

1 **Speed Prediction Model on Four Lane Urban Arterials under Mixed Traffic Conditions**
2 **by using Simultaneous Equation Approach**

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1 ABSTRACT

2 Speed is a fundamental measure of traffic performance of a roadway system. It indicates the
3 quality of service experienced by the traffic stream and it depends on traffic volume or
4 density on the road. In a mixed traffic situation, congestion (or pavement occupancy) on a
5 section will depend upon the number of vehicles of different categories in the traffic stream.
6 For the same value of traffic volume, a vehicle may experience different congestion levels
7 depending upon the proportional share of large size vehicles like heavy vehicles and small
8 size vehicles like motorized two-wheelers. Hence the speed of a vehicle type will depend
9 upon the total density on the road and this total density comprises of densities of individual
10 vehicle types. In the present study field data were collected on different sections of four-lane
11 urban arterials in New Delhi, Jaipur and Chandigarh by video recording method. The speed
12 flow data collected from field shows the parabolic relationship between flow and speed that
13 reproduce the linear speed-density relationship. The present study extends this linear speed-
14 density relation to mixed traffic condition and attempts to develop a set of simultaneous
15 equations relating speed of a vehicle type to the densities of all categories of vehicles in their
16 individual terms. These equations are solved for some assumed values of traffic volume and
17 traffic composition and effect on speed of each vehicle type is explained. It has been
18 observed that there is a gentle reduction in speed of two wheelers from low flow level to the
19 capacity level of flow whereas at the same time reduction in speed of heavy vehicles is
20 steeper for the same flow range. It has been explained on the basis of vehicle
21 manoeuvrability. Two wheelers are small in their physical size and because of better
22 manoeuvrability as compared to the heavy vehicles can able to maintain the speed at high
23 flow level. The degree of damaging effect on speed of heavy vehicle at the same time is high
24 because of poor manoeuvrability. Accuracy of the equations is checked by comparing the
25 observed values of speed with calculated speeds from simultaneous equations.

26 Keywords: Simultaneous equations; Traffic volume; speed; density; urban arterial.

27

1 INTRODUCTION

2 Speed is one of the components of the fundamental relationships of traffic flow theory
 3 other than density and volume. The speeds of individual vehicles have to be specified in the
 4 form of a suitable mathematical model for predicting the speed of next vehicle in the case of
 5 simulation run. Speed has also been recognized as one of the measures that designers can use
 6 to examine road consistency and driver expectancy on roadways. Highway Capacity Manual
 7 (HCM 2010) (1) used free flow speed as a measure for defining level of service on a road.
 8 Many researchers; Cao and Sano (2) Dhamaniya and Chandra (3) Basu et al., (4) have used
 9 speed as a parameter for evaluating the passenger car unit (PCU) for different types of
 10 vehicles on a road. Speed models give an idea to the designers to work out the operating
 11 speed on a roadway. The assessment of operating speeds affords the opportunity to assess the
 12 expected speed changes of individual vehicles traversing successive road elements. In a
 13 mixed traffic condition, vehicle on a roadway occupy any lateral position as and when the
 14 driver find the opportunity. Prediction of speed of individual vehicle becomes very vague
 15 when flow levels changes from low [Figure 1(a)] to very high [Figure 1(b)]. Speed models
 16 for mixed traffic conditions are required to predict the changes in speed of an individual
 17 vehicle due to presence of other vehicles in the traffic stream.



18 Figure 1(a) Speed at low flow levels Figure 1(b) Speed at high flow levels
 19

20 LITERATURE REVIEW

21 Many researchers have put effort for modelling speed especially for the homogeneous
 22 traffic conditions. The pioneering work in this direction was done by Greenshields (5) who
 23 developed a linear relationship between speed and density which was later used to develop
 24 parabolic relation between speed and traffic flow. Himes and Donnell (6) studied the effect of
 25 geometric design features and traffic flow on operating speeds on four-lane highways. Speed
 26 models were developed to account for the endogenous relationship between lane mean speeds
 27 and speed deviation using simultaneous equation framework. Shankar and Mannering (7) also
 28 used simultaneous equation approach to model the speed on a freeway segment. Three-stage-
 29 least-squares estimator was used to evaluate endogenous variable expressed as linear function
 30 of exogenous variable. Adjacent lane mean speeds were found to be endogenous and it was
 31 found that as the adjacent lane mean speed increases, the expected lane mean speed
 32 increased. Speed deviation also depends upon the adjacent lane mean speed. Figueroa and
 33 Tarko (8) developed relationship between free flow speed (FFS) and geometric design
 34 features. A good compilation of worldwide studies of modelling operating speed on different
 35 types of highways is given in Transportation Research Circular E-C151 (9). Dixon et al. (10)
 36 studied the relationship between FFS and posted speed limit on multilane highways in
 37 Georgia, USA. Ali et al. (11) 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 (12) 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 (13) who developed motorcycle operating speed prediction model for analyzing the relationships between the motorcycle operating speed and the passenger cars operating speed. Munawar (14) 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. Dey et al. (15) reported that speed may deviate from 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 unimodal normal distribution to a bimodal or a multimodal distribution. McFadden et al. (16) developed two back propagation artificial neural networks (ANN) to predict operating speed of passenger cars on two-lane rural highways. Najjar et al. (17) 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. (18) developed an operating speed prediction model for trucks on two-lane rural highways for use in design consistency. Al-Ghamdi (19) 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. In a very recent study Ponnu et al. (20) developed vehicle class wise speed volume models on three lane undivided roads in Chennai, India. The outcome of the study shows that linear models perform better than other models for most of the vehicle class. It has also been concluded that multi-class speed flow models with class wise volumes perform better than multi-class speed flow models with total volume in term of PCU/hr. Rao and Rao (21) developed the free flow speed models for urban arterials in New Delhi, India. The proposed model illustrates that road side friction, access point density; number of flyovers and length of section under consideration are found significant variables influencing free flow speed of a vehicle type. 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.

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 anywhere on a road as and where they find the space with no mention of lane discipline. 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 model the speed for different categories of vehicles using speed–density relationship of traffic flow. Speed flow relationship observed from field data replicates parabolic relation and hence it inferences that speed–density would have the linear relationship and the 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.

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 occur 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).

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

Where V_f and K_j are the free flow speed and jam density respectively. 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.

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

Where V_i is the speed of vehicle category i and K_p is the density of vehicle category j in the traffic stream. Here, N is the total number of vehicle categories. The a_i in the above equation would represent the free flow speed 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 in the present study on different sections of four-lane urban arterial roads in India. The speed flow data as observed in the field on different sections of four-lane road with same geometric characteristics are combined and presented in Figure 2. It may be observed that there is a wide variation in speed at a particular flow level; it indicates the different driver behaviour characteristics at different locations. As the flow increases the speed decreases. These data are used to determine the density of traffic stream and speed-density relationships for different vehicle type as explained above.

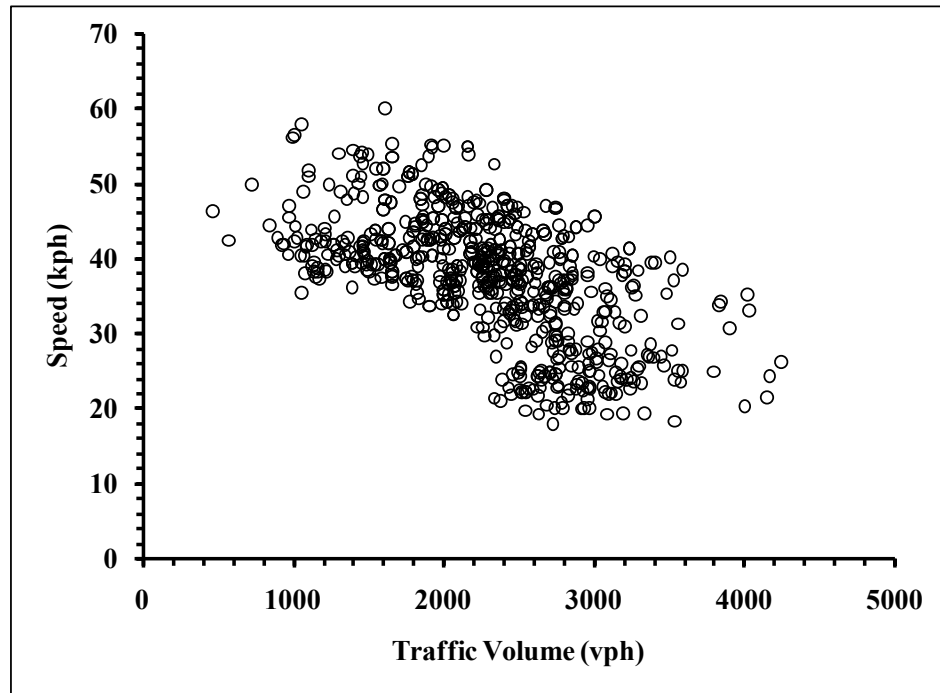


Figure 2 : Speed-flow data observed from field

FIELD DATA COLLECTION

Field data for present study were collected at five urban arterial roads in three cities of India; New Delhi, Chandigarh and Jaipur. All locations were on four-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. 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.

1 Table 1. Observed traffic composition at different sections

Name of the city	Name of Location	Composition (%)				
		Small Car (CS)	Big Car (CB)	Heavy Vehicle (HV)	Three wheeler (3W)	Two wheeler (2W)
N. Delhi	Shanti Path	58.08	11.04	2.03	7.71	21.14
N. Delhi	MTC Marg	49.00	8.80	2.50	18.90	20.80
N. Delhi	Shahjahan Road	45.76	5.76	4.13	18.41	25.94
Jaipur	Hawa Sadak	24.29	10.05	5.19	8.30	52.17
Chandigarh	Setor 35-36 Road	30.80	8.34	3.23	6.89	50.74

2 Table 2. Vehicle categories and their dimensions

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

3 **DEVELOPMENT OF SIMULTANEOUS EQUATIONS**

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

10 Speed data extracted for different categories of vehicles for every 5-min volume count
11 are used to develop the simultaneous speed equations. Since field measurement of traffic
12 density is difficult, attempts have always been made to concentrate on speed-volume
13 relationship and density has been determined using fundamental relationship between speed,
14 flow and density as used by many researchers for heterogeneous traffic; Cao and Sano (2),
15 Dhamaniya and Chandra (3), Lam et al. (23), Edigbe and Furgeson (24), Lum et al. (25).
16 Although if there is any variation in formative density due to heterogeneous traffic, the
17 variation will be taken care by the coefficients a_1 to a_5 . The mathematical form of the
18 proposed model is given in Equation 4.

$$19 \quad V_i = a_0 - a_1 \left(\frac{n_{CS}}{V_{CS}} \right) - a_2 \left(\frac{n_{CB}}{V_{CB}} \right) - a_3 \left(\frac{n_{HV}}{V_{HV}} \right) - a_4 \left(\frac{n_{3W}}{V_{3W}} \right) - a_5 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (4)$$

20 Where 'V' is the speed in m/sec, and 'n/v' is the density of a vehicle type present in
21 the traffic stream. The CS, CB, HV, 3W and 2W are the vehicle categories as described in
22 Table 1.

23 Speed of a vehicle type will be influenced to different extents by the vehicles of
24 different categories and therefore coefficients a_0 to a_5 are expected to be substantially
25 different when speed of individual type of vehicle is modelled. Regression coefficients a_0 ,

1 $a_1, \dots, a_5$ as estimated from field data and combined from eight different roads are given in
 2 Equations 5 to 9. The values given in parentheses are the 't' values of coefficients.

$$3 \quad V_{CS} = 16.12 - 56.69 \left(\frac{n_{CS}}{V_{CS}} \right) - 52.10 \left(\frac{n_{CB}}{V_{CB}} \right) - 71.59 \left(\frac{n_{HV}}{V_{HV}} \right) - 63.60 \left(\frac{n_{3W}}{V_{3W}} \right) - 48.26 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (5)$$

$$4 \quad (105.26) \quad (20.37) \quad (6.92) \quad (7.47) \quad (7.67) \quad (17.13) \quad R^2 = 0.92$$

$$5 \quad V_{CB} = 16.66 - 87.21 \left(\frac{n_{CS}}{V_{CS}} \right) - 152.63 \left(\frac{n_{CB}}{V_{CB}} \right) - 110.75 \left(\frac{n_{HV}}{V_{HV}} \right) - 67.02 \left(\frac{n_{3W}}{V_{3W}} \right) - 59.62 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (6)$$

$$6 \quad (71.80) \quad (13.51) \quad (3.97) \quad (4.99) \quad (4.09) \quad (11.17) \quad R^2 = 0.90$$

$$7 \quad V_{HV} = 12.75 - 38.30 \left(\frac{n_{CS}}{V_{CS}} \right) - 81.33 \left(\frac{n_{CB}}{V_{CB}} \right) - 189.28 \left(\frac{n_{HV}}{V_{HV}} \right) - 39.18 \left(\frac{n_{3W}}{V_{3W}} \right) - 23.08 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (7)$$

$$8 \quad (54.45) \quad (7.66) \quad (8.14) \quad (5.09) \quad (3.01) \quad (9.52) \quad R^2 = 0.83$$

$$9 \quad V_{3W} = 13.15 - 32.47 \left(\frac{n_{CS}}{V_{CS}} \right) - 48.21 \left(\frac{n_{CB}}{V_{CB}} \right) - 40.55 \left(\frac{n_{HV}}{V_{HV}} \right) - 37.60 \left(\frac{n_{3W}}{V_{3W}} \right) - 34.89 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (8)$$

$$10 \quad (69.25) \quad (8.53) \quad (2.99) \quad (3.90) \quad (3.79) \quad (12.19) \quad R^2 = 0.88$$

$$11 \quad V_{2W} = 15.90 - 36.26 \left(\frac{n_{CS}}{V_{CS}} \right) - 46.62 \left(\frac{n_{CB}}{V_{CB}} \right) - 34.74 \left(\frac{n_{HV}}{V_{HV}} \right) - 43.72 \left(\frac{n_{3W}}{V_{3W}} \right) - 69.79 \left(\frac{n_{2W}}{V_{2W}} \right) \quad (9)$$

$$12 \quad (83.10) \quad (10.55) \quad (5.64) \quad (4.84) \quad (5.04) \quad (11.53) \quad R^2 = 0.94$$

13 The 't' values of the coefficients is more than the critical value of 1.96 at 98 percent
 14 level of confidence and hence all the coefficients are significant. Signs of all coefficients are
 15 also logical as increase in density of any category of vehicle would reduce the speed of a
 16 vehicle. The R-square values also indicate good strength of the models in predicting the
 17 speed. Since speed parameter appears on both sides of an equation, these can be solved by the
 18 process of iteration only.

19 Further a correlation matrix is developed between independent variables and the
 20 maximum correlation value was found 0.339 substantiate that the variables are not highly
 21 correlated. This can be explained based on the fact that arrival of vehicles of one category at a
 22 point on the section of the road is expected to be independent of the arrival of vehicles of any
 23 other category and so is the case with density also. However, independence of variables used
 24 in regression equations was checked by drawing a correlation matrix for each variable
 25 separately and the maximum correlation value was found to be only 0.339 between the two
 26 coefficients, indicating that there is no influence of density of one category of vehicle to
 27 another. The typical correlation matrix for small car (V_{CS}) is given in Table 3.

28

Table 3 Correlation Matrix for V_{CS}

Coefficients	a_0	a_1	a_2	a_3	a_4	a_5
a_0	1.000	0.317	0.012	0.083	0.091	0.323
a_1	0.317	1.000	0.339	0.022	0.329	0.314
a_2	0.012	0.339	1.000	0.151	0.097	0.117
a_3	0.083	0.022	0.151	1.000	0.304	0.067
a_4	0.091	0.329	0.097	0.304	1.000	0.130
a_5	0.323	0.314	0.117	0.067	0.130	1.000

The Newton Rapson method is used to solve these simultaneous equations. The method is based upon the convergence of a function to a particular value which satisfies the function. Let 'f' is a function of five different independent variables x_1 to x_5 .

Where;

$$x_1 = n_{cs}/V_{cs}$$

$$x_2 = n_{cb}/V_{cb}$$

$$x_3 = n_{hv}/V_{hv}$$

$$x_4 = n_{3w}/V_{3w}$$

and

$$x_5 = n_{2w}/V_{2w}$$

So the equation 5 to 9 may be rewritten in the form of equation 10 to 14 as given below:

$$f_1(x_1, \dots, x_5) = 56.69 * x_1 + 52.10 * x_2 + 71.59 * x_3 + 63.60 * x_4 + 48.26 * x_5 + \frac{n_{cs}}{x_1} - 16.12 = 0 \quad \dots\dots (10)$$

$$f_2(x_1, \dots, x_5) = 87.21 * x_1 + 152.63 * x_2 + 110.75 * x_3 + 67.02 * x_4 + 59.62 * x_5 + \frac{n_{cb}}{x_2} - 16.66 = 0 \quad \dots\dots(11)$$

$$f_3(x_1, \dots, x_5) = 38.30 * x_1 + 81.33 * x_2 + 189.28 * x_3 + 39.18 * x_4 + 23.08 * x_5 + \frac{n_{hv}}{x_3} - 12.75 = 0 \quad \dots\dots(12)$$

$$f_4(x_1, \dots, x_5) = 32.47 * x_1 + 48.21 * x_2 + 40.55 * x_3 + 37.60 * x_4 + 34.89 * x_5 + \frac{n_{3w}}{x_4} - 13.15 = 0 \quad \dots\dots(13)$$

$$f_5(x_1, \dots, x_5) = 36.26 * x_1 + 46.62 * x_2 + 34.74 * x_3 + 43.72 * x_4 + 69.79 * x_5 + \frac{n_{2w}}{x_5} - 15.90 = 0 \quad \dots\dots(14)$$

Solution of the function [f] could be made by iterative process. As the process is iterative in nature, a programme is written in MATLAB software to get the convergence value.

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

1 with traffic composition keeping total volume at some predetermined fixed value and vice-a-
2 versa.

3 *Variation in speed with traffic volume*

4 Effect of traffic volume on speed of individual vehicle can be studied by solving
5 simultaneous equations at different volume levels keeping predefined proportion of each type
6 of vehicle. Traffic volume observed in field was in the range of 300 veh/hr to 4350 veh/hr.
7 Therefore Equations 5 to 9 were solved for traffic volume varying in steps of 500 veh/hr. The
8 proportional composition of traffic stream was kept fixed with CS, CB, HV, 3W and 2W as
9 30%, 10%, 10%, 10% and 40% respectively.

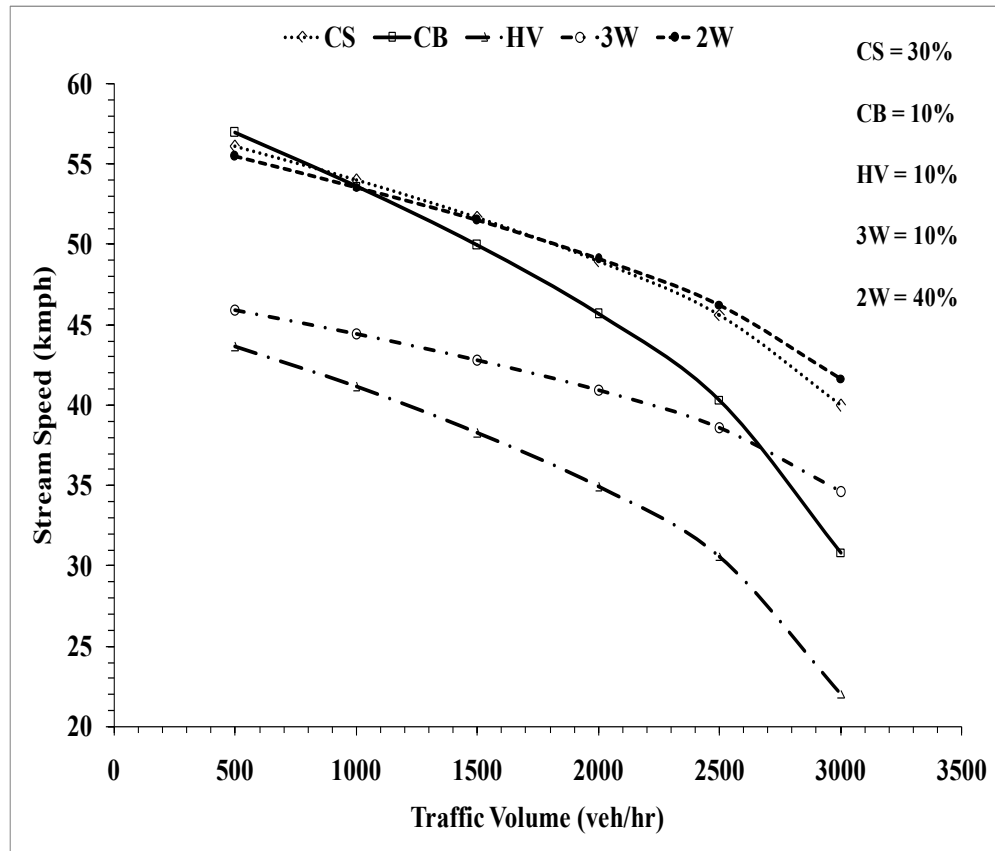


Figure 3: Variation in Speed of Individual Vehicle with Traffic Volume

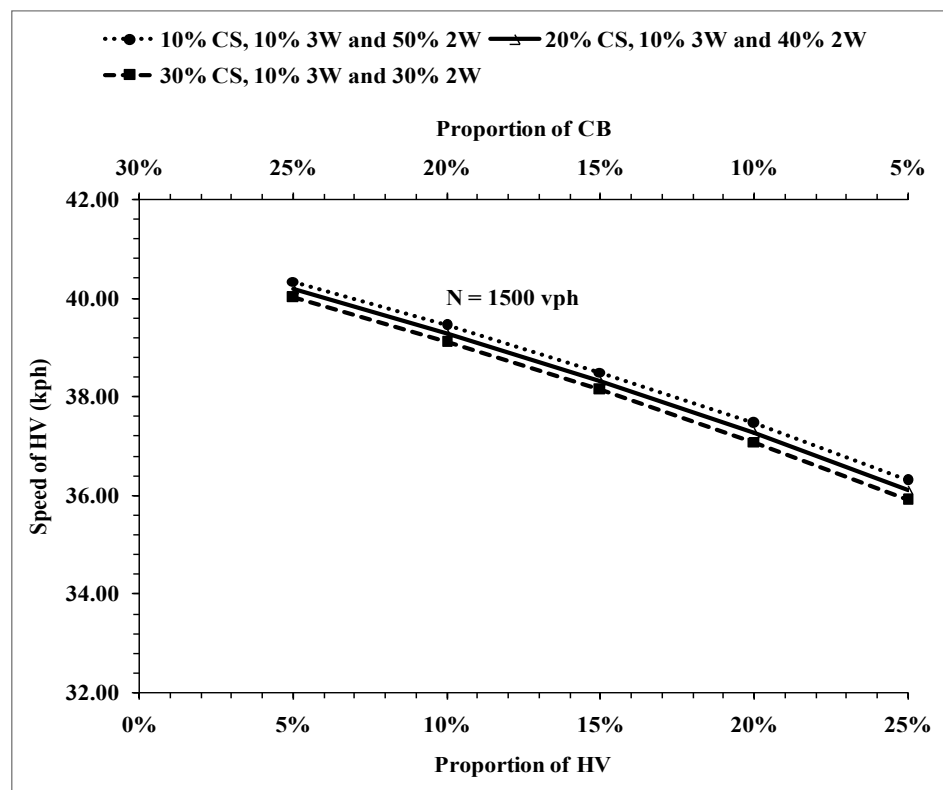
As may be seen from the above figure, that change in speed with traffic volume is less for small sized vehicle such as 2W whereas speed of big sized vehicles like HV is more influenced by traffic volume. For a given road width, increase in traffic volume will cause more density on a road as long as it is below the critical density or the density at maximum volume (capacity). 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 3, 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.

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 300 to 4350 veh/hr. Therefore, simultaneous equations were solved for a predefined volume (1500 vph) and varying the proportions of different types of vehicles. Figure 4 (a) shows the variation in speed of HV with composition of traffic stream. These curves have been drawn keeping the total 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 4 (b). Similar curves may be drawn to see the variation in speed of other vehicles also with traffic composition.

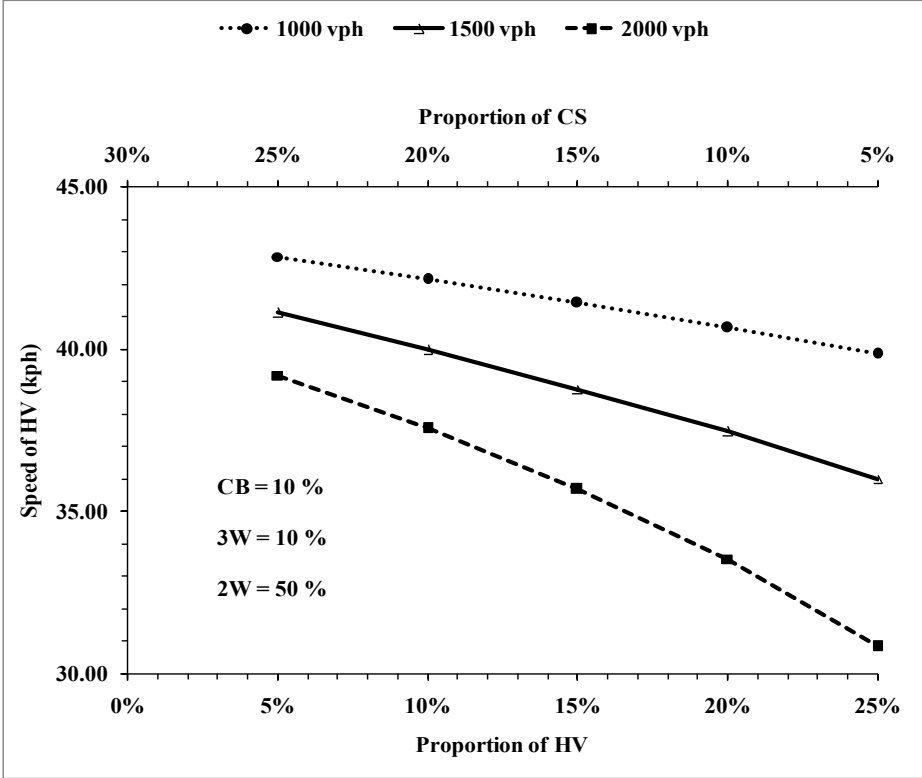
The curves drawn in Figure 4 (a) and 4 (b) indicate that speed of HV decreases with increase in its proportion in the traffic mix. It can be explained on the basis of pavement occupancy on the road. Due to the large size of HV, operating conditions deteriorate at fast rate with increase in their proportion 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 4 (a) to 5 (b) shows few such curves for HV, CB and 3W. Figures 4 (b) and 5 (a) 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 (b) shows the variation in speed of 3W with traffic volume and its proportion in traffic stream. As may be observed that speed of 3W are not influenced much by traffic composition because of its easy manoeuvrability. However speed of 3W significantly changes with traffic volume.



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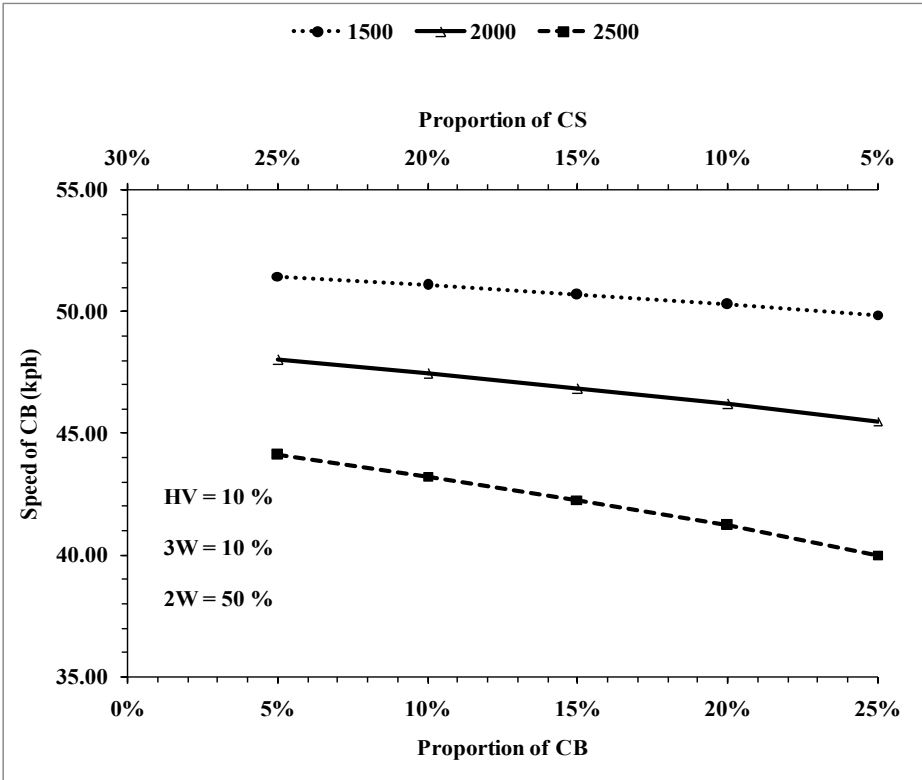
Figure 4 (a): Variation in Speed of Heavy Vehicle with Traffic Composition



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Figure 4 (b): Speed of Heavy Vehicle with Traffic Volume and Composition



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Figure 5 (a): Speed of Big Car at Varying Traffic Volume and Composition

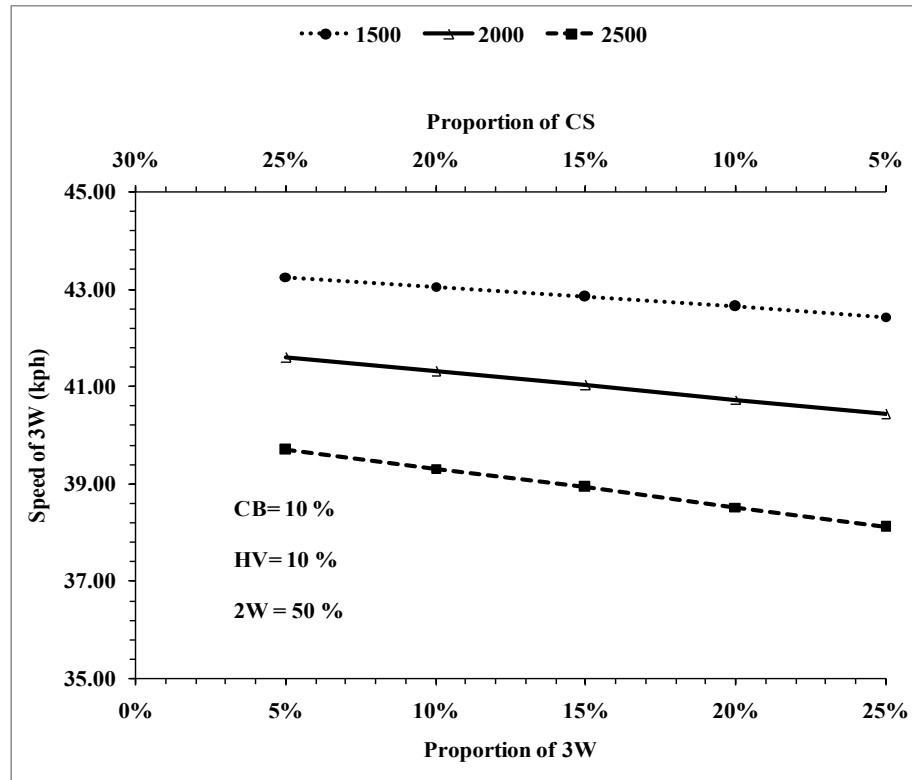


Figure 5 (b): Speed of 3-Wheelers at different Traffic Volume and Composition

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 four-lane divided urban road in New Delhi (Pancheel Marg) with a typical composition of five categories of vehicle in the traffic mix. The CS and CB proportion at this section is observed as 42.82 and 6.60 percent whereas the heavy vehicle proportion was 3.78 percent. The motorized 3W and 2W proportion was found as 20.12 and 26.68 percent respectively. 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 1.68. The critical value of t-statistics, for 5 percent significance level, obtained from standard t-distribution is 1.93. 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.

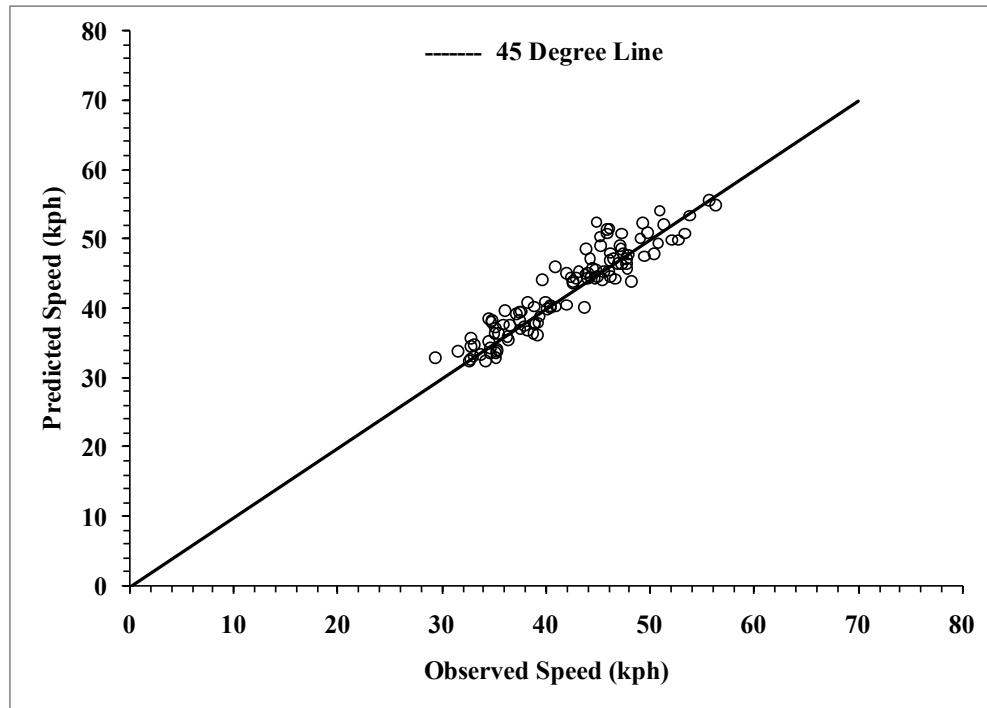


Figure 6: Comparison between Observed and Predicted Speeds

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 the Newton Rapson method is used 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. It is observed that at nearly free flow conditions the speed of big car is highest among all categories of vehicles whereas at the congestion level near to capacity the speed of 2W and small car is more than big car speed. 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 four-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.

1 References

- 2 1. *Highway Capacity Manual* 2010. Transportation Research Board of National Academies,
3 Washington, D. C., 2010.
- 4 2. Cao N.Y. and Sano K., Estimating Capacity and Motorcycle Equivalent Units on Urban
5 Roads in Hanoi, Vietnam, *Journal of Transportation Engineering ASCE*, Vol. 138 No. 6,
6 2012, pp. 776-785.
- 7 3. Dhamaniya, A. and Chandra S., Influence of Undesignated Pedestrian Crossings on
8 Midblock Capacity of Urban Roads *Transportation Research Record 2461*,
9 Transportation Research Board, Washington, D.C., 2014, pp. 137-144.
- 10 4. Basu D., Maitra R.S. and Maitra, B. Modelling Passenger Car Equivalency at an Urban
11 Midblock Using Stream Speed as a Measure of Equivalence. *European Transport-
12 Trasporti Europei* , Vol. 34, 2006, pp. 75-87.
- 13 5. Greenshields, B.D., A Study of Traffic Capacity, *Highway Research Board Proceedings*,
14 Vol. 14, 1935.
- 15 6. Himes, S. C., & Donnell E.T., Speed Prediction Models for Multi-lane Highways: A
16 Simultaneous Equations Approach.” *Journal of Transportation Engineering*, ASCE, Vol.
17 136 No. 10, 2010, pp. 855-862.
- 18 7. Shankar, V., & Mannering F., Modeling the Endogeneity of Lane-Mean Speeds and
19 Lane-Speed Deviations: A Structural Equations Approach. *Transportation Research Part
20 A*, Vol. 32 No. 5, 1998, pp. 311-322.
- 21 8. Figueroa, A., and Tarko, A., Reconciling Speed Limits with Design Speeds. *Rep. No.
22 FHWA/IN/JTRP-2004/26*, Purdue Univ., West Lafayette, Ind. 2004, USA.
- 23 9. Transportation Research Circular Number E-C151, Modelling Operating Speed
24 Synthesis Report, Transportation Research Board of the National Academies,
25 Washington, D.C., 2011.
- 26 10. Dixon, K. K., Wu, C.H., Sarasua, W. and Daniel, J., Posted and Free-Flow Speeds for
27 Rural Multilane Highways in Georgia. *Journal of Transportation Engineering*, ASCE,
28 Vol.125 No. 6, 1999, pp. 487-494.
- 29 11. Ali, A., Flannery A., and Venigalla M., Prediction Models for Free Flow Speed on Urban
30 Streets. Presented at the 86th Annual Meeting of the Transportation Research Board,
31 2007.
- 32 12. McLean, J. R., Observed Speed Distributions and Rural Road Traffic Operations.
33 *Proceedings, 9th Australian Road Research Board Conf.*, Part 5, Australian Road
34 Research Board, Vermont South, Victoria, Australia, 1978, pp. 235–244.
- 35 13. Perco, P., Comparison between Powered Two Wheeler and Passenger Car Free-Flow
36 Speeds in Urban Areas”. *Journal of the Transportation Research Board*, No. 2074,
37 Transportation Research Board of the National Academies, Washington, D.C., 2008, pp.
38 77–84.
- 39 14. Munawar A., Speed and Capacity for Urban Roads, Indonesian Experience, *Proceedings*,
40 6th International Symposium on Highway Capacity and Quality of Service, Stockholm,
41 Sweden, 2011.
- 42 15. Dey P.P., Chandra, S., and Gangopadhaya S., Speed Distribution Curves under Mixed
43 Traffic Conditions” *Journal of Transportation Engineering*, ASCE, Vol.132 No. 6, 2006,
44 pp. 475-491.
- 45 16. McFadden, J., Yang, W., and Durrans, S. R., Application of Artificial Neural Networks to
46 Predict Speeds on Two-Lane Rural Highways.” *Transportation Research Record 1751*,
47 Transportation Research Board, Washington, D.C., 2001, pp. 9–17.

- 1 17. Najjar, Y. M., Stokes, R. W., and Russell, E. R., Setting Speed Limits on Kansas Two-
 2 Lane Highways.” *Transportation Research Record 1708*, Transportation Research Board,
 3 Washington, D.C., 2000, pp. 20–27.
- 4 18. Donnel, E. T., Ni, Y., Adolini, M., and Elefteriadou, L., Speed Prediction Models for
 5 Trucks on Two-Lane Rural Highways.” *Transportation Research Record 1751*,
 6 Transportation Research Board, Washington, D.C., 2001, pp. 44–55.
- 7 19. Al-Ghamdi, A. S., Spot Speed Analysis on Urban Roads in Riyadh.” *Transportation*
 8 *Research Record 1635*, Transportation Research Board, Washington, D.C., 1998, pp.
 9 162–170.
- 10 20. Ponnu, B., Thomas, J., Jha, K., Asaithambi, G. and Srinivasan, K., Vehicle Class-wise
 11 Speed Volume model for Three-Lane Undivided Urban Roads, *Procedia – Social and*
 12 *Behavioral Sciences 104*, 2013, pp. 468-476.
- 13 21. Rao A. M. and Rao K.R., Free Speed Modelling for Urban Arterials – A Case Study on
 14 Delhi” *Periodica Polytechnica Transportation Engineering*; Vol. 43 No. 3, 2015, pp.
 15 111-119.
- 16 22. Lam H.K., Tam M.L., Cao. X and Li X., Modeling the Effects of Rainfall Intensity on
 17 Traffic Speed, Flow, and Density Relationships for Urban Roads *Journal of*
 18 *Transportation Engineering ASCE*, Vol. 139, No. 7, 2013, pp. 758-770.
- 19 23. Edigbe J.B. and Ferguson N., Extent of Capacity Loss Resulting from Pavement
 20 Distress” *Proceedings of the Institution of Civil Engineers*, Transport 158, 2005, pp. 27-
 21 32.
- 22 24. Lum. K.M., Fan. H.S.L., Lam., S.H. and Olszewski P., Speed-Flow Modelling of
 23 Arterial Roads in Singapore. *Journal of Transportation Engineering ASCE*, Vol. 124
 24 No. 3, 1998, pp. 213-222.