DEVELOPMENT OF STEADY STATE FUEL CONSUMPTION MODEL ON HIGH SPEED CORRIDORS

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A B S T R A C T

For a country of India's size and problems the importance of the adequate transportation system becomes obvious. Road construction and maintenance consume a large proportion of the national resources, while the costs borne by the road users for vehicle operation and depreciation are even greater. Investment decisions are to be made with relation to road projects and in order to facilitate in the decision making process there should be adequate data base pertaining to vehicle operation cost(Fuel, Tire, Lubricants etc..) which is a major contributing factor of an road user cost. These inputs are major contributing factors pertaining to vehicle operating cost. A study of fuel consumption of vehicles will go a long way in justifying the investment on road projects resulting in overall reduction of total transportation cost. The present study involves development of fuel consumption inter-relationship under steady state condition for high speed corridors under selected steady speeds for different vehicle types (Passenger car). The test runs are carried out at various speeds for different vehicle classes ranging from the lowest to highest thus yielding the relationship between fuel consumption and speed, road geometrics and surface condition of the pavement. Since the driver is instructed to travel over the test section at constant speed the experiment is known as Steady state fuel experiment. The fuel consumption equation is developed by considering speed, roughness, rise and fall. The equation is developed by deploying Non-linear regression method using Statistical Packages for Social Studies (SPSS) software.

Keywords: fuel cost, Indian highways, RUCS, VOC.

1.0 Introduction

Highways are a major component of the total transportation system in India. Roads bring about all-round development to the region, Hence Road transport is a vital sector in the economy of India with the total length of about 3.3 million kilometer, and India has one of the largest road networks in the world. Roads are the dominant mode of transportation in India today. They carry almost 90 percent of the country's `passenger traffic and 65 percent of its freight. It is well recognized that transport performs a key role in achieving fast economic growth of developing countries. For a country of India's size and problems the importance of the adequate transportation system becomes obvious. Fuel Consumption by vehicular usage has become a major concern not only due to depletion of the energy resource but also due to contribution of vehicular exhaust emissions. Vehicle users are confronted with higher fuel consumption when they compare their fuel consumption with figures put forward by vehicle manufacturers (under standard laboratory conditions).The variation between actual on-road fuel consumption(actual driving conditions)and laboratory conditions occurs due to composite influence of many factors which affect fuel consumption are

- Roadway Factors (Road Surface, Riding quality of the surface, gradient and road width)
- Vehicle related factors (type, make, horse power, tyres, load carried etc..)
- Traffic factors (Speed of the vehicle, volume of traffic)
- Driver habits and behavior
- Fuel characteristics

1.2. Objectives of the Present Study

- To study fuel consumption pattern on varying carriageway widths of multi-lane highways and subsequently develops fuel consumption inter-relationship for various vehicles under steady state condition.
- To determine statistical relationships between the Fuel, speed, road surface condition and vertical profile parameters and on high speed corridors.

2.0. Literature Review

2.1. General:

The highway engineers always have been interested in assessing the cost of operation of vehicles on different types of road surfaces and their relative difference. Moyer investigated the VOC on untreated gravel road and cement concrete road surface as early as 1939. Moyer and Winfrey presented the cost of operating on untreated gravel and cement concrete road surface as early as 1939. Winfrey did the extensive work later on and he presented comprehensive tables for motor vehicle running costs for highway economy studies in 1963.Claffey did extensive research on time and fuel consumption for highway user benefits study. Claffey's tables were published in NCHRP Report 111, which gave the running cost of motor vehicle as affected by road design and traffic. The TRRL did extensive work for U.K conditions and the results were published in RRL reports. Dawson reported the research on VOC in 1970. Kent's work involved determination of fuel consumption rates of trucks and including speed-change cycles, thus covering acceleration and deceleration. Saal's work covered passenger cars and demonstrated how fuel consumption varied with speeds and grades.

2.2. World Bank Studies on Vehicle Operation Cost

The World Bank, which was one of the key international lending institutions, was interested in the economic evaluation of benefits arising from highway improvements, so that they could examine the various schemes put up to them for funding. With respect to vehicle operating costs, major primary research studies were conducted by various institutions in Kenya (1971-75), the Caribbean (1977-82), Brazil (1975-84) and India (1977-83). In this field of research certain key variables can be measured quickly, e.g., vehicle speeds and fuel consumption, while other variables, e.g., vehicle maintenance, can only be observed over longer periods of time. Consequently, each of these studies contained three different components:

(1) Observations of vehicle speeds under normal usage for a stratified sample of the road network;

(2) Controlled experiments to establish fuel consumption speed relations as a function of' road characteristics; and

(3) A user cost survey collecting records over time from large numbers of vehicle operators, for all operating cost components, stratified by road characteristics.

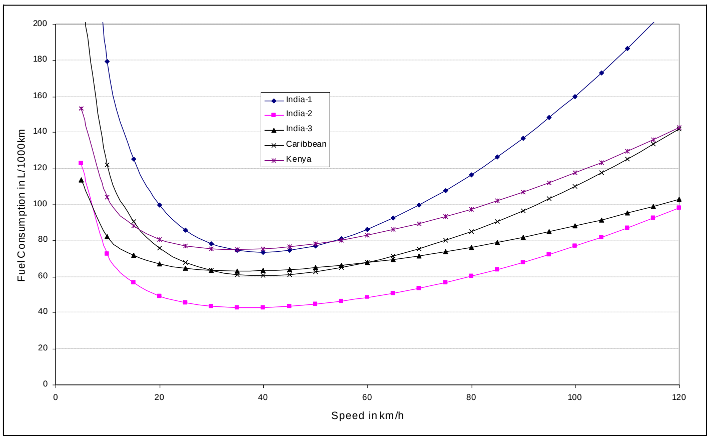


Figure 1: Typical Curves depicting the effect of Speed on Fuel Consumption

The above experiments have conclusively proved that (a) The fuel consumption of all vehicles follows a typical U shaped curve establishing a minimum value at an optimum speed in the neighbourhood of 30-45 km/hr. (b) The fuel consumption is influenced by the type of surface and its riding quality. On good smooth surface, the fuel consumption is low, and as one moves on to surfaces of poor riding quality, the fuel consumption increases. (c)The fuel consumption increases as the vertical gradient increases, similarly, it decreases as the downward gradient increases. (d)The load carried by a vehicle has a great influence on fuel consumption has the power/weight ratio in the case of commercial vehicle goes on decreasing the fuel consumption increases and vice-versa due to greater the load on the vehicle greater the power required hence fuel consumption increases.There are relatively high fuel consumption rates at both low and high speeds with the minimum fuel consumption arising at an “optimum” speed, generally around 30-45 km/h under varying road terrains (as shown in Figure 1). The reason behind this U-shape can **be** simply explained by considering the two extremes. At high speeds, the aerodynamic forces, which are related to the square of velocity, become dominant requiring large quantities of fuel to be consumed. While at low speeds which equate to low tractive power requirements, the idle fuel consumption that powers the engine drag and accessories dominates.

2.3 John P.Zaniewski

Data from a comprehensive study of vehicle operating costs show that the type of road surface can significantly affect fuel economy. Tests were conducted with both cars and trucks travelling on a variety of pavement types. For cars, fuel consumption was not influences by pavement surface type but trucks consumed less fuel on concrete pavements than on asphalt pavements.

In this study they concentrated on asphalt and concrete pavements with intermediate to smooth riding quality (serviceability Index in the range of 3.2 to 4.4). Vehicles were driven on these test section at constant speed of 10, 20, 30, 40, 50, 60, 70 while fuel consumption, speed and other factors were accurately measured. The test for the effect of pavement type on fuel consumption was extremely interesting. The data clearly show the fuel consumption of cars is not effected by type of surface. However in reviewing the truck data, the average fuel consumption on concrete pavement was less than the fuel consumption on asphalt pavement.

In every test at speeds of 20 mph or greater, fuel consumption on asphalt was greater than fuel consumption on Portland cement concrete. The difference in fuel consumption between two pavement surfaces, for comparable roughness, can be as much as two miles per gallon. For the semitrailer truck the fuel consumption on Portland cement concrete pavement was consistently one mile per gallon better than on the asphalt surface. The differences in fuel consumption between two pavements types was approximately 20%.Logic supports this conclusion since trucks cause more deflection on flexible pavements than on rigid pavements. Deflecting the pavement absorbs part of the vehicle energy that would otherwise be available to propel the vehicle. Thus the hypothesis can be made that more energy and therefore more fuel is required to drive on flexible pavements.

2.4 Dinesh V.Ganavir

The important roadway factors affecting fuel consumption can be sub-divided into following categories which are (i) type of the surface (ii) effect of road roughness (iii) gradient, upward or downward. When a heavy wheel load is imposed on a pavement, it deflects in case of black topped pavement due to more deflection than that of cement concrete pavement; the fuel consumption is more in black topped pavement **(CMA, 1997).** The frictional force is dependent on the riding quality of the road surfaces. The poorer the road roughness (riding quality), the greater is the energy required to propel the vehicle and hence higher the fuel consumption **(RUCS, 1982).** The gradient of the road influences fuel consumption, with an upward gradient, the vehicle has to overcome force due to gravity and hence fuel consumption will be more than on a level road. However in case of downward gradient the force of gravity assists in the motion of vehicle and hence fuel consumption is reduced **(RUCS 1982).** The traffic factors that are known to influence fuel consumption are (i) Speed (ii) Volume of traffic (congestion) (iii) Extent of forced stoppages. Speed is one of the most important factors affecting fuel consumption. The relationship between fuel consumption per unit distance and speed is generally in the form of a U-shaped curve, having the lowest value at an optimum speed usually between 30 and 50 km/hr. At speeds less than or more than the optimum, the fuel consumption is more. The traffic volume effect the fuel consumption as the vehicle is subjected to acceleration, deceleration and thus fuel consumption goes up. As traffic volume on a particular road stretch increases traffic congestion prevailing which result in increased fuel consumption.

3.0. Study Methodology and Data Collection

3.1. Methodology Adopted

In order to achieve the objectives outlined above, adopted methodology for developing Fuel Consumption equations is shown in Fig. 2.

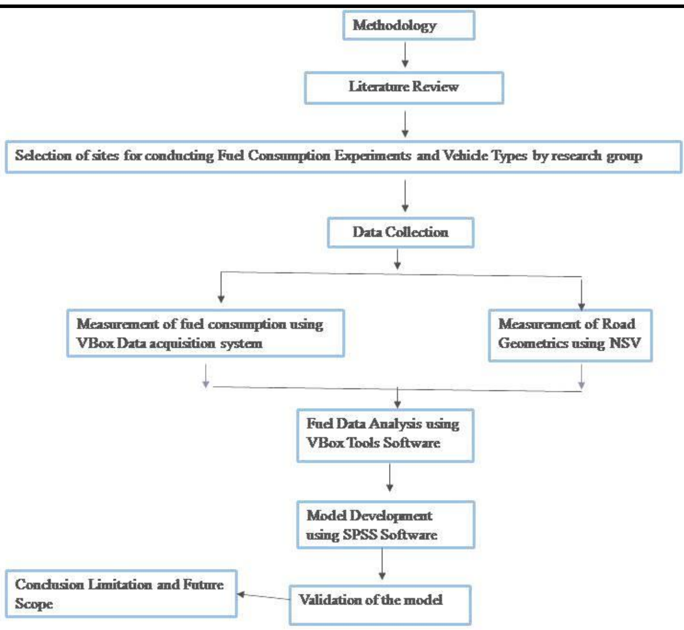


Fig 2: Flow Chart Illustrating Study Methodology

As can be seen from the Fig. 2, identification of test sections have been done at the first instance to collect data related to fuel consumption for different types of vehicles plying on multilane highways. The fuel consumption data has been collected using instrumented vehicle fitted with V-BOX and fuel flow meter. For the purpose of collecting road geometry data such as road roughness, rise and fall, network survey vehicle (NSV) has been used. Under this approach, accurate measurement of fuel consumption is made on pre-selected vehicles when operating for a short distance on roads with known route characteristics and at selected speeds. The fuel consumption experiments were conducted and the data collected were used to developing fuel consumption equations. In order to maintain steady speeds of the given range by the drivers, the test section of at least 1 km was chosen. The driver was asked to drive the vehicle maintaining constant speeds starting from 20 kmph to 70 kmph at increments of 10 Km/hr. For every steady speed at least two runs were conducted to find the fuel consumption. The vehicle types considered in the present study include small car (cars up to 1400 cc classified as SC), big car (cars beyond 1400 cc classified as BC) and Two Axle Heavy Commercial Vehicles (HCV) for fuel consumptions experiments were used.

4.0. Development of Fuel Consumption Equations:

Fuel consumption of the vehicles are highly dependent on the vehicles operating speed and also the road geometry characteristics namely roughness, rise and fall etc. The pay load also influences fuel consumption in case of commercial vehicles. As per the methodology explained in previous section, fuel consumption data has been collected using V-Box under congested state conditions. Apart from the fuel and speed data collection, road geometry namely roughness, rise and fall also collected of the same test sections. Fuel consumption equations under steady state developed in with influencing variables of speed, roughness, rise and fall. The developed fuel consumption equations under steady state for different vehicle types are described in subsequent sections.

4.1. Steady State Fuel Consumption Equations

Fuel Consumption is one of the main components of VOC. It plays a major role in influencing the overall VOC. An attempt has been made to develop the Fuel Consumption equation using experimental data collected through the steady state fuel consumption experiment. Three vehicles were used in the fuel consumption experiments, Tata truck was used under three different loading conditions (i.e. empty, half loaded and fully loaded) thereby simulating vehicles with different power-weight ratio. The fuel consumption experiments were performed under well controlled condition, in which the values of all the important independent variables were known. Only one variable namely speed was allowed to change in each set of experiment on each test sections with each of the test vehicles. The test sections of roads were selected so that the values of those variables associated with the geometry and surface condition of the road covers the full range of values. In this way the relationship between fuel consumption speed and the characteristics of the road could be obtained reasonably easily.

For Petrol Driven Small Cars:

$$FC = 30 + \frac{641.092}{V} + 0.002V^2 + 0.001RG + 0.747RS - 0.574FL$$

For Diesel Driven Big Cars:

$$FC = 35 + \frac{611.13}{V} + 0.004V^2 + 0.001RG + 1.052RS - 1.297FL$$

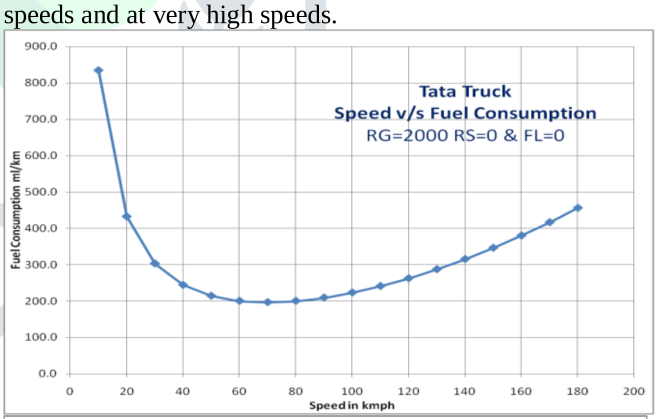
For Truck:

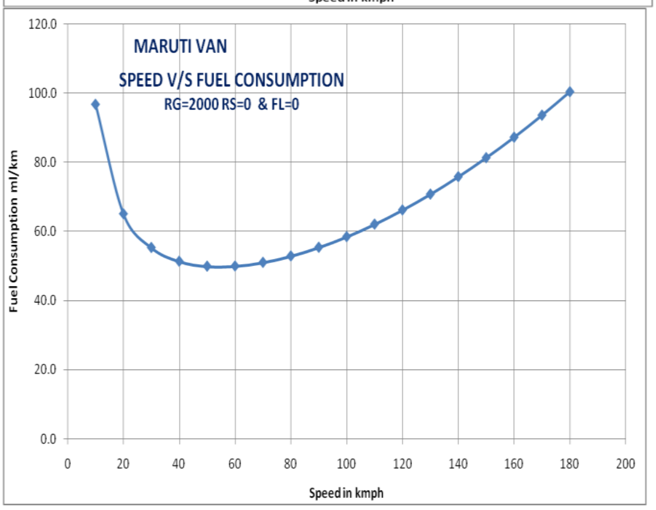
$$FC = 50 + \frac{8109.53}{V} + 0.12V^2 + 0.006RG + 4.35RS - 5.148FL - 7.274\frac{P}{W}$$

FC=Fuel Consumption in ml/km
V=Speed in kmph
RG=Roughness in mm/km
RS=Rise in m/km
FL=Fall in m/km
P/W=Power Weight Ratio.

4.2 Effect of Speed on Fuel Consumption:

In order to understand the shape of the fuel consumption curve, the fuel consumption of the various experimental vehicles at various speeds has been plotted in the below Figure 3 .The roughness value has been taken as 2000mm/km and the Rise and Fall is taken as zero. It can be seen that the curve follows a typical U-shaped curve in each case. The minimum fuel consumption occurs at the optimum speeds. Table 1 presents the typical fuel consumption pattern of the vehicles when driving on a good road surface on a level stretch at different speeds. It can be inferred that the fuel consumption increases at very low speeds and at very high speeds.





Roughness in mm/km	Fuel Consumption expressed in percentage as Roughness varies relatively from smooth surface		
	Maruti Van	Tata Sumo	Tata Truck
1000	100.0	100.0	100.0
2000	102.0	101.7	103.7
3000	104.1	103.5	107.4
4000	106.1	105.2	111.1
5000	108.2	106.9	114.8
6000	110.2	108.7	118.5

Speed in kmph	Fuel Consumption expressed in percentage of optimum		
	Maruti Van	Tata Sumo	Tata Truck
10	193.8	173.6	618.0
20	130.4	118.5	291.5
30	110.8	104.1	186.5
40	102.9	100.0	138.4
50	100.0	101.0	114.3
60	100.1	105.1	103.0
70	102.2	111.7	100.0
80	105.9	120.4	102.9
90	110.9	130.9	110.3

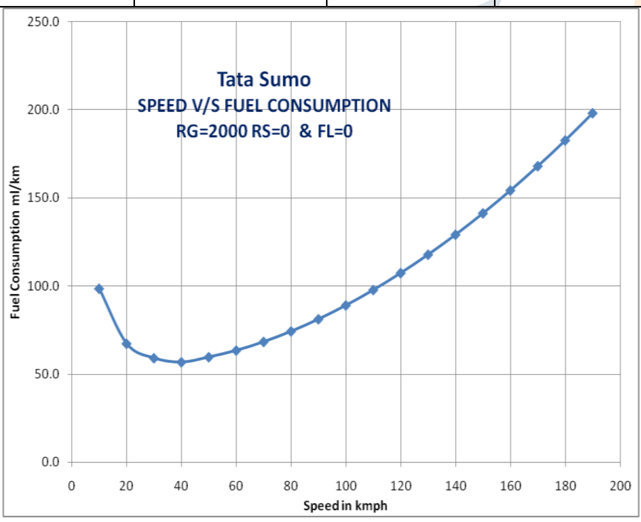
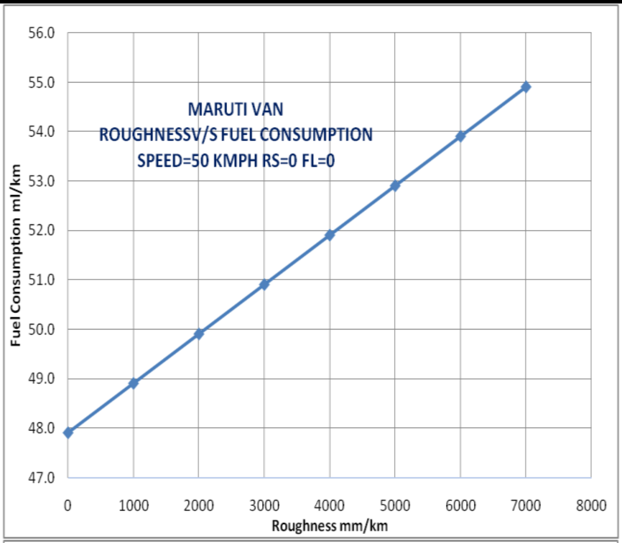


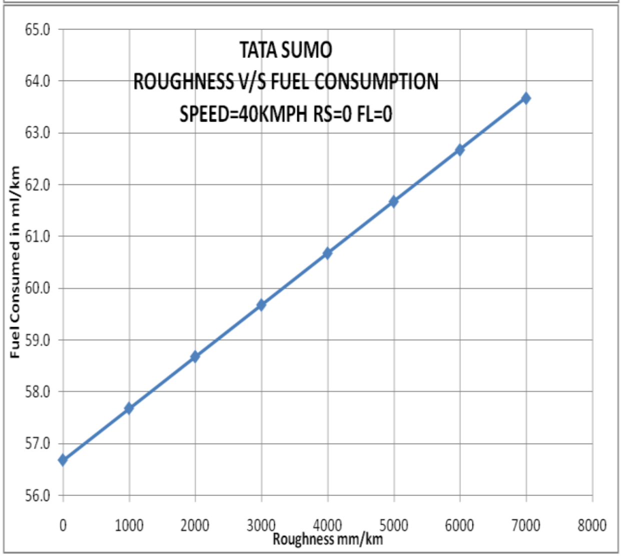
Fig 3: Steady State Fuel Consumption of Different Vehicle Types under Varying Speeds

Table 1: Fuel Consumption of Experimental vehicles at Varying Speeds:

4.3 Effect of Roughness on Fuel Consumption:

The given below Figures 3 illustrate the effect of roughness on fuel consumption. The Figures has been plotted for optimum speed where fuel consumption is minimum and the road roughness is considered as good riding quality (RG=1000) and the vertical profile has been kept zero (RS=0,FL=0). Table 2 depicts the fuel consumption of the different vehicles while travelling at the optimum speeds on varying surface conditions. As the road roughness increases, fuel consumption increases correspondingly.





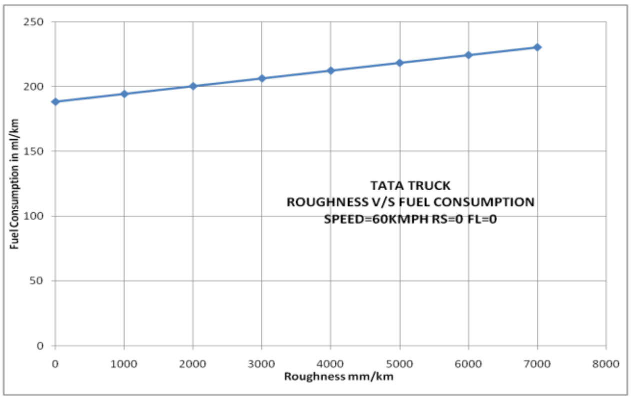


Fig 4: Effect of Roughness of steady State Fuel Consumption of Different Vehicle Types

Table 2: Fuel Consumption of Experimental vehicles at Varying Roughness Values

4.3 Effect of Rise on Fuel Consumption

Figures 4 illustrate the consumption of fuel of experimental vehicles on a good surface condition (RG=2000 mm/km) with varying upward gradient for a vehicle travelling at a optimum speed. The Table 3 give the fuel consumption of various vehicles while climbing on an upward gradient of different values. With a 3.5 percent upward gradient the fuel consumption is 1.5, 1.64 and 1.90 times the value on a level road for a Maruti van, Tata Sumo and Tata Truck.

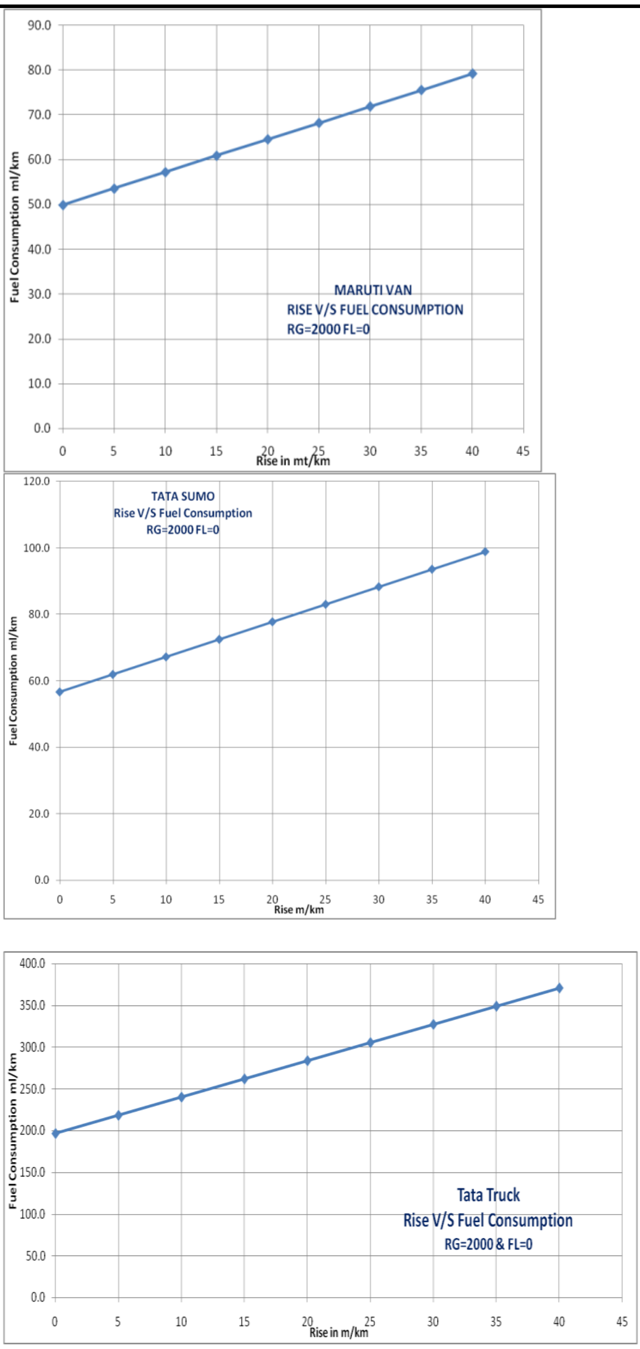


Fig 5: Effect of Rising gradient of road on steady State Fuel Consumption of Different Vehicle Types

4.4 Effect of Loads on Fuel Consumption

Figure 5 indicates the fuel consumption of Tata truck under varying P/W ratios. As the loading on the truck increases the P/W ratio decreases which indicates that there is an increase in fuel consumption. Fuel consumption has been obtained in by considering the level surface with a good surface condition (RG=2000, RS=0 and FL=0). It is observed that fuel consumption increase by 58% as the P/W ratio decreases from 15.7kw/tonne (no load condition) to 5.7kw/tonne (GVW). Further it is observed that the proportional increase in fuel consumption considerably gets reduced for every additional payload.

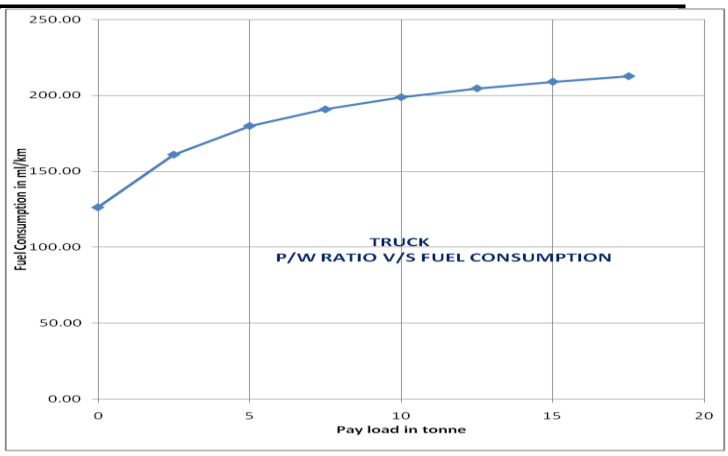


Figure 6: Effect of Power-to-Weight Ratio on Tata Truck Fuel Consumption

5. Validation of the Developed Models

The validation of the developed models is carried out by performing the following two statistical tests.

- Root Mean Square Error (RMSE).
- Chi-square test for Goodness of Fit.

5.1 Validation of the Developed Models for Maruti Van

1) RMSE for Maruti Van= 4.32 ml/km (N=12)

2) χ^2 estimated was found out to be less than the χ^2 observed from the table for 5% level of significance. This expresses that only 5% of the sample size are unable to explain the goodness of fit of the model. Hence the developed model can be able to predict the fuel consumption with good accuracy.

$$\chi^2 \text{estimated } 1.13 < \chi^2 \text{ table } 4.57$$

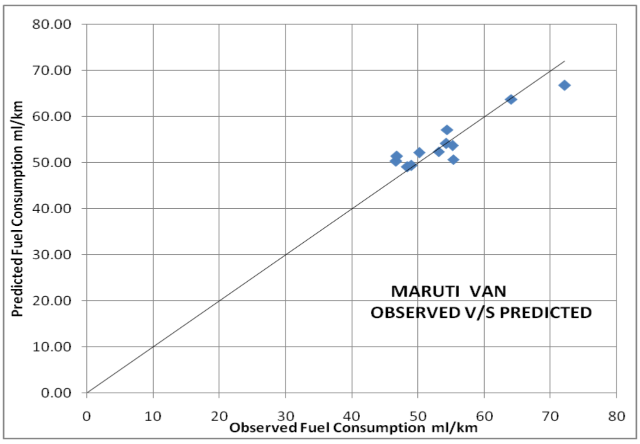


Fig 7: Graph Plotted Observed versus Predicted Fuel Consumption for Maruti Van

5.2 Validation of the Developed Models for Tata Sumo

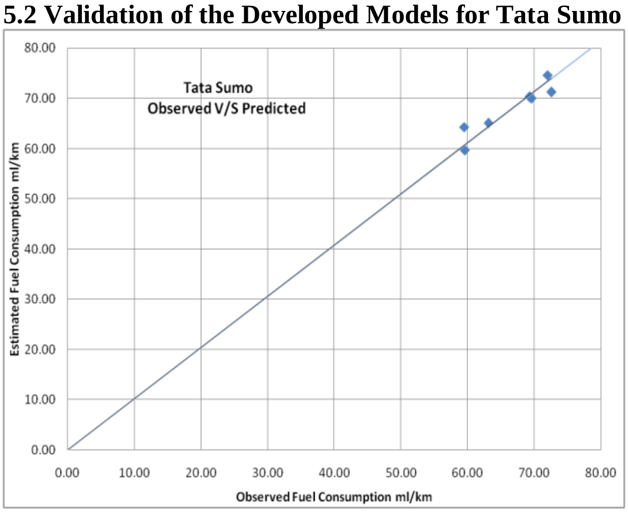


Fig 8: Graph Plotted Observed versus Predicted Fuel Consumption for Tata Sumo

1) RMSE for TATA Sumo=3.8 ml/km (N=7).

2) χ^2 estimated was found out to be lesser than the $\chi 2$ observed from the table for 10% level of significance. This expresses that at the 90% significance level the samples are able to explain goodness of fit of the model. As the sample size considered for measuring significance was too less.
χ^2estimated is 2.0 < χ^2 table is 2.20.
df= N-1= 7-1 = 6.

5.3 Validation of the Developed Models for Tata Truck
1) RMSE for TATA Truck=27.4 ml/km (N=22)
2) Tata Truck: χ^2 estimated was found out to be less than the $\chi 2$ observed from the table for 5% level of significance. This expresses that only 5% of the sample size are unable to explain goodness of fit. Hence the model is valid to estimate the fuel consumption. Hence the developed model can be able to predict the fuel consumption with good accuracy.
χ^2estimated is 2.01 <χ^2 table is 11.6.
df= N-1= 22-1 = 21.

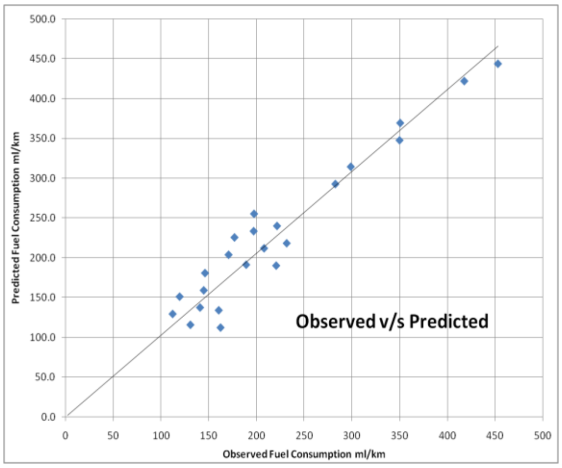


Fig 9: Graph Plotted Observed versus Predicted Fuel Consumption for Tata Truck

6. Conclusion
In the present study, maiden attempt has been made to identify the need and thus develop the steady state fuel consumption equations for specific vehicle types operating on varying widths of multi-lane divided carriageways. The conclusions drawn are given below:

- It is interesting to know that Steady state fuel consumption experiments on selected vehicles confirm the traditional U-shape curve and optimum fuel consumption for Petrol Car is 50 ml/km, 60 ml/km for Diesel Car and 127 ml/km for trucks on plain terrain (i.e. no vertical profile) with an optimum speed and the road roughness of 2000mm/km.
- It is observed that speed plays a vital part in the fuel consumption. Fuel consumption for Maruti van, Tata sumo and Tata truck increases by 30%, 19% and 193% at steady speed of 20 km/hr compared to their respective optimum steady speed fuel consumption.
- It is observed that fuel consumption increases by 11% 10.8% and 18.5% for Maruti van, Tata sumo and Tata truck respectively for optimum steady speed on a poor road surface condition (RG=6000) w.r.t that of a good road surface condition (RG=1000).
- It is observed that fuel consumption increases by 51%, 65% and 90% for Maruti van, Tata Sumo and Tata truck travelling at optimum steady speed at an upward gradient of 3.5% when compared to vehicles travelling on level surface and it is observed that fuel consumption decreases by 35%, 60% and 79.6% for Maruti van, Tata sumo and Tata truck compared to the level surface at a downward gradient of 3%.
- It is observed that fuel consumption of trucks increase by 58% as the P/W ratio decreases from 15.7 kw/tonne (no load condition) to 5.7kw/tonne (GVW). Further it is observed that the proportional increase in fuel consumption considerably gets reduced for every additional payload.
- Validation exercise were also carried out for all the developed models and the statistical tests yielded good accuracy of the model in predicting the values with respect to the observed values of fuel consumption as the RMSE for Maruti van, Tata sumo and Tata truck were 4.3 ml/km, 3.8 ml/km and 27 ml/km respectively. Further, the χ^2estimated value is less than χ^2 tabled value in the case of Maruti van implying that the developed model is able to predict the fuel consumption with good accuracy. However, the χ^2estimated of 2.0 was lesser than χ^2 tabled value (of 2.20) in the case of Tata Sumo as the sample size considered for measuring significance was too less hence model failed to explain goodness of fit at 95% confidence interval. For Tata truck χ^2estimated 2.01 <χ^2 table 11.6 which again indicates the model is replicating the observed fuel consumption fairly accurately.

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