



Modeling of Congestion: A Tool for Urban Traffic Management in Developing Countries

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Abstract

In order to formulate rational traffic management measures for urban roads, it is essential to understand the effect of different types of vehicle on congestion. The effect of different types of vehicle on congestion has been captured on the basis of marginal congestion. Using congestion models, the marginal congestions have been estimated for different road widths, traffic compositions and on-street parking levels. The peak hour vehicular composition and volume level vary for different roads in an urban area. Therefore, for assessing the operating conditions for different roads based on a comparable quantitative measure, the marginal congestion caused per Passenger Car Unit (PCU) of mixed traffic stream has been estimated and denominated 'Marginal Congestion Index (MCI)'. The use of MCI for prioritization of management actions for different urban roads is discussed. It is shown that a congestion model explicitly accounts for the effects of traffic composition and volume level. Therefore, the effect of different types of vehicles on congestion at all traffic volumes could be estimated using congestion models. Altogether, modeling of congestion is established as a tool for formulating rational traffic management measures for urban roads in developing countries.

Keywords: Congestion; Urban transport; Traffic management; Developing countries.

Introduction

The rapid growth of traffic congestion on urban roads and the resulting impediment to urban mobility is a serious concern to urban management professionals and decision makers. In attempting to alleviate the congestion on urban roads, it is commonly found that the expansion and improvement of roads is restricted by increasingly tight fiscal and physical constraints. However, addressing the problem through rational traffic management measures like restricting the entry of certain types of vehicle during peak periods of traffic flow or enforcing congestion pricing is considered to be a more acceptable alternative.

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Urban traffic in most of the developing countries is heterogeneous in nature, and the effects of different types of vehicle on congestion are unlikely to exert the same influence. For formulating rational traffic management measures, it is necessary to quantify the effect of different types of vehicle on congestion under prevailing roadway, traffic and control conditions. In the present paper, this has been achieved by estimating incremental and marginal congestions caused by different types of vehicle in a mixed traffic stream. Modeling of congestion has been used as a tool for estimating incremental and marginal congestions.

Any change in prevailing roadway and control condition is likely to influence the congestion level as well as the effect of different types of vehicle on congestion. Therefore, the effect of road width and control condition (i.e. on-street parking level) on similar vehicle types has been studied at different flow levels. The role of marginal congestion in improving the rationality of traffic management measures has been discussed. In order to account for dissimilar roadway, traffic and control conditions for different roads in an urban area, the marginal congestion caused per Passenger Car Unit (PCU) of mixed traffic stream under prevailing roadway, traffic and control conditions, has been estimated and defined as 'Marginal Congestion Index (MCI)'. The use of operating MCI in prioritization of management actions has been discussed.

Modelling of Congestion

A measure of congestion should be simple, well defined and easily understood. The method of measuring congestion should also be cost effective, accurate and easy for implementation. A balanced quantification of congestion should embody a combination of volume (e.g. total traffic volume, volume to capacity ratio, traffic volume per lane etc.) and operational (e.g. speed, delay, travel time, density etc.) characteristics of traffic stream (Pignataro 1973). However, the traditional measures of congestion (Lomax 1988; Witheford 1988; Hashimoto 1990; Turner 1992; Lakshmana Rao & Sridhar 1995; Parbat 1996) are based on either volume or operational characteristics of traffic stream. Combining volume and operational characteristics of traffic movement, Maitra, Sikdar & Dhingra (1999) developed a methodology for the quantification and modeling of congestion on urban roads, which has been followed in the present paper. The area under the observed speed-flow curve is used as a measure of loss in freedom of movement; and congestion is expressed as a percentage loss in freedom of movement. Therefore, the measured congestion is a dimensionless quantity. A road is considered to have a congestion value of zero at free-flow operation, a 100 per cent congestion at maximum flow, and more than 100 per cent congestion at unstable or forced-flow operations. Therefore, any operating condition in the stable flow zone will have a congestion value between zero and 100 per cent.

On a road, the congestion level (CG_V) at a traffic volume ' V ' is expressed as given in *Equation 1*.

$$CG_V = \left(\frac{V}{V_L} \right)^{\sum_{i=1}^n p_i m_i + 1} * 100 \quad (1)$$

where,

- n =number of vehicle types in mixed traffic stream,
- i =a vehicle type (e.g. car, bus, truck etc.) present in mixed traffic stream,
- p_i =proportion of vehicle type 'i' in mixed traffic stream and
- V_L =limiting traffic volume representing 100 per cent congested operation, which is estimated as given in *Equation 2*.

$$V_L = \left[\frac{1}{a} \left(1 - \frac{S_L}{S_f} \right) \right]^{\frac{1}{\sum_{i=1}^n p_i m_i}} \quad (2)$$

where,

- S_f =free-flow speed of traffic,
- S_L =speed at or near capacity representing 100 per cent congested operation. 'a' and 'm_i' (i= 1,...,n) are model coefficients, which are calibrated from speed-flow relationship given in *Equation 3*.

$$S_V = S_f \left[1 - a \left(\frac{V}{C} \right)^{\sum_{i=1}^n p_i m_i} \right] \quad (3)$$

where,

- S_V =speed of traffic stream at a traffic volume 'V' and
- C =traffic capacity of the road under consideration.

A large number of observations are required to calibrate the speed-flow model given by *Equation 3*. The derived coefficients 'a' and 'm_i' (i= 1,...,n) are then used to calculate the limiting traffic volume (V_L) representing 100 per cent congested operation as given by *Equation 2*. The derived coefficients and estimated limiting traffic volume are then used in *Equation 1* for estimating congestion level (CG_V) corresponding to a given traffic volume 'V'.

Data Base and Congestion Models

In order to demonstrate the methodology for quantifying the effects of different types of vehicle on congestion and also for studying the variations for different road widths and on-street parking levels, several congestion models were necessary. In the present paper, congestion models developed by Maitra, Sikdar & Dhingra (1999, 2000) have been used to study the effect of road width/ parking intensity on the contributions of different types of vehicle on congestion. In order to study the effect of different types of vehicle on congestion for various levels of on-street parking, about 1.1m carriageway of a study road (A. S. Marg Road, Mumbai, India) having 5.2m width in one direction was

occupied by parked vehicles and thereby leaving a clear width of 4.1m for unidirectional through traffic movement. Level of on-street parking was defined based on the intensity of uniformly spaced vehicles parked parallel (using part of the shoulder and part of the carriageway) along the side of the study road. For defining heavy intensity of on-street parking, maximum possible number of cars were parked parallel along one side of the study road. For defining medium level of on-street parking every alternative parked vehicles used for defining heavy parking level, was removed and therefore, the number of uniformly placed parked vehicles was 50% of that used for creating heavy parking level. Similarly, for defining low level of on-street parking, every alternative parked vehicles used for defining medium parking level was removed. Therefore, the number of parked vehicles for defining low level of on-street parking was 50% of that used for defining medium level of on-street parking. For defining no parking condition on the same study road, all parked vehicles were removed. *Table 1* summarises the congestion models used in the present work. Each congestion model was accepted after a careful review of R^2 value, t-values, F-value and sign of the coefficients.

Table 1: Coefficients of Congestion Models for Different Road Widths and Levels of On-street Parking .

Name of the Road, Level of Parking and Model R2	Road Width (m)	'a'	m_i for different vehicle types							
			C	N	B	T	L	W	A	
B.S. Ambedkar Marg: (No Parking) ($R^2=0.882$)	13.0	0.601	----	0.610	----	-----	0.937	-----	1.273	NA
Eastern Express Highway: (No Parking) ($R^2=0.935$)	10.3	0.605	----	1.257	----	-----	0.657	-----	0.643	0.465
M. Karve Road: (No Parking) ($R^2=0.942$)	7.0	0.660	0.748	0.746	0.982	0.424	0.513	0.562		NA
L.B.S. Marg: (No Parking) ($R^2=0.907$)	6.8	0.612	----	1.073	----	-----	1.598	-----	0.626	0.876
N.S. Patkar Marg: (No Parking) ($R^2=0.871$)	6.5	0.691	----	0.827	----	-----	1.619	-----	0.562	NA
A.S. Marg: (No Parking) ($R^2=0.951$)	5.2	0.724	1.381	1.817	2.296	1.613	1.675	1.016		0.676
A.S. Marg: (Low Parking) ($R^2=0.930$)	4.1	0.800	1.821	1.958	1.456	0.357	2.154	1.055		0.838
A.S. Marg: (Medium Parking) ($R^2=0.874$)	4.1	0.816	1.732	1.203	1.480	1.783	0.240	0.901		1.032
A.S. Marg: (Heavy Parking) ($R^2=0.885$)	4.1	0.830	0.968	1.666	1.159	0.627	1.033	1.397		0.783

Note C: Old Technology Car, N: New Technology Car, B: Bus, T: Truck, L: Light Commercial Vehicle, W: Two Wheeler, A: Auto (Three Wheeler) and NA: Vehicle type not present on the particular road

During the last decade, several new models of passenger car have been launched in the Indian market. These cars are called “New Technology Cars”. In general, most of these cars are smaller in size with superior speed capabilities and acceleration/deceleration characteristics as compared to the cars, which were dominating the Indian market in the past (Kadiyali & Viswanathan 1993). The traditional cars, which are still in use, are referred to as “Old Technology Cars”. For some of the study roads, separate data was available for old and new technology cars. For these roads, old and new technology cars have been considered separately in congestion models. For other roads, old and new technology cars have been considered together. Similarly, wherever separate data was available for bus, truck and light commercial vehicles, they have been considered separately in congestion models. For other roads, these three vehicle categories have been considered together in congestion models.

Incremental and Marginal Congestions

On the basis of congestion model developed for a road, the level of congestion at different traffic compositions and volume levels can be estimated. In reality, the traffic composition and volume level vary with time. Also, the increase in congestion due to the addition of a new vehicle will depend on the type of vehicle, volume level, composition of traffic stream, roadway width, etc. In the present paper, the increase in congestion level caused by each vehicle type present in a mixed traffic stream has been estimated using the congestion model (*Equation 1*). The volume and composition of traffic stream before the addition of a new vehicle are called ‘base volume’ and ‘base composition’ respectively. Similarly, the increase in congestion level due to the addition of a new vehicle at a base volume is termed ‘incremental congestion’. Naturally, for a base volume and base composition, the incremental congestions will be different for different types of vehicle. As the hourly traffic volumes used in congestion models were based on 5-minute duration traffic data, an addition of 1 vehicle in 5-minute interval resulted in an increase in the hourly volume by 12 vehicles, which was expressed in Passenger Car Unit (PCU) using appropriate PCU values recommended for Indian conditions (CRRI 1988; IRC 1990). The incremental congestion caused by vehicle type ‘i’ at a base volume ‘V’ is estimated as given in *Equation 4*.

$$IC_{iV} = \left(\frac{V_i^*}{V_{Li}^*} \right) \sum_{i=1}^n p_i^* m_i + 1 - \left(\frac{V}{V_L} \right) \sum_{i=1}^n p_i m_i + 1 \quad (4)$$

where,

IC_{iV} = Incremental congestion caused by vehicle type ‘i’ at a base volume ‘V’

V_i^* = Traffic volume after the addition of vehicle type ‘i’ at a base volume ‘V’

p_i^* ($i=1,2,\dots,n$) is the composition of traffic stream after addition of vehicle type ‘i’ at a base volume ‘V’. Certainly, this will be different from the base composition. The traffic volume after joining of vehicle type ‘i’ is estimated by *Equation 5*.

$$V_i^* = V + 12 PCU_i \quad (5)$$

where, PCU_i = Passenger Car Unit (PCU) value for vehicle type 'i'.

V_{Li}^* is limiting traffic volume representing 100% congested operation after the change in composition due to the addition of vehicle type 'i' in the stream. A change in traffic composition due to the joining of vehicle type 'i' at base volume V , results V_{Li}^* to be different from V_L .

Incremental congestion is actually felt by all the vehicles in a traffic stream. Therefore, the total additional congestion to the traffic stream due to the addition of a vehicle type was estimated and termed as marginal congestion (MC). The concept of marginal cost has been used widely in transportation economics (Small 1992; Khisty & Lal 2002), especially in the context of congestion pricing. Existing literature consists of significant contributions made by researchers in conceptualizing the framework for road pricing with reference to marginal cost (Newbery 1990; Hau 1992a, 1992b; Rosenberg 2002; Michael 2002; Nakamura & Kochelman 2002; Paulley 2002). However, most of these works considered homogeneous traffic stream dominated by passenger cars, as the use of private vehicles has been a major cause of congestion in most of the developed countries. There has not been adequate emphasis on the applicability of congestion pricing for mixed traffic operations, where the effect of different types of vehicle on congestion is different. The concept of variable pricing for different types of vehicle is becoming increasingly popular in developing countries. In some of the recent road projects in India, different charges have been fixed for different types of vehicle (Bongirwar & Momin 2000; Rao et al. 2002). However, currently there is no rational basis for the variation of charges for different types of vehicle. Using the congestion model developed for mixed traffic environment, the marginal congestion caused by different types of vehicle has been estimated. The marginal congestion (MC) caused by vehicle type 'i' at a volume level 'V' is computed as given in Equation 6.

$$MC_{iv} = \frac{\left[V_i^* \left(\frac{V_i^*}{V_{Li}^*} \right)^{\sum_{i=1}^n p_i^* m_i + 1} - V \left(\frac{V}{V_L} \right)^{\sum_{i=1}^n p_i m_i + 1} \right]}{12} \quad (6)$$

Marginal congestion for different types of vehicle has been estimated using Equation 6 for all the study roads. The estimated MC values for A.S. Marg road are shown in Fig. 1. It is observed that marginal congestion varies with vehicle type and traffic flow level. The value of marginal congestion is negligible at lower traffic volume but becomes significant with increase in volume. Although, all types of vehicle cause more marginal congestion at higher traffic volumes, the effect is significant for larger vehicles like buses or trucks.

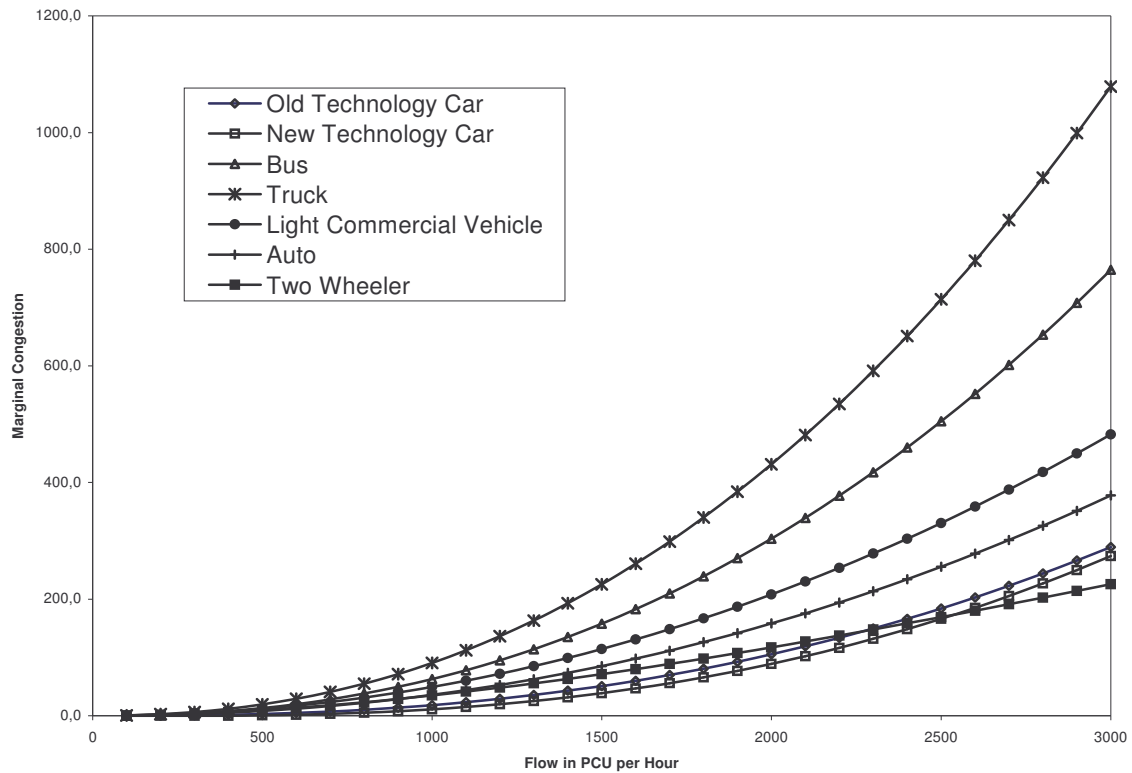


Figure 1: Marginal Congestion Caused by Different Types of Vehicle for A.S. Marg Road.

The knowledge of marginal congestion caused by different types of vehicle can be used as a basis for formulating traffic management measures like restricting the entry of certain types of vehicle on congested roads. For prevailing roadway, traffic and control conditions, if it is required to reduce the level of congestion, the marginal congestions caused by different types of vehicle for the given flow level can be studied and the entry of the vehicle type causing the maximum marginal congestion can be restricted. For the A.S. Marg road, it is found that larger vehicles like trucks cause more congestion than other types of vehicle at higher traffic volumes. Therefore, on A. S. Marg road, restricting the entry of trucks during the peak hours of traffic flow will be beneficial. The concept of marginal congestion can be used as a basis to improve the rationality of traffic management measures for a road.

The estimated *MC* can be utilised for providing a basis for charging different types of vehicle in a mixed traffic stream. For a road, *MC* depends on the flow level and composition of traffic. Therefore, in the case of electronic road pricing system, the marginal congestion caused by different types of vehicle can be calculated in a dynamic manner based on the volume and composition of traffic for each of the pre-specified time intervals (e.g. 5 min, 10 min etc.). However, even in the absence of sophisticated electronic instruments, *MC* can be used as a basis for congestion pricing. Congestion is normally severe during the peak periods of traffic flow and the duration of these peak periods (say, 8.00 a.m. to 10 a.m. and 5.00 p.m. to 7 p.m.) can be ascertained using traffic flow data. Based on average volume and composition of traffic during peak

period, *MC* caused by different types of vehicle can be estimated and used for variable pricing in mixed traffic operations.

Marginal congestion caused by different types of vehicle has been estimated for all the study roads. *Table 2* shows the variation of marginal congestion values for different road widths. The *MC* values shown in *Table 2* correspond to a flow level of 3000 PCU per hour. It is clearly observed that for all the vehicle types, *MC* values are greater when the carriageway width is smaller. However, the increase in marginal congestion due to reduction in road width is not the same for all types of vehicle due to the variations in vehicle size and maneuverability. As two-wheeler is the smallest vehicle, the increase in *MC* is the least due to the reduction in available carriageway width. On the other hand, the increase in *MC* for trucks is the maximum and trucks remain as the most detrimental vehicle type to the traffic stream. The marginal congestion caused to the traffic stream by other types of vehicle lies in between the above two extreme cases (i.e. two-wheelers and trucks) depending upon the size and ease of maneuverability of vehicle types. A comparison of *MC* caused by trucks for different roads clearly justifies the need for banning the entry of trucks on narrower roads, especially at higher flow levels.

Table 2: Variation of Marginal Congestion for Different Road Widths.

Name of the Road	Available Road Width (m)	C	N	B	T	L	W	A
B. S. Ambedkar	13.0	----- 84 -----			----- 300 -----		80	NA
E.E. Highway	10.3	----- 139 -----			----- 481 -----		104	167
M. Karve Road	7.0	208	212	133	526	314	133	NA
N. S. Patkar	6.5	----- 221 -----			----- 597 -----		156	NA
A.S. Marg	5.2	289	274	226	1079	483	226	378

Note C: Old Technology Car, N: New Technology Car, B: Bus, T: Truck, L: Light Commercial Vehicle, W: Two Wheeler, A: Auto (Three Wheeler) and NA: Vehicle type not present on the particular road

The effect of on-street parking on the marginal congestion caused by different types of vehicle was also analysed. The marginal congestion caused by different types of vehicle corresponding to a flow level of 2000 PCUPH for various levels of on-street parking is shown in *Table 3*. It is observed that all types of vehicle become more detrimental to the traffic stream with an increase in the intensity of on-street parking. However, the effect for bigger vehicles like buses and trucks are predominant. *Table 2* and *Table 3* show that *MC* values vary logically with the change in roadway (e.g. width of carriageway) or control (e.g. level of on-street parking) condition.

Table 3: Variation of Marginal Congestion for A. S. Marg Road with Different Levels of On-street Parking.

Level of On-Street Parking	Available Road Width (m)	C	N	B	T	L	W	A
Zero	5.2	105	89	304	431	208	117	158
Low	4.1	125	150	433	525	262	158	202
Medium	4.1	185	167	450	731	291	189	243
Heavy	4.1	190	227	636	838	382	244	252

Note C: Old Technology Car, N: New Technology Car, B: Bus, T: Truck, L: Light Commercial Vehicle, W: Two Wheeler and A: Auto (Three Wheeler)

It is convenient to charge different types of vehicle on a road in proportion to *MC* values for operating traffic volume and composition. However, it is observed from *Table 2* and *Table 3* that *MC* values are sensitive in a logical manner to roadway width or control condition (e.g. on-street parking). Therefore, it is also necessary to understand the role of roadway or control conditions while formulating congestion mitigation measure like restricting the entry of certain types of vehicle or enforcing congestion charging mechanism. For example, if a road width is reduced due to roadside encroachment or vehicles parked on-street, it will result into a different nature of interactions among different types of vehicle in congestion. Accordingly, all the vehicle types, especially the larger vehicles may become more detrimental to the traffic stream. However, the urban management professional should also understand that a larger vehicle would be less damaging if the encroachment or the on-street parking is removed and the full carriageway width is available for through traffic movement. Level of congestion depends on roadway, traffic and control conditions; and therefore, the rationality of mitigation measures should be considered in relation to not only the traffic volume or composition, but also the roadway and control conditions.

Marginal Congestion Index

The marginal congestion caused by a vehicle type depends on the composition and volume of traffic on the road. However, the peak hour vehicular composition and traffic volume level normally vary for different roads in an urban area. In order to assess the operating conditions for different roads based on a comparable quantitative measure, the marginal congestion caused per PCU of mixed traffic stream is estimated. To account for dissimilar conditions of operation for different roads, the MCI for a road at a volume level 'V' is estimated as shown in *Equation 7*.

$$MCI_v = \frac{\sum_{i=1}^n MC_{iv} * p_i}{\sum_{i=1}^n PCU_i * p_i} \quad (7)$$

MCI values were estimated for all the study roads and a comparison of these values for different widths of road is shown in *Fig. 2*. Similarly, *Fig. 3* shows the variation of *MCI*

value for different levels of on-street parking. It is observed that *MCI* value at different flow levels varies in a logical manner with available road width or level of parking. *MCI* values can be used to prioritise management actions of congestion mitigation measures such as congestion pricing, restricting the entry of certain categories of vehicles during peak period, etc. for different roads in an urban area, even when the road width, traffic composition and control conditions (e.g. parking) are different. Thus, as an added advantage, expert judgments for management actions can be provided using *MCI* values. Based on peak hour traffic flow and composition, the operating *MCI* values for different roads can be estimated and used for prioritization of management actions. Naturally, a road with maximum operating *MCI* should be taken first for implementing congestion mitigation measures.

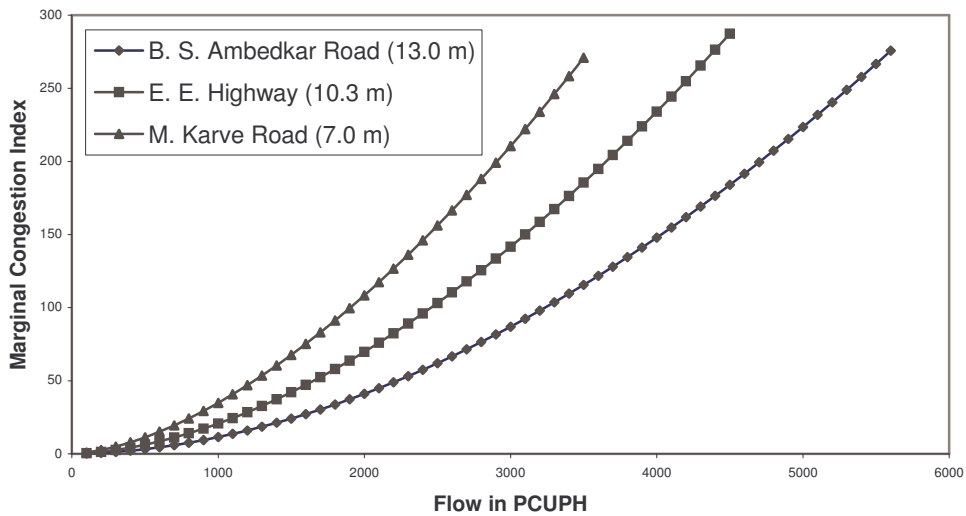


Figure 2: Marginal Congestion Index for Different Widths of Road.

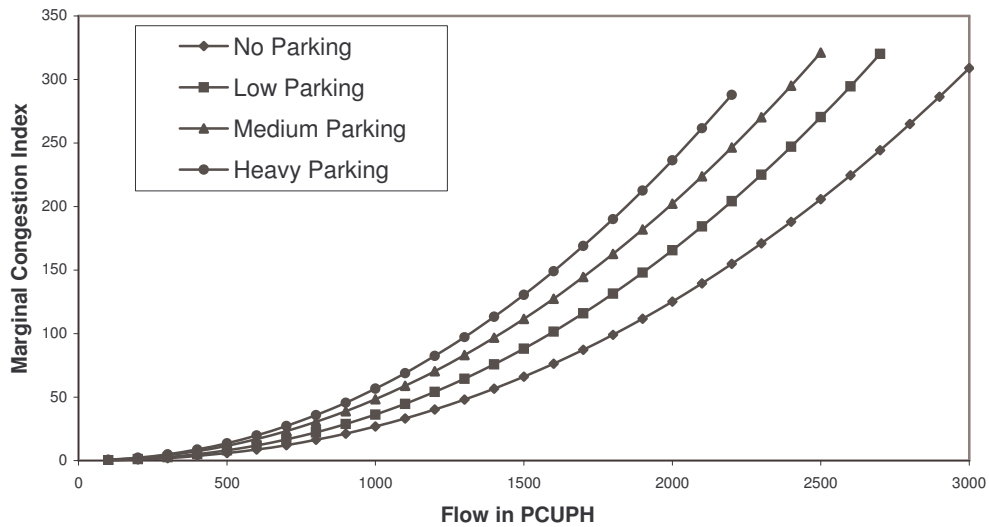


Figure 3: Marginal Congestion Index for Different Levels of On-street Parking.

Conclusions

The effect of different types of vehicle on congestion is one of the key information required for formulating rational traffic management measures in mixed traffic operations. In the present paper, the effect of different types of vehicle on congestion has been captured through marginal congestion. It has been shown that on a road, the amount of marginal congestion varies in a logical manner with vehicle type and flow level. Therefore, marginal congestion could form a basis for formulating rational traffic management measures like restricting the entry of heavy vehicles or enforcing variable pricing in mixed traffic operations. The variation of marginal congestion of similar vehicle types for different road widths and parking levels have been studied. A comparison of marginal congestions for different road widths or parking levels clearly brought out the necessity for considering the rationality of mitigation measures in relation to not only the traffic composition or volume level, but also the roadway and control conditions.

In an urban area, all the roads are unlikely to operate with the same vehicular composition and traffic volume. In order to prioritise management actions of congestion mitigation for different roads with dissimilar operating conditions, it was required to assess the performance of different roads based on a comparable quantitative measure. In the present paper, this has been achieved through the development of *MCI*. The use of *MCI* for prioritisation of management actions for different urban roads has been discussed.

While estimating marginal congestions, it has been shown a congestion model explicitly accounts for the effects of traffic composition and volume level. Therefore, the effect of different types of vehicle on congestion at all traffic volumes could be estimated using a congestion model. However, it may be noted that measurements like marginal congestions, as obtained from congestions models, are essentially traffic engineering based measurements. Such measures are extremely useful, but are based on theoretical perspective. Therefore, alongwith such measures it is also necessary to consider relevant social and political issues before recommending traffic management measures like road pricing in mixed traffic operations. Finally, the present study is focused on a single road and network effects are not explicitly considered. It will be meaningful to consider the network effects while formulating recommendations.

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