Queue Discharge Characteristics at Signalised Intersections Under Mixed Traffic Conditions

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Abstract

The evaluation of capacity at signalized intersection is an important component in the planning, design, operation and management of transportation system. Presently, the methodologies available for the estimation of capacity of signalised intersections are based on the concept of saturation flow (s). The study describes the headway, speed, and acceleration characteristics of vehicles during queue discharge after green onset under mixed traffic condition. For the present work data were collected at different signalized intersections in the city of Bhubaneswar, India under mixed traffic conditions. It has been found that the queue discharge headways shows an unmistakable pattern of gradual compression as queuing vehicles are discharged in succession. In this paper the speed at which the vehicles move during queue discharge for three different categories of vehicles (2-wheeler, 3-wheeler, and car) are also analysed. The acceleration characteristics of different category of vehicles released from stop after the green onset are also analysed in this paper and are explained by the non-uniform acceleration model in the form of $(dv/dt) = \alpha - \beta v$. The average values of α and β for different category of vehicles are estimated.

Keywords: Saturation flow, signalised intersection, saturation flow region, Non uniform acceleration, clearing speed.

1. Introduction

The assessment of performance of signalised intersections often require the determination of capacity of approach lane or lane group, the intersection clearing speed of queued vehicle and the acceleration characteristics of vehicles during queue discharge. The fundamental element of a signalised intersection is the periodic stopping and starting of the traffic stream. When a signal turns green from red, first of the stopped vehicles (1st vehicle of the queue) starts to move and cross the intersection. Then, the second vehicle in the queue and so on. As the queue of vehicles moves the headway measurements with respect to a fixed point or line (say STOP line) are taken. If many queues of vehicles are observed at a given intersection and the average headway is determined, and this average headway tend towards a constant value. Greenshields (1935) found that the average discharge headways become constant after the first three or four vehicles.

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The intersection clearing speed is the average speed of individual category of queued vehicles when the vehicles clear the intersection (upstream to downstream) during queue discharge. Highway Capacity Manual, a number of signal optimization models, and a number of traffic simulation models.

The constant headway achieved is referred to as the saturation headway (h_s) because it is the average headway that can be achieved by a saturated, stable moving Speed of vehicles indicates the quality of service experienced by motorists. In a mixed traffic situation of the type prevailing in India, speed is considerably influenced by composition of traffic stream (Mehar et al. 2013). The clearing speed is measured to characterize the efficiency of the intersection. When the vehicles start to move after the green onset, the vehicles start accelerating. Acceleration characteristics in standstill condition, during overtaking, lane-changing, car-following and under free-flow traffic condition are important in simulation studies also (Dey et al., 2008). The acceleration characteristics of individual category of vehicles help to assess the operating cost, fuel consumption and pollution emissions, as well as for determining geometric, stopped and queuing components of overall delay and it is a key issue in relation to the accuracy of simulation models. Danielis and Chiabai estimated the cost of air pollution from road transport in Italy. Danielis and Rotaris (2000) studied on pollution in Italy. The present study was undertaken with the following objectives:

1. To study the headway characteristics of vehicles during queue discharge and to determine the saturation headway (h_s) and the region of saturation flow in mixed traffic conditions;
2. To study the intersection clearing speed of vehicles corresponding to the different position of vehicles in the queue;
3. To study the acceleration characteristics of three predominant category of vehicles and to establish a relation between the acceleration rate and the speed for individual category of vehicles.

Traffic scenario in India

India is a vast developing country and a home to around 1.3 billion people with wide range of income gap. The roads of India are a perfect example of the prevailing economic disparity and vehicles like motorcycle, auto rickshaw (motorised three wheelers), bus, truck, SUV (sports utility vehicle), moped, bicycle, manual carts can be seen sharing the same road space with advanced German cars. Table 1 shows the composition of different types of vehicles in India.

Table1: Vehicle size and sales characteristics

Vehicle Type	*Domestic Market Share*	*Length (m)*	*Width(m)*
Passenger vehicles	15.07	3.65	1.50
Commercial Vehicles	4.66	10.10	2.45
Three Wheelers	2.95	2.60	1.25
Two Wheelers	77.32	1.85	0.70

*Association of Indian Automobiles Association (2011 - 12)

As presented in Table 1, the two-wheeler vehicle is predominant and significantly smaller in size than other types of vehicles.

Problems of mixed traffic

Heterogeneous or mixed traffic systems operate very differently, compared to homogeneous traffic systems. The traffic in mixed flow is comprised of fast moving and slow moving vehicles or motorized and non-motorized vehicles. The vehicles also vary in size, manoeuvrability, control, and static and dynamic characteristics. Traffic is not segregated by vehicle type and therefore, all vehicles travel in the same right of way. Smaller size vehicles often squeeze through any available gap between large size vehicles and move in a haphazard manner.

2. Queue Discharge Characteristics

2.1 Headway Characteristics

To determine accurate saturation flow rates, start-up lost time needs to be understood and taken into account. The principle of start-up lost time (Bester and Varndell, 2002) can be described as follows:

When the signal at an intersection turns green, the vehicles in the queue will start moving. The vehicle headways can now be described as the time elapsed between successive vehicles crossing the stop line. The first headway will be the time taken until the first vehicle's rear wheels cross the stop line from the light turns green. The second headway will be the time taken between the crossings of the first vehicle's rear wheels until the crossing of the second vehicle's rear wheels over the stop line and so on. In general, the headway value corresponding to the i^{th} vehicle gives the headway between the i^{th} and $(i-1)^{th}$ vehicle. The first driver in the queue needs to observe and react to the signal change at the start of green time. After the observation, the driver accelerates through the intersection from stand-still which results in a relatively long first headway. The second driver performs the same process with the exception that the driver could react and start accelerating whilst the first vehicle began moving. This results in a shorter headway than the first, because the driver had an extra vehicle length in which to accelerate. This process carries through with all following vehicles where each vehicle's headway will be slightly shorter than the preceding vehicle. This continues until a certain number of vehicles have crossed the intersection and start-up reaction and acceleration no longer have an effect on the headways. From this point headways will remain relatively constant until all vehicles in the queue have crossed the intersection or green time has ended. This constant headway is known as the saturation headway and can start to occur anywhere between the third and sixth vehicle in the queue (bester and Meyers, 2007). Figure 1 illustrates the situation described above.

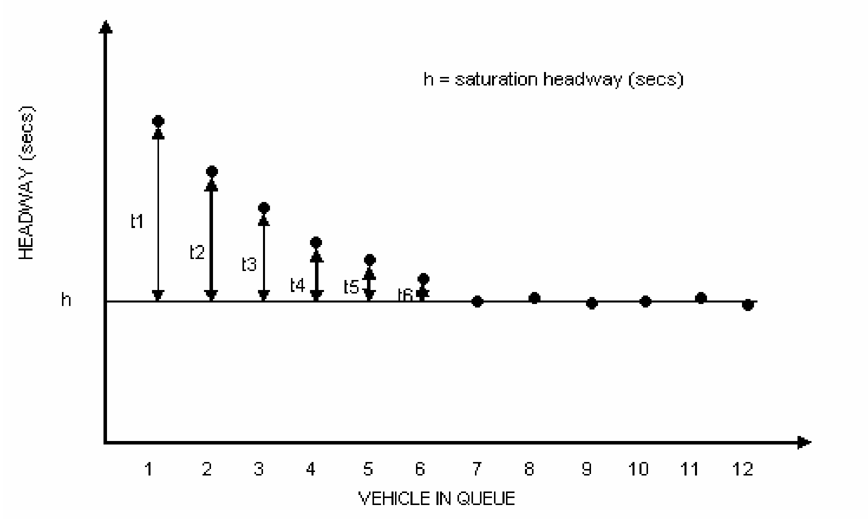

Figure 1: Headways at a traffic interruption

To calculate the saturation headway from the above example in Figure 1 the following equation will be used:

$$h_s = \frac{\sum_{j=n}^{l} (h_j)}{(l-n+1)} = \frac{(h_7+h_8+h_9+h_{10}+h_{11}+h_{12})}{(12+1-7)} \quad (1)$$

h_s = saturation headway, s
h_j = discharge headway of j^{th} queued vehicle, s
n = position of queued vehicle from where saturation flow region started
l = last queued vehicle position

This saturation headway (h_s) can be used to determine the maximum number of vehicles that can be released during a specified green time and also to determine the saturation flow rate, s= 3600/ h_s. The saturation flow rate (s) is an important parameter for estimating the performance of vehicular movement at signalised intersections. Saturation flow rate for a lane group is a direct function of vehicle speed and separation distance. The established concept for the determination of capacity demands the concept of saturation flow (Alcelik-1982; HCM; Teply et al. 1995). On the basis of saturation flow, the capacity of a traffic lane or lane group is determined in HCM as follows:

$$c = s\frac{G+Y-L}{C} \quad (2)$$

Where,
c = capacity of a lane or lane group (vehicles per hour, vph)
s = saturation flow (vph of effective green time)
C = cycle length (s)
G = green interval (s)
Y = signal change or intergreen interval (s)
L = loss time in a single phase resulting from start-up delays and signal change from green interval to yellow warning interval (s)

The above equation is a convenient tool for the capacity estimation of signalised intersection. Its reliability, however, depends on whether the queue discharge rate would quickly reach a steady or the discharge headway becomes steady after green onset.

Saturation flow rate

Saturation flow is a macro performance measure of junction operation. It is an indication of the potential capacity of a junction when operating under ideal conditions (no gradient, no parking or bus stops near the intersection, no pedestrians or cyclists etc.). However, to determine the saturation flow rate from time measurements taken in the field the following equation is used:

$$s = \frac{3600}{h_s} \tag{3}$$

Where: s = saturation flow rate;
3600 = number of seconds per hour;
h_s = saturation headway.

Various factors can influence traffic behaviour and in turn the saturation flow rates. The following factors play a role:

- *Traffic composition and type of traffic mix* (homogeneous or mixed traffic)
- *Vehicle type*- A multitude of different types of vehicles having different static and dynamic characteristics
- *Driver behaviour* - lane discipline and regard towards the traffic signals;
- *Public transport* – different mix of bus types, frequency, stopping places and driving styles
- *Roadside activity* - roadside land uses generate parking and non-transport activities that reduce effective lane width
- *Pedestrians and cyclists*

2.2 Intersection Clearing Speed of Vehicles

Intersection clearing speed of queued vehicles is the average speed at which a queue traverses an intersection (from the upstream to the downstream). The intersection clearing speed of vehicles is helpful in judging the efficiency of an intersection. The general trend is that more the clearing speed during queue discharge, more is the capacity of intersection. Clearing speed is affected by many factors. In a country like India where heterogeneous traffic conditions are present, the clearing speed of slow moving vehicle will have an effect on fast moving vehicle. And also, the presence of any slow moving vehicle in the queue affects the speed of other following vehicles during queue discharge. Thus, the clearing speed does not vary significantly by category of vehicles. So it will depend on the speed and acceleration characteristics of leading vehicle. The clearing speeds are not affected by any downstream conditions. The understanding in clearing speed with queue position is required to judge the performance of the signalised intersection after the green signal light allocation. When the queue is waiting to move from rest at the start of green, the leading vehicle in the queue will take maximum time to cross the intersection due to the increased perception-reaction time by the driver and also due to start-up lost time by the initial vehicles in the queue. And as the queue position increase the perception-reaction time of the driver and the start-up lost time will gradually decrease. Therefore, the clearing speed will initially be low and will increase gradually to a more or less constant value (at the moment perception-reaction time and start-up lost time has reached a minimum value).

2.3 Acceleration Characteristics of Vehicles

Information of vehicle acceleration is required in computing the fuel economy and travel time values, and in estimating how a normal traffic movement is resumed after a breakdown in traffic flow patterns. Vehicle acceleration characteristics depend upon the type of vehicle, its size and weight and the engine power to propel it. Most passenger car motorists, however, routinely utilize only a portion of the maximum acceleration of which their vehicles are capable. For some situations, average acceleration rates may be applicable. Observations of vehicles in motion supports the concepts that the maximum vehicle acceleration occurs when starting from the rest, the ability to accelerate attenuates with higher vehicle speeds, and there is some maximum speed beyond which a vehicle cannot accelerate further, as implied by the linear conceptualization of acceleration. This is not generally possible when a vehicle is moving at moderate or high speeds. It is due to the maximum accelerating force being available from rest, and that force can exceed the tractive force provided by the friction between the tires of the drive wheels and the pavement.

Basic factors influencing acceleration performance

The acceleration characteristic of vehicles depends upon the difference between the power available from the engine and the power required to overcome resistance to motion. An interpretation of the implications of constant torque is fundamental for understanding the relationship between vehicle speed and acceleration capability. To first approximation engine power is the product of propulsive force and speed, i.e.

$$P_e = F_p * V \tag{4}$$

Where, P_e is power, F_p is propulsive force, and V is forward velocity.
Second, force equals mass times acceleration,

$$F=MA \tag{5}$$

Where F is force, M is mass, and A is acceleration
At the beginning of this development, ignore any natural retardation such that $F=F_p$.
By combining equations (4) and (5) with $F_p= F$, the following result is obtained:

$$A = \frac{1}{V}\left(\frac{P}{M}\right) \tag{6}$$

Equation (6) shows that the maximum upper bound on acceleration falls off (decreases) in a manner that is inversely proportional to the forward speed of a vehicle.

Equations for linearly decreasing acceleration

Vehicle acceleration achieved by vehicles while accelerating from stop or from a lower initial speed to a higher speed is not constant, but varies inversely with the speed of vehicle. It decreases from an initial high value to zero as the desired speed of the vehicle is achieved. The linearly decreasing acceleration model can be written as a differential equation and integrated to derive the following relationships.

$$\frac{dv}{dt} = \alpha - \beta v \tag{7}$$

Where, α is the maximum acceleration and β is the rate of change in acceleration with speed of vehicle. The speed-time and distance-time relationships are developed by integrating the Equation (7). If the speed of the vehicle is v_0 at time t=0, then $\int_{v_0}^{v} \frac{dv}{\alpha - \beta v} = \int_0^t dt$. From which

$$v = \frac{\alpha}{\beta}\left(1 - e^{-\beta t}\right) + v_0 e^{-\beta t} \tag{8}$$

Again, substituting *dx/dt* for *v* and integration of the Equation (8) gives the distance-timerelationship as given by equation (9)

$$x = \frac{\alpha}{\beta}t - \frac{\alpha}{\beta^2}\left(1 - e^{-\beta t}\right) + \frac{v_0}{\beta}\left(1 - e^{-\beta t}\right) \tag{9}$$

Where, x is the distance traveled by the vehicle in time period t. If the vehicle is starting from rest, v_0 is equal to zero. The rate of acceleration becomes zero as the drives achieve its desired speed. Therefore, the maximum attainable speed (v_{max}) is $v_{\max} = \frac{\alpha}{\beta}$.

3. Background Literature

Literature on queue discharge characteristics of vehicles at signalised intersections under mixed traffic conditions where large proportion of the traffic does not follow the rules of the road is limited. Sharma and Swami (2012) studied on the effect of turning lane at signalized intersection under mixed traffic conditions in India. Arkatkar and Arasan (2012) studied on vehicular interactions under heterogeneous traffic conditions in India. Methew and Ravishankar (2012) studied the car flowing behavior in mixed traffic conditions. Khan and Mani (2000) studied to model the heterogeneous traffic flow in India.

The design of traffic signal timing and evaluation of intersection performance is done based on the available saturation flow data. Rahman et al. (2005) compared the saturation flow rates at signalised intersections in Yokohama and Dhaka. Lin and Thomas (2005) opined that the saturation flow do not reach stabilized maximum value after the fourth queuing vehicle enters the intersection. Mccoy and Heimann (1990) assessed the effect of driveway traffic on saturation flow rates at signalised intersections. Fujiwara et al. (1994) studied on saturation flow rates at urban signalised intersections in winter season. Stokes et al. (1986) assessed the effectiveness of simple linear regression for the estimation of saturation flows at signalised intersections. Stokes (1989) reported the factors affecting the capacity of signalised intersections. Lin et al. (2004) studied the variations in queue discharge patterns and their implications in the analysis of signalised intersections in Taiwan. Fusco et al. (2013) investigated the effect of signal synchronization on the traffic flow patterns at signalised intersections. Table 2 (Turner and Harahap, 1993-a and 1993-b) shows the saturation flow rates obtained at different places.

Bhattacharya and Mandal (1982) studied the clearing speed of vehicles at 23 different intersections in Calcutta. They reported that the clearing speed of cars at the intermediate position was significantly dependant on the clearing length (clearing speed (m/s) = 0.17 * clearing length, m). Chandra et al. (1996) studied at 19 intersections to determine the clearing speed for different category of vehicles. They hypothesised that the clearing speed of each vehicle type was depending on the total traffic volume, the saturation flow rate and the clearing speed of the different vehicle types.

Table 2: Previous studies on saturation flow rates

Study	*Country*	*Mean (pc/h/ln)*	*Sample Size*
Webster & Cobbe	UK	1800	100
Kimber et al.	UK	2080	64
Miller	Australia	1710	-
Branston	UK	1778	5
H.E.L.Athens	Greece	1972	35
Shoukry & Huizayyin	Egypt	1617	18
Hussain	Malaysia	1945	50
Coeyman & Meely	Chile	1603	4
Bhattacharya & Bhattacharya	India	1232	20
De Andrade	Brazil	1660	125

Loutzenheiser (1938) reported the maximum acceleration of 1.74 m/s^2 at speeds of 0 to 8.05 km/h, and the acceleration rate dropped linearly to 0.45 m/s^2 at speeds of 104.7 to 112.7 km/h. Beakey (1938) also observed that the maximum acceleration followed an approximate straight-line decrease to zero at maximum speed for each vehicle and average acceleration of car was about 0.4 m/s^2. Bellis (1960) developed a linearly decreasing relationship with α = 1.67 and β = 0.1229 for trucks. Dockerty (1966) studied accelerations of queue leaders from stop lines. St. John and Kobett (1978) found that the acceleration was linearly decreasing function of speed of the form ($\alpha - \beta V$) with a value of α = 3.36 and β = 0.0803 for car and α = 5.19 and β = 0.1478 for truck on a level terrain. Paul S. Fancher (1983) reported the acceleration characteristics of vehicles influencing the highway design. Dey and Biswas (2011) studied the acceleration characteristics of queue leaders at signalised intersections under mixed traffic condition. Glauz et al. (1980) established a linear relationship with α = 2.5 and β = 0.104 for the slowest ten percent of motorists and α = 2.85 and β = 0.0853 for passenger cars. Evans and Rothery (1981) collected speed and acceleration data on the characteristics of 15, 138 queued motorists crossing a trap after stopping for a red traffic signal. Rai Choudhary and Rao (1989) opined that the acceleration was in two phases, both of which was represented by linearly decreasing equation with different set of α and β. Bonneson (1992) showed very strong linear relationship between acceleration-speed with α = 2.02 and β ranging from 0.1184 to 0.1326. Gary Long (2000) reported that at the start of motion accelerations were about 15 percent faster for passenger cars and 45 percent faster for SU (single unit) trucks than design accelerations. Dey et al. (2008) established linearly decreasing relationship for nine categories of vehicles plying on Indian two-lane roads. Kumar and Rao (1996) found a good relation between acceleration rates and overtaking time on two-lane roads. Wang et al. (2004) collected field data to analyze acceleration rates of different vehicles using Global Positioning System (GPS) and developed a quadratic relationship between acceleration and speed for straight and turning maneuvers. Bham and Benekohal (2002) proposed a dual regime constant acceleration model which provides higher value of acceleration rate at lower speed and lower acceleration rate at higher speed. Bokare and Maurya (2011) presented the acceleration behavior through manual gear transmission (MGT) of a vehicle and fitted the data from first to fourth gear as polynomial. For fourth to fifth gear transmission, linear variation was found. Brooks (2012) determined acceleration characteristics of various vehicles at starting from rest, and during overtaking operations. Mehar et al. (2013) studied on speed and acceleration characteristics of different types of vehicles on multi-lane highways in India.

4. Field Study and Data Collection

For the present study data were collected at different signalised intersections of Bhubaneswar city, Odisha. The following criteria were also taken into consideration during the selection of intersections:

- The gradient for normal intersections should be as flat as possible
- Standard lane width should be available
- The intersections should be free from the bus stops, parked vehicles, the pedestrian movements and any type of side friction
- The queues of through traffic should be long enough
- The queue should contain mostly all type of vehicles

4.1 Field data on headway

Data were collected on different weekdays on all the intersections. In all, 467 cycles of traffic data were collected at different signalised intersections. Queuing vehicle refer to those vehicles that are stopped by the red light and those join the stationary queue of vehicles. Due care was also taken to eliminate the data of vehicles that did not stop before the stop line. The platoons of traffic within which vehicles did not stop before entering an intersection, and platoons in which vehicular movements were impeded by pedestrians, cross traffic, or turning vehicles were not considered. As the queue of vehicles moves the headway measurements with respect to a fixed point or line (say STOP line) are taken as follows:

- The first headway is the time lapse between the initiation of green signal and the time that the rear wheel (car-following laws assume that the drivers follow the rear bumper of the leader, not the front bumper, Ref: Li and Prevedours-2002; Cohen-2002) of the first vehicle in the queue cross the stop line.
- The second headway is the time lapse between the time that the first vehicle’s rear wheels cross the stop line and the time that the second vehicle’s rear wheels cross the stop line.
- Subsequent headways are similarly measured.
- During over saturated condition, only the headway of those vehicles that cleared the intersection by using green time of a phase was considered.

The headway data were collected with the help of stopwatch with an accuracy of 0.01 s. The discharge headway data were collected for the vehicles in each queue position.

4.2 Field data on speed

Speed data were collected for about 3-4 hours using video recording at each intersections. Only the vehicles in queue and leaving intersection as the signal turns green and going straight were selected for the speed study. For data collection, the stop line at an intersection was used at the first reference mark. The width of the intersection was considered for the calculation of speed. For example, a stretch of approximate width of 37 meters (~18.5 m + 18.4 m) i.e. equal to the intersection width (for example NALCO square intersection) was considered to calculate the speed in that particular intersection. The total width of the intersection was divided into four equal parts as shown in Figure 3. The time required to cover the individual parts (t_1, t_2, t_3, t_4 respectively) by each and every vehicle was extracted from the recorded film with an accuracy of 0.01s. A total of about 650 observations were taken for the speed study.

4.3 Field data on acceleration

Data were collected by video recording and only the vehicles in queue and going straight were selected. Throughout the operation, vehicles were picked at random from traffic stream. Due care was also taken to eliminate the data of vehicles that did not travel freely i. e. the movement during clearing the intersection was interrupted by any conflicting vehicle (i. e. diverging, merging, and crossing conflict) and pedestrian movements. For data collection, the stop line at an intersection was used at the first reference mark. A stretch of approximate 35 - 40 metre i.e. equal to the intersection width was considered for the analysis of acceleration characteristics in our study. Time required for travelling the intersection's four quarters is t_1, t_2, t_3, t_4 respectively were noted from the recorded film with an accuracy of 0.01 s. A total of more than 500 observations were taken for the acceleration study.

5. ANALYSIS OF DATA

5.1 Analysis of headway data

The saturation headway was calculated from the collected headway data. Table 3 shows the headway statistics of collected data on signalised intersections. For the present study, the average discharge headway or saturation headway is calculated by averaging the discharging headway of all vehicles in the saturation flow region as given in the following equation and it is 1.57 s and the saturation flow rate, s = 3600/1.57 = 2293 vphpl.

$$h_s = \frac{\sum_{j=n}^{l} (h_j)}{(l-n+1)} \tag{10}$$

Table 3: Headway statistics

Queue position	*Mean (s)*	*S. D. (s)*	*Sample size*
1	2.96	1.12	467
2	2.59	0.97	467
3	2.13	0.94	467
4	1.91	0.67	467
5	1.86	0.85	467
6	1.63	0.73	467
7	1.58	0.68	467
8	1.67	0.58	412
9	1.58	0.61	395
10	1.48	0.48	390
11	1.65	0.52	388
12	1.68	0.49	363
13	1.51	0.66	345
14	1.63	0.74	293
15	1.51	0.46	265
16	1.65	0.44	213
17	1.56	0.52	197
18	1.61	0.43	197
19	1.5	0.31	197
20	1.41	0.29	197
21	1.60	0.31	181
22	1.50	0.26	181
23	1.45	0.33	181
24	1.55	0.38	181
Saturation headway*, s	1.57	--	--

**Saturation headway was calculated by averaging the headways of all the vehicles in the saturation flow region.*

To provide a better insight into the nature of queue discharge, the headway data given in Table 3 are represented graphically in Figure 2. The average discharge headways become stable from the 6th position of the discharged queue of vehicles. In aggregate, the average queue discharge headways exhibit an unmistakable trend of gradual compression as queuing vehicles are discharged in succession. Li and Prevedouros (2002) and Lin et al. (2004) also reported that the queue discharge headway tends to compress as the discharge of a queue progresses.

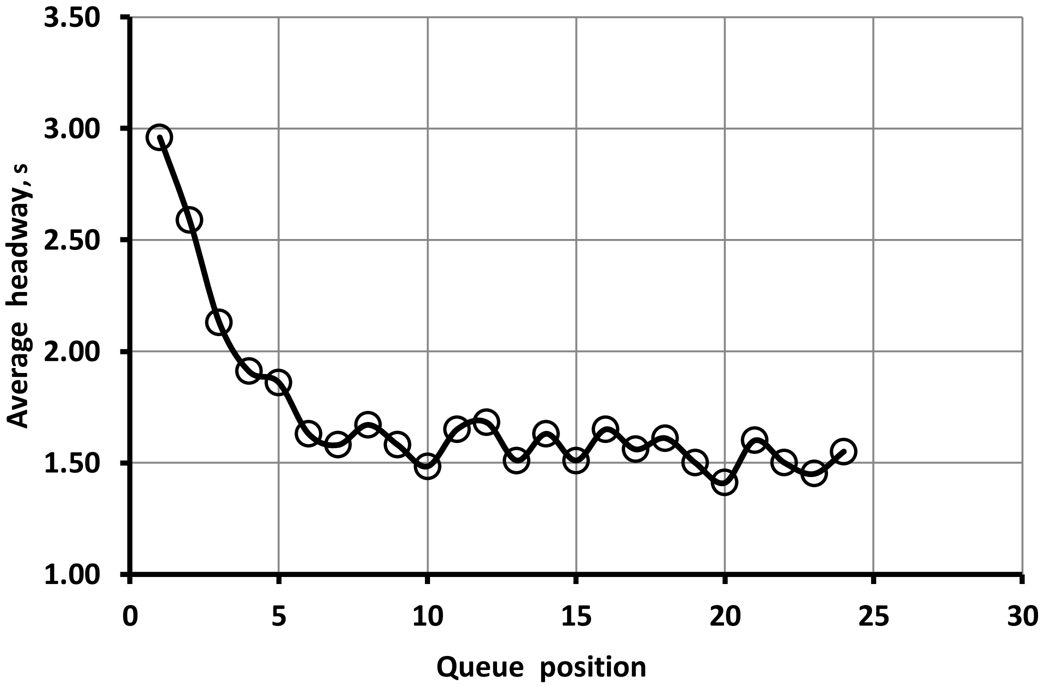

Figure 2: Characteristics of queue discharge headways

5.2 Analysis of speed data

The collected data were analysed to calculate speed of vehicle clearing the intersection. The details of average time required by all the queued vehicles during queue discharge are given in Table 4 and plotted in Figure 4. From the Figure 4 it is clear that irrespective of the position of the vehicle in the queue (i. e. ith vehicle in the queue), time required (t_1, t_2, t_3, and t_4) to traverse the individual equal parts of the intersection width decreases. It is obvious that initial time (t_1) required to cover the first ¼ th distance of intersection width is more due to the perception reaction time of the driver and initial lost time. After this the clearing time (t_2, t_3, t_4) decrease as the vehicle accelerates and the speed of the vehicle is in the increasing order. Therefore, time required (t_2, t_3, t_4) to cover equal distances are in the decreasing order. Again as the queue position increases (i.e. ith, (i+1) th vehicle), the time required to traverse any particular width of the intersection decreases. It is due to the fact that any (i + 1)th vehicle starts to move from the upstream of the stop line. Therefore, the (i + 1)th vehicle attains some speed when it crosses the stop line and obviously time required to clear the intersection width decrease as compared to the previous ith vehicle.

Figure 3: Intersection at NALCO square, Bhubaneswar

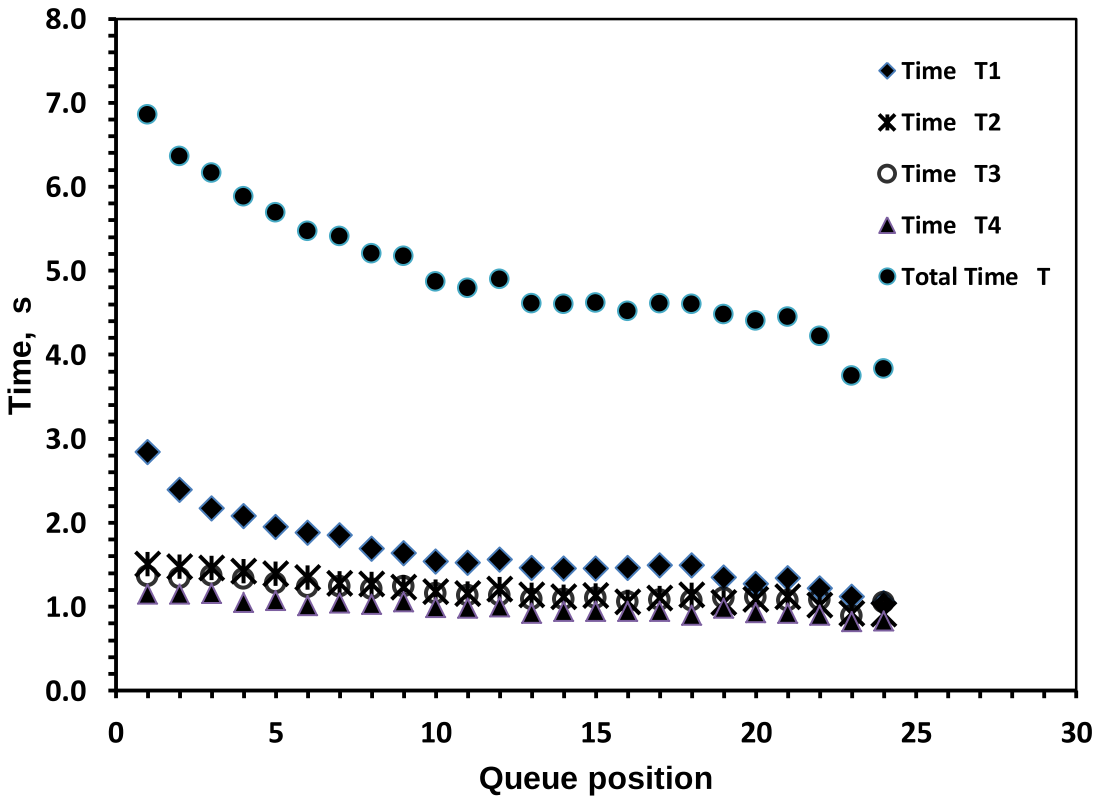

Figure 4: Intersection clearing time v/s position of the vehicle in the queue

Table 4: Intersection clearing time statistics of vehicles during queue discharge

Queue Position	*Average T_1 (s)*	*Average T_2 (s)*	*Average T_3 (s)*	*Average T_4 (s)*	*Total (s)*
1	2.84	1.51	1.36	1.15	6.86
2	2.39	1.48	1.34	1.15	6.36
3	2.17	1.46	1.37	1.16	6.16
4	2.08	1.42	1.33	1.05	5.88
5	1.95	1.39	1.28	1.07	5.69
6	1.88	1.35	1.23	1.01	5.47
7	1.85	1.28	1.24	1.04	5.41
8	1.69	1.27	1.21	1.03	5.20
9	1.64	1.23	1.24	1.06	5.17
10	1.54	1.18	1.16	0.99	4.87
11	1.52	1.16	1.13	0.98	4.79
12	1.56	1.21	1.13	1.00	4.90
13	1.46	1.14	1.09	0.92	4.61
14	1.45	1.12	1.09	0.94	4.60
15	1.45	1.13	1.10	0.94	4.62
16	1.46	1.06	1.06	0.94	4.52
17	1.49	1.10	1.08	0.94	4.61
18	1.49	1.14	1.07	0.90	4.60
19	1.35	1.05	1.10	0.98	4.48
20	1.27	1.09	1.11	0.93	4.40
21	1.34	1.12	1.07	0.92	4.45
22	1.22	1.02	1.08	0.90	4.22
23	1.12	0.92	0.89	0.82	3.75
24	1.04	0.91	1.05	0.83	3.83

The intersection clearing speed of the vehicles was calculated by dividing the intersection width by the time required to cover the corresponding width of the intersection. The average clearing speed of vehicles was calculated for the first half and last half of the intersection width for each queue position. The average intersection clearing speed was also calculated and the details are given in Table 5 and also presented in Figure 5. As may be seen that the clearance speed is varying from 19 km/h to 35 km/h. As the position of the vehicle in the queue increases, the clearing speed increases. The initial vehicles take longer time due to perception-reaction time and additional time required to accelerate to a reasonable speed to cross the intersection. The later vehicles in the queue more or less achieve this reasonable speed during crossing the intersection as they start moving from a distance further upstream from the reference point (say STOP line). Therefore, during crossing the reference line (say STOP line) the speed of initial vehicles is quite low as compared to other vehicles in the queue.

Table 5: Intersection clearing speed statistics of vehicles during queue discharge

Queue Position	*V_1(m/s)*	*V_2(m/s)*	*V(m/s)*	*V(km/h)*
1	4.253	7.331	5.379	19.364
2	4.780	7.390	5.802	20.887
3	5.096	7.273	5.990	21.565
4	5.286	7.731	6.276	22.592
5	5.539	7.830	6.485	23.346
6	5.728	8.214	6.746	24.285
7	5.911	8.070	6.821	24.555
8	6.250	8.214	7.096	25.546
9	6.446	8.000	7.137	25.694
10	6.801	8.558	7.577	27.277
11	6.903	8.720	7.704	27.733
12	6.679	8.638	7.531	27.110
13	7.115	9.154	8.004	28.816
14	7.198	9.064	8.022	28.878
15	7.171	9.020	7.987	28.753
16	7.341	9.200	8.164	29.389
17	7.143	9.109	8.004	28.816
18	7.034	9.340	8.022	28.878
19	7.708	8.846	8.237	29.652
20	7.839	9.020	8.386	30.191
21	7.520	9.246	8.292	29.852
22	8.259	9.293	8.744	31.479
23	9.069	10.760	9.840	35.424
24	9.487	9.787	9.634	34.684

Where, V_1 = clearing speed from the reference line to the middle of intersection

V_2 = clearing speed from middle of intersection to the end of intersection

V = Average intersection clearing speed

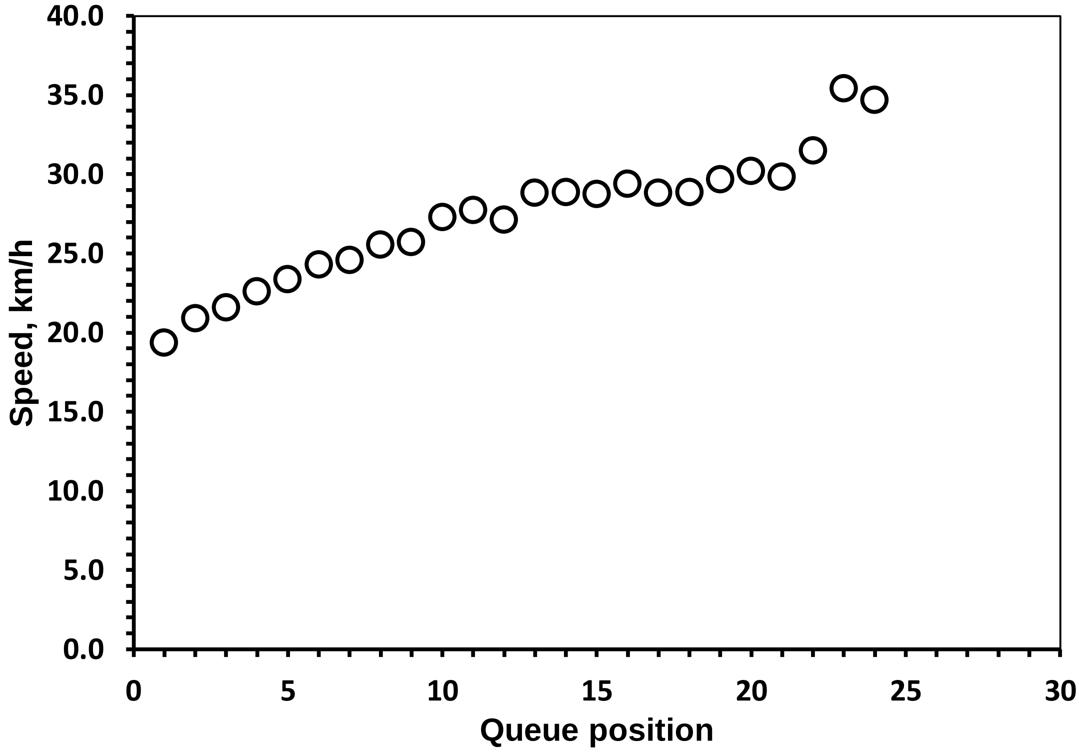

Figure 5: Clearance speed v/s queue position

The average intersection clearing speed of individual category of vehicles (2-w, 3-w, and car) irrespective of the position in the queue was determined and tabulated in Table 6 and compared with the study of Maini and Khan (2000). It is clear that the findings of the present study is in close agreement with the findings of Maini and Khan (2000). The average clearing speed of vehicles do not differ significantly by category of vehicle. This is obvious that though the initial rate of acceleration for car and 2-wheeler is high, but cars and 2-wheelers can not accelerate fully due to the presence of other vehicles.

Table 6: Intersection clearing speed (m/s) of different category of vehicles

Vehicle type	*Average speed from this study*	*Average speed by Maini and Khan (2000)*
2-wheeler	7.42	6.33
3-wheeler	5.78	5.64
Car	7.08	6.11

5.3 Analysis of acceleration data

The data were analysed to establish a relation between the acceleration rate and the speed for different types of vehicles. For each observation, a curve was plotted between the cumulative distance and the time. A 3-degree polynomial was fitted to these data using the method of least square to obtain the distance-time relationship. The distance-time equations obtained for each set of observation were differentiated to get the speed- time and acceleration-time relationships. These equations were used to study the effect of speed on acceleration. Cumulative distance-time data for a randomly chosen 2-wheeler is shown in Figure 6. The curve was then plotted between the acceleration and the speed for the particular vehicle. The equation of the curve is of the form a = α – βv. The acceleration-speed relationship for this 2-wheeler is shown in Figure 7. The similar trend was also observed for other category of vehicles and their acceleration-speed relationships are tabulated in Table 7. The slopes of the curves are different for different category of vehicles showing a varying degree of dependency of acceleration on speed. The coefficients α and β of acceleration-speed equations for each types of vehicle are shown in Table 8.

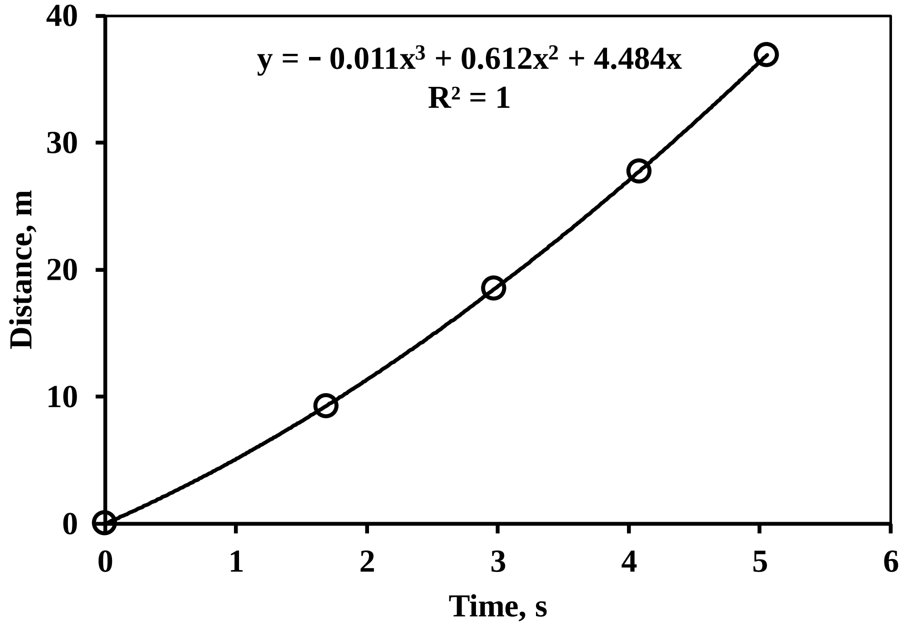

Figure 6: Distance-time graph of a typical 2-wheeler

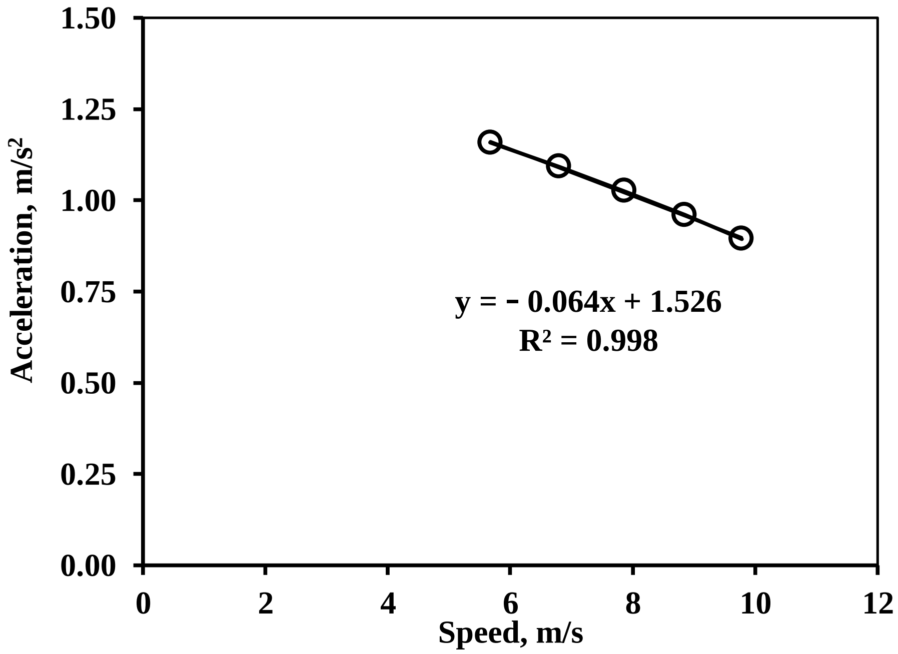

Figure 7: Acceleration-speed relationships for a typical 2-wheeler

Table 7: Acceleration-speed relationships

Type of vehicle	*Relationship*	*R^2 value*
Car	dv/dt = 0.932 - 0.054*v	0.984
Auto rickshar	dv/dt = 0.561 - 0.046*v	0.981
2-Wheeler	dv/dt = 1.244 - 0.078*v	0.993

Table 8: Values of coefficients α and β

Sr. no.	*Coefficients*	*Vehicle Type*	*Average*	*S. D.*
1	α (m/sec^2)	Car	0.932	0.198
	β (sec^{-1})		0.054	0.021
2	α (m/sec^2)	3-Wheeler	0.561	0.116
	β (sec^{-1})		0.046	0.008
3	α (m/sec^2)	2-Wheeler	1.244	0.337
	β (sec^{-1})		0.078	0.034

6. Conclusions

The present paper demonstrates the headway, speed, and acceleration characteristics of vehicles during queue discharge at signalised intersections in India. Estimation of accurate saturation flow rate is the fundamental building block in the management of efficient urban traffic control. The ideal saturation flow rate may not be achieved (observed) or sustained during each signal cycle. There are numerous situations where actual flow rates will not reach the average saturation flow rate on an approach including situations where demand is not able to reach the stop line, queues are less than five vehicles in a lane, or during cycles with a high proportion of heavy vehicles. To achieve optimal efficiency and maximize vehicular throughput at the signalized intersection, traffic flow must be sustained at or near saturation flow rate on each approach. In most HCM analyses, the value of saturation flow rate is a constant based on the parameters input by the user, but in reality, this is a value that varies depending on the cycle by cycle variation of situations and users. The traditional concept of saturation flow may not realistically represent the actual queue discharge characteristics. The HCM provides a standardized technique for measuring saturation flow rate. It is based on measuring the headway between vehicles departing from the stop line, limited to those vehicles between the fourth position in the queue and the end of the queue. For signal designing, it is often necessary to put emphasis on this parameter due to the high degree of fluctuation in this parameter from cycle to cycle. It is also difficult to identify the position of queued vehicle from where the saturation flow region starts or the steady maximum discharge rate of vehicles. The queue discharge characteristics under mixed traffic conditions exhibit a general trend of gradual compression of headways as the queue discharge continues. Contrary to the traditional concept of saturation flow, the discharge rates do not become stable after the fourth queuing vehicle enters the intersection. The average discharge headways become stable from position 6th (sixth) under mixed traffic conditions and the saturation headway is 1.57 s.

The intersection clearing speed for 2-wheeler, 3-wheeler, and car was estimated from the field observations and the speeds are close agreement with the previous studies (Maini and Khan, 2000). The intersection clearing speed of queued vehicles at different queue position was also determined and the speed is in the increasing order. This is obvious that though the initial rate of acceleration for car and 2-wheeler is high, but cars and 2-wheelers cannot accelerate fully due to the presence of other vehicles.

Acceleration characteristics of vehicles have also been examined at different speeds. Acceleration of a vehicle type is higher in initial gears and reduces as speed increases. The acceleration characteristics of vehicles investigated in the present study suggest that the acceleration of vehicles in the queue at signalized intersection and released after the signal turns green can be suitably represented by a linearly decreasing equation of the form $dv/dt = \alpha - \beta v$. For each category of vehicle the average value of α and β are determined from field observations. For any type of the vehicle distance-time relationship is a third degree polynomial and the acceleration rate is maximum when speed is low. Results of this study are very useful for development of simulation program of traffic flow under mixed traffic conditions.

Further study may include few sections on highway signalised intersections to study the discharge characteristics of vehicles under mixed traffic conditions. Further work may be carried out to see the effect of signal timings on the discharge characteristics of queued vehicles.

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