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Procedia - Social and Behavioral Sciences 104 (2013) 342 – 351

Procedia
Social and Behavioral Sciences2nd Conference of Transportation Research Group of India (2nd CTRG)

Speed Prediction Models for Urban Arterials under Mixed Traffic Conditions

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Abstract

The present study extends the basic concept of linear speed-density relation to mixed traffic condition and attempts to develop speed equations for different categories of vehicles generally found on an urban arterial in India. Field data were collected on different sections of urban arterials in New Delhi, Jaipur and Chandigarh by video recording method. All vehicles in the traffic stream were divided into 5 categories and a set of simultaneous equations is developed relating speed of a vehicle type to the densities of all categories of vehicles in their individual terms. These equations are solved for some assumed values of traffic volume and traffic composition and effect on speed of each vehicle type is explained. Accuracy of the equations is checked by comparing the observed values of speed with calculated speeds.

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Selection and peer-review under responsibility of International Scientific Committee.

Keywords: Traffic volume; speed; density; urban arterial.

1. Introduction

Speed is the fundamental measure of traffic performance of a roadway system. It indicates the quality of service experienced by the traffic stream. It is one of the components of the fundamental relationships of traffic flow theory other than density and volume. The speeds of individual vehicles have to be specified in the form of a suitable mathematical model for predicting the speed of next vehicle in the case of simulation run. Speed has also been recognized as one of the measures that designers can use to examine road consistency and driver expectancy on roadways. Highway Capacity Manual (HCM 2010) used free flow speed as a measure for defining level of

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service on a road. Many researchers have used speed as a parameter for evaluating the passenger car unit (PCU) for different types of vehicles on a road. Speed models give an idea to the designers to work out the operating speed on a roadway. The assessment of operating speeds affords the opportunity to assess the expected speed changes of individual vehicles traversing successive road elements. Speed models for mixed traffic conditions are required to predict the changes in speed of an individual vehicle due to presence of other vehicles in the traffic stream.

2. Literature Review

Many researchers have put effort for modelling speed especially for the homogeneous traffic conditions. The pioneering work in this direction was done by Greenshield (1933) who developed a linear relationship between speed and density which was later used to develop parabolic relation between speed and traffic flow. Himes and Donnell (2010) studied the effect of geometric design features and traffic flow on operating speeds on four-lane highways. Speed models were developed to account for the endogenous relationship between lane mean speeds and speed deviation using simultaneous equation framework. Shankar and Mannering (1998) also used simultaneous equation approach to model the speed on a freeway segment. Three-stage-least-squares estimator was used to evaluate endogenous variable expressed as linear function of exogeneous variable. Adjacent lane mean speeds were found to be endogeneous and it was found that as the adjacent lane mean speed increases, the expected lane mean speed increased. Speed deviation also depends upon the adjacent lane mean speed. Figueroa and Tarko (2004) developed relationship between free flow speed (FFS) and geometric design features. A good compilation of worldwide studies of modelling operating speed on different types of highways is given in Transportation Research Circular E-C151 (2011). Dixon et al. (1999) studied the relationship between FFS and posted speed limit on multilane highways in Georgia, USA. Ali et al. (2007) also studied the interrelationship between the FFS, posted speed limit, and geometric design variables along 35 four-lane urban streets in Virginia, and showed that posted speed, median width, and segment length had a significant effect on FFS on urban streets. McLean (1978) studied the effects of horizontal alignment on speeds in Australia. Desired speed and radius of curve were taken as parameters to determine the design speed. The speed behaviour of motorcycles was studied by Perco (2008) who developed motorcycle operating speed prediction model for analyzing the relationships between the motorcycle operating speed and the passenger cars operating speed. Munawar (2011) developed the speed models for urban roads in Indonesia. Pedestrian movement, number of non-motorised vehicles, stopping city buses, parking/stopping passenger cars, entry and exit vehicles are taken as the independent variables. Katti et al. (1988) determined the degree of constraint for the mixed traffic on urban arterials against varied traffic volume levels. Bunching and pre and post bunching behaviour is considered in developing the regression models for the proportion of free and constrained vehicles. Sarna et al. (1989) studied the affect of auto rickshaw on speed of the traffic stream for Delhi roads. They developed the regression model and find out that speed reduces with increase in proportion of auto rickshaw in total traffic stream. Kumar and Madhu (2004) studied the effect of autorickshaws on traffic stream and deduced that speed reduces marginally due to the presence of auto rickshaw as long as their proportion in the traffic stream is upto 15 percent. Koshy and Arasan. (2005) developed a microscopic simulation model to analyze the influence of bus stops on traffic flow in urban area. The average traffic speed near bus stop, for various bus dwell times was observed. Dey et al. (2006) reported that speed may deviate form the normal curve as the traffic becomes heterogeneous due to large variation in speeds of slow and fast moving vehicles. Such variation causes the speed distribution curve to deviate from generally accepted unimodel normal distribution to a bimodel or a multimodel distribution. McFadden et al. (2001) developed two back propagation artificial neural networks (ANN) to predict operating speed of passenger cars on two-lane rural highways. Najjar et al. (2000) also developed neural-network-based speed models to establish a relationship between the roadway characteristics and the 85th percentile speed (V_{85}) on Kansas two-lane highways. The model predicted V_{85} with an average degree of accuracy of about 96 percent. Donell et al. (2001) developed an operating speed prediction model for trucks on two-lane rural highways for use in design consistency. Al-Ghamdi (1998) analyzed spot speed data on urban roads in Riyadh and found that obtaining the 85th percentile speed from

regression modelling gives much better estimates than those from the normal approximation model. There are many more studies reported in the literature on speed prediction models, but majority of these studies are either for the two lane or multilane rural highways under homogeneous traffic conditions. There are very few studies on urban arterials under mixed traffic conditions.

3. Research Objective

Traffic stream in India and other developing countries are of mixed nature where vehicles of different types occupy the same roadway width and move any where on a road as and where they find the space. Such kind of traffic flow characteristics cause frequent changes in the traffic stream speed and it is required to predict the actual speed for such traffic conditions for better planning and design of roadway system. The objective of the present study is to develop the speed prediction model for different categories of vehicles using speed–density relationship of traffic flow. It is hypothesized that speed of each vehicle present in the traffic stream is affected by the traffic density on the road and this density in the case of mixed traffic is the sum of densities of different vehicle types. Simultaneous speed equations are generated for the vehicles present in the traffic stream and then these equations are solved to predict the speed of a vehicle type for any traffic volume and composition of traffic mix.

4. Research Methodology

Speed is the function of traffic, geometric parameters and environmental conditions of a roadway system. However, for a given facility, geometric parameters and environmental conditions remain unchanged during field observation time, and therefore, traffic characteristics like traffic composition, traffic volume and traffic density should govern the changes in speed. It is understood that the relative interaction between the vehicles depends on flow and proportion of a particular vehicle type in the traffic stream. Increase in the flow would result in the increase in density and therefore frequent changes in the stream speed and individual vehicle speed. The composition accounts for any change in the traffic and changing degree of damaging effect at different volume levels. The vehicular interaction and all other geometric influences culminate in the speed and the physical size of a vehicle is supposed to indicate manoeuvrability, acceleration or deceleration capability and space occupancy on the road which are crucial in the measurement of density. Basic Greenshield's equation relating speed with density is given by Equation (1).

$$V = V_f \left(1 - \frac{K}{K_j} \right) \quad (1)$$

The above equation in general form can be written as

$$V = a - bK \quad (2)$$

Where V is the stream speed at density K, and 'a' and 'b' are the regression coefficients. In a mixed traffic situation, density (or pavement occupancy) will vary with relative proportion of small and large size vehicles in the traffic stream. Also the speed of different types of vehicles will be influenced to different extents due to change in the composition of traffic stream. Therefore, it will be logical to consider total density K, on the road as composed of densities of individual vehicle types. In other words, the above equation can be rewritten for mixed traffic flow as given below.

$$V_i = a_i - \sum_{j=1}^N b_{ij} * K_j \quad (3)$$

Where V_i is the speed of vehicle category i and K_j is the density of vehicle category j in the traffic stream. N is the total number of vehicle categories. The a_i in the above equation would represent the free flow speed (FFS) of vehicle type i. The above formulation will allow setting of as many equations as the number of vehicle categories

in the traffic stream and thereby evaluation the effect of traffic volume and composition on speed of each category of vehicle.

Field data on five minute classified traffic volume count and speed are collected on different sections of six-lane urban arterial roads in India. These data are used to determine the density of traffic stream and speed-density relationships for different vehicle type as explained above

5. Field Data

Field data for present study were collected at eight urban arterial roads in three cities of India; New Delhi, Chandigarh and Jaipur. All locations were on six-lane divided roads with raised kerb on either side and standard lane width with no gradient and curvature. The basic consideration in selection of a section was that it should be free from the effect of intersection, bus stop, parked vehicles, curvature, gradient, pedestrian movement and any other side friction. Also, the sections should have wide variations in proportions of different categories of vehicles. Traffic studies were planned to determine the traffic volume, composition of traffic stream, and the speed of different types of vehicles at selected road sections. A section of about 500 m was selected having uniform traffic operating conditions with no access point and a longitudinal trap of 60 m was made in the middle of this section for measurement of flow and speed. Since it was not possible to cover the entire stretch of 500 m in the camera view, speed measured on this trap length was taken as the average speed on 500 m section. The data were collected through video camera at each section on a typical weekday during 6:00 AM to 6:00 PM. The video camera was mounted on the stand and placed at a vantage point so as to cover the entire length of the trap. The recorded film was replayed in the laboratory to extract the desired information. All vehicles in the traffic stream were divided into 5 categories as shown in Table 1. Even in the same category of car there are several models plying on Indian roads. Therefore, cars are also divided into two categories as small car (standard car) and big car. Small car in Table 1 represents all cars having their engine power of around 1400 cc and average length and width of 3.72 m and 1.44 m respectively. The big car is the one having length of 4.58 m, width 1.77 m and engine power of around 2500 cc. The size of a vehicle was measured in field by taking its maximum length and maximum width. In case where more than one type of vehicle is included in a category (for example motorized two wheeler) the average dimensions were considered. Table 2 shows the observed vehicle categories and their sizes.

Table 1. Observed traffic composition at different sections

| Section Number | Composition (%) | | | | |
|----------------|-----------------|--------------|--------------------|----------------|----------------|
| | Small Car (CS) | Big Car (CB) | Heavy Vehicle (HV) | 3-wheeler (3W) | 2-wheeler (2W) |
| I | 38.30 | 5.10 | 2.60 | 20.60 | 33.40 |
| II | 51.50 | 5.96 | 4.00 | 10.43 | 28.11 |
| III | 30.35 | 10.66 | 9.82 | 17.74 | 31.43 |
| IV | 31.27 | 12.59 | 4.36 | 20.30 | 31.47 |
| V | 30.12 | 10.38 | 10.35 | 15.43 | 33.72 |
| VI | 46.50 | 7.55 | 3.64 | 12.70 | 29.61 |
| VII | 26.50 | 4.00 | 1.52 | 10.48 | 57.50 |
| VIII | 32.80 | 3.65 | 2.28 | 8.00 | 53.27 |

Table 2. Vehicle categories and their sizes

| Vehicle Type | Vehicles included | Length (m) | Width (m) | Rectangular Plan Area (m ²) |
|---------------|-----------------------|------------|-----------|-----------------------------------------|
| Small Car | Car | 3.72 | 1.44 | 5.36 |
| Big Car | Big utility vehicle | 4.58 | 1.77 | 8.11 |
| Heavy Vehicle | Standard bus | 10.10 | 2.43 | 24.54 |
| 3-wheeler | Auto-rickshaw | 3.20 | 1.40 | 4.48 |
| 2-wheeler | Scooters, Motorcycles | 1.87 | 0.64 | 1.20 |

6. Development of Simultaneous Equations

Recorded film was replayed on a large screen monitor and 5-minute classified traffic volume counts were made. To ensure accuracy in the count, vehicles of one particular category were counted in one round of play of the film and the film was rewound as many times as the number of vehicle categories in the count. For measurement of speed of vehicles included in the 5-min count, time taken by a vehicle to cover the trap length of 60 m was noted with an accuracy of 0.01 s using a software developed for this purpose.

Speed data extracted for different categories of vehicles for every 5-min volume count are used to develop the simultaneous speed equations. Since density (K) is difficult to measure in field, it is estimated as the number of vehicles of a particular category counted in every 5 minute interval divided by their average speed. The mathematical form of the proposed model is given in Equation 4.

$$V_i = a_0 - a_1 \left(\frac{n_{CS}}{V_{CS}} \right) - a_2 \left(\frac{n_{CB}}{V_{CB}} \right) - a_3 \left(\frac{n_{HV}}{V_{HV}} \right) - a_4 \left(\frac{n_{3W}}{V_{3W}} \right) - a_5 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{4}$$

Where ‘V’ is the speed in m/sec, and ‘n’ is the number of vehicles crossing the measurement point per second (vps). CS, CB, HV, 3W and 2W are the vehicle categories as described in Table 1.

Speed of a vehicle type will be influenced to different extents by the vehicles of different categories and therefore coefficients a₀ to a₅ are expected to be substantially different when speed of individual type of vehicle is modelled. Regression coefficients a₀, a₁,.....a₅ as estimated from field data and combined from eight different roads are given in Equations 5 to 9. The values given in parentheses are the student ‘t’ values of coefficients.

$$V_{CS} = 16.96 - 43.80 \left(\frac{n_{CS}}{V_{CS}} \right) - 35.93 \left(\frac{n_{CB}}{V_{CB}} \right) - 62.05 \left(\frac{n_{HV}}{V_{HV}} \right) - 52.44 \left(\frac{n_{3W}}{V_{3W}} \right) - 33.16 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{5}$$

(202.30) (37.48) (9.11) (4.93) (17.11) (25.51) R² = 0.915

$$V_{CB} = 17.36 - 30.21 \left(\frac{n_{CS}}{V_{CS}} \right) - 77.98 \left(\frac{n_{CB}}{V_{CB}} \right) - 81.01 \left(\frac{n_{HV}}{V_{HV}} \right) - 62.65 \left(\frac{n_{3W}}{V_{3W}} \right) - 47.34 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{6}$$

(109.62) (15.74) (6.90) (5.36) (10.98) (17.68) R² = 0.874

$$V_{HV} = 13.50 - 15.98 \left(\frac{n_{CS}}{V_{CS}} \right) - 27.51 \left(\frac{n_{CB}}{V_{CB}} \right) - 151.68 \left(\frac{n_{HV}}{V_{HV}} \right) - 41.74 \left(\frac{n_{3W}}{V_{3W}} \right) - 37.70 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{7}$$

(82.96) (9.64) (3.80) (8.00) (6.96) (14.22) R² = 0.745

$$V_{3W} = 13.92 - 22.67 \left(\frac{n_{CS}}{V_{CS}} \right) - 11.29 \left(\frac{n_{CB}}{V_{CB}} \right) - 45.01 \left(\frac{n_{HV}}{V_{HV}} \right) - 53.29 \left(\frac{n_{3W}}{V_{3W}} \right) - 35.16 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{8}$$

(141.16) (17.75) (4.06) (3.88) (14.00) (25.14) $R^2 = 0.825$

$$V_{2W} = 16.35 - 26.90 \left(\frac{n_{CS}}{V_{CS}} \right) - 38.29 \left(\frac{n_{CB}}{V_{CB}} \right) - 24.39 \left(\frac{n_{HV}}{V_{HV}} \right) - 45.98 \left(\frac{n_{3W}}{V_{3W}} \right) - 42.83 \left(\frac{n_{2W}}{V_{2W}} \right) \tag{9}$$

(146.09) (20.02) (4.99) (3.75) (10.66) (25.78) $R^2 = 0.836$

‘t’ statistics show that all coefficients are significant at 98 percent level of confidence as all values are more than critical value of 1.96. Signs of all coefficients are also logical as increase in density of any category of vehicle would reduce the speed of a vehicle. High R^2 values indicate good strength of the models in predicting the speed. Since speed parameter appears on both sides of an equation, these can be solved by the process of iteration only. A program was written in MATLAB software to solve these simultaneous equations.

7. Sensitivity Analysis

In a mixed traffic situation, speeds of different types of vehicles are expected to be influenced to different extents due to any change in the traffic volume and its composition. Traffic volume in terms of ‘vehicle per hour’ may vary widely depending upon the traffic mix. The same proportional composition of traffic stream may occur at different values of total volume on a road. Also, the different proportional composition may occur at same traffic volume. Therefore, it will be interesting to see the variation in speed of individual vehicle with traffic composition keeping total volume at some predetermined fixed value and vice-a-versa.

7.1. Variation in speed with traffic volume

Effect of traffic volume on speed of individual vehicle can be studied by solving simultaneous equations at different volume levels keeping predefined proportion of each type of vehicle. Traffic volume observed in field was in the range of 500 veh/hr to 7000 veh/hr. Therefore Equations 5 to 9 were solved for traffic volume varying from 1000 veh/hr to 5500 veh/hr in steps of 500 veh/hr. The proportional composition of traffic stream was kept fixed with CS, CB, HV, 3W and 2W as 30%, 10%, 10%, 10% and 40% respectively.

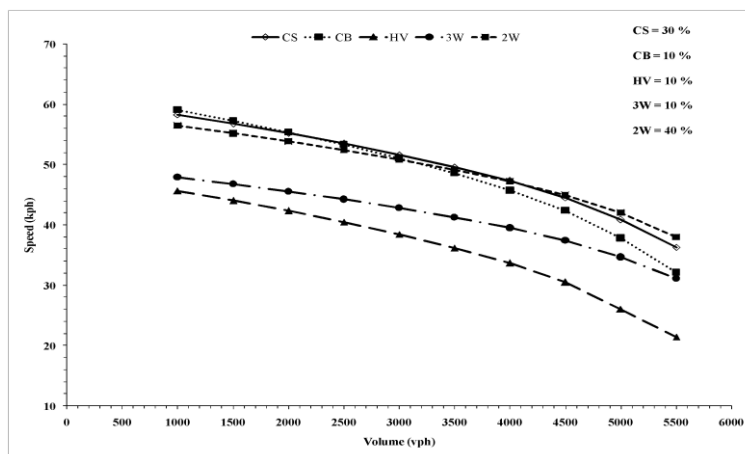


Fig. 1. Variation in Speed of Individual Vehicle with Traffic Volume

As may be seen from the above figure, that change in speed with traffic volume is less for small sized vehicle such as 2-wheeler whereas speed of big sized vehicles like HV is more influenced by traffic volume. For a given road width, increase in traffic volume will cause more density on a road (as long as it is below the level of jam density). Therefore, vehicles will move at a reduced speed but the extent of reduction will be different for different type of vehicles. The small sized vehicles like 2W and 3W due to their lesser space requirement and better manoeuvrability can squeeze to any lateral space available between large size vehicles. Therefore they are not affected much by the increase in traffic volume, but they create poorer operating conditions for HV and CB. As shown in Figure 1, there is a steep reduction in speed of large size vehicles (CB and HV) with increase in traffic volume whereas speed curves of 2W and 3W are flatter.

7.2. Variation in speed with traffic composition

Traffic composition of a stream may change with traffic volume or at the same volume level from one count period to another. The observed traffic volume in the field data was in the range from 500 to 7000 veh/hr. Therefore, simultaneous equations were solved for a predefined volume (2000 vph) and varying the proportions of different types of vehicles. Figure 2 shows the variation in speed of HV with composition of traffic stream. These curves have been drawn keeping proportions of CS, 3W and 2W at 70 percent, while CB and HV contribute the remaining 30 percent in a complementary manner. The fixed 70 percent of CS, 3W and 2W is also varied in complementary fashion to generate three curves as shown in Figure 2. Similar curves may be drawn to see the variation in speed of other vehicles also with traffic composition.

The curves drawn in Figure 2 indicate that speed of HV decreases with increase in its proportion in the traffic mix. It can be explained on the basis of pavement occupancy on the road. Due to the large size of HV, operating conditions deteriorate at fast rate with increase in their proportion in the traffic stream. Standard car, on the other hand is of smaller size and hence their presence will improve the speed of HV also.

A number of curves can be generated to show the complete variation in speed of a vehicle type with both traffic volume and proportion. Figures 3 to 5 show few such curves for HV, CB and 2W. Figures 3 and 4 indicate that speed of HV and CB does not change much, with proportion of these vehicles at low volume levels, but the effect of proportion becomes prominent at higher traffic volumes. It is again attributed to the low level of interaction between the vehicles and more freedom to vehicles at very low volume levels. Figure 5 shows the variation in speed of 2W with traffic volume and its proportion in traffic stream. As may be observed that speed of 2W are not influenced much by traffic composition because of its easy manoeuvrability. However speed of 2W significantly changes with traffic volume.

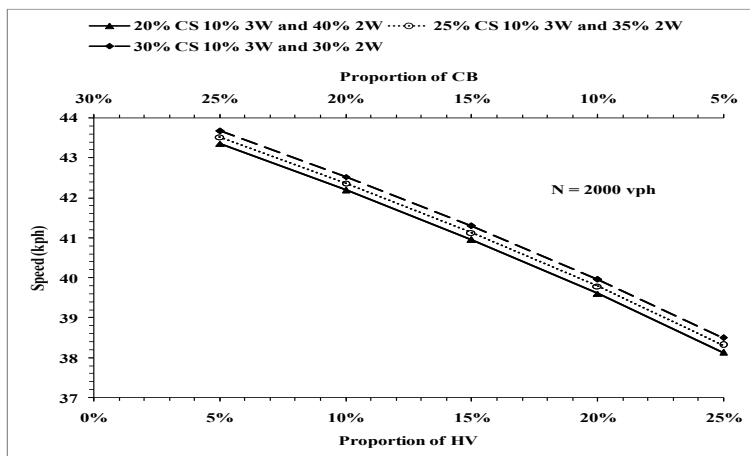


Fig. 2. Variation in Speed of Heavy Vehicle with Traffic Composition

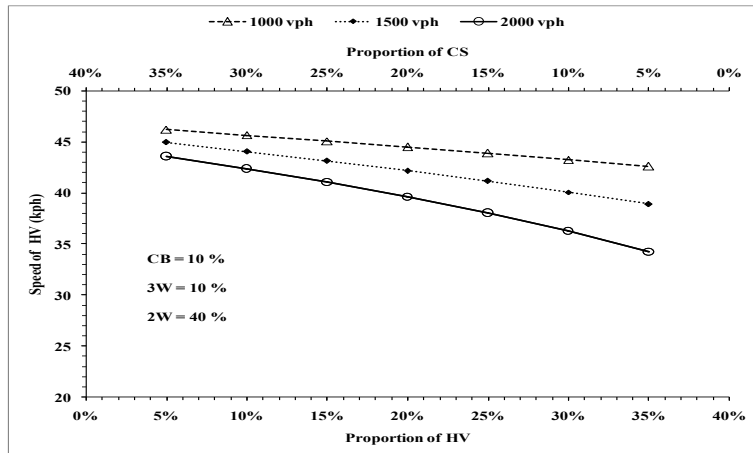


Fig. 3. Speed of Heavy Vehicle with Traffic Volume and Composition

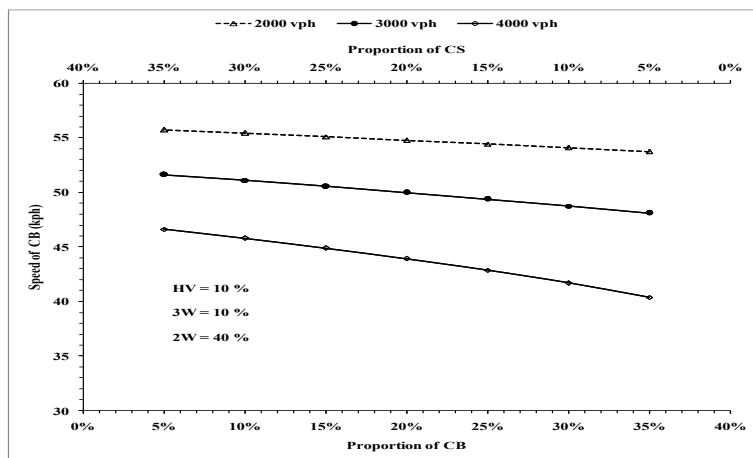


Fig. 4. Speed of Big Car at Varying Traffic Volume and Composition

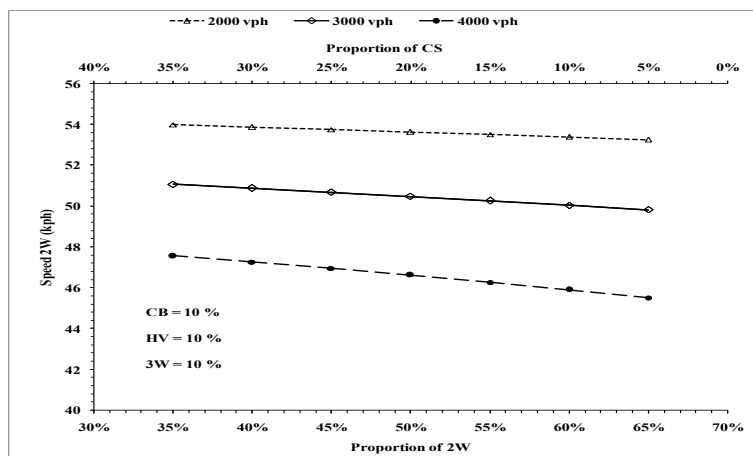


Fig. 5. Speed of 2-Wheelers at different Traffic Volume and Composition

8. Validation of Speed Models

In order to check the accuracy of speed equations developed in this study, field data were collected at one more section of six-lane divided urban road in New Delhi. Five-minute classified volume count and average speed of all categories of vehicles in the 5-minutes were extracted from the video. Simultaneous equations were solved for observed traffic volume and composition in five minute count and the speeds thus obtained are designated as predicted speeds. The predicted speed values are plotted against the observed speeds of individual vehicle in each count in Figure 6. It can be seen that speed values of different categories of vehicles truly lie on a 45 degree line and hence there is a good agreement between two sets of speed values. Further a paired t-test was conducted as a measure of statistical validation between observed and model predicted speed values of all categories of vehicles. It is found that the value of t-statistics, calculated based on observed data (t_0), is 1.73. The critical value of t-statistics, for 5 percent significance level, at 54 degree of freedom, obtained from standard t-distribution is 2.00. Thus, the t-statistics based on the observed data is less than the corresponding table value and hence there is no statistically significant difference between the predicted and observed speeds.

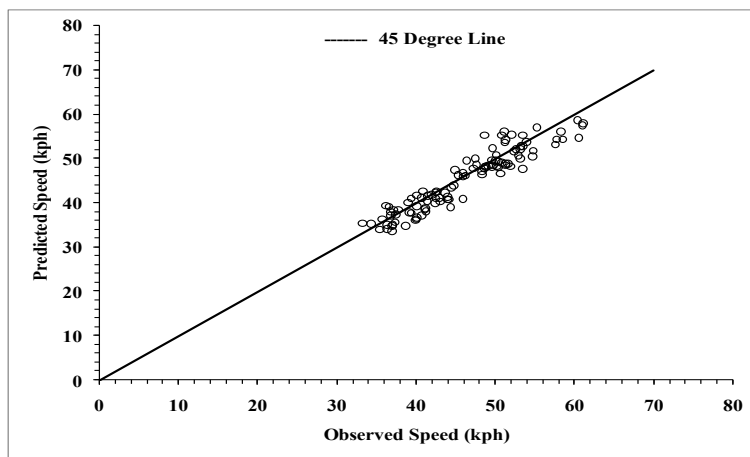


Fig. 6. Comparison between Observed and Predicted Speeds

9. Conclusions

The proposed model is one of its kind and may be used to predict speeds of individual category of vehicles to study the various heterogeneous traffic scenarios. In the present study the model was used to check the sensitivity of speed with traffic volume and traffic compositions. Various traffic scenarios are generated and variation in speed of individual vehicle is shown graphically. 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 of individual category of vehicles. These equations are then solved for varying composition of traffic stream at fixed values of traffic volume and for varying volume levels at fixed traffic composition. As the solution is based on iterative process, a mathematical program is developed in MATLAB software to solve these equations. The variation in speed for different types of vehicles is demonstrated graphically with traffic volume and traffic composition. It is observed that speed of a vehicle type decreases with increase in traffic volume which is obvious also. The change in speed with traffic volume is less for small sized vehicles such as 2 and 3-wheelers and higher for big sized vehicle like big car and heavy vehicles. This is attributed to the manoeuvrability of a vehicle type. Further, the variation in speed of a vehicle is studied with traffic composition also.

Accuracy of the proposed model is checked by collecting speed data at one additional section of six-lane road. The simultaneous equations are then solved for each five minute traffic count and speed of each vehicle type was

obtained. These speeds were found in good agreement with observed speed in field. The t test also indicated there was no significant difference between predicted speeds and observed speed data. The model is developed for five categories of vehicle in the traffic mix, but the methodology can be used to any number of vehicle categories. These equations are useful in predicting the speed of a vehicle at a given volume or composition of traffic stream which is crucial in estimation of PCU factors.

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