Full Length Research Paper

Estimation of Roadway Capacity of Eight-lane Divided Urban Expressways under Heterogeneous Traffic Through Microscopic Simulation Models

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The aim of the study is to develop a microscopic simulation model by considering eight-lane divided urban expressway. For this purpose, the partially access controlled Delhi - Gurgaon Expressway which handles about 220,000 vehicles/day has been considered. From the collected data, speed - flow equations of different vehicle types on eight-lane divided urban expressways have been developed using PARAMICS simulation software. The developed simulation model has replicated the ground conditions realistically with the mean percentage error in speed ranging about 2 to 15% across all vehicle types considering the heterogeneous traffic mix prevalent on Indian urban roads. The study revealed that the roadway capacity of eight-lane divided urban expressways is about 11,435 passenger car units/hour/direction. Further, the formation of virtual lanes by vehicles (that is, formation of eight virtual lanes in just the one direction of eight-lane divided carriageway) has been extensively examined and its impact on roadway capacity has been estimated. It was observed from this study that the roadway capacity of eight-lane divided urban expressways under no virtual lanes condition (that is, traffic plying on the demarcated four lane in one direction of eight-lane divided carriageway) would obviously reduce the roadway capacity by about 15%. At the same time, it is to be noted that though the imposition of restriction on virtual lanes decreases the average free speeds by 7%, it would enhance the safety situation due to less vehicular interactions.

Key words: Free speed, speed-flow equations, roadway capacity, lane change behaviour, urban expressways.

INTRODUCTION

The sustained economic growth in India in recent years has brought opportunities and challenges to the planning and management of the Indian transportation system. Like in other developing countries, the transportation system in India is characterized by limited roadway infrastructure and the lack of operation and management experience. Among the most critical issues in highway planning and management, is to determine the roadway capacities of any inter-city highway/ urban expressway. Though India has one of the largest road networks in the world, the available road infrastructure and public transport services in the metropolitan cities are highly inadequate for achieving faster movement of commuters in comparison with the situation prevalent in the cities of the developed world. The major urban arterials connecting important location within metropolitan cities are in need of capacity augmentation, pavement strengthening, rehabilitation of bridges, improvement of riding quality, provision of traffic safety measures, etc. The aforementioned gross inadequacies in the existing inter-city and urban road network coupled with congestion caused by heterogeneity in traffic mix is contributing to huge economic losses in terms of high road user cost (RUC) which is also contributing to high rate of road accidents. Realising the present shortcomings in the transport sector, the Government of India has initiated massive construction programmes of highways linking major cities / activity centres and urban

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expressways. Moreover, the automobile industry and road design standards in India have also undergone tremendous changes in the recent decade. Therefore, it was considered necessary to take a look at the changing trends of prevailing speed - flow characteristics considering the emerging urban multi-lane highways/ expressways in the metropolitan cities.

In this paper, an attempt has been made for the first time to explicitly study the free speed and speed - flow characteristics on eight-lane divided urban expressways in plain terrain. In order to assess these characteristics, speed under free flow and congested conditions coupled with traffic flow data was extensively collected on Delhi - Gurgoan Expressway. From the collected data, speed - flow equations have been evolved for different vehicle types based on microscopic simulation models developed in PARAMICS software environment. Subsequently, roadway capacity for eight-lane divided urban expressways is evolved with reasonable degree of authenticity under the prevailing heterogeneous traffic conditions. The impact of typical Indian driving behavior, that is, how the lane discipline (formation of virtual lanes) and lane change behavior affects roadway capacity on eight-lane expressways has been assessed through microscopic simulation approach.

CAPACITY OF MULTI-LANE HIGHWAYS

Earlier studies

The studies accomplished for multi-lane highways are discussed here. As such, the determination of highway capacity is one of the most important applications of any traffic theory (Kerner, 2004). Some previous theories and empirical researches focused on the interrelationships among the influence of capacity, traffic features, geometric elements, environmental conditions and temporal weather factors on interrupted multi-lane highways (Hoban, 1987; Iwasaki, 1991; Ibrahim and Hall, 1994; Shankar and Manering, 1998). Many years of research has led to the development of theories and methodologies in roadway capacity analysis in the developed countries. For example, the highway capacity manual (HCM) developed in the United States of America describes roadway capacity under ideal conditions and then estimates practical capacities under prevailing conditions in the field. US-HCM 2000 (TRB, 2000) suggested that a maximum flow rate that can be achieved on a multilane highway is 2200 Passenger Car Units (PCU)/hour/lane. The Danish method is also a modification of U.S. HCM to suit Danish conditions. The adjustment factors in the Danish method cause a steeper capacity reduction than in US-HCM 2000 as the conditions become less ideal and therefore, the capacity under ideal conditions on a four-lane highway is 2300 PCU/hour/lane on Denmark highways (Nielsen and Jorgensen, 2008). Similarly, in Finland and Norway too, US-HCM 2000 (TRB, 2000) was followed with minor modifications to suit the local conditions and the roadway capacities obtained by the Finnish and Norwegian methods for multi-lane highways is 2000 PCU/hour/lane. The structure of the Swedish method is similar to the US-HCM (1995) and it uses the 1995 HCM adjustment factors for the roadway width, whereas other adjustments factors are mostly omitted. Consequently, the Swedish method yielded higher capacity estimates and the estimated capacity of four-lane divided highways was 4200 PCUs/h per direction (Luttinen and Innamaa, 2000). The Australian method for analysis of capacity was basically same as that of US-HCM method with the basic difference being additional modification has been suggested for specific problems. Under ideal conditions, the average minimum headway of 1.8 s was considered and maximum flow of 2000 vehicles per hour per lane was assumed. The succeeding paragraph focuses on the roadway capacity evolved in Asian countries like Indonesia and China for multi-lane highways wherein largely heterogeneous traffic conditions as experienced on Indian highways is witnessed.

Bang et al. (1997) in their study for establishing Indonesia HCM mentioned travel speed (synonymous with journey speed) as the main measure of performance of road segments, since it is easy to understand and to measure, and is an essential input to road user costs in economic analysis. In this study, the capacity of multi-lane highways has been estimated as 2300 light vehicles (LVs)/hour/lane for Indonesian multi-lane highways. In the case of Chinese conditions, based on the field data collected, VTI highway simulation model was calibrated and validated and this model was used for the determination of passenger car equivalents (PCE) and speed-flow relationships for different terrain types in parallel with multiple regression analysis of empirical speed-flow data. The results showed that the free-flow speeds of vehicles were substantially low and that the roadway capacity was also marginally lower (2100 PCEs per lane on four-lane divided carriageways) under Chinese conditions as compared with the values obtained for Indonesian multi-lane highways. Further, Yang and Zhang (2005) have established based on their extensive field survey of traffic flow on multi-lane highways in Beijing and subsequent empirical model development, that the average roadway capacity per hour per lane on four-lane, six-lane and eight-lane divided carriageways is 2104, 1973 and 1848 PCUs respectively. This is unlike HCM results obtained for many developed countries which prescribe that average capacity per lane on different highways is equal as they assume that highway capacity is constantly proportional to the number of lanes on multi-lane divided carriageways.

Based on the review of mentioned studies in both developed and developing countries, it is obvious that the roadway design and traffic control practices are mostly
country or region specific and hence cannot be simply transferred to any country for direct applications. In this context, it is to be noted that the roadway capacity and the conditions for adjustment are vastly different on Indian roadways as the local roadway design (that is, lane width, curves and grades), vehicle size and more importantly, traffic mix and behaviour of a driver especially lane changing and lane discipline phenomenon are entirely different. Further, since there is no systematic approach to this problem, coupled by a lack of fundamental data, the adjustment factors from say, the US HCM 2000 (TRB, 2000) cannot be easily revised and applied to Indian highways. This is because adherence to lane discipline characterizes homogeneous traffic in the developed nations whereas very loose lane discipline describes heterogeneous traffic which is very much an integral part of all roadways in India including multi-lane highways. This is due to fast moving vehicle cars, goods vehicles, motorized two wheelers sharing the same road space with bicycles, farm tractors, tractor trailers and other types of slow moving vehicles (like cycle rickshaw, animal drawn vehicles, etc.) on the Indian traffic scene accounting for varying proportion on multi-lane highways depending on its geographical location. Ironically, most of the models discussed earlier developed for homogeneous condition are not applicable for the heterogeneous traffic prevalent on Indian roads. Eventually, the first major research effort in India in this direction was done as part of the RUCS-1982 (CRRI, 1982) and this was followed by URUCS-1992 (Kadiyali and Associates, 1992) and URUCS-2001 (CRRI, 2001). IRC-64 (1990) suggested the tentative design service volume (DSV) of 40,000 PCUs for the four-lane divided carriageway in plain terrain which is significantly lesser than the values evolved in most of the developed and developing countries and therefore the need was felt for revisiting the DSV values evolved under IRC-64. Consequently, many research studies (Kadiyali et al., 1991; Tiwari et al., 2000; Velmurugan et al., 2002, 2004, 2009, 2010; Chandra and Kumar, 2003; Reddy et al., 2003; Chandra, 2004; Errampalli et al., 2004, 2009; Dey, 2007) aimed at assessing the roadway capacity for varying carriageway widths including single lane, intermediate lane, two-lane bi-directional and four-lane divided carriageway widths covering different terrains have been carried out during the last two decades. URUCS-2001 (CRRI, 2001) recommended tentative roadway capacity of 70,000 to 90,000 PCUs/day for a four-lane divided carriageway in plain terrain (1750 to 2250 P CU/hr/lane considering 10% peak hour flow). Chandra and Kumar (2003) studied the effect of roadway width on capacity under different volume capacity ratios and varying proportions of vehicles. Shukla (2008) studied the mixed traffic flow behavior on four-lane divided highway for varying conditions of traffic volume and shoulder and developed a simulation model for the observed traffic flow to estimate roadway capacity under these conditions. To understand the traffic flow behavior on four-lane divided highways under mixed traffic condition, the arrival pattern of vehicles, speed characteristics, lateral placement of vehicles and overtaking behavior was analyzed. Shukla (2008) further reported that the roadway capacity of four-lane divided carriageways as 4770 vehicles/hour in each direction is estimated for ‘all cars’ situation. This exhaustive look at the literature indicates that no substantial work has been carried out for establishing the roadway capacity for varying carriageway widths on multi-lane highways and urban roads, and urban expressways for the heterogeneous traffic mix prevalent on Indian highways with reasonable degree of confidence; hence, this research endeavor can be termed as a significant attempt in this direction.

**Need for microscopic simulation**

The traditional capacity estimation methods assume homogeneous conditions and lane discipline; however, it is not applicable for Indian conditions. In such circumstances, roadway capacities could be either underestimated or overestimated. Capacity estimation primarily depends on vehicular movements on the road stretch and in this regard, lane change behaviour and lane discipline can severely affect the movements. On Indian roads, vehicles seldom observe lane discipline and make their own virtual lanes instead of the demarcated physical lanes. The conventional methods ignore vehicle movements and interactions and these behaviours cannot be explained which has great impact on speed-flow relationships and capacity estimation. In the absence of accounting for such situations, the output might be far from reality. As described earlier, microscopic simulation considers each and every vehicle movement on a roadway and hence such a lane change behaviour and vehicle interactions can be described. More realistic estimation of speed-flow relationships can be achieved through microscopic simulation system which can lead to the estimation of capacity with reasonable degree of accuracy. Such microscopic simulations are able to model individual vehicles and pedestrians in a large area and it is possible to estimate realistic speed-flow characteristics and capacity considering all possible lane change behaviour even under heterogeneous traffic conditions. Further, these techniques are highly useful in estimating the traffic characteristics under different traffic flow and driver behaviour conditions which cannot be observed on the field. However, it is to be borne in mind that the data collection task needed to develop the microscopic simulation can be a bit tedious and cumbersome. To arrive at speed-flow characteristics and establish capacity norms through microscopic simulation, one has to model the flow of individual vehicles in a detailed manner for which established
Table 1. Details of selected test sections for traffic data collection on Delhi - Gurgaon expressway.

<table>
<thead>
<tr>
<th>Test section number</th>
<th>Location</th>
<th>Direction</th>
<th>Number of lanes in each direction</th>
<th>Carriageway width (m) in one direction</th>
<th>Time (h)</th>
<th>Trap length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Km 26.0 (near IFFCO Intersection)</td>
<td>Gurgaon to Delhi</td>
<td>4</td>
<td>16.5*</td>
<td>06:40 - 10:00</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>Km 26.0 (near IFFCO Intersection)</td>
<td>Delhi to Gurgaon</td>
<td>4</td>
<td>16.5*</td>
<td>06:40 - 10:00</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>Km 15.0 (near Mahipalpur)</td>
<td>Gurgaon to Delhi</td>
<td>4</td>
<td>16.5*</td>
<td>15:40 - 19:00</td>
<td>130</td>
</tr>
</tbody>
</table>

* including 2.5 m wide paved shoulder.

Figure 1. Uncongested and congested parts of speed-flow curve.

simulation packages can be used. The data collection and methodology followed for this phase is explained further.

MATERIALS AND METHODS

Data collection

As mentioned earlier, the primary objective of the present study is to develop realistic speed-flow equations for estimating the roadway capacity of eight-lane divided urban expressway. In order to achieve the envisaged objective, speed-flow studies were conducted on fully access controlled Delhi-Gurgaon Expressway. The videography survey was conducted by capturing the traffic plying during the morning and evening time periods on both directions of travel. The details of the test sections are given in Table 1.

Adopted methodology

Speed-flow curves

In the present study, the traffic flow data was proposed to be analyzed by typically dividing the traffic volume into two segments corresponding to congested and uncongested traffic conditions as shown in Figure 1 (Yao et al., 2009). The two segments encompass the following:

i. Uncongested (Upper Part): Traffic related to uncongested and queue discharge states

ii. Congested (Lower Part): Traffic related to queuing state (Stop and Go)

It is proposed to analyze these two parts separately and determine the speed-flow relationships accordingly in the present study. Different models including linear, exponential, polynomial, logarithmic, power, Akcelik and Bureau of Public Roads (BPR) are available for speed-flow analysis as given in Table 2. However, linear models are adopted for the sake of simplicity in understanding these relationships between speed and flow for both upper part (uncongested) and lower part (congested) of the curve in the present study. Using this procedure, the speed-flow equations for different vehicle types on eight-lane divided urban expressway are developed. In this study, the roadway capacity is considered as the intersecting point of best speed-flow models developed for the upper and lower part as shown in Figure 2.

Framework for microscopic simulation model

One aspect kept in mind while applying traffic simulation technique is that there are no universally accepted procedures for conducting the calibration and validation of any road network. The
Table 2. Functional form of candidate models for speed-flow curves.

<table>
<thead>
<tr>
<th>Name of the Equation</th>
<th>Functional Form</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>( v = -\alpha x + \beta )</td>
<td>Not always advisable; Reaches zero speed at high ( F/F_{cap} )</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>( v = -\alpha \ln x + \beta )</td>
<td>Not always advisable; Has no value at ( x = 0 ).</td>
</tr>
<tr>
<td>Exponential</td>
<td>( v = \alpha v_f \exp(-\beta x) )</td>
<td>Has all the required traits for equilibrium assignment</td>
</tr>
<tr>
<td>Power</td>
<td>( v = \alpha /x^\beta )</td>
<td>Not always advisable; It goes to infinity at ( F/F_{cap} ) at ( x = 0 ).</td>
</tr>
<tr>
<td>Polynomial</td>
<td>( v = -\alpha x^2 - \beta x + \gamma )</td>
<td>Not always advisable; It reaches zero speed at high ( F/F_{cap} )</td>
</tr>
<tr>
<td>Bureau of Public Roads (BPR)</td>
<td>( v = v_f / (1 + \alpha(x)^\beta) )</td>
<td>Has all the required traits for equilibrium assignment</td>
</tr>
<tr>
<td>Akcelik</td>
<td>( V = L/[L/v_f + 0.25((x-1) + \sqrt{(x-1)^2 + \alpha x})] )</td>
<td>Has all the required traits for equilibrium assignment.</td>
</tr>
</tbody>
</table>

\( v = \) speed; \( \alpha, \beta \) and \( \gamma \) = global parameters for equation; \( x = F/F_{cap} \) ratio; \( v_f \) = free - flow speed; \( F = \) flow; \( F_{cap} = \) flow at capacity; \( L = \) link length.

Figure 2. Capacity estimation from speed-flow curves.

Responsibility lies with the modeler to implement a suitable procedure which provides an acceptable level of confidence in the model results. The methodology followed for the microscopic simulation is shown in the form of flow chart in Figure 3.

From Figure 3, it can be observed that the data collection is the first and foremost requirement for understanding speed-flow characteristics on urban expressways. To capture lane change behavior on these high speed corridors, videography method was adopted for data collection. The input parameters considered, adopted network design along with traffic demand data used for the development of simulation model coupled with calibration and validation processes are described in detail in the subsequent sections. During data collection at Mahipalpur section of Delhi - Gurgaon Expressway, it was observed that vehicles are plying on seven virtual traffic lanes though the demarcated lanes available are only four lanes in each direction of travel.

Due to this reason, the flow levels were abnormally high during the peak hours hovering around 17,000 vehicles/h. Accordingly, in the simulation run also, it was decided to consider seven virtual lanes for traffic movement matching with the observed ground conditions despite the fact that the available road width is only 14 m which can cater ideally to four lanes (measuring 3.75 m lane width) in each direction of travel. However, the observed pattern of traffic movement (as witnessed during video data decoding) deteriorated even further during the evening peak hours as the traffic movement was observed to ply on eight virtual lanes as shown in Figure 4.

Consequently, the observed ground conditions were replicated in the simulation process by resorting to eight virtual lanes for the last one hour of simulation. To analyze speed against flow and develop equations, estimated speed values were considered for all the vehicle types under congested flow conditions to plot the scatter diagrams of the speed of vehicles and the corresponding flows.

Input parameters

In this study, the first step in the calibration and validation process involved choosing of suitable model parameters like vehicle characteristics, aggressiveness, awareness, target headways and reaction times that provided realistic results. The range of suitable values for these parameters has been established through calibration of the PARAMICS model. Most of these were chosen based on previous experience in using the model in similar urban conditions. Much emphasis was laid on comparison of modeled and observed flows as well as classified vehicle speeds as described further.
Lane Change Behaviour

Video Recording Method

Data Collection

Data Extraction and Analysis

Preparation of Input Parameters for Microscopic Simulation

Development of Microscopic Traffic Simulation Model in PARAMICS Software

Calibration and Validation of Simulation model

Estimate Output: Speed and Flow

Development of Speed Flow Model

Estimation of Capacity under different Scenarios of lane discipline and lane change behaviour

Figure 3. Methodology for estimating speed-flow equations and capacity of urban expressways.

Road network design

The link-node diagram is the blueprint for constructing the microscopic simulation model. The diagram identifies which streets and highways will be included in the model and how they will be represented. The link-node diagram was created through the PARAMICS Modeller suite. Nodes are placed in the model using x-y coordinates. Links were used as connectors between these nodes. A test link of 300 m has been created. This is to create a buffer distance for the vehicles before entering the marked section (130 m). This has been done to ensure that generated vehicles reach a stabilized flow state before entering the section. Figure 5 shows the schematic representation of the test network created in PARAMICS. The physical and operational characteristics of the links are given as input into the model which included category of the road (major highway), number of lanes (4), lane width (3.75 m) and lane speed (90 kmph).

Traffic operations data

Traffic operations and management data for links consist of warning data (incidents, lane drops, etc.), regulatory data (speed limits, variable speed limits, high-occupancy vehicles (HOVs), high-occupancy toll (HOT), lane use, etc., information (guidance) data (dynamic message signs and roadside beacons) and surveillance detectors (type and location). In this study, loop detectors of length 130 m are placed in the link in both directions which replicate the trap length in real case as shown in Figure 5. These detectors deduce the number of classified vehicles and speeds of different classes of vehicles are used for the validation purpose.

Traffic demand data

Traffic demands are defined as the number of vehicles and the percentage of vehicles of each type that traverse the study area during the simulation time period. Furthermore, it may be necessary to reflect the variation in demand throughout the simulation time period. As discussed earlier, nine vehicle types were considered for simulation modelling. The configuration of these vehicles like physical attributes, acceleration/deceleration rate, proportion, etc., severely affects the capacity of the roadway.

Model calibration

Calibration is the adjustment of model parameters to improve the model’s ability to reproduce local driver behavior and traffic performance characteristics. Calibration is performed on various components of the overall model. Calibration is necessary because no single model can be expected to be equally accurate for all possible traffic conditions. Even the most detailed microscopic simulation model still contains only a portion of all of the variables
that affect real-world traffic conditions. Since no single model can include the whole universe of variables, every model must be adapted to local conditions. Every microscopic simulation software program comes with a set of user-adjustable parameters for the purpose of calibrating the model to local conditions. Therefore, the objective of calibration is to find the set of parameter values for the model that best reproduces local traffic conditions. During the calibration phase, the global capacity-related parameters in the simulation model were adjusted to best replicate local field measurements such as speed and volume and thus arrive at the possible capacity using the calibrated model after subjecting the model to validation process.
Table 3. PCU factors adopted based on IRC specifications (IRC: 64-1990).

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>PCU factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor cycles (MC) and scooters (SC)</td>
<td>0.5</td>
</tr>
<tr>
<td>Auto rickshaws (A)</td>
<td>1.0</td>
</tr>
<tr>
<td>Cycle rick and other slow vehicles (OT)</td>
<td>1.5</td>
</tr>
<tr>
<td>Small cars (≤1400 cc) (CS) and big cars (CB)</td>
<td>1.0</td>
</tr>
<tr>
<td>Cycles (CY)</td>
<td>0.5</td>
</tr>
<tr>
<td>Buses (B) and mini buses (MB)</td>
<td>3.0</td>
</tr>
<tr>
<td>Tractors and tractor trailers (TT)</td>
<td>3.0</td>
</tr>
<tr>
<td>Light commercial vehicles (LCV)</td>
<td>1.0</td>
</tr>
<tr>
<td>Two-axle commercial vehicles (HCV)</td>
<td>3.0</td>
</tr>
<tr>
<td>Multi-axle commercial vehicles (MCV)</td>
<td>3.0</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Traffic data analysis

The speed and flow data was analyzed by classifying the vehicles into the following categories namely, cars - which is further sub-classified into two categories, small cars (engine capacity ≤ 1400 cc) and big cars (engine capacity > 1400 cc); two wheelers (TW); auto rickshaws (Autos); buses, light commercial vehicles (LCV); two-axle heavy commercial vehicles (HCV) and multi-axle heavy commercial vehicles (MCV). As mentioned earlier, the recorded video was replayed in the laboratory for decoding purposes and the required data were decoded through manual method. The vehicles were categorized into the afore said categories and the primary data extracted from video recording were volume and space mean speed of individual vehicles during every five minute time interval. The extracted data was analyzed to get the classified traffic volume count and was used for deriving speed - flow relationship for each category of vehicle and thus estimate the capacity. The passenger car unit (PCU) values as per IRC:64-1990 as given in Table 3 were applied to convert traffic volume of different vehicle types into single unit. The traffic volume, composition and average speed for all the three sections are shown in Figures 6, 7 and 8 respectively. A close look at Figure 6 illustrates that the traffic has substantially increased to reach morning peak at 08:30 h as the traffic flow is hovering between 7,000 and 10,000 PCU/h at Section 1 and 2 respectively on Delhi - Gurgaon Expressway whereas it caters to the evening peak traffic of about 17,000 PCU/h at 18:35 h on Section 3 of the Delhi - Gurgaon Expressway. Figure 7 demonstrates that the average speed on Section 1 and 2 is almost varying between 50 and 60 kmph whereas it is mostly varying between 25 and 50 kmph on Section 3 during the data collection period which reduces drastically to less than 20 kmph during the evening peak hour as depicted in Figure 7. Figure 8 reveals that the cars and two wheelers obviously dominate the traffic flow ranging from 92 to 97% of the total volume on both the directions. This scenario clearly describes the dominance of personalised cars and two wheelers on this road section thus
Figure 7. Variation of average speeds on different test sections.

Figure 8. Observed traffic composition on different test sections.

highlighting the urbanized nature of the test sections.
Validation results of simulation model

The calibrated microscopic simulation model is validated by comparing the observed and simulated values. Figure 9 shows the comparison between observed and simulated volumes for Sections 1, 2 and 3 on Delhi - Gurgaon Urban Expressway. The average percentage of error and Root Mean Square Error (RMSE) were determined by comparing the observed and simulated flows and shown in Figure 9.

From Figure 9, it can be seen that developed simulation model is reasonably representing the ground conditions in terms of number of vehicles simulated during each five minute time period as the average error is ranging between 4 and 10% and RMSE value is hovering between 23 to 116 Vehicles/5 min. To validate the developed simulation model, the average speeds of the different vehicles were also compared for different sections of Delhi - Gurgaon Urban Expressway as given in Table 4. From Table 4, it can be observed that error between observed and simulated speeds of all the vehicles is ranging between 19 to 27%. From these results, it can be inferred that the mean percentage error and RMSE of different vehicle types for both speed and volume are quite reasonable indicating that the developed simulation model is able to predict vehicular behavior with fair degree of accuracy.

Speed - flow equations and roadway capacity through simulation model

Using the developed simulation model, the speed data for different vehicle is estimated under different traffic volume conditions for eight-lane divided urban expressway and used to arrive at the speed-flow
Table 4. Error between average observed and simulated speeds on the study sections.

<table>
<thead>
<tr>
<th>Type of vehicle</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. observed speed (kmph)</td>
<td>Avg. simulated speed (kmph)</td>
<td>Mean error (%)</td>
</tr>
<tr>
<td>Two wheeler</td>
<td>63.59</td>
<td>72.49</td>
<td>14</td>
</tr>
<tr>
<td>Autos</td>
<td>41.60</td>
<td>54.92</td>
<td>32</td>
</tr>
<tr>
<td>Small car</td>
<td>71.74</td>
<td>79.63</td>
<td>11</td>
</tr>
<tr>
<td>Big car</td>
<td>72.64</td>
<td>78.46</td>
<td>8</td>
</tr>
<tr>
<td>Bus</td>
<td>60.43</td>
<td>68.90</td>
<td>14</td>
</tr>
<tr>
<td>LCV</td>
<td>53.76</td>
<td>63.97</td>
<td>19</td>
</tr>
<tr>
<td>HCV</td>
<td>52.33</td>
<td>67.51</td>
<td>29</td>
</tr>
<tr>
<td>MCV</td>
<td>42.10</td>
<td>62.73</td>
<td>49</td>
</tr>
<tr>
<td>All vehicles</td>
<td>55.94</td>
<td>71.05</td>
<td>27</td>
</tr>
</tbody>
</table>

relationships for different classes of vehicles. The speed estimation from the data of IFFCO intersection (Sections 1 and 2) and Mahipalpur (Section 3) of Delhi - Gurgaon Expressway has been done using PARAMICS and the scatter diagrams of the speed of vehicles and the corresponding flows were plotted. After critical observation of the data, it was decided to split these data into two parts: congested and uncongested parts of the speed - flow relationships. The data of IFFCO intersection (Sections 1 and 2) was taken for the upper part of the speed-flow relationship area (that is, uncongested) since the data observed during the off-peak morning hours while the Mahipalpur data (Section 3) was taken for the lower part (that is, congested). On the basis of this, these two data are considered separately and separate speed - flow equations were developed for uncongested and congested areas. In case of congested conditions, the stop and go scenarios were introduced to get the data spread into all the regions of congested. The estimated speed in relation with the flow conditions are pictorially shown in Figure 10 for different vehicle types. The developed speed-flow relationships for different vehicle types plying on eight-lane divided urban expressway are shown in Table 5.

From Figure 10a and b, it can be clearly seen that $R^2$ value is very high for two wheelers, cars, buses, LCV whereas for the remaining vehicle type, $R^2$ is moderate. Based on this result, it can be said that the developed speed-flow equations for the test section, that is, eight-lane divided urban expressways are good in terms of statistical validity and can be applied to predict speeds for any given traffic volume data with reasonable amount of accuracy. Accordingly, the developed speed-flow equations based on “all cars” were utilized to estimate roadway capacity for eight-lane divided urban expressway and the capacity is shown in Figure 11.

From Figure 11, it can be seen that the roadway capacity was estimated to be 11,544 PCUs/h/direction for the eight-lane divided urban expressways. To demonstrate the validity of developed speed - flow equations through microscopic simulation model, the estimated free speed which is the intercept of the equations (at flow almost equal to 0 vehicles/h) are compared with the observed free speeds and presented in Figure 12.

Figure 12 illustrated that the error between observed and simulated free speeds is less than 10% and from this, it can be concluded that developed speed - flow equations through simulation model is able to predict the traffic phenomenon on multi-lane highways more realistically as the prediction error in free speeds on eight-lane divided carriageway is less. Thus, the evolved roadway capacity through simulation approach can be adjudged to be realistic for the heterogeneous traffic conditions observed on eight-lane divided urban expressways.

Impact of virtual traffic lanes on roadway capacity

As discussed earlier, the Indian drivers always tend to travel on urban corridors in more than designated physical lanes. On Delhi - Gurgaon Expressway, vehicles were traveling on 8 virtual lanes vis-à-vis is the
availability of only 4 physical lanes in each direction (Figure 4). This particular driving behavior bound to have severe impact on speed, flow and roadway capacity and moreover on the road safety as the interactions among

Figure 10a. Developed speed - flow relationships from calibrated simulation models.
Table 5. Speed-flow equations for different vehicle types on eight-lane divided urban expressways.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Speed - flow equations</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two wheelers</td>
<td>Uncongested: $y = -0.005x + 90.57$</td>
<td>0.948</td>
</tr>
<tr>
<td></td>
<td>Congested: $y = 0.002x + 8.295$</td>
<td>0.831</td>
</tr>
<tr>
<td>Autos</td>
<td>$y = -0.00331x + 70.0$</td>
<td>0.589</td>
</tr>
<tr>
<td>Small cars</td>
<td>Uncongested: $y = -0.006x + 103.39$</td>
<td>0.964</td>
</tr>
<tr>
<td></td>
<td>Congested: $y = 0.002x + 8.674$</td>
<td>0.872</td>
</tr>
<tr>
<td>Big cars</td>
<td>Uncongested: $y = -0.006x + 105.00$</td>
<td>0.955</td>
</tr>
<tr>
<td></td>
<td>Congested: $y = 0.002x + 8.603$</td>
<td>0.858</td>
</tr>
<tr>
<td>All cars</td>
<td>Uncongested: $y = -0.00619x + 104.0$</td>
<td>0.961</td>
</tr>
<tr>
<td></td>
<td>Congested: $y = 0.00215x + 8.637$</td>
<td>0.860</td>
</tr>
<tr>
<td>Bus</td>
<td>$y = -0.004x + 84.00$</td>
<td>0.781</td>
</tr>
<tr>
<td>LCV</td>
<td>$y = -0.006x + 86.86$</td>
<td>0.828</td>
</tr>
<tr>
<td>HCV</td>
<td>$y = -0.004x + 80.94$</td>
<td>0.547</td>
</tr>
<tr>
<td>MCV</td>
<td>$y = -0.004x + 75.00$</td>
<td>0.418</td>
</tr>
<tr>
<td>All vehicles</td>
<td>Uncongested: $y = -0.006x + 99.58$</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>Congested: $y = 0.002x + 8.177$</td>
<td>0.872</td>
</tr>
</tbody>
</table>

$y =$ speed (kmph); $x =$ flow (PCU/hr/Dir).

the vehicles increases. To understand the impact of virtual traffic lane driving resorted by the Indian drivers, the roadway capacity of eight-lane divided expressway has been estimated by restricting the vehicles to travel in the available 4 physical lanes in each direction of travel during the simulation run. However, lane changes were allowed within the available 4 lanes. Further, the impact of restriction of lane changes has been studied as well, that is, vehicles are allowed to travel only on the 4 available physical lanes without resorting to any lane change. These two scenarios are considered in the simulation model and roadway capacities were estimated under these behaviors. The details can be found elsewhere (Velmurugan et al., 2010). Figure 13 shows the typical comparison of roadway capacities and free speeds of cars on eight-lane divided urban expressways under varying scenarios.

From Figure 13, it can be observed that the restriction of a road user to travel on available physical lanes on eight-lane divided urban expressway would lead to a reduction of roadway capacity (9796 PCU/h/direction) by about 15%. It can also be observed that this contributes to a reduction of about 7% in free speeds (cars) as well because of the restriction of virtual lanes. From the figure, it can also be observed that the restriction of lane change would lead to further reduction of 9% in roadway capacity (8941 PCU/h/direction); however marginal increment in speed (about 1%) can be observed. Since the formation of virtual lanes has obviously increased the roadway capacity as well as free speeds, the road users are inclined to resort to the formation of virtual lane under the heterogeneous traffic conditions prevalent on Indian roads. However, the restriction of such behavior would certainly enhance the road safety but at the cost of marginal reduction in roadway capacity.

Conclusions

In this study, free speed profiles and speed-flow equations of different vehicle types for eight-lane divided urban expressways has been established for the first time in the country based on microscopic simulation models and subsequently roadway capacity has been estimated with reasonable degree of authenticity for the prevailing heterogeneous traffic conditions. Further, the lane change behaviour of different vehicle types has been extensively studied and its impact on roadway capacity has been critically evaluated on these eight-lane divided urban expressways. The conclusions drawn from the studies are summarized as follows:

i. The maiden attempt to segregating the speed-flow data into uncongested and congested traffic conditions
has been successfully accomplished in the present study and subsequently roadway capacities has been estimated through simulation.

ii. The study revealed that the roadway capacities estimated through microscopic simulation approach (2859 PCU/Hr/Lane) in this study has replicated ground conditions more realistically for eight-lane divided urban expressways.

iii. The present study affirms that the adoption (through developing adjustment factors) of the roadway capacities determined for developed world scenarios would not yield realistic results.

iv. The simulation study carried out in this paper has substantiated the fact that the lane change behavior significantly influences the vehicular movements on a road section and thus affects the roadway capacity.

It can be observed from this study that the restriction of a road user to travel on available physical lanes on eight-lane divided urban expressway would lead to a reduction of roadway capacity (9796 PCU/Hr/Direction) by about 15%. It can also be observed that there would be a reduction of about 7% in free speed (cars) as well because of the restriction of virtual lanes. From these results, it can also be observed that the restriction of lane change would lead to further reduction of 9% in roadway capacity (8941 PCU/Hr/Direction); however, marginal increment in speed (about 1%) can be observed. Since the formation of virtual lanes would obviously increase the roadway capacity as well as free speeds, the road users are inclined to resort to the formation of virtual lane under the heterogeneous traffic conditions prevalent on Indian roads. However, the restriction of such behavior

Figure 10b. Developed speed - flow relationships from calibrated simulation models.
Figure 11. Roadway capacity of eight-lane divided urban expressways evolved through microscopic simulation model.

Figure 12. Comparison between observed and simulated free speeds.

would certainly enhance the road safety but at the cost of marginal reduction in roadway capacity.

LIMITATIONS AND FUTURE SCOPE

It may be noted that the driver behaviour has been calibrated for the parameters defined through the PARAMICS software taking into account the traffic flow and road conditions prevalent on typical sections of eight-lane divided urban expressway located on plain terrain considering the heterogeneous traffic conditions and the lane change behaviour as observed in the field. Though the error seems to be reasonable, it is proposed to
consider additional test sections so as to further improve the predictive capability of the developed simulation model. Considering these inherent limitations in this study, the geographical transferability of the developed simulation model developed in this study can be tested through collection of traffic data on other eight-lane divided urban expressways/ carriageways located on plain terrain road sections spread over the country.

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Errampalli M, Velmurugan S, Ravinder K, Gangopadhyay S (2009). “Speed - flow characteristics of high speed corridors in India.” Presented at 14th International Conference of Hong Kong Society for Transportation Studies (HKSTS), Hong Kong.

Figure 13. Typical comparison of roadway capacity and free speed of cars on eight-lane divided urban expressways for different driving behaviour.