SPEED-FLOW ANALYSIS FOR INTERRUPTED OVERSATURATED TRAFFIC FLOW WITH HETEROGENEOUS STRUCTURE FOR URBAN ROADS

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Abstract: Speed–flow functions have been developed by several transportation experts to predict accurately the speed of urban road network. HCM Speed-Flow Curve, BPR Curve, MTC Speed-Flow Curve, Akçelik Speed-Flow Curve are some extraordinary efforts to define the shape of speed-flow curve. However, the complexity of driver's behaviour, interactions among different type of vehicles, lateral clearance, co-relation of driver's psychology with vehicular characteristics and interdependence of various variables of traffic has led to continuous development and refinement of speed-flow curves. The problem gets more tedious in case of urban roads with heterogeneous traffic, oversaturated flow and signalized network (which includes some un-signalized intersections as well). This paper presents speed-flow analysis for urban roads with interrupted flow comprising of heterogeneous traffic. Model has been developed for heterogeneous traffic under constraints of roadway geometry, vehicle characteristics, driving behaviour and traffic controls. The model developed in this paper shall predict speed, delay, average queue and maximum queue estimates for urban roads and quantify congestion for oversaturated condition. The investigation details oversaturated portion of flow in particular.

Keywords: oversaturated flow, interrupted flow, traffic congestion, intersection, heterogeneous traffic, microscopic simulation, average delay time per vehicle, average speed, queue length, level of service (LOS).

1. Introduction

Traffic streams are described by three variables: density (k), speed (v), and flow (q), measured respectively in vehicles per lane per km, km per hour, and vehicles per lane per hour. At the macroscopic level, these variables are defined under stationary conditions at each point in space and time, and are related by the identity $q = k \times v$. Driver behaviour creates a second functional relationship between the three variables. Though studied for several decades; understanding about the shape of this curve continues to evolve. The precise shape on a given road segment depends on various factors. These include the number and width of traffic lanes, grade, road curvature, speed limit, location vis-à-vis entrance and exit ramps, weather, mix of vehicle types, proportion of drivers who are

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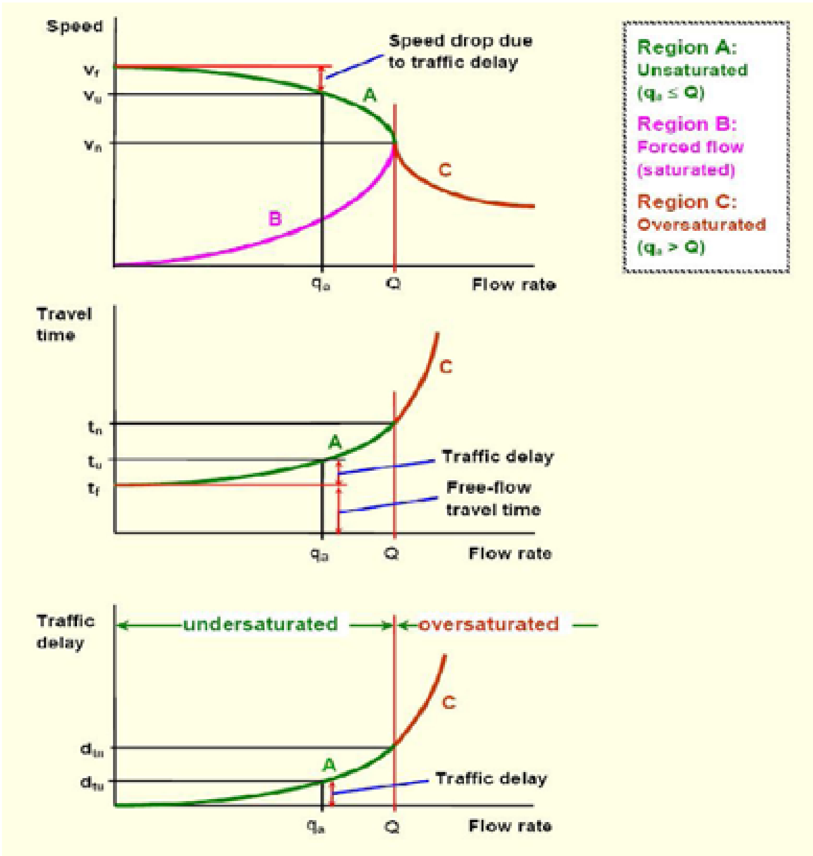

Fig. 1.
Speed, Travel Time and Delay as a Function of Flow Rate for Uninterrupted Traffic Streams
Source: Akçelik (2003)

familiar with the road, and idiosyncrasies of the local driving population (Lindsey et al., 1999; Akçelik, 2003; Dowling, 2004; Roux et al., 2002).

In Fig. 1 region A represents under-saturated conditions with arrival flows (q_a) below capacity ($q_a \leq Q$) which is associated with uninterrupted travel speeds. Uninterrupted travel speed at a given flow rate (v_u) is between v_f and v_n ($v_f \geq v_u \geq v_n$) where v_f is the free-flow speed and v_n is the speed at capacity. With increasing flow rate in Region A, speeds are reduced below the free-flow speed due to traffic delays resulting from interactions between vehicles. Region B represents the forced (congested) flow conditions with flow rates reduced below capacity ($q < Q$) which are associated with further reduced speeds ($v < v_n$) as observed at a reference point along the road. In this region, flow rates (q) are reduced flow rates due to forced flow conditions, not demand flow rates (q_a). Region C represents oversaturated conditions, i.e. arrival (demand) flow rates above capacity ($q_a > Q$) which are associated with reduced travel speeds ($v < v_n$) observed by travel through the total section, e.g. by an instrumented car. In this case, the flow represents the demand flow rate which can exceed the capacity value as measured at a point upstream of the queuing section (Akçelik, 2003).

The HCM classifies urban and suburban roads with signalised intersections spaced at less than 3 km as urban streets. The speed of vehicles on urban street is influenced mainly by street environment, vehicle interaction and traffic control. Flows may be classified as uninterrupted flows and interrupted flows. In uninterrupted flow, traffic flow condition results from interactions among vehicles in traffic stream between vehicles and the geometric and environmental characteristics of the roadway. These flows do not have external elements such as traffic signals which might interrupt the traffic flow. However, interrupted-flows have controlled and uncontrolled access points that can interrupt the traffic flow. These access points include traffic signals, stop signs, yield signs and other types of control that stop traffic periodically or slow it significantly, irrespective of amount of traffic (Transportation Research Board, 2001). So far, urban roads have not been the priority of researchers and investigations are more confined to freeways and highways. There is a need to further investigate the shape of speed-flow curves for the urban road scenario which comprises of heterogeneous traffic, interrupted flows and have demand more than volume (oversaturated condition) most of the times. An investigation of oversaturated flow is very much relevant for developing countries. This paper presents speed-flow curves, delay estimates, maximum queue and average queue estimates for a representative urban road network. The curve of congestion is also developed. Thus, speed, delay, maximum queue, average queue, congestion and capacity of urban roads can be calculated for these curves.

2. Simulation Model

The simulation tool used in this paper is VISSIM 5.3 (official license available). VISSIM uses the psycho-physical driver behaviour model developed by WIEDEMANN (Roux et al., 2002). The basic concept of this model is that the driver of a faster moving vehicle starts to decelerate as he reaches his individual perception threshold to a slower moving vehicle. Since he cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. This results in an iterative process of acceleration and deceleration. Stochastic distributions of speed and spacing thresholds replicate individual driver behaviour characteristics. VISSIM's traffic simulator not only allows drivers on multiple lane roadways to react to preceding vehicles, but also neighbouring vehicles on the adjacent travel lanes, are taken into account. Moreover, approaching a traffic signal results in a higher alertness for drivers at a distance of 100 m in front of the stop line. VISSIM simulates the traffic flow by moving "driver-vehicle-units" through a network. Every driver with his specific behaviour characteristics is assigned to a specific vehicle. As a consequence, the driving behaviour corresponds to the technical capabilities of his vehicle. Attributes characterizing each driver-vehicle-unit are: (1) technical specifications of the vehicle, e.g. length, maximum speed, potential acceleration, actual position in the network, actual speed and acceleration (2) behaviour of driver-vehicle-unit, e.g., psycho-physical sensitivity thresholds of the driver (ability to estimate, aggressiveness), memory of driver, acceleration based on current speed and driver's desired speed (3) interdependence of driver-vehicle-units, e.g. reference to leading and following vehicles on own and adjacent travel lanes, reference to current link and next intersection, reference to next traffic signal (PTV Vision, 2010).

3. Data Collection, Model Calibration and Validation

Jaipur city in India is chosen to study interrupted oversaturated flow as the city size, its roads, type of vehicles, mixed traffic and driver's aptitude represent most of the countries where this type of flow is a daily phenomenon. A representative network of urban road network, comprising of two signalized intersections and one un-signalized intersection in between, is decided to investigate speed-flow characteristics, delay, queues and congestion of urban roads. The VISSIM simulation snap shot is shown in Fig. 2. The study is conducted for this network as a whole so that curves for this network will provide a realistic estimate of traffic variables in urban road scenario.

The model construction procedure consists of (i) identification of important geometric features (ii) collection and processing of traffic data (iii) analysis of mainline data to identify recurring bottlenecks (iv) VISSIM coding (v) calibration based on observations from (iii). Calibration is the process by which individual components of simulation model are refined and adjusted so that simulation model accurately represents field measured or observed traffic conditions. With regard to calibration, traffic simulation model contain numerous variables to define and replicate traffic control operations, traffic flow characteristics and driver behaviour. VISSIM simulation model contains default values for each variable, but also allows a range

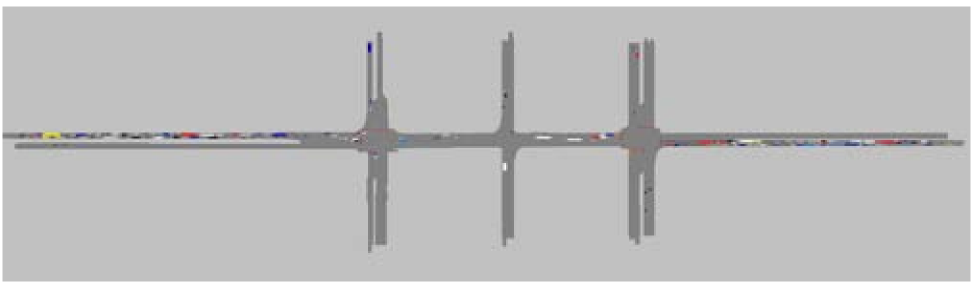

Fig. 2.
VISSIM Simulation Snap Shot

Table 1
Traffic Composition

Percentage of traffic composition (time: 08:00-20:00)					
Car/Jeep/ Taxi/SUV	Two wheeler	Three wheeler	Bus	HGV	Slow moving vehicle
37	41	11	5	1	5

of user applied values for each variable. These variables are changed as per field measurements and observed conditions (PTV Vision, 2010). The geometry of existing network from Danik Bhaskar intersection to JDA intersection on Jawahar Lal Nehru road (4-lane divided; with lane width 3.5 m) was created using links and connectors which are the building blocks of VISSIM network. The number of lanes per road and width of each lane, left turning lanes on each approach road, central median, traffic islands and other road features were specified as per existing. After creation of network, the vehicle input for various links was given. The traffic composition is given in Table 1. This is followed by specifying the various routes in which vehicles travelled and the volume of these vehicles in each route is specified. The other features viz. positioning of speed limits, conflict zones, stop signs, signal heads are specified as per existing. The data collection points, travel time sections, queue counters and nodes are placed. The Indian driving behaviour is calibrated for the following parameters: standstill longitudinal distance between the stopped vehicles, headway time in seconds, following variation which restricts the longitudinal oscillation and indicates how much more distance than desired distance a driver allows before he intentionally moves closer to vehicle in front, threshold for entering 'following' controlling the start of deceleration process, following threshold which controls the speed differences during the 'following' state, speed dependency of oscillation, oscillation acceleration, standstill acceleration, minimum headway, maximum deceleration of vehicle and trailing vehicle for lane change, overtaking characteristics, minimum lateral distance at different speeds, waiting time for diffusion. The vehicles are calibrated for desired speed distribution, weight distribution, power distribution and model distribution. The links are assigned behaviour according to driving behaviour. On Indian roads, because of heterogeneity of traffic, it is difficult to enforce lane discipline. Hence, vehicle occupies lateral positions on any part of road based on space availability, overtake within lane from both the sides.

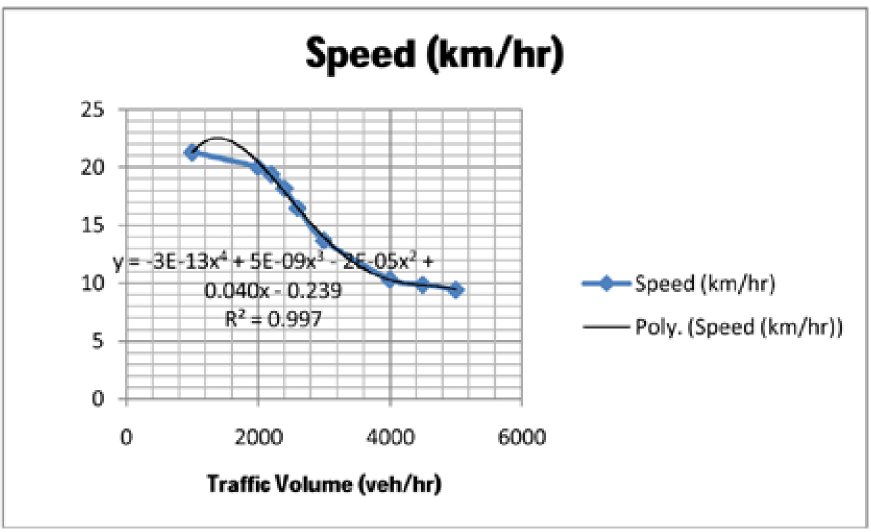

Fig. 3.
Speed-Flow Curve

The validation of the model was carried out by comparing maximum queue length simulated by model for existing intersection on each approach road with field observed values. The simulation model was given multirun with 20 random seed numbers and average of 20 simulation runs was taken as final output of the model. The value of t-statistic, calculated based on observed data (to) for all the four approach road on both the signalized intersections is below 2.00. The critical value of t-statics for level of significance of 0.05, at 19 degrees of freedom is 2.093. Thus, value of t-statistic, calculated on the basis of observed data, is less than the corresponding table value. This shows that there is no significant difference between the simulated and observed queue lengths.

4. Flow Curves for Interrupted Flow

The model validated as above is used to investigate the shape of speed-flow curve for varying volumes and estimating delay, maximum queue, average queue and congestion. The values shown are the average of 20 simulation runs with different random numbers so as to have reasonable results to conclude.

Fig. 3 shows the shape of Speed-Flow curve. The oversaturated portion of curve follows the equation (Eq. (1)):

$$Speed = -3E-13\,(Flow)^4 + 5E-09\,(Flow)^3 - 2E-05(Flow)^2 + 0.0404\,(Flow) - 0.2396 \quad (1)$$

The R^2 value is 0.9977. The capacity can be determined as the point where the oversaturated flow starts. The capacity corresponds to Level of Service (LOS) determined from delay as discussed in Fig 4.

Fig. 4 shows the shapes of delay-flow curve. The oversaturated portion of curve follows the equation given by Eq. (2):

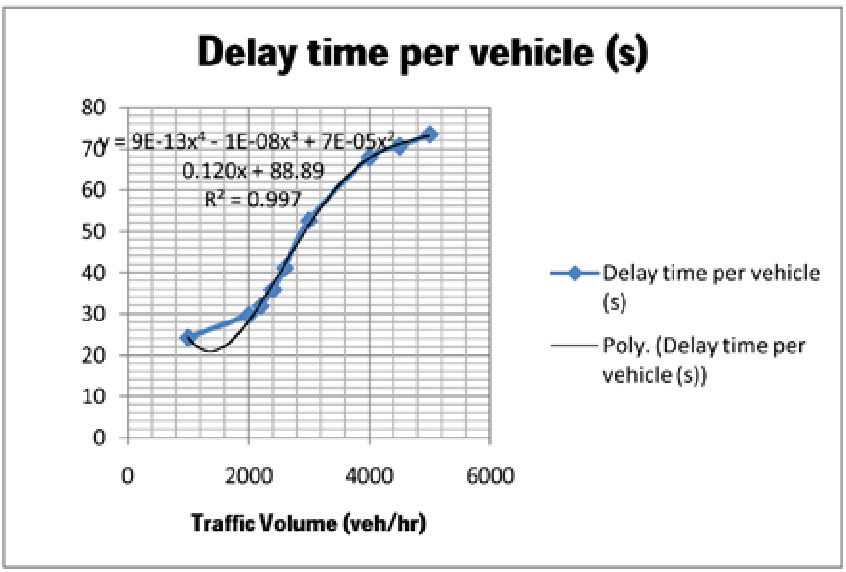

Fig. 4.
Delay-Flow Curve

Delay = 9E – 13 $(Flow)^4$ – 1E – 08 $(Flow)^3$ +7E – 05$(Flow)^2$ – 0.1206 (Flow) + 88.892 (2)

The R^2 value is 0.9977. The capacity can be determined from delay-flow curve as the point where oversaturated flow starts. It is corresponding to same point as that of speed-flow curve in Fig. 3.

Fig. 5 shows the shapes of average queue-flow curve. The oversaturated portion of curve follows the equation given in Eq. (3):

Average Queue = -2E – 09 $(Flow)^3$+2E – 05$(Flow)^2$ – 0.0396 (Flow) + 26.388 (3)

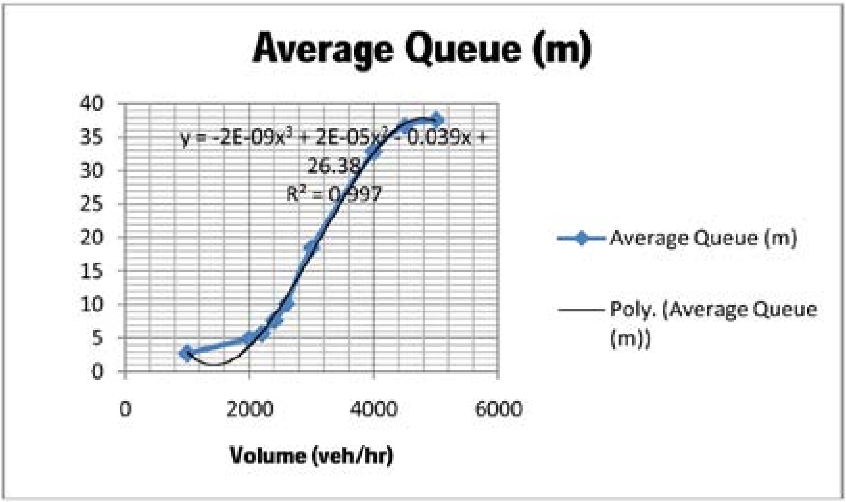

Fig. 5.
Average Queue-Flow Curve

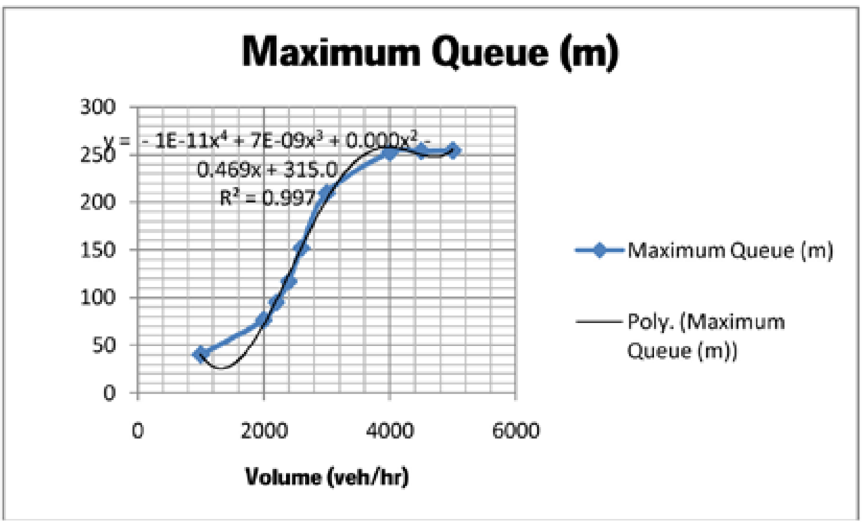

Fig. 6.
Maximum Queue-Flow Curve

The R^2 value is 0.9975. The capacity can be determined from average queue-flow curve as the point where oversaturated flow starts. It is corresponding to the same point as that of speed-flow curve in Fig. 3.

Fig. 6 shows the shapes of maximum queue-flow curve. The oversaturated portion of curve follows the equation given in Eq. (4):

$$\text{Maximum Queue} = 1E-15\,(\text{Flow})^5 - 1E-11\,(\text{Flow})^4 + 7E-09\,(\text{Flow})^3 + 0.0002(\text{Flow})^2 - 0.4698\,(\text{Flow}) + 315.05 \quad (4)$$

The R^2 value is 0.997. The capacity can be determined from maximum queue-flow curve as a point where oversaturated flow starts. It corresponds to the same point as that of speed-flow curve shown in Fig. 3.

The loss in freedom of movement can be measured as the area under the speed-flow envelope (between the free-flow operation and the actual operating condition), and the congestion is quantified as the percentage loss in freedom of movement under prevailing roadway, traffic, and control conditions (Maitra, 1999). Thus, the area under the Speed-Flow envelope between any two operating points on it represents loss in freedom of movement between these two traffic conditions, hence congestion. Similarly, congestion for oversaturated flow can be defined as loss in freedom of movement with respect to traffic condition prevailing at capacity to account for oversaturated state of flow.

Fig. 7 shows the congestion curve for oversaturated state. The congestion is quantified with respect to traffic condition at capacity. The curve may be given by the following equation (Eq. (5)):

$$\text{Congestion with respect to traffic condition at capacity} = 247.7\,(v/c)^2 - 461.1\,(v/c) + 212.9 \quad (5)$$

Here R^2 value is 0.999.

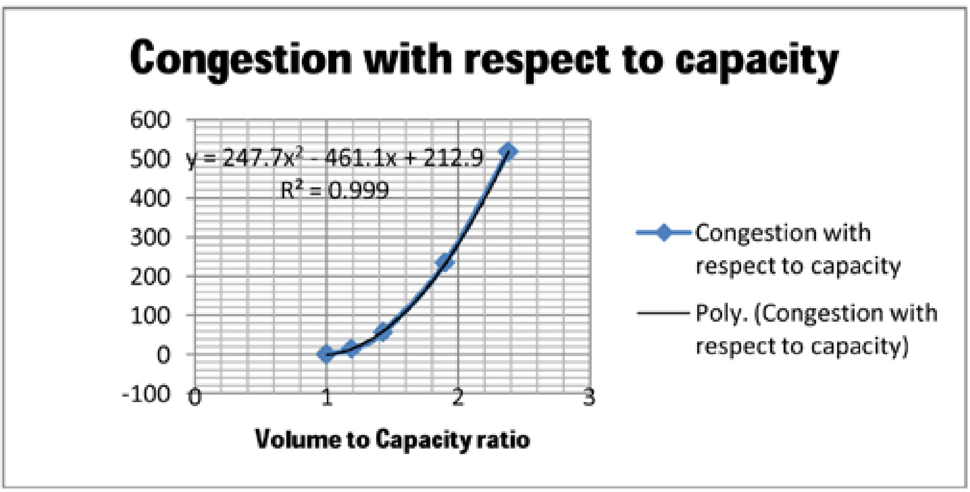

Fig. 7.
Congestion Curve for Oversaturated Flow

4.1 Comparison of Shape of Speed-Flow Curve with BPR, MTC, Updated BPR, and Akçelik Speed- Flow Functions

Fig. 8 shows Speed v/s Volume to Capacity ratio variation for results obtained in this paper and Fig. 9 shows BPR, MTC, Updated BPR, and Akçelik Speed-Flow functions for Arterials (Singh, 1999). The shape of Speed-Flow curve obtained resemble with updated BPR curve and hence in agreement with established theories. However, curve obtained in this paper predicts more realistically the performance of an urban network with heterogeneous traffic and interrupted flow.

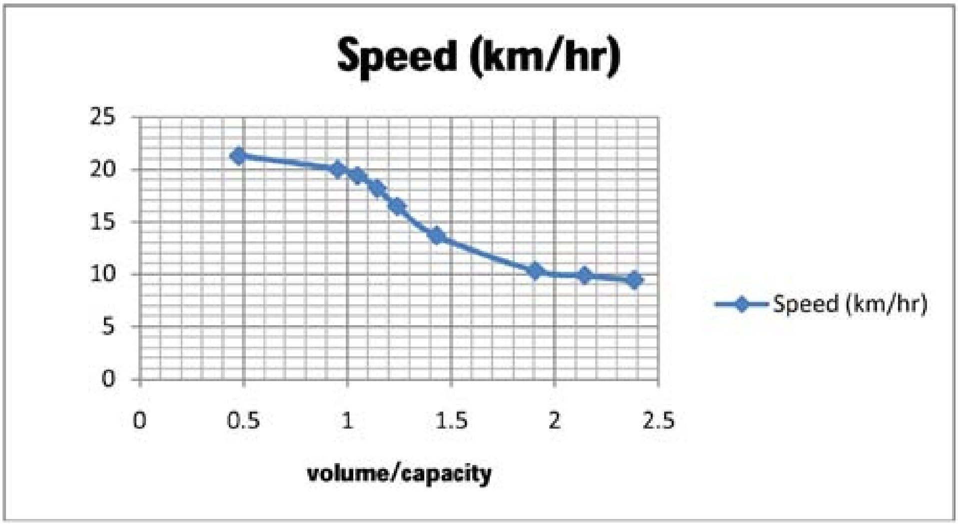

Fig. 8.
Speed v/s Volume to Capacity Ratio Curve

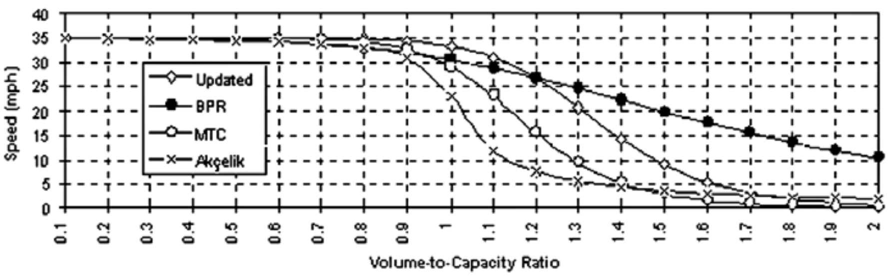

Fig. 9.
BPR, MTC, Updated BPR, and Akcelik Speed-Flow Functions for Un-Interrupted Flow for Arterials
Source: Singh (1999)

5. Conclusion

This paper presents speed-flow curves for urban roads with interrupted-oversaturated flow and heterogeneous traffic. The models developed in this paper predict speed, delay, average queue, maximum queue estimates with varying volume, for urban roads. The oversaturated portion of flow is investigated in detail and a congestion curve is also derived to quantify congestion. The model also predicts capacity which interestingly corresponds to all the measures of effectiveness (MOEs) investigated. The investigation and analysis presented in this paper gives more realistic values of speed, delay, queue, congestion and capacity as the investigation is based on total performance of network.

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ANALIZA FUNKCIJE "BRZINA-TOK" POVREMENO PREKINUTOG, FORSIRANOG SAOBRAĆAJNOG TOKA NEHOMOGENE STRUKTURE ZA GRADSKE SAOBRAĆAJNICE

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Sažetak: Funkcije "brzina-tok" definisane su od strane više eksperata iz oblasti saobraćaja sa ciljem preciznog predviđanja brzine na gradskoj putnoj mreži. HCM "brzina-tok" kriva, BPR kriva, MTC "brzina-tok" kriva, Akçelik "brzina-tok" kriva, predstavljaju pokušaje određivanja funkcionalne zavisnosti brzine i protoka vozila. Međutim, složenost ponašanja vozača, interakcija među različitim kategorijama vozila, udaljenost bočnih smetnji, povezanost ponašanja vozača sa karakteristikama vozila i međuzavisnost različitih promenljivih veličina saobraćajnog toka doveli su do stalnog unapređivanja i usavršavanja kriva "brzina-tok". Problem postaje složeniji u slučaju gradskih saobraćajnica sa nehomogenim, forsiranim tokom i putnom mrežom sa signalizacijom (koja takođe obuhvata pojedine nesignalisane raskrsnice). Ovaj rad prikazuje analizu funkcije "brzina-tok" za gradske saobraćajnice sa povremeno prekinutim tokom nehomogene strukture. Model je razvijen imajući u vidu geometriju kolovoza, karakteristike vozila, ponašanje vozača i regulisanje saobraćaja. Model koji je nastao u ovom radu predvideće brzinu, vremenske gubitke, daće procenu prosečne i najduže kolone u slučaju gradskih saobraćajnica i odrediće stepen zagušenja u uslovima forsiranog toka. Istraživanje se posebno odnosi na deo forsiranog toka.

Ključne reči: forsirani tok, povremeno prekinuti tok, zagušenje saobraćaja, raskrsnica, nehomogeni saobraćaj, mikroskopska simulacija, prosečni vremenski gubici po vozilu, prosečna brzina, dužina kolone, nivo usluge.