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Congestion Characteristics of Interrupted Flow for Urban Roads with Heterogeneous Traffic Structure

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Abstract. Traffic congestion is a severe trepidation to transportation engineers for its unrestrained growth and consequential losses. This paper presents congestion models and speed-flow analysis for urban roads with interrupted flow comprising of heterogeneous structure of traffic. Models have been developed for heterogeneous traffic under constraints of roadway geometry, vehicle characteristics, driving behaviour and traffic controls. The growth of congestion with flow in unsaturated and oversaturated states of flow has been analysed and quantified. The congestion model developed in this paper shows that there exist different regions of congestion- flow behaviour that can be characterized by different rate of change of congestion and the severity of congestion becomes tremendous for oversaturated flows. Different levels of service have been proposed to define operating conditions using more realistic parameter 'congestion'.

1 Introduction

Traffic congestion is one of the main liabilities of present time [1]. It occurs when the cost of travel is increased by the presence of other vehicles, either because speed falls or because greater attention is required to drive safely [2]. It is a price that people pay for the different benefits derived from agglomeration of population and economic activity. Since the land is scarce and road capacity is costly to construct, it would be uneconomical to spend heavily to increase capacity to the extent that travel become congestion-free. Since demand for travel depends on the cost, improvements in travel conditions induce people to take more trips, and it would probably be impossible to eliminate congestion [3]. Traffic engineers often compare traffic with fluid, assuming that certain volume must flow through the road system. But urban traffic may be more comparable to a gas that expands to fill available space [4]. Congestion can be defined as traffic condition caused by a downstream bottleneck, or increase in travel time compared to low traffic conditions. The selection of congestion performance indicators and data collection techniques must be carefully coordinated with the definition adopted to capture the true nature of congestion [5].

Transportation researchers have long struggled to find satisfactory ways to describe and analyse congestion, as evident from the large number of often competing approaches and models that have been developed. Early researchers developed models based on fluid dynamics, but congestion, unlike fluid flow, is not a purely physical phenomenon but rather the result of people's trip-making decisions and minute-by-minute driving behaviour. One should therefore expect the quantitative and qualitative, characteristics of congestion to vary with automobile and road design, rules of the road, pace of life, and other factors. Efforts have been made by many researchers to understand and quantify congestion, however, it is found that most of the works have been concentrated on the area wise quantification of congestion i.e., Congestion Severity Index [6], Roadway Congestion Index [1], Percentage of Congested Freeway [1], K-Factor [1], Lane Mile Duration Index, Freeway Congestion Index [7].

Models calibrated and validated in a developed country may not fit well a developing country for the difference in traffic conditions [2].

1.1 Quantification of congestion

The level of congestion varies with roadway, traffic control conditions, and operating traffic volume. While majority of studies regarding congestion are based on highways, quantification of congestion on urban roads has been attempted by several researchers [8-11]. Since, 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), the congestion can be quantified as the percentage loss in freedom of movement under prevailing roadway, traffic, and control conditions [12].

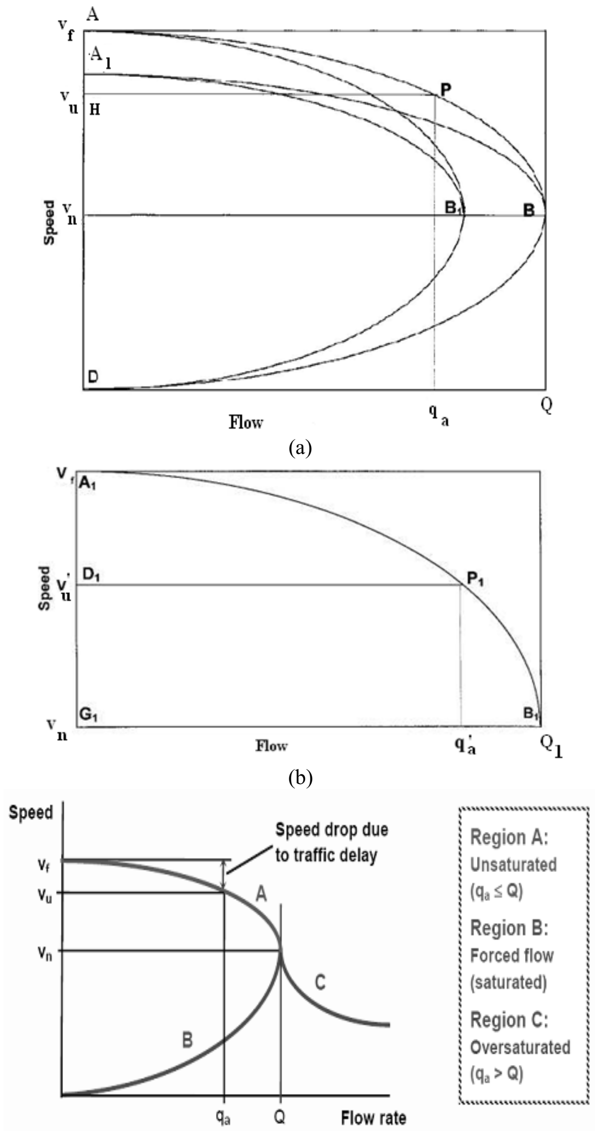
Fig. 1 (a) and 1 (b) represents quantification of congestion proposed by [12]. Although, the worst operating condition represented by point D (*Figure 1a*) normally be defined as 100% congestion; the behaviour of midblock traffic is seldom observed in the range BD (the lower portion of speed-flow envelope). Therefore, point B (i.e., the capacity) should be taken as traffic condition representing 100% congestion. With the capacity as 100% congested operation, the generality of the philosophy of quantification of congestion remains valid, and when the lower envelope or a part of it is observed, it will be representing forced flow with the quantified congestion more than 100%. Therefore, in that case, a point near the capacity in the stable flow zone may be taken to represent 100% congestion. In *Figure 1(b)* Point A_1 represents the operation with free-flow speed v_f, whereas point B_1 represents a 100% congested operation in the stable flow zone with a realized speed v_n and volume level Q_1. Therefore, 100% congested operation represented by point B_1 indicates an amount of loss in freedom of movement equivalent to an area $A_1B_1G_1$ under the envelope. Similarly, the amount of loss in freedom of movement for an operating point P_1, represented by a flow level q_a', and realized speed v_u' under the same operating conditions, can be expressed as the area $A_1P_1D_1$. Consequently, congestion at operating point P_1 can be expressed as (Area $A_1P_1D_1$/ Area $A_1B_1G_1$)*100 (Maitra *et al.,* 1999).

1.2 Unsaturated, saturated and oversaturated flows

In Fig. 1 (c) region A represents under- saturated conditions with arrival flows (q_a) below capacity ($q_a \le Q$). Travel speed at a given flow rate (v_u) is between v_f and v_n ($v_f \ge v_u \ge v_n$) 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 [13-14].

1.2.1 Interrupted traffic flow

Flows may be further 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 [15].



(c)

Figure 1. Representation of quantification of congestion (a) Unsaturated and saturated flow (b) Unsaturated flow (c) Unsaturated, Saturated and Oversaturated Flows.

1.3 Level of Service (LOS) based on congestion

LOS has also been defined by several researchers based on quantified congestion. Since quantified congestion is a measure of loss in freedom of movement that accounts for the variation of speed level with increase in traffic volume (along with its character) under prevailing roadway, traffic, and control conditions, the congestion level is a logical and better measure of effectiveness (MOE) to define LOS in a quantitative manner.

The degradation of quality of operation and increase in congestion level due to traffic volume is not uniform at all flow levels. To represent the variation of level of service through congestion in a complete manner, 10 different levels of service have been proposed by researchers with congestion levels of 5, 10, 20, 30, 40, 50, 60, 80, and 100%; distinguishing nine LOS (A – I) within the stable flow zone, and one LOS (J) with congestion more than 100%, indicating the unstable (forced) flow. The limiting values of congestion for different LOS are stated to be consistent with the usual shape of the speed-flow curve with a relatively lesser speed drop near free-flow operation and sharp drop near the capacity flow. The service volumes are governed by congestion levels, and therefore, any change in prevailing roadway, traffic, and control conditions would normally be reflected by the changes in service volumes corresponding to various levels of service [12].

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 [16]. 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 meters 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 [16].

3 Data collection, model calibration and validation

Jaipur city in India is chosen to investigate interrupted heterogeneous flow as the city size, its roads, type of vehicles, mixed traffic and driver's aptitude represent most of the developing countries where interrupted, heterogeneous and oversaturated flow is a daily phenomenon. A representative network of urban road network, comprising of two signalized intersections (label 1&5 in *Fig 2*), one un-signalized rotary intersection in between (label 4 in *Fig 2*) and two minor T-junctions (label 2&3 in *Fig2*) was decided to explore speed-flow and congestion characteristics of urban roads. The total length of the representative network was 4 km; it was neither too long nor too short and is a reasonable distance to have preciseness of results incorporating elements of bigger network. 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 simulation 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 of user applied values for each variable. These variables are changed as per field measurements and observed conditions [16].

The geometry of existing network from Danik Bhaskar intersection to JDA intersection on Jawahar Lal Nehru road (4-lane divided with lane width 3.5m) 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 heterogeneous with Car/Jeep/Taxi/SUV :37%; Two wheeler : 41%; Three wheeler :11%; Bus : 5%; HGV :1%; Slow moving vehicle : 5% (traffic data for time : 08:00-20:00 on February 28, 2012). 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 roads of most of the developing countries including India, 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. The validation of the model was carried out by comparing maximum queue length simulated by model for existing intersections on each approach road with field observed values. The simulation model was given multi-run 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.

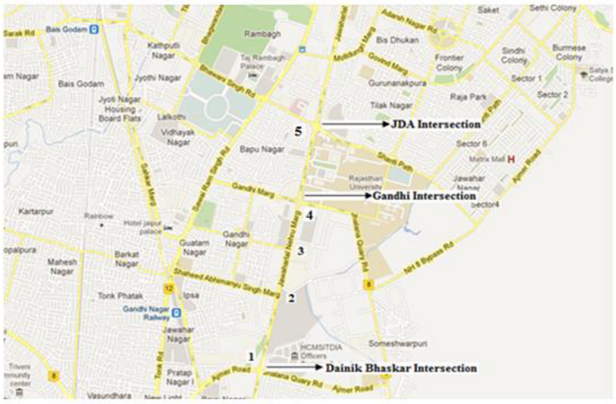


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Figure 2. The representative network for study from dainik bhaskar intersection to JDA intersection

4 Estimation of congestion

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

4.1 Speed–flow curves and determination of capacity

Fig. 3(a), 3 (b) and 3 (c) shows the shape of Speed-Flow curve. The oversaturated portion of curve (Fig. 3 a) follows the equation (1)

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

The R^2 value is 0.9977.

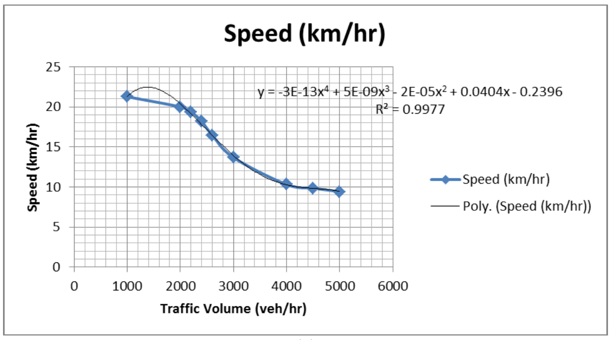
In order to do detailing of Speed-Flow curve for unsaturated part of flow, investigations are carried out to explore it with more flows values up to capacity. Fig. 3 (b) shows the shape of Speed-Flow curve for unsaturated condition. The unsaturated portion of curve follows the equation (2).

$$\text{Speed} = -2E\text{-}12(\text{Flow})^4 + 1E\text{-}08(\text{Flow})^3 - 4E\text{-}05(\text{Flow})^2 + 0.039(\text{Flow}) + 6.162 \qquad (2)$$

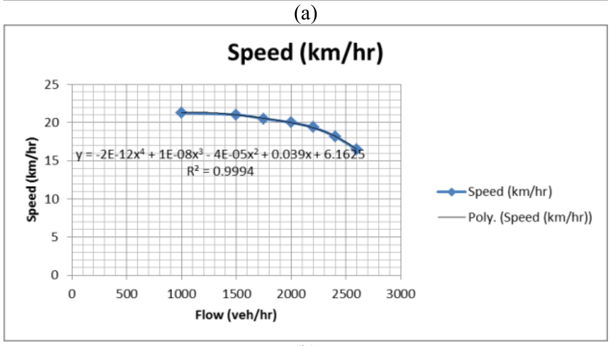
$R^2 = 0.999$

Since the oversaturated flow starts where unsaturated flow ends, the capacity may be defined as the point of intersection of these two curves i.e., curves defined by (1) and (2) respectively. In this case the capacity is 2200 veh/hr.

Fig. 3 (c) shows the consolidated Speed-(v/c) curve for unsaturated as well as oversaturated states of interrupted flow.



(a)



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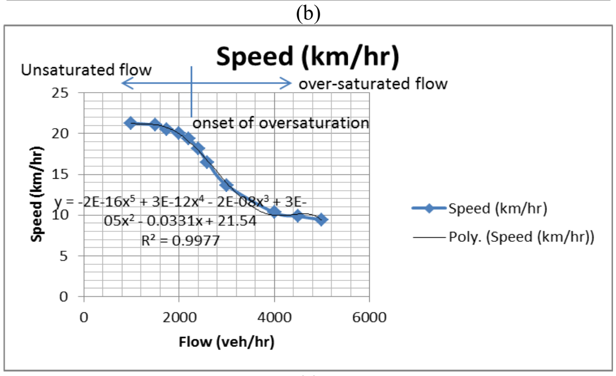

(c)

Figure 3. Speed-Flow Curve (a) oversaturated details (b) unsaturated details (c) consolidated curve.

4.2 Model for congestion

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.

4.2.1 Congestion for unsaturated flow conditions

For unsaturated flow condition congestion curve is shown in Fig. 4. The equation of curve is given by *equation (3)*. Here the congestion value at capacity is taken as 100%.

$$\text{Congestion (\%)} = 415.54(v/c)^5 - 696.94(v/c)^4 + 600.07(v/c)^3 - 277.49(v/c)^2 + 64.623(v/c) - 5.8154 \quad (3)$$

$R^2 = 1$

The curve follows fifth order polynomial as given by equation (3).

The Fig. 4 Shows that within under-saturated condition of flow the congestion starts visibly growing up at v/c approximately equal to 0.5. The rate of congestion becomes tremendous after v/c ratio 0.8 and achieves full congestion at capacity. Congestion which is merely 25% at v/c ratio 0.8 increases four times at capacity and becomes 100%.

4.2.2 Congestion in over-saturated condition of flow

Fig. 5 shows the congestion curve for oversaturated state. The congestion is quantified with respect to traffic condition at capacity. Here, in order to demonstrate a clear depiction of congestion of oversaturated flow with respect to traffic condition at capacity, congestion at a point near capacity is taken as zero and a new term congestion ratio is defined similar to v/c i.e., (congestion at v/ congestion at c). The curve may be given by the following *equation (4)*:

$$\text{Ratio of Congestion at a flow to congestion at capacity} = 247.7 (v/c)^2 – 461.1 (v/c) + 212.9 \quad (4)$$

Here R^2 value is 0.999.

Here, ordinate represents ratio of congestion at an operating point and congestion at capacity while abscissa represents volume to capacity ratio.

4.2.3 Overall congestion scenario

If congestion is plotted for both unsaturated and oversaturated flows, taking congestion at capacity as 100%, the congestion characteristics shows that rate of built up congestion up to capacity is with slower rate which increases significantly after capacity. The consolidated congestion curve for both unsaturated and over-saturated condition is shown in Fig. 6.

$$\text{Congestion (\%)} = -4884.2(v/c)^4 + 31093(v/c)^3 - 46704(v/c)^2 + 24182(v/c) - 3659.7 \quad (5)$$

$R^2 = 0.9998$

Equation (5) represents the total congestion curve. Equation (3) and (4) can be used for precise calculation in unsaturated and over-saturated condition respectively, while equation (5) represents overall scenario. It can be seen that at v/c ratio 1.25, congestion is 20 times that of capacity; at v/c ratio 1.5, congestion grows by 80 times of value at capacity. Beyond v/c ratio 1.5 the traffic condition deteriorates severely and at v/c ratio 2.0, congestion becomes 300 times while at v/c ratio 2.4 it becomes 520 times that of value at capacity. Since, any change in prevailing roadway, traffic, and control conditions gets reflected by the changes in service volumes and the service volumes corresponding to various levels of service are governed by congestion levels, the level of service (LOS) may be redefined based on congestion levels. LOS may be defined for a network with interrupted heterogeneous flow, separately for under-saturated flow and oversaturated flow. For under-saturated flow proposed LOS (A-E) may correspond to congestion level (0.05, 0.10, 0.30, 0.50, and 1.00) and for oversaturated flow LOS (I-L) may correspond to (20, 60, 300 and beyond). These levels correspond to congestion curve.

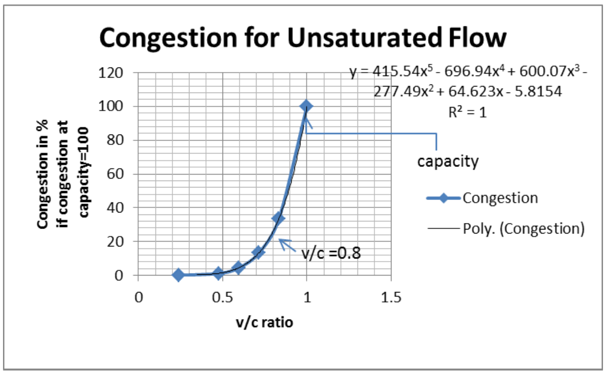

Figure 4. Congestion Curve (detailing for un-saturated flow).

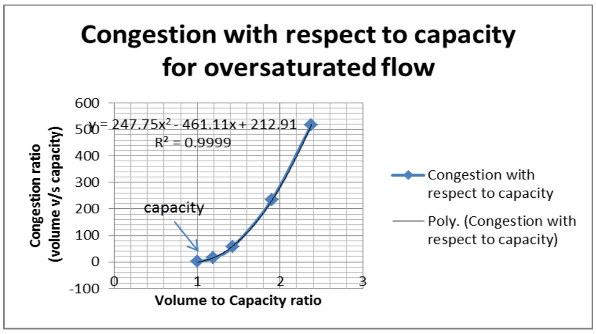

Figure 5. Congestion curve for oversaturated flow.

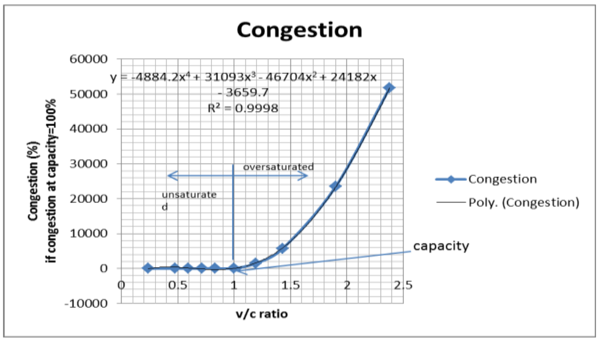

Figure 6. Congestion Curve (un-saturated and oversaturated flow combined).

5 Conclusion

This paper presents speed-flow and congestion-flow curves for urban roads observing interrupted flow with heterogeneous structure of traffic. The models are developed for speed-flow in unsaturated and oversaturated flow conditions under constraints of roadway geometry, vehicle characteristics, driving behaviour and traffic controls. The capacity of road is determined as the point of intersection of Speed-Flow curve for oversaturated flow and Speed-Flow curve for unsaturated flow. The speed-flow curves are used to quantify congestion and models are developed for congestion in unsaturated state and oversaturated state. The onset of congestion, its growth with flow and its behaviour in unsaturated flow as well as oversaturated flow is analysed. It has been found that within under-saturated condition of flow the congestion starts visibly growing up at v/c approximately equal to 0.5; rate of congestion becomes tremendous after v/c ratio 0.8 and achieves full congestion at capacity. Congestion which is merely 25% at v/c ratio 0.8 increases four times at capacity and becomes 100%. In oversaturated condition of flow, at v/c ratio 1.25, congestion is 20 times that of capacity; at v/c ratio 1.5, congestion grows by 80 times of value at capacity. Beyond v/c ratio 1.5 the traffic condition deteriorates severely and at v/c ratio 2.0, congestion becomes 300 times while at v/c ratio 2.4 it becomes 520 times that of value at capacity. The investigation and analysis presented in this paper gives more realistic values of speed, capacity and congestion as the investigation is based on total performance of network and the model captures both operational characteristics as well as volume characteristics of interrupted heterogeneous flow through simulations.

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