement concrete road respectively. The vehicle traveled 8.7496% more over cement concrete road than bituminous asphalt road.

Capital cost or initial investment cost of a concrete cement road was 77.0694% and 109.4109% higher than bituminous and mastic asphalt roads respectively. Bituminous asphalt roads were 18.2649% costlier than mastic asphalt roads in case of capital investment.

Maintenance cost was highest for cement concrete roads. It had 177.9479%% and 137.8401% more maintenance cost than mastic asphalt and bituminous asphalt road respectively. There was 16.8634% higher maintenance cost in bituminous roads than mastic asphalt roads.Considering 40 years, cement concrete roads would take only 576717 Rs. (approx.), whereas mastic asphalt roads would rather take (2 * 207491) = 414982 Rs. and bituminous asphalt roads would take (4 * 242481) = 969924 Rs. **Maintenance cost-wise bituminous asphalt roads are highest in the long-run, comparatively 68.1802% and 133.7268% costlier than concrete cement and mastic asphalt roads.**

Annual fuel cost was lowest for cement concrete road, it was 8.7496% and 7.3528% more fuel efficient monetarily than bituminous and mastic asphalt road. Mastic asphalt road showed better fuel efficiency cost-wise than bituminous asphalt road (around 1.3011%)

For estimating the total cost including fuel cost approximately, it had been realized that cement concrete road was the costliest among others. Cement concrete road was approximately 3.4799% and 26.8281% costlier than bituminous and mastic asphalt road respectively. In the same manner, bituminous roads were 22.563% costlier than mastic asphalt roads.

Table 5.1: Comparison between various road surfaces

Road Surface	Mastic-Concrete	Bituminous-Concrete	Mastic-Bituminous
Mileage	+7.3528%	+8.7496%	-1.3011%
RRC	+9.0465%	+8.802%	-0.2247%
Capital Cost	+109.4109%	+77.0694%	+18.2649%
Maintenance Cost	+177.9479%	+137.8401%	+16.8634%
Fuel Cost	+7.3528%	+8.7496%	+1.3011%

Now, for emission parameters, during complete combustion of 1 liter of petrol, CO2 and SO2 produced the maximum and minimum amount of 2.534581 kg and 0.0000689 kg respectively.

The plot below shows the distribution of emission values of the parameters in descending order of frequency with a line of the entire cumulative on the secondary axis as a percentage of total.

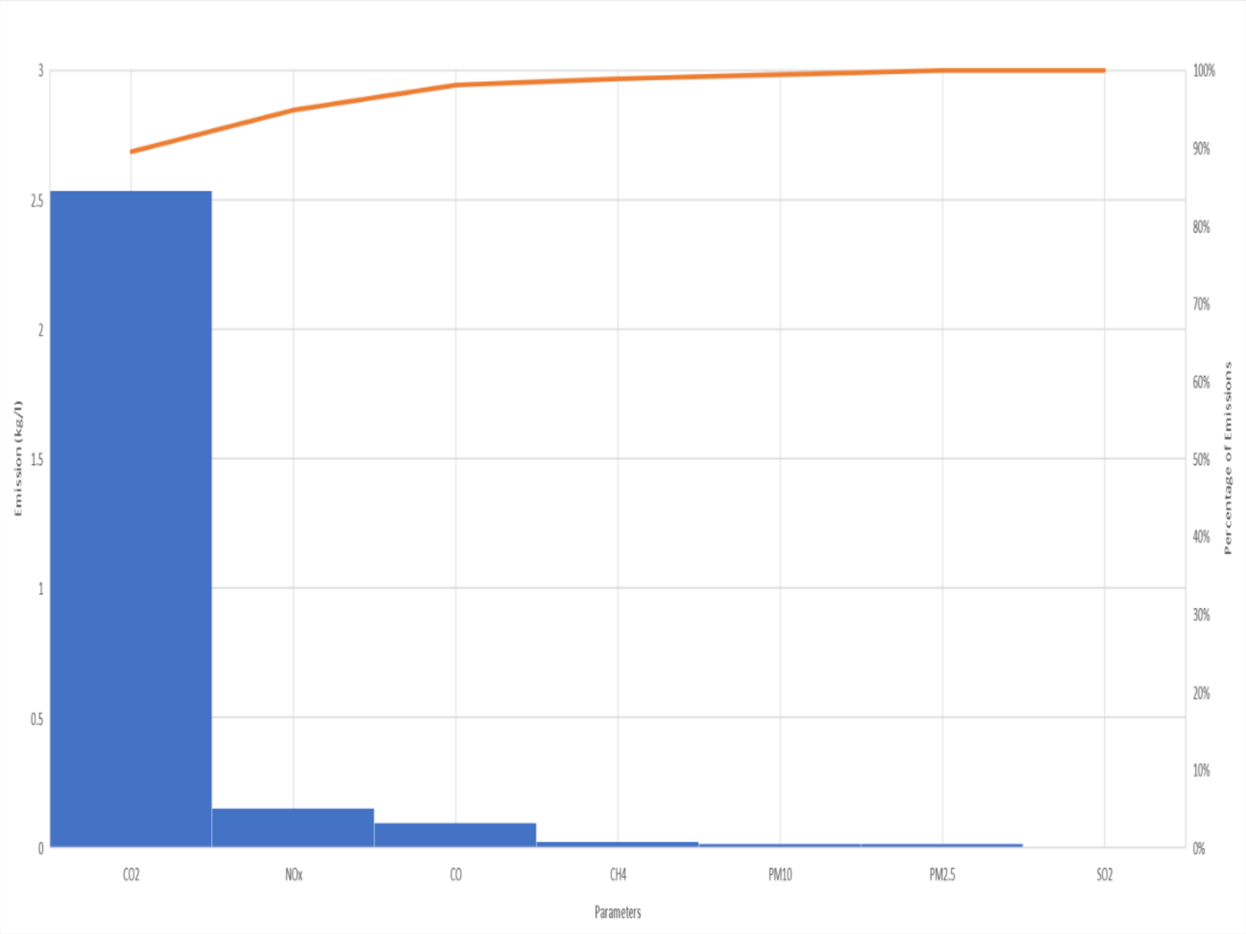

Figure 5(a): Pareto chart of emission parameters

Comparison of approximate average annual emissions of different parameters during full combustion of 1 liter of fuel over three types of roads can be interpreted by the below figure which represents the comparison of the percentage that each type of road contributes to the total and it shows how much the percentage of each type contributes.

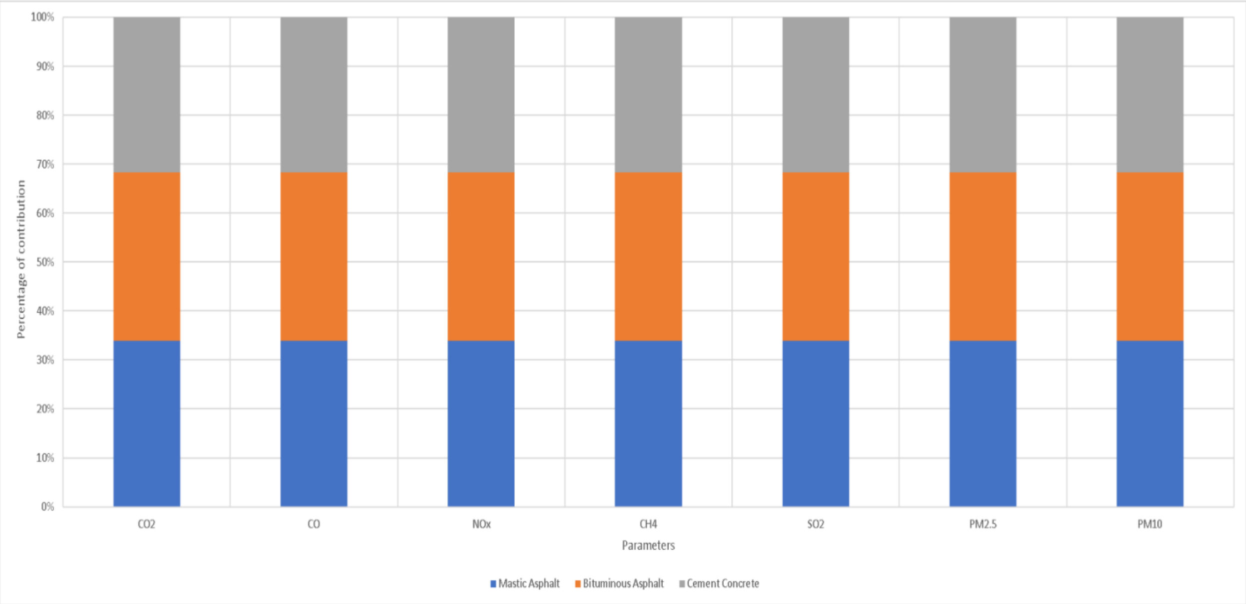

Figure 5(b): Representation of average annual emissions over different roads

Concrete roads were the most efficient in terms of different emission parameters than the other two types of roads. The figure below describes the contribution percentage of approximate average annual emission in kg/l over three types of roads.

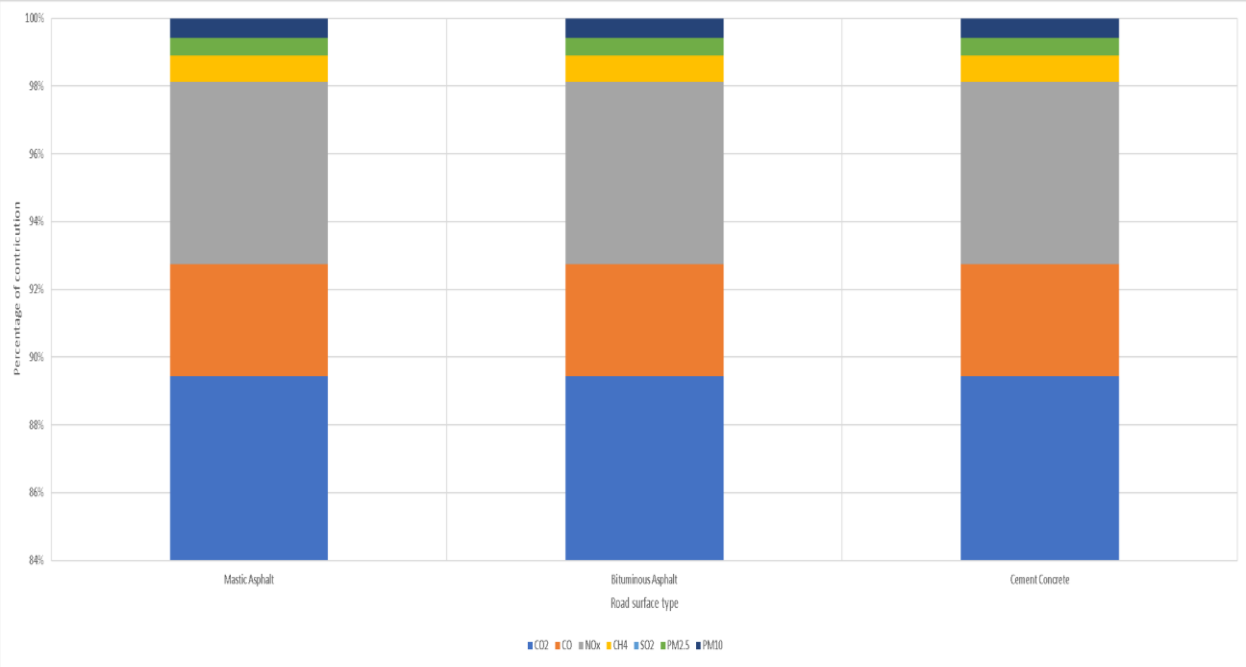

Figure 5(c): Percentage of contribution of different emission parameters over various types of roads

Chapter 6: Conclusions and future work

This kind of analysis or study could be helpful for decision and policy makers because the knowledge of GHG savings and energy consumption is the starting point for any public policy related to vehicles. With this information, regional planning and mobility plans will foster more sustainable urban transport policies for these terrains. At the same time, this approach offers more realistic information about the energy needed to run these vehicles and also the patterns of the use of this energy. This information is useful to reinforce the necessary e-infrastructure. A last accomplished objective is to put in evidence that there exist alternative approaches, easy to be implemented, that can improve the current emission measurement procedure. The calculations will assist policymakers, automakers, and consumers in assessing the level of GHG benefits provided by vehicles while also providing a foundation for related energy efficiency and ambient air quality. Therefore, this could be a help for future researchers aiming to deepen the research in this field of interdisciplinary study. Megacities and their regulations constitute the main barrier for an optimized vehicle (electric or not) to be driven efficiently with minimal emissions. The new models of balanced and sustainable mobility developed in the larger cities are based not only on the type of fuel used but also on controlling fuel management to optimize consumption and emissions. Driver behavior is conditioned to a set of random and inevitable events that do not actually depend on the driver, but on urban design and traffic control regulations. The influence on consumption of those events has been analyzed from a probabilistic point of view and a reference speed cycle and method for computation have been developed to allow for route characterization. Using this characterization, it is possible to predict the expected energy consumption of an actual vehicle driving an actual route and obeying regulatory constraints. This method can help policymakers anticipate side effects of policy actions related to consumers when selecting a route or vehicle. This work would enhance the transportation of people and goods as part of the production process; therefore, if companies need to reduce their environmental impacts, both logistics and commuting routes must be improved to select the optimal (in terms of fuel efficiency and pollutant emissions) fleet composition and to manage vehicles in the most efficient way.

Asphalt produced from the hot mix process at a batch plant required more energy during the year than cement concrete produced at a ready-mix plant. The main reason for this occurring was the higher energy requirements for asphalt during the manufacturing phase. Concrete was determined to only need to have its raw materials (water, aggregate, and cement) mixed together while manufacturing asphalt requires constant heat to keep the bitumen (petroleum-based binder that makes up 5.2% of finished asphalt roads by mass) from solidifying while at the batch mix plant. Asphalt roads of length 1 km require 73% more energy than concrete roads.

Majority of asphalt roads require more frequent repairs resulting in concrete requiring just almost 1/12th of the annual maintenance costs for asphalt. It would take a while before the entity started to see the benefits of using concrete (around 13-15 years after initial paving) but this was determined to be acceptable considering the final savings from concrete use were twice the initial expenses.

It was determined that concrete roads were more fuel efficient than asphalt roads by a small margin for 1 km length over the lifespan period but over the total kilometers driven by a driver annually, savings of gas were hugely present. These savings were determined to be significant enough to include the comparison as support of the concluding statement that concrete is (in general) a superior pavement than asphalt.

Determining which type of road surface is more environmentally friendly and cost effective is a difficult process which will never be 100% correct, due to varying stress loads and environmental damage that will occur over time. However, after considering the step-by-step process lifetime of both concrete and asphalt (From the gathering and manufacturing of raw materials through the end of life/recycling stage) and analyzing the monetary cost and environmental effects of each process, a more or less valid conclusion was made that should influence the future of road surfaces. Concrete is a more environmentally friendly and cost-efficient surface, due to the reduced values of energy usage and monetary cost, as well as a higher fuel efficiency for drivers. This accumulation of data firmly concludes that concrete is a more environmentally friendly and cost-efficient paving and that it should be considered more readily when creating new road surfaces. There are numerous ways to improve the energy emissions and cost of both asphalt and concrete. The factors that can be improved upon include recycling, manufacturing processes, and maintenance amount. To improve these roads, more slag needs to be added, which allows it to be lighter in color than traditional concrete aggregates and decreases the absorbance and CO_2 released. There are many options for reducing the cost and effectiveness of recycling concrete. New technologies are being developed including the usage of microwave technology and recycling in place, which could increase recycling yield by up to 70-75%. Also, increasing the use of Cold-In Place recycling would reduce energy usage by 45-50% and monetary cost by up to 35%. Manufacturing in the future will more likely involve increasing the depth and strength of both asphalt and concrete, which will increase the initial lifespan and decrease the cost of maintenance. Manufacturing costs could also be decreased by companies allowing a higher concentration of recycled asphalt road to be added to the mixture and used to create new asphalt. The best way to improve the cost of asphalt is to make it more durable, the constant repairs that are needed quickly boost the cost and make asphalt the less cost efficient, but simpler, type of pavement. If concrete is to eventually replace asphalt, the manufacturing process of cement must be made more efficient, since this step of the process accounts for more than 55% of the energy consumed by concrete.

Regarding the optimal quantitative characterization of a road surface for predicting the rolling resistance, more work is to be done. Mean Profile Depth (MPD), although a purely empirical adaptation of the sand patch test-derived Mean Texture Depth (MTD) to laser profiles, is widely used. This combined with correlations with diverse rolling resistance measurements makes it a practical choice when a texture measure needs to be extracted from laser profile data. In one of the recent studies i.e. (Sandberg et al.,2011) MPD was combined with a physically intuitive envelope procedure that improved correlations significantly. Taking fundamental physical considerations into account when using laser profiles or other new measurement techniques for surface characterization seems promising. A similar trend can be seen in the development of macro models, from the simple and purely empirical approach of coast-down modeling to elaborate models based on physical principles. Because of advances in numerical computation resources, it is now possible to model the tire pavement contact zone in much in a more detailed way than previously. This development will continue and likely be combined with more detailed tire models. Tire modeling depends on the overall purpose of modeling. In a recent study (Nielsen et al., 2010), it has been estimated that potential savings in fuel consumption and pollutants emissions from optimizing the road with respect to rolling resistance represent a value to society as large as the entire cost of maintaining the pavement. Because optimization in an asset management system requires reliable models of rolling resistance, further research in rolling resistance modeling is guaranteed by their benefits to society [54].

Small variations in average speed can have a larger impact on the vehicle fuel consumption than the typical range of pavement roughness or macro texture. The total excess fuel consumption was highly sensitive to future traffic growth projections. The pavement macro texture has a significantly higher impact on excess fuel consumption of vehicles than pavement roughness.

Energy could be saved by taking proper measures against rolling resistance and energy used during maintenance. Two-wheeler vehicles in ideal constant speed conditions use energy because of wind drag, transmission loss, and rolling resistance. Rolling resistance is dependent on vehicle rolling friction, tire loss, macro-texture, unevenness, and loss due to water or snow present on the road surface. As lower rolling resistance saves fuel, lowering rolling resistance on high traffic roads would save more money and energy. Rolling resistance is more important for light weight vehicles as they are more affected by wind aerodynamically than heavy vehicles. At lower speed, rolling resistance becomes more significant than higher speed while wind forces play a crucial part. It is necessary to have a low rolling resistance where vehicles speeding up or riding at constant speed does not matter as vehicle slowing down does not use much energy and here lowering rolling resistance is not equivalent to energy saving. Low rolling resistance is important on road stretches where traffic is at constant speed. High volume roads would suffice more from lowering rolling resistance for energy saving.

IRI (International Roughness Index) for evenness and MPD for macro texture have a very strong influence on total energy or fuel consumption and GWP (Global Warming Potential). More than 92% energy is consumed at use-phase considering 40 years of road lifespan. Also, if IRI increases 3 times, annual energy consumption will increase 3 times. Similarly, if the decrease of MPD is 30%, annual energy profit would increase by 80%. Pavement smoothness typically has the most important influence on rolling resistance.

Concrete roads might be more fuel efficient than asphalt roads in either high temperature or heavy loading situations. However, this might not always be the case. It is difficult to make direct comparisons to the fuel consumption of an asphalt pavement to that of concrete due to inherent differences in pavement texture (both macro and micro), structural capacity, and smoothness. While the effects of texture and smoothness on road surface vehicle interaction are well-established, more work needs to be completed to further develop and determine the interaction of pavement stiffness and vehicle fuel economy.

Mega texture has a very negative impact on rolling resistance. The more the texture of the road, the more the rolling resistance. Texture can change the rolling resistance of the road by 10-15%. But it is very difficult to quantify exact real changes in ground texture under traffic or rehabilitation work.

COPERT software is a model developed by the European Environment Agency for macro scale vehicle emissions and statistically analyzes the distribution of technical level, activity characteristics, and vehicle operating conditions [55]. In future, CO, CO_2, NOx, and PM emissions of vehicles will be calculated using the COPERT model in the study region. It is based on the basic emission factors and displays vehicles' emissions from various countries and regions. It also combines a mathematical model capable of calculating emissions from statistical data on emission sources at the country level. Research would be carried out with COPERT to evaluate the effect of current and future greenhouse gas mitigation policies on CO_2 emission models on the fleet of vehicles and other types of road transportation [56]. The calculation principle of COPERT is based on the basic emission factor, and the column correction coefficient is used to calculate the vehicle emission factor under actual conditions. To reflect the vehicle emission levels of different countries and regions, the COPERT model can calculate the correction factor on the basis of the local information input by the user and obtain a localized emission inventory. COPERT model used to assess the effect of emission reduction policies on greenhouse gas emissions [57]. The study compared different energy alternatives with the goal of reducing CO_2 emissions, but only predicting a single emission gas is not enough to provide a reference for comprehensive decision making. We can estimate the emission factors of vehicles through the COPERT model [58]. To improve accuracy of model estimation, vehicle activity data must be in tally with real work or world conditions. The data of the COPERT model mainly come from the bench test data accumulated by EU countries. The classification, emission standards, and test conditions of motor vehicles in our country are similar to those in the EU. The latest COPERT model used advanced technologies of vehicle emission testing to update major parameters and the actual road emission factor of heavy and light vehicles; the calculation results are closer to the actual emissions of motor vehicles, which is favored by different researchers [59-60].

In future, if the roads or pavements can be constructed using geo-polymer or plastic waste materials instead of asphalt or concrete or bituminous, which is still far away in our country due to lack of infrastructure, we will then get higher fuel efficiency and lower emission parameters from use and maintenance phase. Also, by changing the driving cycle along with the driver's behavior might impact in the results. If changing gears in the vehicle was allowed and bumper to bumper distances were optimal and the test was carried out with some congestion factor with the proper measurement of tire inflation pressure variation, the results might definitely differ.

Concluding this thesis by focusing more on the future works that is to properly measure the impacts of rolling resistance forces over different road surfaces including all of the necessary parameters and for the case of emission characteristics more focus to be given on PCU and considering other types of vehicles too, to get the actual scenario in the study region.

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