Methodology for simulating heterogeneous traffic on expressways in developing countries: a case study in India

Shriniwas Arkatkar*, S. Velmurugan2, Ravikiran Puvvala3, Balaji Ponnu3 and Sukrit Narula3

The prevailing roadway and traffic conditions on expressways in India are vastly different when compared with the other roads in India and in addition, there is no perfect lane-discipline. Nevertheless, there is not much research literature available specific to these categories of roads in India. The knowledge of roadway capacity is an important basic input required for planning, design, analysis, and operation of roadway systems. Hence, this work aims to model traffic flow on Indian urban expressways with specific reference to Delhi–Gurgaon expressway and estimate its capacity using the micro-simulation model using VISSIM 5-40. For this purpose, the field data collected on traffic-flow characteristics on expressways was used in calibration and validation of the simulation model. The validated simulation model was then used to develop fundamental traffic–flow relationships, namely, speed–flow, speed–area occupancy, and flow–area occupancy for the traffic-flow levels, starting from near-zero until the capacity of the facility. The capacity of an eight-lane divided urban expressway in level terrain with 14-0-m wide road space (one direction of traffic flow) was found to be in the range of 9700–0 000 vehicles/h. In this study, through sensitivity analysis using simulation model, the following relationships, (i) percentage trucks in the traffic stream and capacity-level flow and (ii) percentage of trucks in the traffic stream and capacity-level traffic-stream speed, were also developed. The results and the overall methodology followed in this study for modeling traffic flow on expressways in India to determine the capacity estimates under varying traffic compositions may be very useful for the practitioners and also for the continuing efforts to prepare an Indian Highway Capacity Manual.

Keywords: Heterogeneous traffic, Highway capacity, Traffic simulation

Introduction

An urban expressway is defined as an arterial highway for motorized traffic, with divided carriageways for high speed travel, with full control of access, and usually provided with grade separators at location of intersections. They are the highest class of roads in the Indian road network. Higher design speeds, restriction on slow moving vehicles, and varied traffic composition with high amount of cars characterize these roads. With such operational difference and with many urban expressways such as Delhi–Gurgaon, Delhi–Noida Direct flyway, Noida–Greater Noida expressway, being in existence and more number of them such as the Kundli–Manesar–Palwal expressways being built, a thorough understanding of their traffic operation is imperative. Traffic flow on Indian expressways is quite interesting to be studied because of two reasons. First, the traffic is multi-class mainly, with vehicles such as cars and pickups having high maneuverability and heavy vehicles such as trucks and buses having less maneuverability. The speed of these vehicles may vary from 40 to ~ 100 km h\(^{-1}\). Traffic movement on Indian expressways may be said to be quasi-lane disciplined, with some vehicles following a lane-based driving and many others not. Moreover, the level of lane discipline may change.

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significantly based on the traffic-flow level and its composition. Such lack of lane discipline can be attributed to combination of factors, namely level of enforcement and education. Indian drivers are not educated about the importance of sticking to their lanes other than for overtaking and improving driving speeds. There are neither video cameras mounted at select locations of the roads nor a central monitoring system that reports violations. Consequently, the vehicles tend to take any lateral position along the width of roadway based on the space availability. When such different types of vehicles with varying static and dynamic characteristics are allowed to mix and move on the same roadway facility, a variable set of longitudinal and transverse distribution of vehicles may be noticed from time to time. Hence, expressways remain as a partially heterogeneous traffic characterized by a low level of lane discipline. Given this significant difference in the nature of traffic flow in expressways in relation with other kind of roads in India as explained earlier, there are not much research work on either design or operation of these facilities.

There is a very less literature available on capacity of expressways which has also found a statement in the eleventh Five Year plan (2007–2012) report. Considering all the above, it is imperative and timely to initiate a study on the capacity of expressways depending on the carriageway/roadway widths and other relevant parameters. Thus, this study is aimed at developing capacity estimates for urban expressway segments under varying traffic conditions, which will help in meeting the country’s need for design, analysis, operations, and management of expressways. To accomplish this goal, the traffic flow on the Delhi–Gurgaon expressway has been studied and modeled through simulation. The results of the study may be very useful for the practitioners and also for the continuing efforts to prepare an Indian Highway Capacity Manual.

Literature review

Simulation has been recognized as one of the best tools for modeling of traffic flow under homogeneous as well as heterogeneous conditions. Fellendorf and Vortisch (2001) presented the possibilities of validating the microscopic traffic-flow simulation model VISSIM, both on a microscopic and on a macroscopic level in homogeneous flows. Hossain (2004) calibrated the heterogeneous-traffic model in VISSIM to match saturation flows measured by video at an intersection in the city of Dhaka, Bangladesh. Matsuhashi et al. (2005) assessed the traffic situation in Hochiminh city in Vietnam, using image processing technique and traffic simulation model (VISSIM). It was found that the high number of motorcycles in the network interfere with other vehicles which reduces average speed of traffic stream drastically. Further, the simulation model was applied for deriving the benefits of increasing the share of public transport. Lownes and Machemehl (2006) performed sensitivity of car-following parameters in VISSIM. Huang and Tang (2007) calibrated Verkehr in Staedten simulation using VISSIM, for a bay rapid transit project by visual verification and moreover, acceptance criteria were defined for volumes. Zhang et al. (2008) conducted a study using VISSIM to evaluate a proposed feedback-based tolling algorithm to dynamically optimize high-occupancy toll lane operations and performance. Ishaque and Noland (2009) demonstrated the feasibility of modeling vehicle–pedestrian interactions using VISSIM and provided a tool for evaluating policies that affect both vehicle and pedestrian flows.

Many researchers tried to build their own simulation software for studying heterogeneous traffic flow. Marwah and Ramesh (1978) used simulation technique to study the interaction between vehicles in mixed traffic-flow. The simulation model included unimpeded, overtaking and restricted stream logics, formulated for a two-lane two-way highway. Simulation runs were performed for homogenous car traffic at different volume levels, and for mixed traffic, consisting of two types of vehicles – passenger car and one of the other vehicles being either, truck, scooter, horse-drawn vehicle, bullock cart, or bicycle. The level-of-service (LoS) of mixed traffic was specified in terms of operating speed of passenger cars. Speed–volume relationships were developed for the two vehicle combinations. The results indicated that the interaction between vehicles was a function of volume level and traffic composition. Marwah and Bandyopadhyay (1983) developed a computer-simulation model for a road section having four lanes – two in each direction, with signaled intersections, based on the traffic data collected in Kolkata (Calcutta) city. The different types of vehicles considered in the model were car, mini-bus, single-deck bus, double-deck bus, and tram. Deterministic inputs to the model included the number of lanes, slope of road, curvature of the road, vehicle characteristics like free speed, acceleration rate, deceleration rate, etc. Stochastic inputs included driver’s characteristics like overtaking, gap acceptance, and traffic characteristics like headway distribution, volume, speed, etc. The output included the position of the vehicle on the road system with respect to time, speed of the vehicle, total travel time, journey speed, etc. Ramashaya (1988) developed simulation models to depict mixed traffic flow on single-lane one-way, two-lane one-way, and two-lane two-way traffic roads. The model considered the lane concept in which the passing maneuver was permitted using the shoulder portion of the pavement. The model used the car-following logic for maintaining safe gap between vehicles. The model assumed that any fast vehicle would overtake the leading slow vehicle, provided the lateral clearance is greater than a prescribed minimum value. Experiments were done up to volume levels of 800 vph. Validation of the model was based on comparison of observed and simulated speed distributions. Raghavachari et al. (1993) developed a simulation model for pedestrian movement at uncontrolled urban intersections. The model used to study the interactions between pedestrians and vehicles at the intersections in terms of delay suffered. Bhannumurthy and Adityam (1993) developed a simulation model for predicting the delays and queue characteristics at signalized intersections. Agarwal et al. (1994) developed a simulation program in FORTRAN language for heterogeneous traffic flow at a four-legged, right-angled, uncontrolled intersection. The pseudo-random numbers were generated using the mixed congruential method to generate long sequence of random numbers. Seven different categories of vehicles were considered in the study. The model has been validated using the field observed headway data.
The applicability of the model has been checked with the obtained total delay and queue length for the different approaches. Isaac and Veeraragavan (1995) developed a mixed traffic-flow simulation model for estimation of urban road capacities and studied the effect of variation in traffic composition. Linear and lateral space-gap models were developed, both for one-way and two-way flows, to study the effect of speed and vehicle type on space gaps. Kumar and Rao (1996b) simulated traffic operations on two-lane highways. For updating the state of the system during simulation runs, a combination of time scanning and event scanning procedures were adopted. Headways were sampled from specified statistical distributions. As a measure of validation, the output from the simulation model was compared with the field data observed. Traffic was simulated to replicate the observed field conditions and the average journey speeds of different categories of vehicles were compared with the observed values. The validation indicated that the model could reasonably estimate the journey speeds of vehicles on two-lane highways within the range of flow levels considered for the study. Kumar and Rao (1996a) modeled the traffic flow and characteristics at a yield controlled T-intersection using simulation. The model generated vehicle arrivals using shifted negative exponential distribution. The output of the model was analyzed to obtain overall average delay and the average acceleration-deceleration delay for the intersection. It was observed from the results that the delay increases linearly with an increase in the major road volume up to a certain point and thereafter it increases exponentially. Khan and Maini (1999) reviewed the various models of heterogeneous traffic flow. The authors pointed that the performance of vehicles in mixed traffic flow depends on the road geometry, prevailing traffic conditions and the static and dynamic properties of vehicles. The authors discussed that when fast moving vehicles follow slow moving vehicles, because of the size, speed, and vehicle width, unique decision-making takes place for overtaking and passing. The authors also suggested that sheer width of roadway often determines the range of driver behavior, and hence the interaction among vehicles. Maini and Khan (2000) analyzed the discharge characteristics of heterogeneous traffic at signalized intersections. Marwah and Singh (2000) developed a traffic-flow simulation model to study the LoS under heterogeneous traffic condition. The model was applied to simulate traffic flow on a two-lane road with 7-0-m width of carriageway, for different flow levels. The operating characteristics considered for the analysis to define LoS are journey speed of cars, journey speed of motorized two-wheelers, concentration, and road occupancy. The comparison of simulated and observed output indicates the capability of the simulation model to realistically represent the complex heterogeneous traffic flow with 35% motorized vehicles and 65% non-motorized vehicles. Rajagopal and Dhingra (2002) investigated the usefulness of traffic simulation models in the assessment of traffic management strategies. Traffic simulation was shown to be a useful tool for evaluating the effects of lane additions or deletions. Arasan and Kashani (2003) studied the platoon dispersal characteristics of heterogeneous traffic streams using simulation technique. The entire road space has been considered as a single unit made of small imaginary squares (cells of convenient size), thus transforming the entire space into a matrix. The vehicles were represented with dimensions (including the lateral and longitudinal clearances) as rectangular blocks occupying a specified number of cells. Coordinate system has been implemented to locate the position of a vehicle with respect to fixed origin. Arasan and Koshy (2005) developed a heterogeneous traffic-flow simulation model to study the various characteristics of the traffic flow at micro level under mixed traffic condition on urban roads. The vehicles are represented, with dimensions, as rectangular blocks occupying a specified area of road space. The positions of vehicles are represented using coordinates with reference to an origin. For the purpose of simulation, the length of road stretch as well as the road width can be varied as per user specification. The model was implemented in C++ programming language with modular software design. The model is also capable of showing the animation of simulated traffic movements over the road stretch. Dey et al. (2008) developed a simulation program coded in Visual Basic language. The authors performed number of simulation runs to determine the capacity of a two-lane road and to study the effect of traffic mix, slow moving vehicles, and directional distribution of traffic on capacity and speed. Mathew and Radhakrishnan (2010) presented a methodology for representing non-lane-based driving behavior and calibrating a micro-simulation model for highly heterogeneous traffic at signalized intersection. Calibration parameters were identified using sensitivity analysis, and the optimum values for these parameters were obtained by minimizing the error between the simulated and field delay using genetic algorithm. Velmurugan et al. (2010) studied free speed profiles and plotted speed–flow equations for different vehicle types for varying types of multi-lane highways based on traditional and microscopic simulation model VISSIM and subsequently estimated roadway capacity for four-lane, six-lane, and eight-lane roads under heterogeneous traffic conditions with reasonable degree of authenticity. Gundaliya et al. (2010) developed a grid-based modeling approach akin to cellular automata (CA) for heterogeneous traffic-flow simulation. The road space is divided into a grid of equally sized cells. Moreover, each vehicle type occupies one or more cells as per its size unlike CA traffic-flow model where each vehicle is represented by a single cell. Model needs inputs such as vehicle size, its maximum speed, acceleration, deceleration, probability constants, and arrival pattern. The position and speed of the vehicles are assumed to be discrete. The speed of each vehicle changes according to its interactions with other vehicles, following some stochastic rules depending on the circumstances. The model is calibrated and validated using real data and VISSIM. The results indicate that grid-based model can reasonably well simulate complex heterogeneous traffic as well as offers higher computational efficiency needed for real time application. Mallikarjuna and Ramachandra Rao (2011) found that the vehicle size, mechanical characteristics, lateral distribution of vehicles, and the lateral gaps maintained by them are found to be more suitable microscopic traffic variables. Data on these variables have been used in modifying the cell structure and the updating procedures of the CA-based traffic-flow
model. Bains et al. (2012) developed a model in VISSIM for simulating the traffic on Mumbai–Pune expressway and estimating the capacity values.

Many research studies (Kadiyali and Vishwanathan 1991; Tiwari et al. 2000; Velurugan et al. 2002; Chandra and Kumar 2003; Reddy et al. 2003; Chandra 2004; Dey et al. 2008; Erramallli et al. 2009; Velurugan et al. 2009; Arasan and Arkatkar 2010; Arkatkar and Arasan 2010) aimed at assessing the roadway capacity based on empirical and combination of empirical and simulation approaches, for varying carriageway widths including single-lane, intermediate-lane, two-lane bi-directional, four-lane, and six-lane (multi-lane) divided carriageway widths covering different terrains have been carried out during the last two decades. With regard to the estimation of capacity of expressways “US – Highway Capacity Manual (HCM)–2010” is the most referred document through the Ministry of Road Transport and Highways (India) (MORTH) (2010) and had stipulated tentative capacity figures without undertaking detailed studies. In the absence of capacity and LoS guidelines for expressway segments between interchanges, in India, MORTH has given a user friendly method considering the default values given in TRB-Highway Capacity Manual of USA (HCM-2010) and subjective adoption of the necessary parameters. Based on the review of literature both at national and international levels, the following important points have been identified: (i) although most of the researchers in India in the past have aimed at assessing the roadway capacity for varying carriageway widths, but only a limited number of studies have been carried out to determine the capacity of expressways in India and (ii) the guidelines suggested by HCM may not be applied directly under Indian conditions, as the conditions are relatively different on Indian expressways. In view of the above points and considering the fact that a huge network of expressways has been planned in future, there is an urgent need to determine the capacity of such roads for appropriate design.

Objectives of the study

The general objective of the research work reported here is to develop fundamental traffic–flow relationships (flow–speed–area occupancy) and thus deriving capacity estimates for an eight-lane divided urban expressway basic section, under traffic conditions prevailing in India. Field data collected on traffic-flow characteristics such as free speed, acceleration, lateral clearance between vehicles, etc., were used in calibration and validation of the simulation model. The model was developed using commercially available simulation package, named, VISSIM. The validated simulation model was then used to develop fundamental traffic–flow relationships. It was also applied to carry out sensitivity analysis to characterize the effect of variation in percentage of trucks in traffic stream on its capacity values and stream speed.

Overview of the simulation model

The simulation model, followed in the present study is shown in the form of a flow chart in Fig. 1. Data in the form of videos collected from the study site was analyzed and this information is used for building the simulation model in the software VISSIM 5.40. Then, the model was calibrated and validated for rendering it suitable for replicating the conditions at site. The validated simulation model then was used to simulate traffic over a wider range of traffic volume and traffic composition to estimate roadway capacity and to carry out sensitivity analysis for fulfilling the objectives of the present study.

Model calibration and validation

The comparison of the model to reality is carried out by tests that require data on the system’s behavior and the corresponding data produced by the model. The input data required for the above-mentioned heterogeneous traffic-flow model are related to four aspects, namely road geometrics, traffic characteristics, driver reaction time, and vehicle performance. The power of simulation as a tool for the study of traffic flow lies in ability of the model to include the effect of the random nature of traffic. Hence, the random variables associated with traffic flow such as free-flow speed distribution, are expressed as frequency distributions and input into the simulation model. These data, pertaining to one direction of traffic flow, were collected at a selected stretch of an expressway for model calibration and validation purposes.

Study stretch and data collection

The Delhi–Gurgaon expressway is an 8-lane divided facility that connects the city of Delhi with one of its busiest suburbs, Gurgaon. The traffic on the expressway was video graphed from a vantage point, during both peak and non-peak hours on March 20, 2012. The study stretch was selected after conducting a reconnaissance survey to satisfy the following conditions: (i) the stretch should be fairly straight; (ii) width of Roadway should be uniform; and (iii) there should not be any direct access from the adjoining land uses. The stretch is a four-lane divided
road with 5-m wide central median. The width of main carriageway, with bituminous surfacing, for each of the two directions of traffic flow, is 14.0 m. The 1.5-m wide shoulder, on both sides, is paved with bituminous mix. In addition, there is no direct access from the adjoining service road because of raised kerbs as shown in Fig. 2a. The overall roadway condition has also been depicted in the form of a Google map in Fig. 2b. The study was limited to only one representative basic section of Delhi–Gurgaon expressway because of high amount of time required for manual data extraction through video data.

Free-flow speeds were ascertained by observing 200–300 vehicles for each of the category of vehicles; during non-peak hours (when the observed traffic flow was <200 vehicles/h). The sample size (200–300) was fixed for each of the category of vehicles separately, based on the observed roadway and traffic conditions. The free-flow maximum, minimum, and mean speeds measured for different vehicle categories and the corresponding standard deviations are shown in columns (3), (4), (5), and (6), respectively, of Table 1a. The speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 100 m. Then, on the same day, the traffic flow on the road was collected for 2 h in the evening peak period from 16:24 to 18:24 h using a digital video camera. This data was then used for the purpose of model validation. A snapshot of the video-captured data is depicted in Fig. 2a. The video was then analyzed at a speed one-eighth of the actual speed to enable recording and measurement of data. The traffic flows observed were 7200 and 8573 vehicles/h in the first and second hours, respectively. Observed traffic composition based on the different categories of vehicles is given in column (2) of Table 1a. Performance parameters such as flow and speed were extracted from the videos at a rate of 25 frames/s for achieving a high accuracy data for every 20-s time interval. This data then was aggregated to obtain parameters such as flow and speed for every 1-, 5-, 30-, and 60 min intervals for the purpose of model validation. The speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 65 m.

The overall dimensions of all categories of vehicles adopted from an earlier study (Arasan and Koshy 2005) are shown in columns (7) and (8) of Table 1a. Any vehicle moving in a traffic stream has to maintain sufficient lateral clearance on the left and right sides with respect to other vehicles/curb/median to avoid side friction. These lateral clearances depend on the speed of the vehicle being considered, speed of the adjacent vehicle in the transverse direction, and their respective vehicle categories. The minimum and maximum values of lateral-clearance share values adopted from an earlier study (Arasan and Koshy 2005) are given in columns (9) and (10) of Table 1a, respectively. The minimum and the maximum clearance-share values correspond to zero-speed and free-speed conditions of corresponding vehicles, respectively. The lateral-clearance share values in between the above-mentioned traffic-flow levels is obtained using linear interpolation in the model. The lateral-clearance share values are used to calculate the actual lateral clearance between vehicles based on the type of the subject vehicle and the vehicle by the side of it. For example, at zero speed, if a truck is beside a big car, then, the clearance between the two vehicles will be 0.40+0.40=0.80 m. The field observed acceleration values of the different categories of vehicles over different speed ranges used for simulation are shown in Table 1b. In the absence of detailed micro-level trajectory data under varying traffic conditions, it was difficult to get lateral clearance characteristics for each of the vehicle categories. Hence, the authors preferred to apply the secondary data. The instantaneous acceleration rates were then estimated for different vehicle types using speed change over time period using extracted frames.

“Area occupancy” has been validated under heterogeneous traffic conditions and it was found that under mixed traffic conditions, “area occupancy” can be a better indicator of traffic density, which indicates the extent of usage of road space (Arasan and Dhivyra 2010) instead of occupancy alone. Based on the study conducted by Arasan and Dhivyra (2010), it was decided to use area occupancy as an alternative parameter to density. The road traffic in developing countries like India is relatively heterogeneous comprising vehicles of wide-ranging static and dynamic characteristics. By virtue
### Table 1 Input data for heterogeneous traffic-flow simulation

**a Vehicular characteristics: composition, free-flow speeds and lateral-clearance share**

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Traffic composition (%)</th>
<th>Free-flow speeds (km h$^{-1}$)</th>
<th>Vehicle dimension, (m)</th>
<th>Lat. clear. share (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max. speed (3)</td>
<td>Min. speed (4)</td>
<td>Mean speed (5)</td>
</tr>
<tr>
<td>BC</td>
<td>20-80</td>
<td>103</td>
<td>78</td>
<td>90</td>
</tr>
<tr>
<td>SC</td>
<td>50-00</td>
<td>96</td>
<td>65</td>
<td>82</td>
</tr>
<tr>
<td>Two-wheeler</td>
<td>22-30</td>
<td>87</td>
<td>33</td>
<td>58</td>
</tr>
<tr>
<td>Three-wheeler</td>
<td>3-30</td>
<td>63</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>Bus</td>
<td>2-20</td>
<td>93</td>
<td>64</td>
<td>79</td>
</tr>
<tr>
<td>LCV</td>
<td>0-60</td>
<td>80</td>
<td>63</td>
<td>73</td>
</tr>
<tr>
<td>Truck</td>
<td>0-60</td>
<td>69</td>
<td>48</td>
<td>60</td>
</tr>
</tbody>
</table>

**b Vehicular characteristics: acceleration values over different speed ranges**

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>0–30 km h$^{-1}$ (m s$^{-2}$)</th>
<th>30–60 km h$^{-1}$ (m s$^{-2}$)</th>
<th>&gt;60 km h$^{-1}$ (m s$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big car</td>
<td>2-15</td>
<td>1-80</td>
<td>1-10</td>
</tr>
<tr>
<td>Small car</td>
<td>2-00</td>
<td>1-60</td>
<td>1-10</td>
</tr>
<tr>
<td>Two-wheeler</td>
<td>1-10</td>
<td>0-70</td>
<td>0-45</td>
</tr>
<tr>
<td>Three-wheeler</td>
<td>0-80</td>
<td>0-30</td>
<td>0-25</td>
</tr>
<tr>
<td>Bus</td>
<td>1-40</td>
<td>1-00</td>
<td>0-45</td>
</tr>
<tr>
<td>LCV</td>
<td>1-30</td>
<td>0-80</td>
<td>0-55</td>
</tr>
<tr>
<td>Truck</td>
<td>1-00</td>
<td>0-62</td>
<td>0-46</td>
</tr>
</tbody>
</table>

**c Calibrated parameters (Wiedemann-74 model) for the present study**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated values</th>
<th>*Default values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average standstill distance</td>
<td>1-35 m</td>
<td>2-0 m</td>
</tr>
<tr>
<td>Additive part of safety distance</td>
<td>0-25</td>
<td>2-0</td>
</tr>
<tr>
<td>Multiplicative part of safety distance</td>
<td>0-35</td>
<td>3-0</td>
</tr>
<tr>
<td>Minimum look-ahead distance</td>
<td>127 m</td>
<td>0-0 m</td>
</tr>
<tr>
<td>Maximum look-ahead distance</td>
<td>250 m</td>
<td>250 m</td>
</tr>
</tbody>
</table>

of their wide-ranging characteristics, the vehicles do not follow traffic lane and occupy any lateral position over the width of roadway depending on the availability of road space at a given instant of time and hence, it is nearly impossible to impose lane discipline under such conditions. To analyze such characteristics of heterogeneous traffic, it becomes necessary to consider the whole of the width of the road as a single unit. Hence, when the occupancy concept is applied to heterogeneous traffic, it is necessary to consider the area (length and width) of the detection zone and the area of vehicles as the bases. Hence, formulation (equation (1)) developed by Arasan and Dhiyva (2010) was used for the purpose of estimating a surrogate measure, namely area occupancy in place of density of traffic

\[
\text{Area Occupancy} = a_i \sum (t_i) \frac{AO}{AT}
\]

where \(t_i\) is time during which the detection zone is occupied by vehicle \(i\) in s and the subscript, AO stands for area occupancy, \(a_i\) is the area of the detection zone occupied by vehicle \(i\) during time \(t_i\), in square meters, \(A\) is the area of the whole of the road stretch in square meters, and \(T\) is the total observation period in s. This derived micro-level parameter may be checked for the purpose of validating developed simulation model. Accordingly, the travel time for each of the vehicle category was extracted at the observed flow levels very carefully for the purpose of estimating area occupancy. Then, the values of area occupancy were estimated using the travel times, individual vehicle category areas and total area of the detection zone along with the total time under consideration.

**Simulation model development**

The results of recent study by the authors suggested that the degree of lane discipline on multi-lane road like Delhi–Gurgaon expressway is \(~75\%\) (Ponnu et al. 2014). In the present study, the authors intended to apply a simulation model for modeling traffic flow on Delhi–Gurgaon expressway, where the traffic follows reasonable lane discipline. However, at the same time, there are few vehicles which do not follow lane discipline at all. Hence, this situation may be regarded as a partially heterogeneous or quasi-heterogeneous. With the available parameters of traffic flow in VISSIM (vehicle model, desired speed distribution, traffic composition, and flow, Wiedermann-74 car-following model, etc.) for calibration and based on some studies by few researchers under Indian conditions as given in literature review, it was felt by the authors that it may be appropriate to use VISSIM for modeling traffic flow on a road like Delhi–Gurgaon expressway.

A model, which accurately represents the design and operational attributes of the study stretch in the simulation software, is known as the “base model.” When this base model is calibrated and validated to replicate the actual or ground conditions, the model can be used to study different characteristics that were not defined by the user as an input. For example, the width of the road can be defined and in turn the capacity of this road could be measured. The validated base model can also be used to develop a simulated scenario, which is desired to be known. The base model development involves the following steps: (i) development of base link/network, (ii) defining model parameters, (iii) calibrating the network, and (iv) validating the model.

**Development of base link/network**

Development of a link/network that accurately depicting the physical attributes of a test site is an important stage in the modeling process. The basic key network building components in VISSIM are links and connectors. In this simulation model, a unidirectional four-lane simulation test section link spanning 1000 m was created representing the study stretch located on the Delhi–Gurgaon expressway, as explained above. Actually, it was observed that the traffic-flow conditions were quite stable. There was no congestion at the time when data was collected for a distance at least \(>\) 500 m. Hence, it was assumed that the space mean speeds obtained using simulation over a distance of 1000 m may not be significantly very different from the observed speeds which were measured over a space of 65 m for the purpose of validation. In addition, extra links of length 200 m each were provided at the beginning and end of the main stretch for buffering process. The test section and the buffer links were joined using the connectors. The buffer links provided the spatial warm-up sections for vehicles entering and exiting the test section, thereby ensuring accurate results.

**Defining model parameters**

**Vehicle model**

Vehicle model, which deals with defining the dimensions of each vehicle type that are plying on the test stretch, is considered for the simulation. It is also used to define the acceleration values for different categories of vehicles. The dimensions, namely the width and the length, were considered for the present simulation model as per the description given in Table 1a. The acceleration values over different speed ranges were given as input as per Table 1b.

**Desired speed distribution**

The simulation model requires the desired speed parameters of vehicles to initialize and assign the speed during their placement in the simulation stretch. The desired speed parameters obtained through field measurement during lean traffic periods on the study stretch. The desired speed of a vehicle depends on make of the vehicle, the age of the vehicle, the level of maintenance of the vehicle, and the age, gender, and the behavior of the driver (Arasan and Krishnamurthy 2008). These factors fall over a wide range under Indian conditions. This is the reason for a wide range in the value of desired speeds of cars. Hence, the category of cars (which was found to be the maximum in the observed traffic composition) was further divided into two categories as: small cars and big cars based on their physical size and engine size. The desired speed distribution curve (generally an “S” shaped curve: cumulative normal distribution plot) for each category of vehicles (big cars, small cars, motorized two-wheelers, motorized three-wheelers, buses, trucks, and light commercial vehicles) was given as input to the simulation model in
VISSIM. The maximum and minimum values of the speed and distribution between these values were defined in the model. Adequate care was taken to ensure that the speed distribution defined in VISSIM represented the values observed in the field. The variation in free-flow speeds for a particular vehicle category was incorporated through Normal distribution parameters based on actual field observations.

Traffic composition and Flow
Traffic composition and flow based on the field observations were given as an input to simulation model for the given time interval.

Driving behavior characteristics
The driving behavior characteristics mainly include these two features, namely car-following behavior and lateral distance. The psycho-physical driver behavior-based Wiedermann-74 car-following model had been used for simulating the vehicle-following behavior. The parameters of this car-following model, including safety distance during standstill, additive, and multiplicative parts of safety distance, are given in Table 1c. These values were chosen based on trial-and-error method, taking the values obtained in the study by Mathew and Radhakrishnan (2010) as base values. For defining the lateral distance between the vehicles, the location of the vehicle on a lane, minimum lateral distance at different speeds, etc. were given as input (column (9) and (10) of Table 1a). As discussed earlier, based on the observed traffic-flow characteristics, it was felt that Delhi–Guragaon expressway may be considered as an urban multi-lane road, particularly because of presence of smaller vehicles like two-wheelers and three-wheelers in significantly high proportion (25%). In addition, using car-following parameters is more relevant particularly when the traffic-flow level is sufficiently high that the following behavior may be observed prominently on the roadway. This situation on Delhi–Guragaon expressway may be reasonably comparable with the situation observed by Mathew and Radhakrishnan (2010) on urban road.

Calibration of the simulation model
Calibration is a process of refining the model to replicate observed data and observed site conditions to a sufficient level of accuracy in order to satisfy the model objectives. This process involves refining the characteristics, namely desired speed distribution, acceleration/deceleration of vehicle, mechanical characteristics of the vehicle, minimum safety distance, minimum lateral distance, and driving behavior characteristics. By giving these parameters as an input to simulation model, simulation runs have to be carried out in order to estimate the output. In the present simulation model, the outputs were the traffic flows and average speed of the vehicles for 10 different random seed values. In all 15–20 random seed values attempted, finally 10 random seeds were chosen based on the criteria of getting minimum standard deviation and also maximum accuracy in terms of %error while comparing it for a particular variable like vehicle speed, area occupancy, and also stream speed. In this case, more consideration was given to a micro-level parameter, i.e. area occupancy. In VISSIM, one second can be actually resolved in 1–10 parts. For the purpose of this study, the level 5 was chosen which implies that the whole simulation system gets updated at every 0.2 s. Hence, the scanning interval technique is 0.2 s in the present study.

All the simulations were run for a total time of 7400 s including a temporal warm-up period of 200 s to ensure accurate simulation results. Flow for each 1 h from 2 h of field data was fed, which improved the degree of match between the observed and the simulated. As explained above, a different driving behavior was considered for each vehicle type to account for heterogeneity in the traffic. There was no perfect strict lane discipline among the vehicles, as observed from the video (Fig. 2a). Hence, an entire road width-based simulation where there was a lane model having an effective width of four lanes was considered in the simulation. Thus, each vehicle was free to choose any lateral position and overtakes from any side during the simulation on this four-lane width, without any lane-discipline, similar to the observed conditions on study stretch.

The minimum look-ahead distance, which defines the distance a vehicle can see forward in order to react to vehicles in front or to the side of it set to a value of 127 m, was found to be appropriate for the present situation. This value of 127 m was taken based on the calibration and validation study conducted by Mathew and Radhakrishnan (2010). With a zero (default) value of minimum look-ahead distance, the vehicles were found to be overlapping over each other because of sudden accelerations/decelerations in the speed of the vehicles. The value of 127 m was also found to be appropriate keeping in view the higher speeds on Delhi–Guragaon urban multi-lane highway. The other values were chosen as per the defaults, as given in the VISSIM manual (PTV AG 2012), which produced the observed conditions with required accuracy. The simulated values and the observed values (speed, flow, and area occupancy) were compared and the error was computed. If the error was within the limits, the calibration process was stopped or otherwise the parameters were modified and simulation runs were carried out. This process was repeated and the simulation runs were made till the error was within the satisfactory limits. The calibration process in the form of a flow chart is shown in Fig. 3a.

Validation of the simulation model
Validation is the process of checking the results obtained from the calibrated model in terms of simulated values against field measurements for parameters such as traffic flows, average speeds, and area occupancies. The observed traffic volume and traffic composition were given as input to the simulation process. The simulation runs were made with 10 random number seeds for a total run time of 7400 s including temporal warm-up period of 200 s to ensure accurate simulation results. A sample simulation run is shown in Fig. 3b. The average speeds of vehicles from a single run was noted and then the average speed for each vehicle category from all the 10 runs were taken as the final output from the model. The inter-arrival time gaps of the heterogeneous traffic flow of vehicles was assumed to follow negative exponential distribution (Arasan and Koshy 2003) and the free speeds of different categories of vehicles, based on the results of an earlier
3 Calibration of the simulation model

The comparison of the observed and simulated speed values, flow values, and area-occupancy values for every 1-, 5-, and 15-min intervals within the 2 h (observed traffic) in successive runs indicates that the critical value of "t-statistic" is lesser than the value of estimated "t-statistic" obtained from standard t-distribution table. This implies that there is no significant difference between the observed and simulated traffic-flow parameters, for a level of significance of 5%.

Model Application

The VISSIM model can be applied to study various traffic scenarios for varying roadway and traffic conditions. In this study, the application of the model is to study the relationship between traffic flows, speed, and area occupancy on an urban expressway with six categories of vehicles as given in column (2) of Table 1a, under varying traffic conditions such as traffic-flow levels and traffic composition.

Fundamental relationships and capacity

One of the basic studies in traffic-flow research is to examine the relationships between speed–flow and density of traffic. The capacity of the facility under these mixed traffic conditions for different roadway and traffic conditions can be estimated using these relationships. In this study, speed–flow–area-occupancy relationships were developed using the validated simulation model for a heterogeneous flow, considering traffic compositions and roadway conditions, same as that observed in the field (Fig. 2c). The average speed of the traffic stream was plotted for different simulated flows, starting from 1000 vehicles/h to the capacity-level flow. The following procedure was adopted for finding the capacity of the facility for developing the speed–flow relationships. During successive simulation runs with increments in traffic flow from near-zero volume level, there will be a commensurate increase in the exit volume at the end of simulation stretch. After, a specific number of runs, the increments in the input traffic volumes will not result in the same increase in the exit volume. Such a decrease in exit volume (in spite of increase in the input) in successive runs indicates that the facility has reached its capacity. The speed–flow–area-occupancy relationships thus developed based on the every 1- and 5-min intervals speed, flow, and area-occupancy data for an eight-lane divided expressway (roadway space based on the four lanes in one direction of traffic flow) are depicted in Fig. 5a–e, respectively. The 5-min interval speed, flow, and area-occupancy data (24 points) obtained from the field observed data for 2 h was also plotted in Fig. 5c–e. It is evident from the figures that the curves follow the well

![Flow chart for Calibration of the simulation model](image1)

![Snapshot of simulation runs in VISSIM](image2)

*a flow chart for calibration of the simulation model; b a snapshot of simulation runs in VISSIM.*
established trends. These graphs were plotted based on the average speed, flow, and area-occupancy values, derived through the output of 10 random runs. The estimated values of capacity (vehicles/h/direction), thus obtained using simulation model, based on every 1- and 5-min interval data, for the observed traffic composition, are given in Table 3a. From the figures, it may be noted that the observed traffic flow is ranging from a medium to the higher volume levels.

In addition, the speed corresponding to each of the volume levels in this range was estimated as stream speed. It is observed that with successive increments in traffic volume (dependent variable), there is a commensurate decrease in the speeds. When the volume reaches the capacity level, the increase in the traffic volumes may not result in the same amount of increase in the exit volume (actual volume which can pass a given section on the expressway) resulting in

4 Comparison of observed and simulated traffic-flow characteristics (model validation)
a decrease in the rate of traffic flow. A few successive decreases in the exit volume (in spite of increase in the value of traffic flow) indicate that roadway has reached its capacity along with further reduction of speeds. The same concept was applied in determining the capacity-level flow for the observed and simulated conditions. Currently, there are no guidelines available on the capacity values of urban expressways given by IRC. However, it may be noted that the guidelines provided by Ministry of Road Transport and Highways (MORTH), Government of India, is based on the US Highway Capacity Manual 2010. This guideline suggests that the capacity under ideal conditions for basic freeway segments can be considered as 2400 passenger cars/h/lane. Hence, this implies that the capacity value for four lanes in one direction of traffic flow may be taken as ~9600 passenger cars/direction. The estimated capacity value is found to be in the range of 9700–10,500 vehicles/h for one direction of traffic flow based on the time intervals (1 and 5 min) considered in the present study.

Effect of composition on capacity and fundamental relationships

One of the objectives of the present study was to carry out sensitivity analysis to characterize the effect of variation in percentage of trucks in traffic stream on its capacity values and stream speed. For this experiment, the present study considered the predominant vehicle categories (cars and trucks) as observed in the field. The effect of composition on the roadway capacity was studied in the following manner. First, a cars-only traffic stream was simulated for a four-lane road space having width of 14·0 m in one direction of traffic flow using a validated simulation model for mixed traffic conditions. Although, there was a “cars-only” situation, the logic of traffic-flow movement was same as observed in mixed traffic conditions. This simulation experiment was mainly conducted to develop the relationship between the proportion of trucks and capacity value keeping all other traffic conditions same. The traffic stream speed and flow relationship was developed as explained above. Using this relationship, the capacity of the facility was found. Similarly, different proportions (10, 20, 30, 40, 50, 60, 70, 80, and 90%) of trucks were added in the cars-only traffic stream and simulations were run, and then the capacity values were estimated. The simulations were run for 100% of trucks traffic stream also. The speed–flow relationships developed for these 11 traffic compositions are depicted in Fig. 6a. From the figure, it may be noted that the capacity of the given roadway facility decreases as the proportion of trucks in the stream increases, which is quite intuitive. This graph was plotted based on the average speed and flow values, derived through the output of 10 random runs. In order to quantify this decrease in the capacity and capacity-level traffic-stream speed values (critical speeds) with increase in the percentage of trucks, the two best-fit relationships were developed, which are shown in Fig. 6b. The capacity-level flows and critical speeds, estimated from the above speed–flow relationships (Fig. 6a, developed using validated simulation model) for different possible compositions (considering cars and trucks as predominant vehicle categories as observed in the field) as given in Table 3b, were used for developing the relations and the same are presented in Fig. 6b. The capacity reduction from 9915 vehicles/h to 6180 vehicles/h (~37%) may be considered as significantly high, particularly on urban multi-lane highway having four lanes in each direction, where the free-flow speeds are relatively higher when compared with the other roads in India.

It may be seen that the capacity-level critical speed reduces linearly with increase in percentage of trucks from 10 to 100% in the traffic stream of most important vehicle categories, cars, and trucks. It can be also noted that the capacity value (flow) decreases non-linearly with increase in percentage of trucks from 10 to 100% in the traffic stream. It can be found from the figure that the capacity value drops down sharply as the percentage of trucks increases from 10 to 50% and beyond 50%, the curve becomes flat. This indicates that the increase in percentage of trucks in the traffic stream comprising of most important vehicle categories, cars and trucks, significantly reduces capacity, from 10 to 50% of trucks, beyond which its effect is insignificant as depicted in Fig. 6b. This means that the level of impedance caused by inferior vehicle category (in reference to cars) is negligible when the traffic stream consisting of cars and trucks under mixed traffic conditions consists of ≥50% of trucks. These relationships may be quite useful for planning, design, and management of roadway facilities. In addition, these relationships may be quite useful keeping in view the absence of reasonably accurate roadway capacity values and LoS-related guidelines for expressways.

The fundamental relationships speed–flow–area-occupancy were also developed for three different compositions as (i) 20% of trucks and 80% of cars, (ii) 50% of trucks and 50% of cars, and (iii) 80% of trucks and 20% of cars, for a four-lane road space having width 14·0 m in one

Table 2 Model validation: comparison of observed and simulated flows and speeds

<table>
<thead>
<tr>
<th>Traffic-flow parameter</th>
<th>Traffic interval (min)</th>
<th>t-statistic value</th>
<th>t-critical value</th>
<th>P-value</th>
<th>Critical P-value</th>
<th>Degrees of freedom</th>
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<tbody>
<tr>
<td>Speed</td>
<td>5</td>
<td>1.520</td>
<td>2.07</td>
<td>0.22746</td>
<td>0.05</td>
<td>23</td>
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<tr>
<td>Speed</td>
<td>15</td>
<td>0.997</td>
<td>2.37</td>
<td>0.35308</td>
<td>0.05</td>
<td>7</td>
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<tr>
<td>Speed</td>
<td>30</td>
<td>1.030</td>
<td>3.18</td>
<td>0.38017</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>Flow</td>
<td>5</td>
<td>0.950</td>
<td>2.07</td>
<td>0.35181</td>
<td>0.05</td>
<td>23</td>
</tr>
<tr>
<td>Flow</td>
<td>15</td>
<td>0.081</td>
<td>2.37</td>
<td>0.44942</td>
<td>0.05</td>
<td>7</td>
</tr>
<tr>
<td>Flow</td>
<td>30</td>
<td>0.558</td>
<td>3.18</td>
<td>0.61559</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>A-O</td>
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<td>2.07</td>
<td>0.59831</td>
<td>0.05</td>
<td>23</td>
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<tr>
<td>A-O</td>
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<td>2.37</td>
<td>0.75729</td>
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<td>A-O</td>
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<td>3.18</td>
<td>0.83989</td>
<td>0.05</td>
<td>3</td>
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</tbody>
</table>

A-O: area occupancy.
direction of traffic flow using a validated simulation model. These developed fundamental relationships based on every 3-min and 5-min speed, flow, and area-occupancy simulated data are depicted in Fig. 7a–f. From Fig. 7a and b, it may be noted that based on the considered three compositions, there are three distinctly different but well established relationships of speed–flow. Whereas, the effect of change in composition is not distinctly different in the case of speed–area occupancy and flow–area-occupancy relationships as can be seen from Fig. 7c–f. It can be seen that the values of area occupancy of the traffic streams, with three different compositions, are nearly close to each other and hence, it can be concluded that the relationship between flow, speed, and area occupancy mostly remains unaffected by change in

\[ y = 1E-07x^2 - 0.004x + 81.82 \\
R^2 = 0.519 \]

\[ y = -1E-07x^2 + 0.0016x + 78.622 \\
R^2 = 0.837 \]

\[ y = -545.84x^2 + 136078x + 1550.2 \\
R^2 = 0.97023 \]

\[ y = -1E+06x^2 + 207063x + 284.5 \\
R^2 = 0.9565 \]

\[ y = 2737.1x^2 - 534.17x + 80.327 \\
R^2 = 0.8784 \]
traffic composition. It can also be seen that the values of area occupancy of the three homogeneous traffic streams are nearly the same for any given flow level in spite of the change in the traffic composition. This conclusion was also reported in an earlier study by Arasan and Dhivyaa (2010), in which the authors plotted fundamental relationships using 1-h simulated data on multi-lane roads. However, in this study this finding is further corroborated based on every 3- and 5-min speed, flow, and area-occupancy simulated data on urban expressways, and these are depicted in Fig. 7a–f.

Hence, the simulation experiments carried out in this study suggest that under mixed traffic conditions, for characterizing the effect of traffic composition on traffic-flow characteristics (flow, speed, and area occupancy), the fundamental relationship of speed–flow may be the most appropriate than speed–area-occupancy and flow–area-occupancy relationships. The fundamental relationships plotted with the observations and parameters estimated taking time interval <1 min for the vehicular traffic flow prevailing on Delhi–Gurgaon expressway; it may be difficult to discern any trend satisfactorily. Hence, as the authors have considered the time interval of 5 and 15 min (Fig. 4c and f) and time interval of 3 and 5 min (Fig. 7e and f), the values are relatively lesser. However, it may be noted that with the

<table>
<thead>
<tr>
<th>Traffic composition</th>
<th>Estimated capacity, vehicles/h/direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Truck</td>
<td>6180</td>
</tr>
<tr>
<td>90% (t)–10% (c)</td>
<td>6255</td>
</tr>
<tr>
<td>80% (t)–20% (c)</td>
<td>6300</td>
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<tr>
<td>70% (t)–30% (c)</td>
<td>6360</td>
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<td>60% (t)–40% (c)</td>
<td>6420</td>
</tr>
<tr>
<td>50% (t)–50% (c)</td>
<td>6480</td>
</tr>
<tr>
<td>40% (t)–60% (c)</td>
<td>6540</td>
</tr>
<tr>
<td>30% (t)–70% (c)</td>
<td>6600</td>
</tr>
<tr>
<td>20% (t)–80% (c)</td>
<td>6660</td>
</tr>
<tr>
<td>10% (t)–90% (c)</td>
<td>6720</td>
</tr>
<tr>
<td>0% (t)–100% (c)</td>
<td>6780</td>
</tr>
</tbody>
</table>

(a) Speed-Flow relationships for different % trucks compositions

(b) Relationships between capacity and critical speed with varying % trucks

6 Effect of composition of trucks on roadway capacity
Effect of traffic composition on traffic-flow parameters

Increase in proportion of trucks (80%) the area-occupancy value has become double (increased from 10 to 20%), which may be considered as logical. Further, it may be quite interesting to conduct a comparative study in future on quantifying level of interaction among different vehicle types under mixed traffic conditions using both the fundamental relationships, namely (i) stream speed and flow and (ii) flow–area occupancy for varying roadway conditions.
Findings
The following are the important findings of this study:

1. The validation results of the simulation model VISSIM used for this study indicate that the model is capable of replicating the heterogeneous traffic flow on expressways to a satisfactory extent.

2. From the speed–volume curve developed using the simulation model, it is found that, for the observed traffic composition, capacity of a eight-lane divided urban expressway in level terrain with 14-0.0.m wide road space hovers in the range of 9700–10 500 vehicles/h for one direction of traffic flow based on the time intervals (1 and 5 min) considered for the study. The capacity value is expressed in vehicles/h, as this work is not related to the estimation of passenger car unit values.

3. The simulation experiments carried out in this study under developing countries like India suggest that under mixed traffic conditions, for characterizing the effect of change in traffic composition on traffic-flow characteristics of a given expressway, the speed–flow relationship may be the most appropriate.

4. Based on the simulation experiments, it was found that under mixed traffic conditions prevailing on expressways in developing countries like India, the capacity-level critical speed reduces linearly with increase in percentage of trucks from 10 to 100% in the traffic composition of a stream, comprising only two vehicle categories: cars and trucks. It can be also noted that the capacity-level value (flow) decreases non-linearly with increase in percentage of trucks from 10 to 100% in the traffic composition of a stream, comprising only two vehicle categories: cars and trucks.

5. Under mixed traffic conditions, on expressways, the increase in percentage of trucks from 10 to 50% in the traffic composition of a stream, comprising only two vehicle categories: cars and trucks, reduces the capacity significantly and beyond 50%, the further increase in percentage of trucks, is found to be insignificant.

6. The results and overall methodology followed for modeling traffic flow on expressways along with the capacity values for varying traffic compositions, estimated in this study, may be very useful for the practitioners and stakeholders for traffic management and level of performance assessment. The study also may be very useful for the continuing efforts to prepare an Indian Highway Capacity Manual.

7. The present study is focused on modeling of traffic flow using extracted traffic-flow video-captured data for two-peak hours on a basic section of Delhi–Gurgaon expressway. It is further planned to collect more traffic data over a wider range of traffic flows and check the validity of the model. Although the results of the present study are applicable only for the basic sections of expressways in India, it may be considered as an attempt toward a national level effort for carrying out studies in connection with continuing efforts of preparing Indian Highway Capacity Manual.

8. It may be quite interesting to conduct a comparative study in future on quantifying level of interaction among different vehicle types under mixed traffic conditions using both the parameters, namely traffic-stream speed and area occupancy for different roadway conditions on expressways.

Limitations of the study
The driver’s behavior considered in this study can be refined further to consider many more physiological and psychological factors.

Future research scope
This study can be further extended to study the following aspects:

1. There is a further need to conduct more research on developing fundamental macroscopic traffic-flow diagrams for better understanding of various boundary conditions.

2. Area occupancy can be used as a parameter of surrogate measure for the density for developing LoS criteria.

3. Developing a concept of stochastic capacity estimates under heterogeneous traffic conditions prevailing on expressways in India. Such estimates would account for vehicle composition in the traffic stream.

4. The empirical relationship between lateral and clearance share data for different possible pairs of vehicle categories based on the field observed data over a wider range of speeds may refine the validation results further.

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