Modelling U-turning behaviour of vehicles at mid-block median openings in multilane urban roads

Ankit Gupta*, Satyajit Mondal and Vinay Kumar Sharma

Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi 221 005, India

Gap acceptance and lateral placing of vehicles are considered as prime parameters for analysing the behaviour of U-turning in vehicles at un-signalized median opening in urban areas. Critical gap is the sole parameter in gap acceptance phenomenon where critical position gives the vehicle's location during U-turn operation. Data for this study were collected using video photography at six median openings on a six-lane road and three median openings on a four-lane road from two different cities of India. Data as extracted by categorizing the traffic stream into five different classes such as two-wheelers, three-wheelers, car/SUVs, LCVs (light commercial vehicles) and HCVs (heavy commercial vehicles). Three different methodologies (namely the traditional method, INAFOGA and modified Raff's method) were utilized to estimate the critical gap. Critical position of vehicles is estimated using the markings on the pavement surface. Regression technique was used for modelling critical gap and position using different variables for each motorized mode. All the proposed models have a high coefficient of determination value which indicates its high significance level. Modelling of critical position for 3-wheelers was not framed as the *P*-value for each variable was higher than 0.05. The reason could be the randomness in data because of the undisciplined lateral movement of three-wheelers. A design recommendation for right turn pocket lanes near the median opening area is proposed especially for U-turning traffic based on the percentage of the U-turning traffic and maximum critical position of vehicles from the median edge.

Keywords: Critical position, critical gap, gap acceptance, median opening, U-turning vehicles.

RAPID civilization has increased the number of vehicles significantly in the last two decades. In most of the signalized intersections, U-turning movements are not permitted so as to improve the operational condition of intersection by optimizing the conflict points. Hence, openings are provided in the median in divided urban roads at an adequate interval particularly for U-turn operations. Median openings are quite effective to access opposing traffic without creating any conflicts between the vehicles travelling through the stretch and vehicles taking U-turn operation. While the turning operation through median openings is complex due to the opposing high speed traffic stream. Most of the median openings in India are uncontrolled. Thus a U-turning vehicle needs to accept a time or gap between the arrivals of successive vehicles through traffic of the opposite lanes to perform a safe turn. This is the gap acceptance phenomenon of U-turning vehicles. Critical gap is the time gap between two successive vehicles during which a U-turning vehicle may decide to cross or merge with the traffic stream. It is the minimum time interval that allows a vehicle to merge or cross the opposite traffic flow safely. The duration of critical gap affects the waiting time and merging time of the U-turning vehicles and also the behaviour of vehicles in the opposite traffic stream. Values of critical gap that are accepted vary for different vehicle classes and are dependent on various parameters such as types of U-turning vehicles, several stream parameters of opposing lane traffic, geometrical elements of the carriageway including the median, etc. The U-turn operation sometime creates congestion resulting in reduction of roadway capacity in both the vehicle approach lanes. In most cases, it is observed that a larger radius is required for huge vehicles to turn 180 degrees which increases the delay, fuel consumption and are prone to accidents[1]. U-turning region is defined as a hypothetical road space where a larger number of automobiles try to share the available space at the same time, thus creating more conflict as shown in Figure 1. Critical position is the distance of

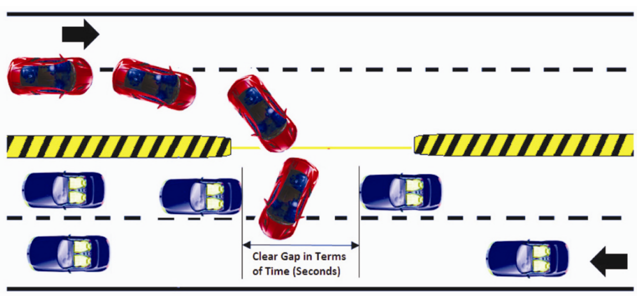

Figure 1. U-turning operation at median opening.

*For correspondence. (e-mail: ankit.civ@iitbhu.ac.in)

the left wheels of a merging vehicle from the median edge when the vehicle starts to merge with the opposing traffic through median opening. U-turning vehicles choose their possible position at the median opening area based on vehicle dimension and gaps between standing vehicles.

Capacity estimation of these median openings is significantly critical as all the parameters are discrete in nature, making it more difficult to formulate a suitable methodology for Indian non-lane based heterogeneous traffic stream. Hence, two major aspects such as critical gap and critical position are evaluated for each motorized mode at uncontrolled median openings. Therefore, this study considers the following objectives:

- To analyse the effect of lag, accepted gap, rejected gap and merging time on critical gap of U-turning vehicles.
- To evaluate the effect of carriage way width, accepted gap and merging time on critical position of U-turning vehicles.
- To develop a model for critical gap and critical position of different U-turning vehicles at uncontrolled median openings under mixed traffic conditions.

Literature review

Many studies have been made in the last few decades to understand the gap acceptance[2–7,9–11] and position of vehicles[11–16], especially in the case of median openings. Various methodologies and models were accepted related to gap and position of vehicles, though most of them were basically suited for homogeneous traffic conditions. The majority of studies usually considered the accepted and rejected gaps as the prime variables for evaluating critical gap of vehicles. The critical position was estimated based on the position of the left side of the four wheelers position at the median opening during their U-turn operation. In the case of two-wheelers, the front wheel was considered as it specifies the vehicle position correctly.

Studies on gap acceptance

The estimation of critical gap is a key parameter to analyse and design a median opening. It is difficult to measure the critical gap from the field directly. A number of studies were conducted on gap acceptance of vehicles since the last few decades especially in median openings. The gap acceptance behaviour was also analysed for vehicles travelling through uncontrolled intersections. Results obtained[2] show that the distribution of critical gap is influenced by the driver's socio-economic characteristics, except waiting time, time of day, and trip purpose. While the mean critical gap is influenced by the total opposing traffic flow, number of major-approach lanes, presence of a median with a right-turn lane, manoeuvre type, speed of vehicles on major roads and time of the day. The driver's psychology has a significant influence on gap acceptance especially during congestion[3]. Also, during recurring congestion smaller gaps are accepted by the drivers which lead to a significant impact on field capacity. Various studies have proposed several methodologies[4–6] for critical gap estimation. Methodologies like likelihood procedure, Hewitt's method and influence area for gap acceptance (INAFOGA) method are effectively used worldwide although, certain significant differences are observed for estimation of critical gap between each of the methodology[5]. For developing countries, studies have reported that the critical gap values obtained by INAFOGA method were 28–41% more than those obtained by Harder's method[6] were 18–31% more than that obtained by the Probability Equilibrium method and were 5.93% and 16.38% more than the values obtained by Traditional and Modified Raff's method respectively[7]. Application of simulation approach provides a satisfactory result where researches have concluded that the total delay, the average delay and average queue length per vehicle increased nonlinearly with increase in flow levels[9]. Though several methodological approaches are available for critical gap estimation, merging behaviour approach is found more suitable than other methods due to its methodological background and this behaviour of vehicles is considered to estimate the gap values[10]. The gap value of vehicles obtained using merging behaviour approach decreases with increase in approaching traffic.

Studies on vehicle's position

A significant effort was made by researchers to find the vehicle's position during its U-turn operation at the median area. The critical position of vehicles is an important element for designing the median area as well as carriage way of the road section. Several influencing factors on lateral position of vehicles are analysed. The presence of edge line on the road has a significant impact on speed and lateral position of motorized road users[11]. Researchers found that the lateral position of vehicles towards the centre line shifted with change in speed of the vehicles and analysed the variation in the shifting of lateral position in the absence and presence of edge line on the road. Distribution of lateral position is also analysed[12] for mixed traffic stream where the result shows that the placement of vehicles may follow a unimodal or a bimodal curve depending on the percentage of slow and fast moving vehicles. A new method was introduced for determination of the lateral position by observing the vehicle's heading angle through a homographic and Lucas-Kanade optical flow techniques[13]. Whereas the lateral speed was determined by the heading angle and the vehicle's on-board diagnostic (OBD) system. The effect of various elements like road edges, divider, electric poles and raised footpaths on the vehicle's movement as well as on lateral placement was analysed in multilane highways with the use of ultrasonic sensors assembly[14]. Results show that the variation in lateral gap in a median lane for mixed traffic is greater for multilane highways. An increasing trend in variation of the lateral gap in the shoulder lane was also observed for the 6 and 8-lane highways whereas a decreasing trend was observed in the case of 4-lane highways. The results also illustrate that 70% of the lateral gap of all three highways varies from 50 cm to 150 cm in distance from the road edge, whereas two-wheelers (2W) maintain 50–100 cm lateral gap from the road edge. The presence of heavy vehicles significantly influences the driver's behaviour and lateral movement of vehicles[15]. Several conflict points are formed in the median opening area for the non-controllable movement of vehicles through the openings. Therefore, identification of the conflict zone is a major element for designing a U-turn opening especially for mixed traffic streams. Researchers have found that the critical position of a vehicle is influenced by the vehicle size and the road width and it follows a unimodal, bimodal or gamma distribution depending on the road-types (4-lane or 6-lane) and proportion of motorized 2W in the turning volume[16].

Most studies on vehicle positions were done for through traffic movement in a straight section or for an uncontrolled intersection. Limited studies[16] have been made on vehicle's critical position near the median opening especially for urban roads. Therefore, the present study considers evaluating the critical position of U-turning vehicles at the mid-block median opening for multilane urban roads.

The turning movement at the median area significantly influences the traffic stream parameters in both carriage ways. Sometimes, the turning movements create congestion in the opposite through traffic movement, enhances major accidents and interrupts the flow condition of the traffic stream, and results in reduction of capacity of the road section. The queued up U-turning vehicles create a bottleneck condition for the through traffic stream which reduces the stream speed and its capacity. Therefore, problems tackled by drivers at the median openings enhance the interest to study the behaviour of U-turning vehicles at median openings. Several studies have proposed different methods to estimate critical gap[6,7,9,10] and critical position[16] for median openings. The present study attempts the estimation of critical gap using three different methods namely traditional method, INAFOGA method and the modified Raff's method. The critical position of vehicles is estimated using strips marked on the pavement surface at an equal interval of 25 cm each in the field.

Research methodology

The estimations of critical gap and critical position are two important elements to analyse and design a median opening. It is difficult to measure the critical gap directly from the field. However, the accepted and rejected gap of U-turning vehicles can be estimated directly from the field which can be processed using different existing methods for critical gap estimation. In this study, three different methodologies namely traditional method[6], INAFOGA method[7] and the modified Raff's method[10] were utilized for estimation of critical gap. Each method considers different parameters in critical gap estimation. Therefore to obtain a specific value of critical gap for each vehicle type, three methodological approaches are considered. However, in critical position estimation, the carriage way width was divided into a number of sections at 25 cm interval and serially marked from the edge of the kerb to the end of the road section. The markings on the road were made at distances 2.5 to 3.0 m from the start of the opening portion. A flow chart of methodological approach for estimation and modelling of critical gap and critical position is given below (Figure 2).

Study area and data collection

Selection of study area

Mid-block median openings on 4- and 6-lane divided urban roads were considered based on various criteria such as the sections to be free from the signalling system or signs, effects of curves, gradient, side friction, on-street parking, pedestrian movement and non-motorized vehicles. The effect of speed for U-turning vehicles was also neglected. A total of nine median openings from two major cities such as Varanasi and Jabalpur from different states of India were considered. Initially, it was observed that the percentage of vehicles making U-turn at median openings was proportionately higher as the distance of the opening increases from the nearest intersection. Hence a minimum distance of 250 m was considered for the selection of each median opening from its nearest intersection shown in Figure 3. The details of the study sections are shown in Table 1.

Data collection

Data for this study were collected at nine selected median openings in urban areas using video recordings. The recording was done from the top of a building by fixing a camera on a tripod so that the entire median and its vehicular movements can be captured. Figure 4 shows the layout of markings on the pavement surface at an interval of 25 cm for collecting vehicles' position data. Field data were collected during the peak hours of morning and

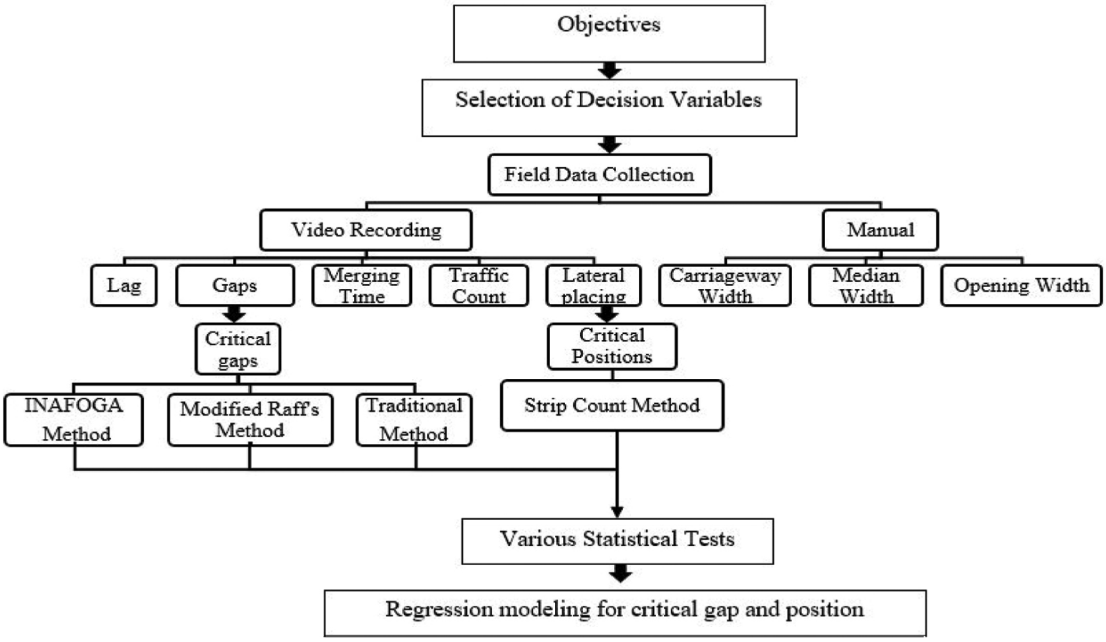

Figure 2. Framework of the present study.

Table 1. Details of the selected study sections

Section	City	Type of carriageway	Width of median opening (m)	Width of median (m)	Width of carriageway (one direction; m)
1	Jabalpur (MP)	6 lane	10.90	1.65	12.32
2			18.75	1.65	12.80
3			11.20	1.65	10.80
4			10.90	1.65	10.50
5			5.10	1.65	12.10
6			4.90	1.65	12.85
7	Varanasi (UP)	4 lane	3.80	1.13	8.90
8			3.50	1.05	7.03
9			6.00	0.80	7.10

evening between December 2015 and February 2016 on typical weekdays.

Data extraction

The field data collected at the selected study sections were extracted to obtain different traffic stream parameters. The traffic flow condition was purely heterogeneous at the study sections, consisting of different categories of vehicles. It was also observed that the same category of vehicles had different vehicle models. All vehicles in the traffic stream were grouped and divided into several categories such as 2-wheelers, 3-wheelers, car/SUV, light commercial vehicles and heavy commercial vehicles (bus, truck, tractor without trolley, traveler, etc.). Essential data were extracted from the recorded video and processed for modelling of critical gap and critical position for individual vehicle category.

Traffic characteristics

Initially the vehicles count in through and U-turning region was extracted by playing the recorded video at a work station. The composition of individual vehicles through traffic and U-turning traffic was estimated for all study sites (Table 2).

Characteristics of merging vehicles

INAFOGA was drawn at the U-turning region using callouts in the Camtasia. Figure 5 shows a rectangular area ABCD where the line BE represents the stop line of the U-turning vehicles after approaching the median opening. The lines CD and AB are the upstream and downstream ends of INAFOGA. The line AB is drawn, from where the U-turning vehicles finally move straight with the conflicting traffic of the opposite lane. Table 3 shows the

Table 2. Compositional share of individual motorized mode at selected study sections

	Traffic volume (veh/h)			Composition of through traffic (%)					Composition of U-turning traffic (%)				
Site	Total	Through traffic	U-turning traffic	2W	3W	CAR/SUV	LCV	HCV	2W	3W	CAR/SUV	LCV	HCV
1	3215	2685	530	62.9	5.8	12.6	1.1	1.1	9.8	2.6	3.4	0.4	0.2
2	1859	1733	126	55.5	15.3	16.7	1.9	3.8	4.9	0.7	0.8	0.3	0.1
3	2257	2103	154	60.0	12.6	13.7	1.6	3.1	4.0	0.6	0.6	0.3	0.1
4	2469	2170	299	70.0	9.0	11.9	2.4	2.7	2.9	0.2	0.6	0.2	0.1
5	2579	2330	249	56.2	23.3	15.9	2.6	0.9	0.5	0.3	0.2	0.1	0.0
6	2885	2561	324	56.2	21.9	17.0	3.2	0.9	0.3	0.2	0.2	0.1	0.0
7	711	515	196	50.6	5.9	11.0	4.5	0.4	7.7	5.1	11.0	3.5	0.3
8	2984	2214	770	44.0	12.3	9.9	5.4	2.6	9.0	9.3	4.4	2.8	0.3
9	2674	2124	550	31.3	28.0	12.2	6.2	1.7	7.0	10.7	2.1	0.7	0.1

Table 3. Details of gap variables of individual vehicle type

Type of carriageway	Vehicle type	Lag (s)			Accepted gap (s)			Rejected gap (s)			Merging time (s)		
		N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
4-lane	2-TW	1579	2.43	1.31	1579	4.44	2.33	1579	2.89	1.95	1579	3.62	1.61
	3-W	1143	3.26	1.15	1143	5.13	3.57	1143	2.72	2.21	1143	3.45	1.24
	Car/SUV	1128	2.58	1.34	1128	7.14	4.70	1128	2.60	1.97	1128	4.89	2.11
	LCV	147	2.76	1.23	147	6.64	3.61	147	2.50	2.26	147	4.81	1.89
	HCV	25	2.13	1.14	25	5.62	2.91	25	3.22	1.51	25	5.05	1.24
6-lane	2-TW	1571	1.18	1.02	1571	3.64	2.42	1571	1.33	1.09	1571	2.70	1.27
	3-W	1176	1.44	1.07	1176	2.80	1.33	1176	1.78	1.23	1176	3.87	2.76
	Car/SUV	1519	1.45	1.18	1519	4.14	1.70	1519	1.99	1.08	1519	3.27	1.04
	LCV	227	1.20	0.98	227	4.46	1.87	227	1.77	1.03	227	3.62	0.64
	HCV	52	2.79	1.12	52	4.15	2.58	52	3.39	2.54	52	3.59	0.61

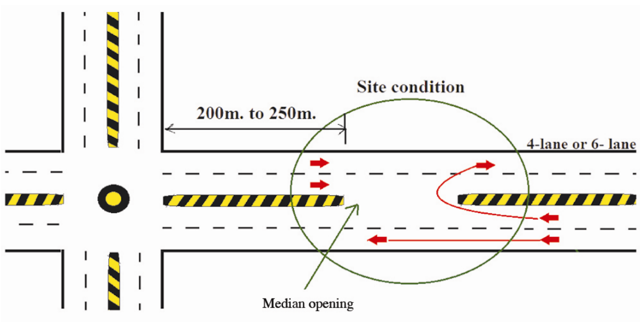

Figure 3. Layout of site condition.

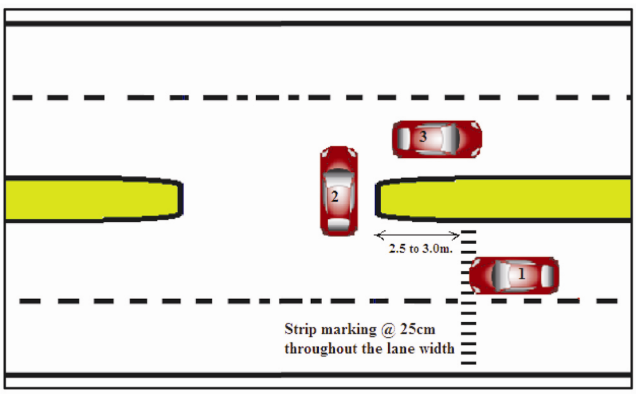

Figure 4. Layout of vehicle's position data collection.

mean value of gap variables to evaluate critical gap for individual vehicle types at 4- and 6-lane divided urban roads.

Position for each vehicle type was calculated using strips marked on the pavement surface at a suitable interval. Critical position of vehicles was calculated from the median edge based on the position of the vehicle in the marked area while taking the U-turn operation. The details of critical position for each vehicle type are shown in Table 4 at the selected study sections.

Analysis and results

Estimation of critical gap

The critical gap was estimated for each motorized mode taking U-turn through median openings using the three different methods mentioned earlier. The frequency distribution based on different aspects was plotted using the above three methods where the intersection point gives the critical gap value for a certain motorized mode. Figure 6 shows the frequency distribution plot for car/SUV on 4- and 6-lane divided roads using the three different methods. The values of critical gap of other motorized modes are given in Table 5 for each study section.

Table 4. Descriptive statistics for critical position (cm) from median edge

	2-W			3-W			Car/SUV			LCV			HCV		
Site	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
1	263.99	92.19	513	388.50	93.57	376	457.49	104.26	497	558.33	105.7	75	792	88.24	25
2	270.12	83.60	343	383.12	88.44	197	452.93	93.28	222	532.69	91.31	39	763.9	35.57	9
3	268.24	85.16	185	378.94	86.78	146	443.78	88.62	221	520.27	94.94	37	778.1	29.15	8
4	264.04	91.38	219	372.26	85.88	155	432.32	89.09	198	539.88	98.96	42	752.5	43.94	10
5	267.00	85.21	200	381.32	76.46	170	461.05	97.35	181	561.25	84.21	20	–	–	–
6	275.68	79.66	111	391.67	85.21	132	453.88	89.76	200	544.64	49.26	14	–	–	–
7	281.05	92.69	537	394.21	87.84	367	450.82	89.91	336	575.00	61.24	27	677.5	52.97	10
8	259.53	85.16	522	384.61	83.19	380	425.56	91.11	401	524.36	101.3	78	647.7	24.89	11
9	261.78	84.35	520	384.91	74.31	396	419.82	87.25	391	507.14	79.48	42	681.3	20.73	14

Figure 5. Schematic diagram of influence area for gap acceptance on a 6-lane divided carriageway in Camtasia 8.6.

Statistical significance of estimated gap values

Single factor ANOVA test was applied for comparing the means to find out the significant relation between various variables of the three different methods. Tables 6 and 7 list the detailed values after applying the ANOVA test.

It is observed from the above table that there is no significant difference in estimated gap values obtained by the three methods and the null hypothesis can be accepted. As the methods use different parameters for calculating critical gap, a paired *t*-test was applied on each pair of two methods to check its significance from each other.

Tables 8–10 show the results of the paired *t*-test performed on each pair. This indicates that there is no significant difference between traditional and INAFOGA method as the *P*-value is >0.05 and the *t*-critical value is also greater than *t*-stat. But the results in Tables 9 and 10 show a significant difference between the concerned methods due to its lower *P*-value and higher *t*-stat value than *t*-critical.

Estimation of critical position

The term 'critical position of merging vehicles' indicates the distance of the left wheels (for left hand drive conditions) of a merging vehicle from the edge of the pavement, i.e. curb side when the vehicle merges at an uncontrolled median opening[16]. The position for an individual vehicle near the median opening was estimated by dividing the pavement width into a number of sections at an interval of 25 cm. As the Indian traffic stream is operated by its left side regulation process, the left part of a merging vehicle is more critical while taking the U-turn operation. Therefore, the position of the left front wheel was observed for each vehicle type while the rear left wheel was considered to estimate the position for motorized 3-wheelers. The estimated position of individual vehicle type was used to generate the frequency table with the least count of 25 cm, to calculate the critical position of each vehicle type. The mean and standard deviation of the critical position were calculated from the frequency distribution plots. Figure 7 gives the frequency distribution plots for each vehicle type for the study section 1.

Figure 7 shows that the frequency data points for each vehicle type follow a normal distribution for study section 1. Each distribution plot shows a high R^2 value, indicates the statistical significance of the field data points. The frequency distribution for each vehicle type is plotted to calculate the mean critical position at every study sections. The mean critical position of vehicles at 4- and 6-lane roads is shown in Figure 8.

It is observed from Figure 8 that the value of the critical position of two wheelers is lesser while HCV has the highest value. It was observed in the field that most of the 2-wheelers were waiting near the kerb side of the inner lane to take the U-turn operation. The critical position of a 2-wheeler is smaller because of its small physical area with less requirement of turning area during U-turn operation. The higher manoeuvrability characteristic of the 2-wheeler facilitates an effortlessness merging with the opposite traffic using lesser road width near the median opening. While the larger physical dimension and less manoeuvrability characteristics of HCVs are the main reasons for high value of mean critical position. It also needs a larger turning radius during the U-turn operation. Figure 8 also shows that with increase in the

Table 5. Critical gap values of different U-turning vehicles at the study sections

Section	Vehicle mode	Critical gap(s) for U-turns at median opening by existing methods (s)		
		Traditional	INAFOGA	Modified Raff
Khalsa College (MP)	2W	2.62	2.62	2.47
	3W	2.63	3.00	2.23
	Car/SUV	3.12	3.71	2.75
	LCV	3.11	3.7	3.16
	HCV	4.89	3.96	3.17
Tripuri Chowk (MP)	2W	2.68	2.62	2.46
	3W	2.62	3.04	2.24
	Car/SUV	3.18	3.79	2.82
	LCV	4.01	3.91	3.78
	HCV	4.98	4.79	4.26
Medical bus stand (MP)	2W	2.71	2.63	2.48
	3W	2.73	3.01	2.25
	Car/SUV	3.02	3.81	2.74
	LCV	3.16	3.89	3.71
	HCV	5.02	4.11	3.94
Khalsa College (MP)	2W	2.82	2.55	1.96
	3W	2.58	3.17	2.06
	Car/SUV	3.16	3.63	2.65
	LCV	3.05	3.86	3.14
	HCV	3.98	3.86	3.18
Medical College (MP)	2W	2.38	3.97	2.07
	3W	2.8	3.53	2.69
	Car/ SUV	3.18	3.67	2.86
	LCV	3.24	3.72	3.09
	HCV	–	–	–
Medical College opposite side (MP)	2W	3.17	3.29	2.87
	3W	2.82	3.51	2.73
	Car/SUV	5.2	4.08	5.86
	LCV	4.31	3.56	3.21
	HCV	–	–	–
Ramnagar highway (UP)	2W	4.09	4.8	6.2
	3W	6.8	5.2	6.45
	Car/SUV	8.6	5.1	7.6
	LCV	4.38	4.73	4.32
	HCV	3.95	3.97	5.47
Old loco colony (UP)	2W	3.94	3.95	2.12
	3W	2.83	3.59	2.73
	Car/SUV	3.98	4.96	3.5
	LCV	2.95	4.2	2.91
	HCV	2.32	3.1	2.86
Railway station (UP)	2W	5.12	3.53	3.13
	3W	3.51	3.25	2.77
	Car/SUV	4.37	5.97	4.15
	LCV	4.52	4.8	4.2
	HCV	5.46	5.49	5.44

vehicle size, the mean critical position of vehicles is also increasing.

Significance of the observed data: a statistical approach

A statistical approach (χ^2 test) was used to check the significance of the observed data. The test was done separately for each motorized mode at every section. The final result is summarized in Table 11.

The mean critical position for different categories of vehicles at each section on 4- and 6-lane roads was calculated and presented in Table 11. The χ^2-test was applied to check its statistical significance. Table 11 shows the result of χ^2-test where the critical value of each vehicle type is greater than the χ^2 value at 24 degrees of

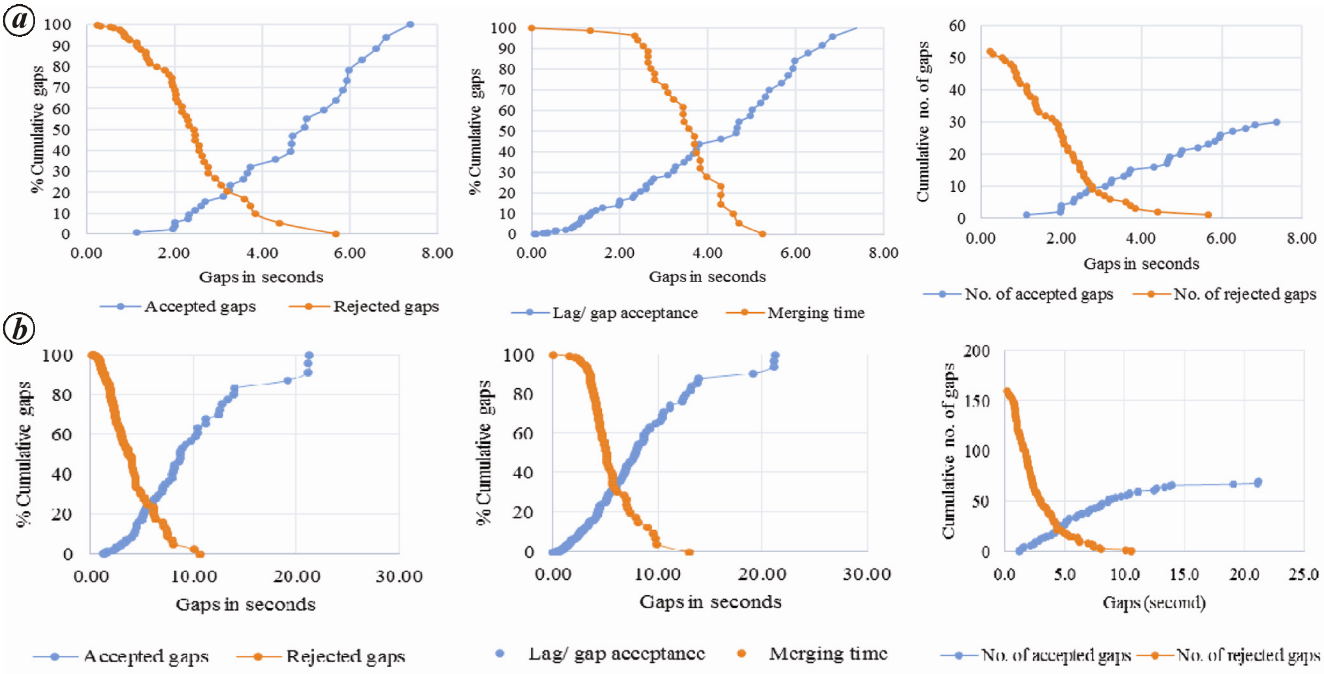

Figure 6. Frequency distribution plot for cars/SUV using traditional method, INAFOGA method and modified Raff's method on (***a***) 4-lane and (***b***) 6-lane roads.

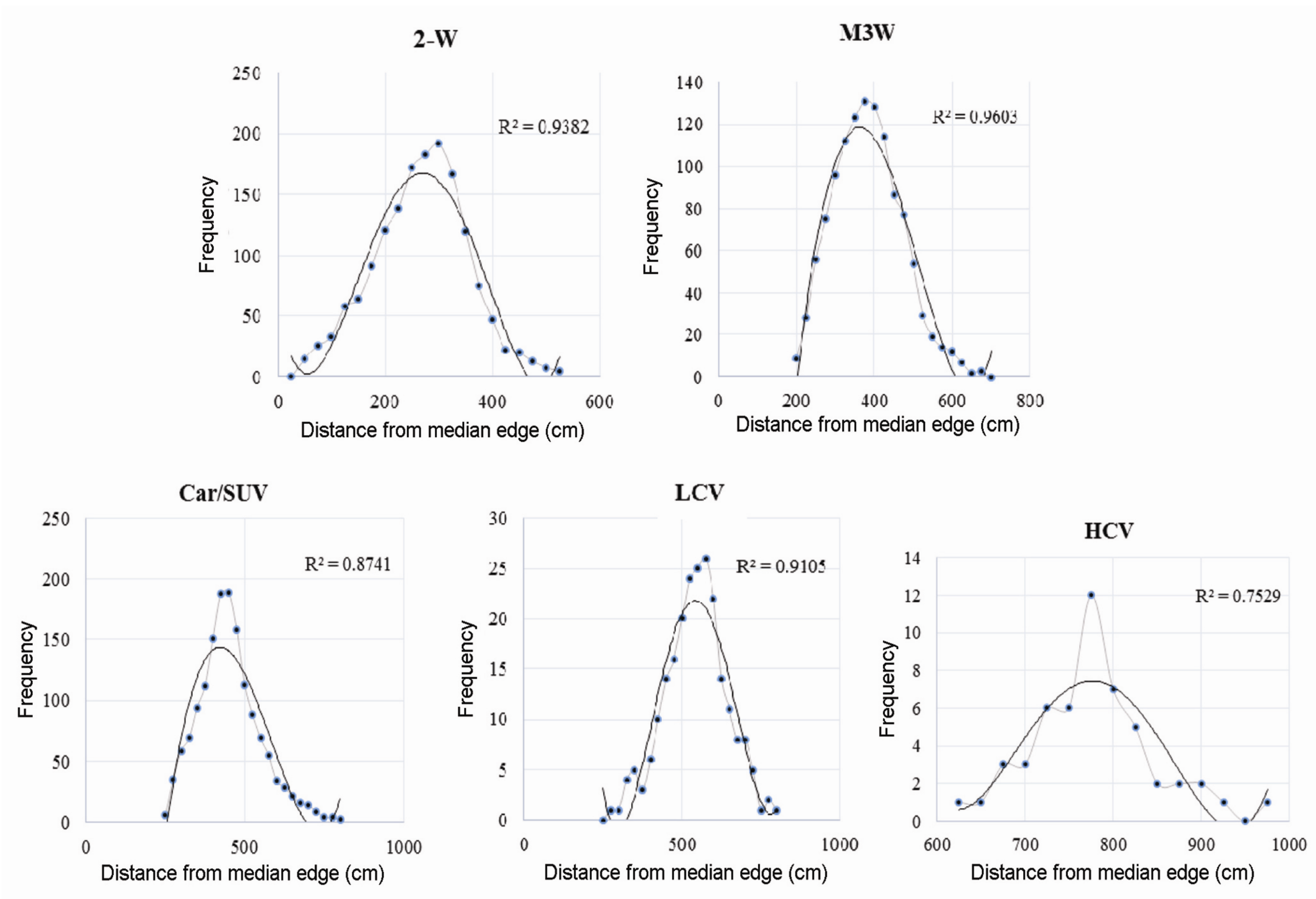

Figure 7. Frequency distribution plots for each vehicle type at study section 1.

freedom and 5% level of significance. It is seen from Table 12 that critical values are greater than the χ^2 value at 4 degrees of freedom and 5% level of significance with higher P-value 0.274 (>0.05), indicates no significant difference between observed and expected values.

Modelling of critical gap

Modelling of critical gap was done considering five different variables such as lag, accepted gap, rejected gap, merging time and conflicting traffic. Regression technique was used to find the empirical relation between the critical gap and independent variables. A base model was first formed for each category of vehicles considering the independent variables. Statistical t-test was applied to check the significant differences between the independent variables considering the base model. The variables whose probability value is less than the significance level (5%) were only considered in the final modelling of critical gap for each category of vehicles.

Table 13 lists the variables with its significant value considered in the final modelling for each vehicle type. Five individual models were proposed for each vehicle type and a generalized model fit to each vehicle class was developed. It was observed that all the proposed models had a high R^2 value which indicates the high implication level of each model except the model proposed for LCVs. The models obtained can be used to estimate the critical gap values using merging time and accepted gap values of vehicles.

Table 6. Descriptive statistics of critical gap

Groups	Count	Sum	Average	Variance
Traditional	36	129.39	3.59	1.60
INAFOGA	36	136.35	3.79	0.62
Modified Raff	36	118.36	3.29	1.75

Table 7. Result of ANOVA test

	ANOVA					
Source of variation	SS	DF	MS	F	P-value	F-critical
Between groups	4.57	2	2.29	1.72	0.18	3.08
Within groups	139.24	105	1.33			
Total	143.82	107				

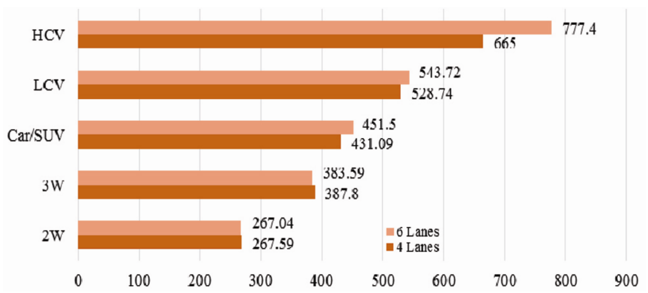

Figure 8. Mean values of critical position of each vehicle type on four lane and six lane divided urban road.

Modelling of critical position

Modelling of critical position was done by considering four different variables such as critical gap, merging time, width of the carriageway and accepted gaps. Multi-linear regression modelling was used to find out the relation between the critical position and the variables. A basic model was formed using significant variables for each vehicle type. A statistical test was applied to check the significance of each variable considered in the base model. The variables whose probability value is less than the significance level (5%) were only considered in final modelling of critical position.

The basic model for two wheeler

$$T_p = 210.04 + 8.64*T_c + 0.03*T_{wc}. \quad (1)$$

The basic model for car/SUV

$$T_p = 363.89 + 4.107*T_a + 0.057*T_{wc}. \quad (2)$$

The basic model for LCV

$$T_p = 289.37 - 55.53*T_c + 47.98*T_{mg} + 25.31*T_a + 0.14*T_{wc}. \quad (3)$$

The basic model for HCV:

$$T_p = 1041 - 73.33*T_{mg}. \quad (4)$$

The basic model for common motorized mode

$$T_p = 199.59 - 73.13*T_c + 75.20*T_{mg} + 47.70*T_a, \quad (5)$$

where T_p is the critical position (cm), T_c the critical gap, T_{mg} the merging time, T_a the accepted gap in seconds and T_{wc} is one-way width of carriage way in cm.

Tables 14–18 show the details of regression analysis with statistical results of the variables. It was observed that all the proposed models had high R^2 value which indicates the high implication level of each model except for common motorized mode. Modelling of critical position for three wheelers was not framed as the P-value for each variable was higher than 0.05. The reason could be the random data obtained because of the undisciplined lateral movement of 3-wheeler drivers.

Discussion

The present study analyses the vehicle's gap and position during its U-turn operation through the median openings

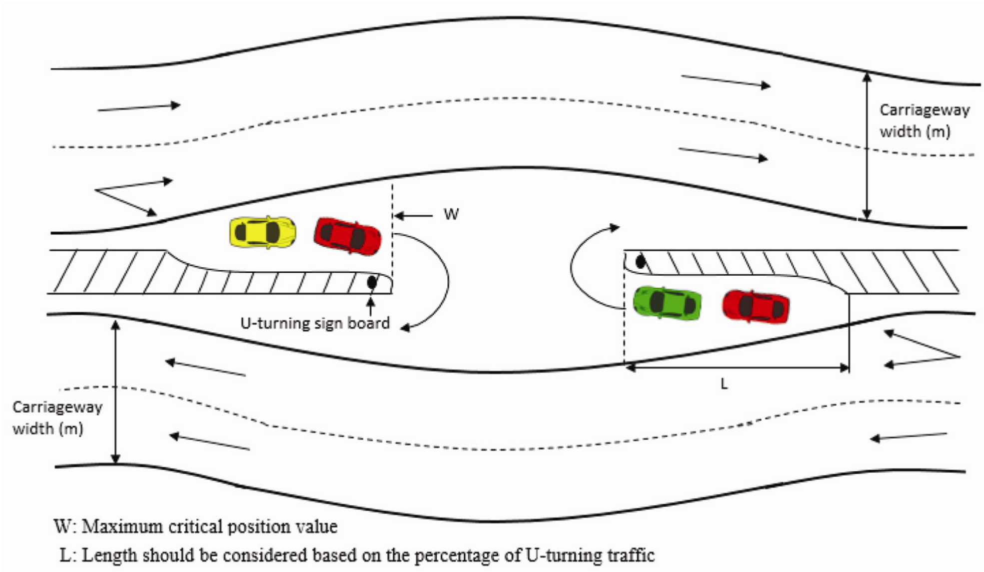

Figure 9. Proposed pocket lane design near the median opening area.

Table 8. Results of paired *t*-test between traditional and INAFOGA methods

Groups	Count	Mean	SD	SE	*t*	DF
Traditional	36	3.59	1.27			
INAFOGA	36	3.79	0.79			
Difference	36	–0.19	0.96	0.16	–1.21	35
t-test	*P* value	*t*-Critical	Lower	Upper	Significance difference	
One tail	0.12	1.69			No	
Two tail	0.23	2.03	–0.52	0.13	No	

Table 9. Results of paired *t*-test between INAFOGA and modified Raff's methods

Groups	Count	Mean	SD	SE	*t*	DF
INAFOGA	36	3.79	0.79			
Modified Raff	36	3.29	1.32			
Difference	36	0.50	0.94	0.16	3.21	35
T-test	*P* value	*t*-Critical	Lower	Upper	Significance difference	
One tail	0.001	1.690			Yes	
Two tail	0.003	2.030	0.183	0.816	Yes	

for divided urban roads. Data were collected using the video photographic technique at six different median openings on 6-lane and three different median openings on 4-lane divided urban roads in the state of Madhya Pradesh and the Varanasi city (Uttar Pradesh), India. Methodologies like traditional method, INAFOGA and modified Raff's method were used to estimate the critical gap values of vehicles. Results show that the critical gap values estimated by INAFOGA method give a result higher than the other two methods. It is also observed that the drivers of 2-wheelers take the smaller available critical gap due to smaller vehicle dimension and high manoeuvrability characteristics. However, HCV takes the higher gap value due its larger vehicle size and less manoeuvrability characteristics. The position of individual vehicles was estimated by observing the left front outer wheel of vehicles except for the motorized 3-wheelers where the rear left outer wheel was considered. The critical position of vehicles is calculated through the frequency distribution plot where a high R^2 value is observed in each plot. Result depicts that the critical position of vehicles significantly increases with increase in physical dimension of the vehicle. Modelling of critical gap and position is done by considering the statistically

Table 10. Results of paired t-test between traditional and modified Raff's methods

Groups	Count	Mean	SD	SE	*t*	DF
Traditional	36	3.59	1.27			
Modified Raff	36	3.29	1.32			
Difference	36	0.31	0.66	0.11	2.81	35
T-test	*P* value	*t*-Critical	Lower	Upper	Significance difference	
One tail	0.004	1.690			Yes	
Two tail	0.008	2.030	0.085	0.528	Yes	

Table 11. Result of chi-square test at all study sections

	Critical position (cm) from median				Critical position (cm) from median			
Section	2-W	3-W	Car/SUV	LCV	2-W	3-W	Car/SUV	LCV
1	263.99	388.5	457.49	558.33	273.08	391.77	452.7	550.76
2	270.12	383.12	452.93	532.69	268.26	384.85	444.71	541.04
3	268.24	378.94	443.78	520.27	263.73	378.36	437.22	531.92
4	264.04	372.26	432.32	539.88	263.29	377.72	436.47	531.02
5	267	381.32	461.05	561.25	273.45	392.31	453.33	551.52
6	275.68	391.67	453.88	544.64	272.68	391.19	452.04	549.96
7	281.05	394.21	450.82	575.00	278.44	399.46	461.60	561.58
8	259.53	384.61	425.56	524.36	260.92	374.33	432.56	526.25
9	261.78	384.91	419.82	507.14	257.58	369.54	427.02	519.51

Summary					Chi-square		
Count	Rows	Columns	DF		Chi-square	*X*-critical	Significance difference
14,732.18	9	4	24	Pearson's	4.541	36.414	No
				Max likelihood	4.538	36.414	No

independent variables using regression analysis technique. The results of this study may help in designing space near the median openings for U-turning and through traffic of opposite lanes and for safe and efficient vehicular movement through the median openings. The results of this study can be applied to estimate the median capacity and design of a median opening with proper opening width and length. The uncontrolled openings can also be transferred into controlled openings through the installation of signalling system with proper timing for safe and efficient vehicular movement through the openings.

Conclusions

This study analyses the behaviour of U-turning vehicles near the median opening for multilane divided urban roads based on the gap between vehicles and their position under mixed traffic conditions. Three different methodologies namely traditional method, INAFOGA and modified Raff's method were applied to estimate the critical gap value. Values obtained by INAFOGA method are found to be 5.93% higher than the traditional method and about 16.38% higher than the modified Raff's method. As the INAFOGA method is solely based on the vehicle dynamics, the wide range of dynamic properties of vehicles give higher values of critical gap estimated by INAFOGA method than the other two methods. The traditional method is also based on vehicle dynamic properties and results in less difference between traditional method and INAFOGA method. The vehicle position data were used for the frequency distribution plot to calculate the critical position of each vehicle type. The distribution plots followed normal distribution having high R^2 value. Results depict that the critical position of two wheeler is smaller due to its small physical size with high manoeuvrability and less requirement of turning area while taking U-turn. However, HCV have largest position value because of its physical size and larger area required for taking U-turn. Five different variables were considered in modelling the critical gap. Regression technique was used to find the empirical relationship between the critical gap and those variables whose probability value is less than the significance level (5%). Each model has a high coefficient of determination (R^2) with low additive constant value which indicates its significance level. A model was also proposed for common motorized mode where the critical gap depends on merging time and accepted gaps with high coefficient of determination and low coefficient value. Multi-linear regression technique was applied to find the relationship between the critical position and the variables whose probability value is less than the

Table 12. Detailed result of Chi-square test for mean critical position of vehicles

	Observed values					Expected values				
	Critical position (cm)					Critical position (cm)				
Section	2W	3W	Car/SUV	LCV	HCV	2W	3W	Car/SUV	LCV	HCV
4 Lanes	267.59	387.80	431.09	528.74	665.00	259.19	373.97	427.88	519.92	699.27
6 Lanes	267.04	383.59	451.50	543.72	777.40	275.44	397.42	454.71	552.54	743.13

Summary					Chi-square			
Count	Rows	Columns	DF		Chi-square	P-value	x-critical	Significant difference
4703.47	2	5	4	Pearson's	5.118	0.275	9.487	No
				Max likelihood	5.122	0.274	9.487	No

Table 13. Critical gap modelling for each motorized mode

Vehicle type	Variables considered	P value	Critical gap model	R^2
2W	Merging time, accepted gap	0.005, 0.010	$T_c = -0.133 + 0.0595T_{mg} + 0.416T_a$	0.922
3W	Merging time, accepted gap	0.002, 0.001	$T_c = 0.113 + 0.337T_{mg} + 0.554T_a$	0.994
Car/SUVs	Accepted gap	0.001	$T_c = 0.199 + 0.817T_a$	0.829
LCVs	Merging time	0.027	$T_c = 1.256 + 0.620T_{mg}$	0.525
HCVs	Accepted gap	0.005	$T_c = 1.822 + 0.492T_a$	0.827
Common mode	Merging time, accepted gap	0.0004, 0.0001	$T_c = 0.106 + 0.385T_{mg} + 0.491T_a$	0.816

T_c, Critical gap; T_{mg}, Merging time of vehicle; T_a, Accepted gap.

Table 14. Result of regression analysis for motorized two-wheelers for critical position

	Coefficients	SE	t Stat	P-value	Lower (95%)	Upper (95%)	R^2
Intercept	210.04	10.37	20.25	0.0000	184.65	235.42	0.842
Critical gap	8.64	1.65	5.24	0.0019	4.61	12.67	
Width of carriageway	0.03	0.01	4.85	0.0029	0.01	0.04	

Table 15. Result of regression analysis for car/SUVs for critical position

	Coefficients	SE	t Stat	P-value	Lower (95%)	Upper (95%)	R^2
Intercept	363.89	13.02	27.95	0.0000	332.03	395.75	0.874
Accepted gaps	4.107	1.45	2.83	0.0298	0.56	7.65	
Width of carriageway	0.057	0.01	6.17	0.0008	0.03	0.08	

Table 16. Result of regression analysis for LCV for critical position

	Coefficients	SE	t Stat	P-value	Lower (95%)	Upper (95%)	R^2
Intercept	289.37	32.95	8.78	0.0009	197.89	380.84	0.970
Critical gap	–55.53	8.36	–6.64	0.0027	–78.74	–32.32	
Merging time	47.98	7.54	6.37	0.0031	27.06	68.90	
Accepted gaps	25.31	2.54	9.95	0.0006	18.25	32.38	
Width of carriageway	0.14	0.01	9.60	0.0007	0.10	0.18	

significance level (5%). All the proposed models had high R^2 value indicating its high significance level except for the common motorized mode. Modelling of critical position for three wheeler was not performed as the P-value for each variable was higher than 0.05. The reason could be the randomness in data because of the undisciplined lateral movement of 3-wheeler drivers. The average number of vehicles passing through the median openings for both 6- and 4-lane divided urban roads is found to be 280 and 505 veh/h respectively.

Design recommendations

The results of this study may be used to design or modify the geometric elements near the median opening area for safe and efficient movements of U-turning traffic. The

Table 17. Result of regression analysis for HCV for critical position

	Coefficients	SE	*t* Stat	*P*-value	Lower (95%)	Upper (95%)	R^2
Intercept	1041.00	41.79	24.91	0.000	933.59	1148.42	0.920
Merging time	–73.33	9.65	–7.60	0.001	–98.14	–48.52	

Table 18. Result of regression analysis for common motorized mode for critical position

	Coefficients	SE	*t* Stat	*P*-value	Lower (95%)	Upper (95%)	R^2
Intercept	199.59	63.77	3.12	0.003	69.69	329.48	0.350
Critical gap	–73.13	32.18	–2.27	0.030	–138.70	–7.57	
Merging time	75.20	23.56	3.19	0.003	27.21	123.19	
Accepted gaps	47.70	19.39	2.46	0.019	8.21	87.20	

geometric design may be modified by providing right turn pocket lanes near the median opening area especially for U-turning traffic. The length and width of the pocket lane can be designed based on the percentage of the U-turning traffic and maximum critical position of vehicles (m) from the median edge, as shown in Figure 9, although the specifications of the pocket lane depend on the traffic and road geometric conditions of the sites. The pocket lane will help in reducing the blockage of through traffic stream and increase safety by reducing the conflicts between U-turning and through traffic. This study can help formulate the geometric features of such type of right turn pocket lanes.

Limitations

This study investigates gap acceptance characteristics and position of each vehicle near the median area and has not looked into the effect of speed and lane width on the gap acceptance of a U-turning vehicle. The speed of U-turning vehicle and lane width of the opposite traffic stream certainly influence the placement of U-turning vehicles which is proposed to be investigated in a future study. The safety aspect associated with U-turning vehicles at the median openings and the effect of geometric elements on position of vehicles near the median area are also proposed to be studied in a future work.

1. Sugiarto, S., Limanoond, T. and Nakatsuji, T., Dropped in capacity and traffic speed of urban arterial: a case study at U-turn section in Aceh Province, Indonesia Aceh. *Int. J. Sci. Technol.*, 2012, **1**(3), 86–93.
2. Hamed, M. M., Easa, S. and Batayneh, R. R., Disaggregate gap-acceptance model for unsignalized T-intersections. *J. Transp. Eng., ASCE*, 1997, **123**(1), 36–42.
3. Gurupackiam, S. and Lee, J. S., Empirical study of accepted gap and lane change duration within arterial traffic under recurrent and non-recurrent congestion. *Int. J. Traffic Transp. Eng.*, 2012, **2**(4), 306–322.
4. Brilon, W., Koenig, R. and Troutbeck, R. J., Useful estimation procedures for critical gaps. *Transp. Res. Part A: Policy Pract.*, 1999, **33**, 161–186.
5. Ashalatha, R. and Chandra, S., Critical gap through clearing behaviour of drivers at un-signalised intersections. *J. Civil Eng., KSCE*, 2011, **15**(8), 1427–1434.
6. Datta, S., *Modelling Critical Gaps for U-turn Vehicles at Median Openings under Indian Mixed Traffic Conditions*, Department of Civil Engineering, National Institute of Technology, Rourkela, 2014.
7. Datta, S. and Bhuyan, P. K., Which method is appropriate-INFOGA or probability equilibrium for critical gap estimation of U-turn vehicles at median openings in urban Indian context? Institute of Research Engineers and Doctors, ISBN: 978-1-63248-028-6; doi:10.15224/ 978-1-63248-028-6-03-92.
8. Sharma, V. K., Mondal, S. and Gupta, A., Analysis of U-turning behaviour of vehicles at mid-block median opening in six lane urban road: a case study. *Int. J. Traffic Transport. Eng.*, 2017, **7**(2), 243–255.
9. Shihan, H. and Mohammed, H. K., Traffic system studies at median U-turn in Baghdad city employing u-sim model. *J. Eng, Develop.*, 2009, **13**(1).
10. Dash, S., Mohapatra, S. S. and Dey, P. P., Estimation of critical gap of U-turns at uncontrolled median openings. *Transp. Lett., Int. J. Transp. Res.*, 2017.
11. Cornelie, J. G., Driel, V., Ragnhild, J. D., Martin, F. A. M. and Maarseveen, V., The effects of an edge line on speed and lateral position: a meta-analysis. *Accident Analysis Prevent.*, 2003, **36**, 671–682.
12. Dey, P. P., Chandra, S. and Gangopadhaya, S., Lateral distribution of mixed traffic on two-lane roads. *J. Transp. Eng., ASCE*, 2006, **132**, 597–600.
13. Yang, J., Estimation of vehicle's lateral position via the Lucas-Kanade optical flow method. *WSEAS Trans. Syst.*, 2015, **11**(8), ISSN: 2224–2678.
14. Mahapatra, G. and Maurya, A. K., Study on lateral placement and speed of vehicles under mixed traffic condition. *Proc. Natl. Conf. Recent Adv. Traffic Eng.* (*RATE*), 2015.
15. Bunker, J. M. and Parajuli, A., Examining lateral positions of cars and heavy vehicles on a two lane, two-way motorway. *Transp. Eng. Australia*, 2006, **10**(2), 129–139.
16. Mohapatra, S. S., Dey, P. P. and Chandra, S., Modelling the critical position of *u*-turning vehicles at uncontrolled median openings. *J. Civil Eng., KSCE*, 2016, **20**(1), 411–420.

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