



Vehicle Movement Mechanism and Delay Variability Analysis at Signalized Intersection by Probe Vehicle Data under Mixed Traffic Condition: A Case Study in India

Krishna Saw^{1*}, Bhimaji Katti¹, Gaurang Joshi¹

¹Department of Civil Engineering, S. V. National Institute of Technology, Surat, India-395007

Abstract

Delay variations at intersections have significant impact on travel time variability among the number of various other attributes. The type of intersection, the levels of traffic volume and composition and traffic control system therein matters in deciding the delays. The signalized intersections have more bearing in this regard particularly on urban corridors. The vehicle arrival pattern, the intersection configuration, the signal cycle and turning movements do influence the vehicle movements, queuing situations and subsequently delays. It is equally important to realize the various delay components due to spatial movements and different movement situations observed at the intersection. The components of the spatial movements are stratified as dilemma and decision zone, intersection conflict area zone, normalizing zone in portions of mid-blocks on both sides of the intersection. Vehicle movement situations are related with the signal indicators such as non-stopped movements during the green period and stopped and queue moving events in red period. The present study addresses these very issues employing two wheeler (2W) and three wheeler (3W) Probe Vehicles as part of the mixed traffic plying on urban corridors as these modes dominate the mixed traffic composition. The study highlights the share of these delay components in total delay variations in supporting the role of signalized intersection in travel time variations.

Keywords: Travel time variability; signalized intersection; delay components; delay time variation.

1 Introduction

Travel time variability is gaining more importance over the mean travel time recently and has attracted attention of the researchers. Many sources are accountable for travel time variability on urban arterial roads besides demand and supply side uncertainties and inconsistency in operating condition (Lomax et al., 2003, Boyles et al., 2010). It has also been recognized that variability of delays at intersections also matters in travel time variability (Chen et al., 2013). The delay at intersection of urban arterial road is larger part of total travel time. For instance, Liu et al., (2006) and Zheng (2011) studied travel time of arterial corridor (large network) comprising of number of signalized intersections and found approximately 50% of travel time accounts to delays

* Corresponding author: Name Family Name (kriscivil_10@yahoo.com)

at signalized intersections. Since larger part of travel time pertains to the delay at intersection, it cannot be ignored in the analysis of travel time variability. Therefore, the number of intersections and their interspacing on urban corridors find due place in estimation of travel time variability. The intersection interspacing of urban arterial roads in the most of Indian cities is very short to an extent of 250m. Such shorter interspacing often leads to increment in intersections on a corridor resulting into larger delay and eventually in higher delay variability. Fu and Hellinga (2000) and Preethi et al. (2014) recognized that delay experienced by vehicle mainly varies due to stochastic arrival and departure process of vehicle at intersection.

Intersection basically acts as a decision box, where drivers decide to reduce the speed or move with the same speed depending upon the traffic signal indicator. Often aggressive drivers attempt to accelerate to avoid the likely red indicator ahead. The zone, where the drivers decide for action can be term as 'dilemma zone'. In this zone the speed of vehicle also get reduced at certain extent. The size of dilemma zone depends upon driver's reaction time with the signal indicator, the vehicle speed and position and road condition (Yang et al., 2014). The large drop-down of speed takes place in intersection area. Both the deceleration and the acceleration operations lead to vehicular delays at the Intersection. Delay at signalized intersection has mainly been grouped into two components i.e. delay due to deceleration & acceleration and stopped delay (Gupta). Chen et al. (2013) and Feng (2014) found that stopped delay at signalized intersection is associated with red phase duration and saturation level of intersection. Darma (2005) suggested that major variables that influence the control delay at signalized intersection are cycle time, inter green time, number of phasing sequence and number of lanes. Significant weightage lies for the share of intersection delay in the overall delay component in travel time. Hence, it is desired to breakdown the delay components with reference to spatial movements of the vehicle and movement pattern at the intersection in realizing the influences thereby and build the intersection delay scenario. The present study aims to focus on these two aspects of signalized intersection as part of the travel time delay variations considering a typical signal system on a traffic corridor in Surat city, Gujarat in India for illustration purpose. Delay variability gives insight to travel time variability and scope for accurate travel time estimation.

2 Research Objectives and Study Approach

2.1 Research Objectives

The main objectives of the present study with reference to an isolated fixed time signalized intersection to focus on:

- Traffic flow behaviour with reference to fixed time signalized intersection,
- Delay measurement and variability.

2.2 Study Approach

Field studies were proposed to collect the traffic volume and composition of the mixed traffic prevailing during peak period at the selected signalized intersection on the study arterial road. Secondly, the vehicle delays are noted through Probe Vehicle trips on a stretch of nearly 850m covering the upstream and downstream areas and the proper intersection area. The data are analyzed for the various delay components and to note

delay variability with reference to the intersection impact. The study stretch is segmented in five slots to note the traffic speed behaviour, prior to intersection proper and thereafter until it regains normal speed.

3 Study Intersection

Signalized intersection selected for this study is located on ring road at SasuMaa Hotel. It is 'T' intersection formed by Athwa–Majura Ring Road of divided six lanes and Nanpura – SasuMaa side road of divided four lanes. Videosnapshot of intersection at Sasu Maa is as shown in Figure 1. The study is focused for the main road traffic flow fromAthwa to Majura gate subjected to signal system at the Junction. The fixed cycle time of the signal system is 180 seconds of which 76 seconds are red signal and 102 seconds of green followed by 2 seconds of amber period for the main road. As such signal system works in three phases (direction wise shown in Figure 1) i.e.

- Main road stretch (AB),
- Right turning from main road to the side road (EF) and
- Right turn from side road to main road (CD).

Three phase signal system of the intersection is presented below.

Direction AB	2	76	102
Direction CD	30	2	148
Direction EF	30	46	2 102

AB –Athwa to Majura, CD –Timiliyawad to Athwa, EF – Majura to Timiliyawad

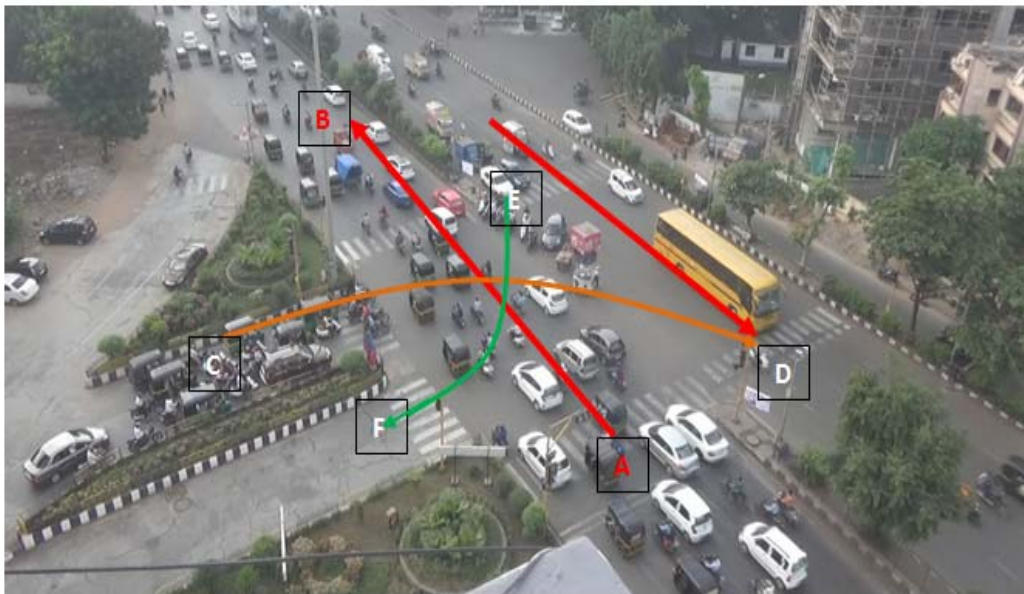


Figure 1: Study signalized intersection

4 Data Base

After carrying physiographical and configuration surveys, following two field studies were carried out in the month of October, 2016.

- Classified Volume Count Survey (CVC)
- Speed and Delay Survey

4.1 Classified Volume Count Survey

Video-graphic survey has been conducted to know the traffic flow and composition pattern for morning peak period (9:45 AM to 11:45 AM) and video camera was fixed in such manner that it covered traffic flow on main and as well side roads. The CVC data was extracted for the arriving traffic at the signal cycle interval basis. The number of vehicles clearing during 102 seconds of green period was also noted for 20 seconds slots. Nearly 25 signal cycles are covered randomly during the peak period in case of study direction i.e. from Athwa to Majura gate. Vehicles are categorized into Two wheeler (2W), Three wheeler (3W), Car, Bus, Light Commercial Vehicle (LCV) and Truck.

4.2 Speed and Delay Survey

In this study, speed profile of corridor was collected using Global Positioning System (GPS) laden Probe Vehicle (2W and 3W) to note the moment to moment variations in speed. This technique provides speed traverse of the study corridor of 850m stretch including the proper intersection which is not possible in other techniques. The study stretch is of 850m including the intersection proper (Figure 2). Twenty random trips were carried in one direction by the Probe Vehicles. Both CVC and speed and delay surveys were carried simultaneously.

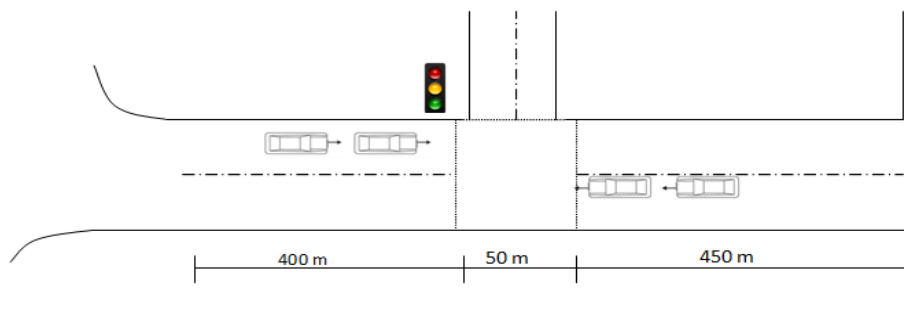


Figure 2: Schematic diagram including study intersection

5 Data Analysis

5.1 Traffic Volume and Composition

Traffic flow of each approach is presented in pcu/hr with due consideration of Passenger Car Unit (PCU) factor for the signalized intersection mentioned in IRC SP: 41 (1994) as shown in Figure 3(a). The traffic flow of major approach in the direction of Athwa to Majura and Majura to Athwa is 4700 pcu/hr and 5500 pcu/hr respectively, whereas from the side road approach in right turning is of 800 pcu/hr and entering from the main road to side is of 925 pcu/hr. Nearly 1600 pcu/hr/lane flow is from Athwa to Majura. The red period of 76 seconds covers both right turning vehicles from and to side approach road.

The traffic composition at this intersection indicates the domination of 2Ws to an extent of 68% of the mixed traffic. The mode wise share of the main road is shown in Figure 3 (b). The share of 4Ws and 3Ws is of almost 15% each. Presence of trucks and other vehicles is quite meager and can be ignored here.

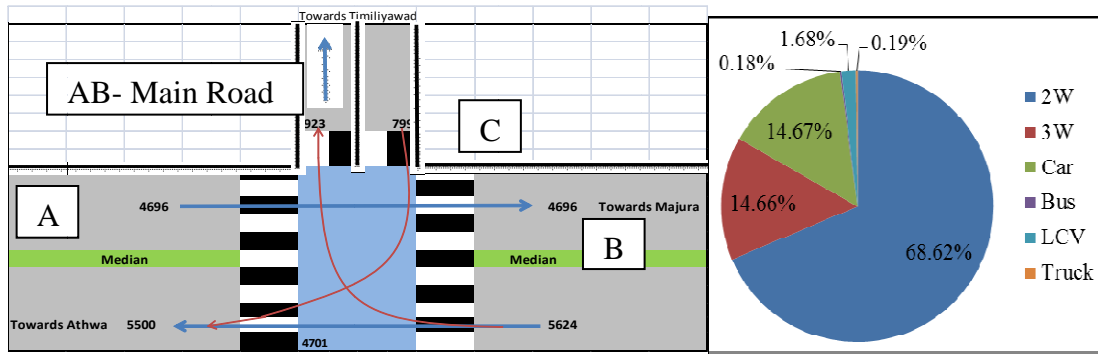


Figure 3 (a): Traffic Volume (pcu/hr)

Figure 3 (b): Traffic Composition

The average queue discharge profile of the main road vehicles in cycle of 102 seconds green periods at every 20 seconds for a cycle is presented in Figure 4. Variation queue discharge rate can be observed, rate reduces at the fag end of green period. Nearly 412 of mixed vehicles (275pcu) have cleared in green period of the cycle. It amounts to clearance of about 8000 vehicles (5500 pcu) in one hour.

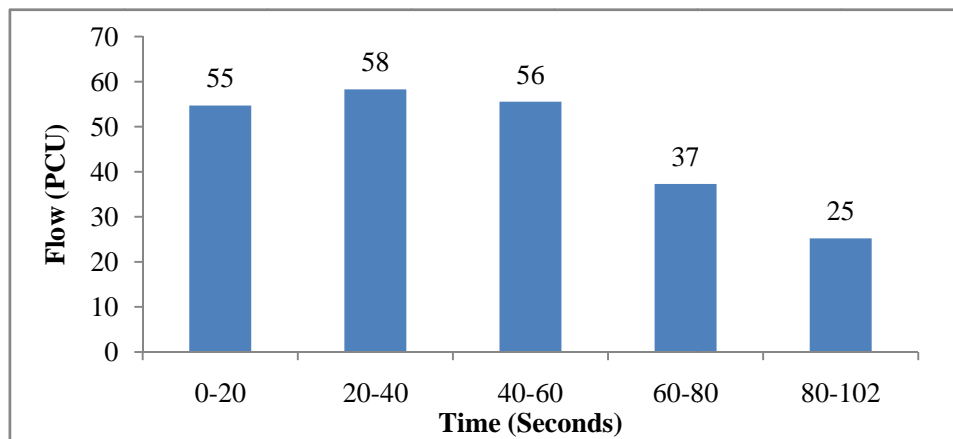


Figure 4: Flow during green period

5.2 Probe Vehicle Speed Variability Analysis

a. Formation of Study Sections

Speed profiles of Probe Vehicles during the peak period are recorded for the study stretch of 850 m inclusive of intersection area. Random trips were carried by adopting both the 2W and 3W as Probe Vehicles. A typical speed profile by carried by Probe Vehicle (2W) as shown in Figure 5 indicates formation of three segments as upstream side, downstream side and middle intersection conflict area. The vehicle movement mechanism can be realized for its variation through the five sections as marked in Figure 6 to form five behaviour zones (Table 1). Zone width variations and average values are extracted from speed profiles of the Probe Vehicles. Two zones are formed in pre and post conflict areas of intersection. The conflict area i.e. Section III, where the vehicle movements take place from the main road to side road and vice versa to result into conflict points.

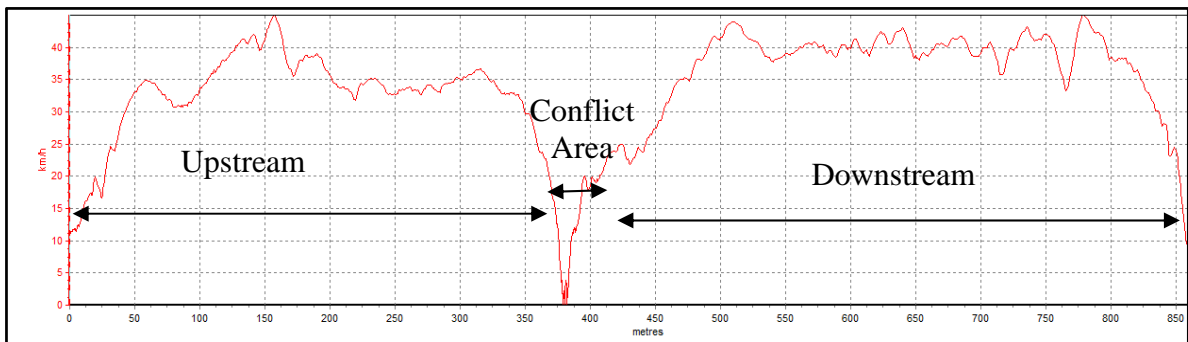


Figure 5: Typical Speed Profile of Probe Vehicle

Table 1: Section zoning particulars

Section	Zone	Distance (m)
Section I	Mid-Block zone (Upstream)	-
Section II	Dilemma and Decision Zone	90 (70-100)
Section III	Intersection Conflict Area	70 (40-130)
Section IV	Normalizing Zone	50 (40-60)
Section V	Mid-block zone (Downstream)	-

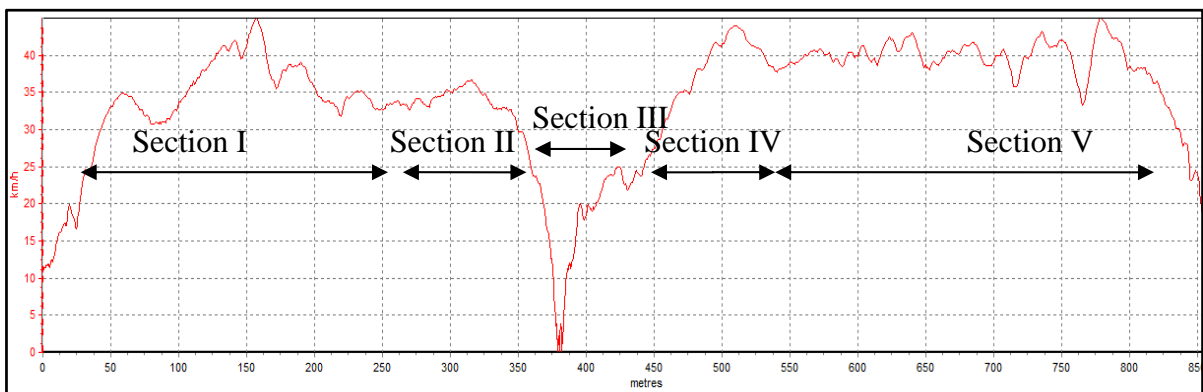


Figure 6: Typical speed profile of Probe Vehicle

b. Vehicle Movement Mechanism

Speed transformation is taking place from mid-block to intersection influence area (Section II and Section III). The driver moves certain distance in dilemma period in section II during which he perceives the situation ahead and decides to accelerate or decelerate or move with the same speed depending upon intersection signal indicators and queuing situation etc. if any. Actual deceleration starts to join the queue or join the moving queue in section III.

Downstream area consists of two sections i.e. normalizing zone and mid-block zone respectively. The vehicle movements from the stopped condition or no stop condition from the stop line at the intersection belong to Section III. Further accelerating and normalizing process take place in Section IV and attain normal speed. Section V pertains to the mid-block. Thus again speed transformation can be observed in post-intersection area.

5.3 Section wise Speed Variations

The speed variations at the intersection approach owe to the driver's decision behaviour depends upon the traffic conditions, signal indications and queue situations. The traffic conditions pertain to approach volume and composition, whereas the signal system deals with magnitude of red and green period of the cycle. The queue situations are related to the vehicle arrival time during red period. Traffic saturation is another factor when related to approach traffic volume and magnitude of red period, the queue length does vary and crawling queue speed come into picture to reach up-to stop line when signal becomes green. Such situations are observed mainly in Section III. The speed profiles observed by the Probe Vehicle-2W for the five sections of the study stretch reflect on the variations of the speeds while passing through the intersection. The statistical measures of the speed variations in the section are presented in Table 2 (a). Section I and Section V reflect the speeds of mid-block in a normal way and decreasing in Section II which is of dilemma zone. The impact of signal can clearly be observed in Section III of the conflict areas, where deceleration phenomenon is predominant and also the significant variation in standard deviation and coefficient of variation (CV) value. The acceleration trends build up the speeds with reference to green signal from stopped condition or moving or entering during the green period without stop in Sections III and IV. The transformation of building of speeds towards normalized speed takes place mainly in Section IV.

Table 2 (a): Statistical measures: sectional speeds (Kmph) of 2W

	Section I	Section II	Section III	Section IV	Section V
Average	32	30	14	29	30
Min	23	26	2	24	23
Max	44	33	26	37	37
StdDev	6	2	9	4	5
CV	0.2	0.1	0.7	0.1	0.2

Similarly speed profiles of Probe Vehicle-3W along with statistical measures are presented in Table 2(b). Speed variation pattern at the sections for the 3W is reflecting slightly lower speeds compared with 2W. However, the speed variations in Sections I and II in case of 3W is slightly different indicating the aggressiveness of 3W accelerating from Section I to Section II to push ahead to stop line. Here also significant in speeds can be observed in Section III with high standard deviation and CV value.

Table 2 (b): Statistical measures: sectional speeds (Kmph) of 3W

	Section I	Section II	Section III	Section IV	Section V
Average	24	26	9	23	24
Min	21	23	2	18	22
Max	26	30	25	28	27
Std Dev	2	3	8	3	2
CV	0.1	0.1	0.9	0.1	0.1

The speed variation patterns of both Probe 2W and Probe 3W vehicles can be observed in their speed profiles shown in the Figure 7. The deceleration and acceleration, aggressiveness of 3W and gradual transformation of speeds in Section III are clearly observed in the figure. The observed speed dropdown at intersection proper amounts to 40 to 45% of stream speed.

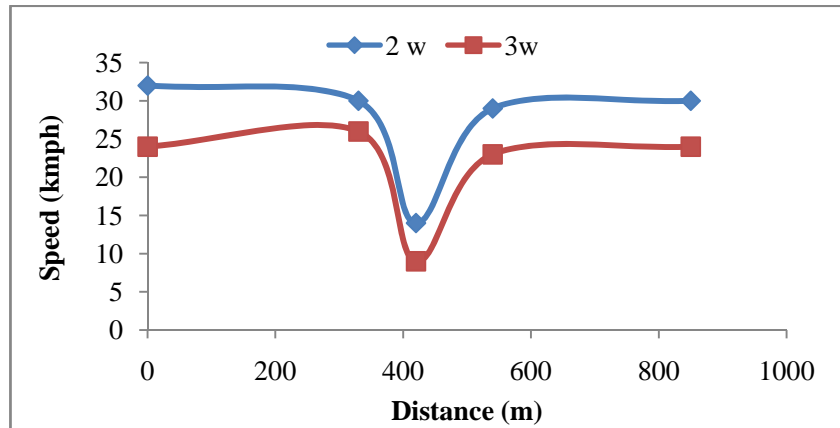


Figure 7: Sectional speed variations of 2W and 3W

6 Vehicular Delay Variability

6.1 Intersection Delay Components

The total intersection delay which is also termed as controlled delay comprises of three components namely deceleration, stopped and acceleration delay. Normally a vehicle decelerates invariably at the intersection irrespective of signal indicators this contributes to deceleration delay. The stopped delay is for the vehicle which stops during the red period, whereas acceleration delay is the time component for a vehicle to move from stop condition to regain normal speed condition. However, vehicles in the queue have additional delay component depending upon the position of the vehicle in the queue and crawling distance up to the stop line. Figure 8 depicts the delay components and various zones that it has to pass through to clear-up the intersection. The acceleration and deceleration rates and kinetic behaviour of movement of vehicles vary mode to mode and drivers. Often the following vehicles are conditioned to follow the leading vehicle particularly in Sections II and III. Stopped delay component clearly dominates over the other two components in overall intersection delay. The figure also links various delay components with the study sections.

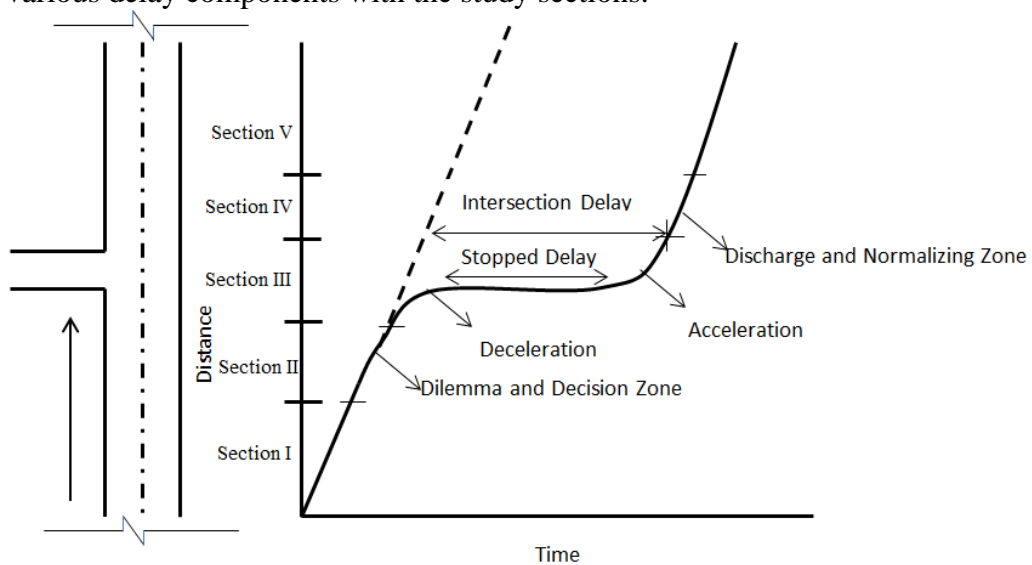


Figure 8: Delay components

6.2 Vehicle Movement Situations in Section III

Eventually the vehicular delays are mainly influenced in Section III wherein “Stop and Go” (Red and Green) signal conditions prevail. The traffic flow at the intersection can be categorized following in four types of vehicle movement situations:

- Non-stop movement
- Non-stop movement but moving along with queue
- Stopping at the commencement of red signal
- Joining the queue at the approach and stopping

These movements have significant bearing on vehicle delays depending upon their arrival with the signal operation system. Obviously vehicles of non-stop movement have least signal impact, whereas delays are quite high for the vehicles that are part of queue. Here red period and queue crawling speeds matters.

Two typical Probe Vehicle trajectories for non-stopped vehicle (non-stop movement) and stopped vehicle (stopping at commencement of red signal) across the study stretch are presented in Figure 9 (a) and 9 (b) respectively.

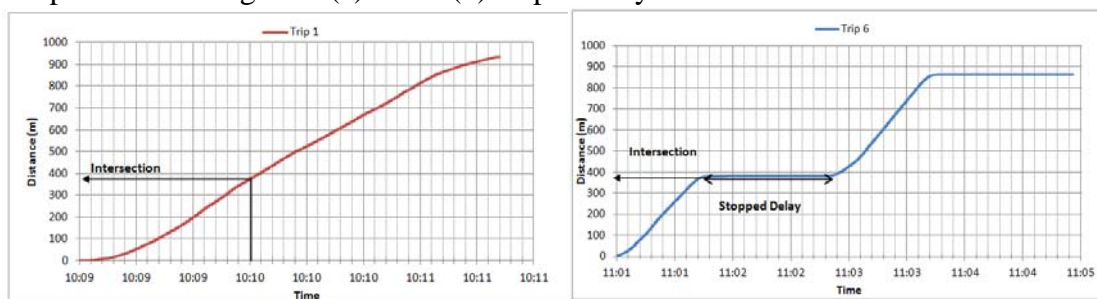


Figure 9 (a): Probe Vehicle trajectory Figure 9 (b): Probe Vehicle trajectory

6.3 Delay Structure

It is required to analyse the intersection delay structure with reference to the three basic delay components of deceleration, stopped and acceleration movements at the signalized intersection. As discussed earlier, the intersection influence distance is split in three Sections as Section II, Section III and Section IV pertaining to dilemma & decision area, intersection conflict area, where intersection conflict prevails and downstream normalizing area with mid-block portion. However, one has also to incorporate the delay occurring for dilemma & decision process, prior to entry to intersection conflict area for section II. Delays in section IV are with reference to the vehicle transition period to reach the normal mid-block flow situation. As far as deceleration at the intersection proper and waiting for the green signal as well accelerating from stop line condition pertain to section III component. Each trip has variation in delay subjected to traffic flow level, degree of saturation, signal indicator and queue length.

The delay in respective section has been computed based on speed dropdown in each section with reference to speed for planned level of service for the mid-block. Since, it is arterial corridor; the planned speed considered is 40 kmph with reference to Level of Service (LoS) C (IRC: 106-1990). The statistical delay measures of these three Sections are presented in Table 3 for 2W and 3W. With reference to fixed time signal

system having 180 seconds cycle length, 102 seconds of green period and 76 seconds of red period in three phases for the main road flow.

From the Table 3, it is observed that the delay in Section III (Intersection Proper) for 2W and 3W is 30 seconds and 40 seconds respectively which is quite high for obvious reason of stoppage and queuing conditions during red period. It is almost 6 times than Section II and Section IV. Observed maximum delay values are 72 seconds and 76 seconds for 2W and 3W respectively in section III which is almost near to the red period. The delay value will increase above the red period, if the vehicle is not able to clear the intersection in one cycle. Mode base delay for the three sections can be compared in Figure 10. The intersection conflict area (Section III) delay amounts to 40% and 53% of the red period for 2W and 3W respectively in the present study. The ratio of stopped delay to red period has been observed 30% for the city bus by Feng, 2014.

Table 3: Statistical measures of delay for 2W and 3W

	2W			3W		
	Section II	Section III	Section IV	Section II	Section III	Section IV
Avg.	5	30	7	6	40	16
Min	2	2	2	4	2	7
Max	8	72	11	10	76	26
Std Dev	2	28	3	2	26	7
CV	0.39	0.92	0.45	0.30	0.66	0.41

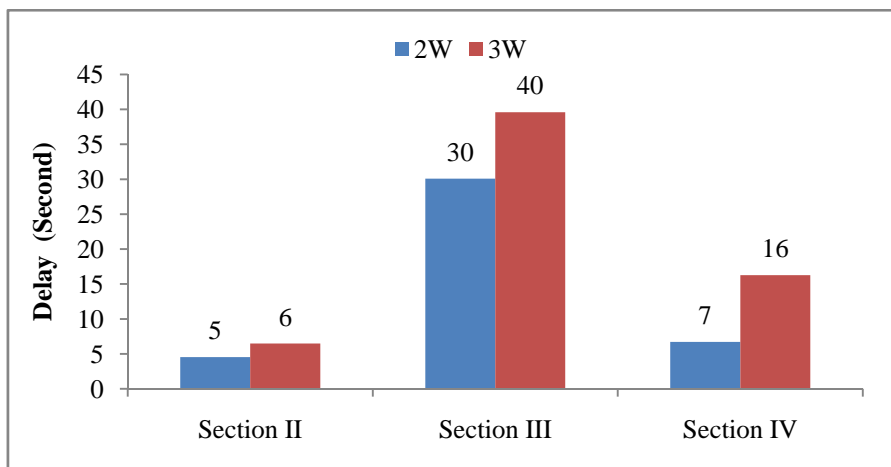


Figure 10: Section wise average delay of 2W and 3W

The proportion of vehicular delay of 2W and 3W indicate nearly 65% to 75% delays pertain to intersection proper and remaining 25% to 35% delays can be assigned to dilemma & decision and normalizing zones (Table 4).

Table 4: Proportion of vehicular delay

	Section II	Section III	Section IV
2W	11%	73%	16%
3W	10%	64%	26%

6.4 Delay Variability on Movement Basis

As earlier discussed, there are four types of vehicle flow mechanism i.e. non-stopped flow (A), non-stop but part of moving queue (B), joining the queue and stopping (C) and stopping at commencement of red signal (D). The green signal prevails in first two cases, whereas the red signal prevails for other two situations. Therefore, the higher delay is obvious in latter case. Figure 11 indicates the intersection delays for all the four vehicle movement covering three sections (Sections II, III, IV). The situation C and D indicate higher delay value for obvious reason.

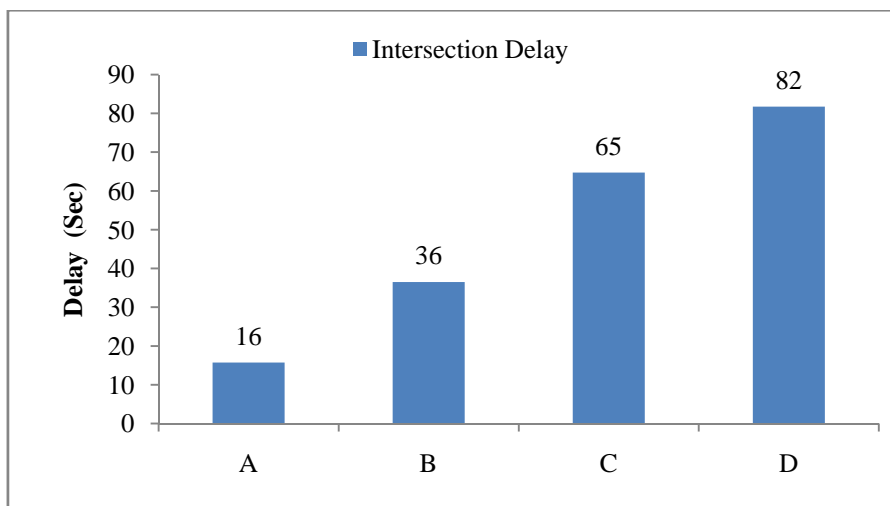


Figure 11: Movement based intersection delay

The above observations can be further updated to reflect the travel time of study stretch through the integration of intersection delay, delay in mid-block area i.e. upstream and downstream areas for the study stretch (850 m) with reference to speed of 40 kmph for LoS C (Table 5). In case of movement 'A', generally vehicles lead the flow; therefore, mid-block delay is on lower side as compared to other movements. Graphical representation of total delay and total travel time for the study stretch are given for each movement situation in Figure 12. The travel time varies for four situations (A, B, C and D). However, one has to note that movements in C situation can be more than all situations, if degree of saturation moves on higher side, wherein vehicles cannot clear in one cycle. Therefore, variations in travel time prevail subjected to proportion of four movements in the traffic stream with reference to signalized system at the intersection.

Table 5: Delay particulars of study stretch (Seconds)

Movements	Intersection Delay	Mid-Block Delay	Total Delay
A	16	20	36
B	36	20	56
C	65	22	87
D	82	13	95

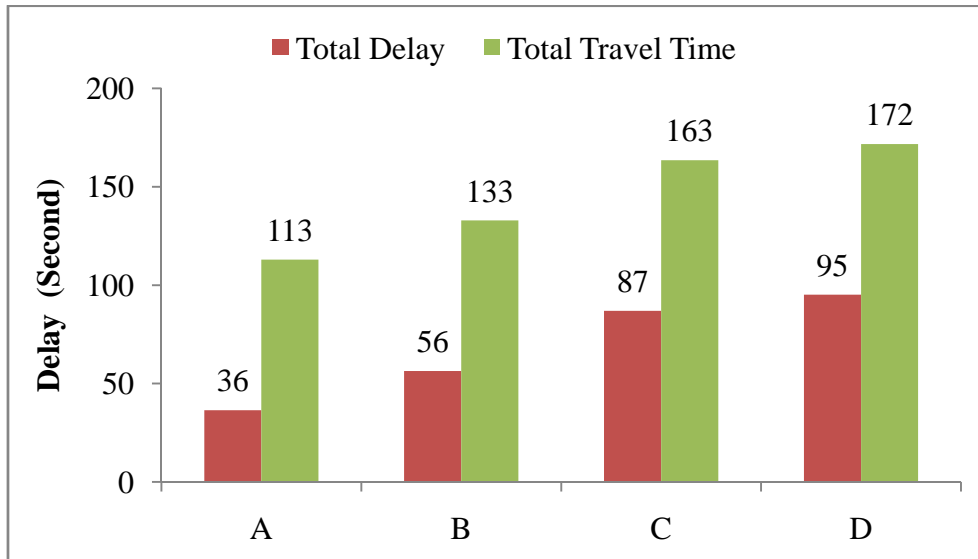


Figure12: Total delay and total travel time

7 Discussion and Conclusion

Travel Time Variability is the main aspect of Travel Time Reliability for the planner and as well the commuters in the urban transport system. As framework of the policy for the design, planning and operation is associated with travel time variability as guiding factor, on the other hand route and mode choice and departure time planning are decisive factors for the commuters. Number of attributes related to traffic, road category and traffic control system and the movement time, whether peak or off peak matter in deciding in travel time, delays and their variations. Here the role of signalized intersection on travel delay is quite significant. Observation of Liu et al. (2006) is that nearly 50% of travel time delay is on account of intersection and so pleaded by Zheng (2011) the variability of travel time that vehicle experience on urban arterial road segments are mainly related to signalized intersection.

The study here emphasizes, the intersection delay with reference to mainly two aspects: spatial movement of the vehicles across the intersection, secondly the movement pattern subjected to signal indicators. Spatial movement are considered in three zones as 'dilemma and decision zone', 'intersection conflict zone' and 'speed normalizing zone' attached with mid-block section on both ends. Decision on stopping, queue joining or entering into intersection and clearing straightway are part of the first zone. Deceleration is the main operation in intersection conflict zone to stop the vehicle or join the queue if the red signal prevails, whereas the speed normalizing take place for the vehicle that has stopped or moving from the queue to attain the normal speeds of mid-block.

The speed profile goes down from mid-block to dilemma zone and further decreases for the stopping condition with high deceleration or queue moving condition in intersection conflict zone and again starts rising with high acceleration rate to reach the mid-block speed in normalization zone. In terms of delays, on other hand delay goes on increasing to the maximum at the stopped condition from dilemma zone and decreases in normalization zone to reach the mid-block speed. For 2W Probe vehicle delays

(Seconds) observed are 5, 30 and 7 for the three zones respectively, whereas delays (Seconds) are 6, 40 and 16 for 3W Probe vehicle in present study. The delay profile slightly differ from mode to mode and the minimum delay profile is for the 2W compare to 3W, 4W and Commercial Vehicles because higher scope of maneuverability and finding gaps to move ahead for the 2W. The commercial vehicles have lower acceleration and deceleration rate. Higher delay for 3W substantiates the lower delays in 2W.

Four patterns of movements prevail at the signalized intersection i.e. non-stopped flow (A), non-stop but part of moving queue (B), joining the queue and stopping (C) and stopping at commencement of red signal (D). Delays (sec) values observed for the four movements patterns are 16, 36, 65 and 82 respectively. Obviously C and D situations are more crucial because of red signal and magnitude of the same. In order to reduce the delay the attempt should be to increase the movement in 'A' pattern with provision of more green period subject to signal design consideration for the prevailing traffic condition. Various delay components presented in the study find the place in calculation of total delays and delay variations to link with travel time variations.

References

- Boyles, S. D., Voruganti, A., Waller S. T. (2010) "Quantifying Travel Time Variability in Transportation Networks", *Center for Transportation Research University of Texas at Austin, Texas*.
- Chen, P., Liu, H., Qi, Hong-sheng, Wang, F. (2013) "Analysis of Delay Variability at Isolated Intersections", *Journal of Zhejiang University-Science A 14 (10)*, pp. 691-704.
- Darma, Y., Karim, R. Md., Jamilah, Md., Abdullah, S. (2005) "Control Delay Variability at Signalized Intersection based on HCM Method", *Proceeding of the Eastern Society for Transportation Studies, 5*, pp. 945-958.
- Feng, W. (2014) Analysis of Bus Travel Time Reliability and Transit Signal Priority at the Stop – to- Stop Segment level, *Ph.D. Thesis*, Portland State University, US.
- Fu, L., Hellinga, B. (2000) "Delay Variability at Signalized Intersections", *Transportation Research Record, Paper No –00-0810*.
- Gupta, S. "Delay at Signalized Intersection", Traffic Engineering, *Indian Institute of Technology, Kanpur, India*.
- IRC SP 41-1994 "Guidelines for the Design of at Grade Intersections in Rural and Urban Areas" published by *The Indian Road Congress, New Delhi, India*.
- IRC: 106 (1990) "Guidelines for Capacity of Urban Roads in Plain Areas" published by *The Indian Road Congress, New Delhi*.
- Liu, K., Yamamoto T., Morikawa T. (2006) "Estimating Delay Time at Signalized Intersections by Probe Vehicles" *Proceedings of International Conference on Traffic and Transportation Studies (ICTTS), 2006: pp. 644-655*.
- Lomax, T., Schrank, D., Turner, S (2003) "Selecting Travel Reliability Measures" *Texas Transportation Institute, US*.
- Preethi, P., Varghese, A., Ashalatha (2014) "Modelling Delay at Signalized Intersections under Heterogeneous Traffic Conditions" *11th Transportation Planning and Implementation Methodologies for Developing Countries, Mumbai, India*.

- Yang, Z., Tian, X., Wang, W., Zhou, X., Liang, H. (2014) “Research on Driver Behavior in Yellow Interval at Signalized Intersections”, *Hindawi Publishing Corporation Mathematical Problems in Engineering*, (2014), pp.1-8.
- Zheng, F. (2011) Modelling Urban Travel Times *Ph.D. Thesis*, Delft University of Technology, Netherlands.