

EFFECT OF U-TURNS ON CAPACITY OF MEDIAN OPENINGS ON MULTILANE URBAN ROADS

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Abstract

Midblock median openings with U-turn provisions are commonly used in urban India to improve accessibility and reduce intersection conflicts. However, their capacity estimation under mixed traffic conditions remains complex. This study evaluates the applicability of the gap acceptance model and proposes an empirical approach to estimate U-turn capacity on multilane urban roads. Field data were collected from two locations in Hyderabad and Kurnool, and critical gap and follow-up time were estimated using Sieglösch's method. A linear empirical model was developed and validated using 61 observations collected from additional locations. A VISSIM simulation model was also calibrated for further analysis. The critical gap and follow-up time were found to be 4.33 and 2.50 seconds, lower than TRB 2010 values, indicating aggressive driver behavior. The empirical model performed well ($R^2 = 0.86$; MAPE = 8.91%). At 2000 pcu/hr, gap acceptance and empirical models predicted capacities of 408 and 552 pcu/hr, respectively. Sensitivity analysis with β ranging from 0.71 to 0.73 showed significant changes in output, highlighting the need for local calibration. The findings offer practical insights for traffic engineers and planners to enhance the design and performance of U-turn facilities in heterogeneous traffic conditions.

Keywords: Median Openings, U-Turn, Empirical Model, Gap-Acceptance Model, VISSIM

Introduction

Capacity is defined as the maximum number of vehicles or passengers a traffic facility can accommodate under prevailing conditions, is a fundamental parameter in intersection and roadway design (Transportation Research Board [TRB], 2000, 2010). Accurate capacity estimation supports effective planning, design, and evaluation of traffic operations. Among various roadway features, U-turn movements at median openings on multilane

urban roads play a critical role in managing local access and reducing intersection conflicts. These mid-block U-turn facilities are increasingly implemented to enhance traffic flow by diverting direct left-turns at intersections, thereby minimizing delays and improving overall network performance. Given their operational significance and growing adoption in urban environments, a precise estimation of U-turn capacity at median openings

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becomes essential for optimizing design and ensuring safe, efficient vehicle movement.

The use of median openings at midblock locations is particularly significant in India, where high traffic volumes, limited intersection spacing, and heterogeneous vehicle composition challenge conventional turning provisions. These U-turn facilities allow right-turn movements from both major and minor streets to be rerouted away from intersections, reducing conflict points and improving signal efficiency. However, estimating the capacity of U-turns at such midblock openings remains complex due to the variability in driver behavior, gap acceptance tendencies, and the absence of standardized design elements such as exclusive U-turn lanes (Sharma *et al.*, 2017).

Despite their widespread use, the operational evaluation of midblock U-turn facilities is underexplored, especially in the Indian context. This study aims to evaluate the applicability of the gap acceptance model and develop a data-driven empirical model to estimate the capacity of U-turn movements at midblock median openings on multilane urban roads under Indian traffic conditions. The specific objectives are: (i) to estimate critical gap and follow-up time using field data, (ii) to develop and validate an empirical model based on observed U-turn discharge and conflicting traffic, (iii) to compare empirical, gap acceptance, and simulation-based capacity estimates, and (iv) to conduct sensitivity analysis of the conflicting factor (β) to support local calibration. The central hypothesis is that empirical models calibrated with local traffic data will outperform standard gap acceptance models in predicting U-turn capacity under mixed traffic conditions.

Gap Acceptance Theory

Gap acceptance theory is widely used to estimate the capacity of non-priority movements at unsignalized intersections and midblock openings. The theory assumes that drivers observe the major traffic stream and accept a gap large enough to safely execute their maneuver (Ashworth, 1968; Kimber, 1989). While this framework is analytically elegant, it presumes consistent driver behavior, homogeneous traffic, and well-defined priorities, which are often absent in Indian traffic. Drivers in India may accept smaller gaps due to prolonged waiting, impatience, or pressure from surrounding traffic resulting in more aggressive and opportunistic merging behavior (Sharma *et al.*, 2017; Sadek *et al.*, 2021). The Highway Capacity Manual (TRB, 2000, 2010) applies this theory in two-way stop-controlled intersections and directional median openings, estimating capacity using parameters like critical gap, follow-up time,

and conflicting traffic volume. However, these models were primarily developed using Western traffic data and may not account for the informal negotiation and flexible decision-making common in mixed traffic environments like India (Amin and Maurya, 2015).

Critical Gap and Follow-Up Time Estimation

Various methods exist for estimating the critical gap, including Raff's method, maximum likelihood estimation, and Siegloch's regression method. Siegloch's technique is particularly effective in saturated conditions and offers a robust regression-based approach to relate accepted gaps and the number of vehicles discharged within a gap (Brilon *et al.*, 1999; Troutbeck, 2014; Mohan and Chandra, 2016). Studies conducted in India have reported critical gap values as low as 3.85 seconds (Dash *et al.*, 2017), which is significantly lower than the 5.6 seconds suggested by TRB (2010) for six-lane divided highways. This discrepancy reflects aggressive driving behavior and lower safety margins typically observed in Indian traffic. Similarly, follow-up time values in Indian studies are comparable to HCM values but can vary with vehicle type and maneuvering speed; for instance, Dash *et al.* (2017) reported a value of 2.17 seconds. International studies also show wide variation in critical gap values. In the United States, Liu *et al.* (2008) reported values ranging from 4.3 to 5.2 seconds, while Mazaheri *et al.* (2020) found values between 4.8 and 6.45 seconds in Iran, and Jenjiwattanakul and Sano (2011) reported 4.5 to 5.8 seconds in Thailand. These variations indicate that local driver behavior, cultural norms, and enforcement environments significantly influence gap acceptance behavior.

Capacity Modeling Approaches

Capacity estimation can be approached using gap acceptance models, empirical models, or simulation-based methods. Gap acceptance models are suitable for analytical evaluations but are sensitive to input parameters such as critical gap and β (conflicting factor). Studies such as Al-Masaeid (1999) and Liu *et al.* (2008) have demonstrated that these models may underestimate capacity under high conflicting volumes and overestimate it when conflicting traffic is light. Furthermore, variation in driver consistency and risk tolerance can lead to unpredictable acceptance behavior, making such models unreliable without calibration (Amin and Maurya, 2015). Empirical models, in contrast, use observed field data to directly relate capacity to influential variables, such as conflicting traffic flow. These models are particularly useful in mixed traffic scenarios and are easier to apply in practical design.

(Kimber, 1989). Simulation tools like VISSIM have also gained popularity due to their ability to incorporate microscopic driver behavior and lane-changing logic (MassDOT, 2020). However, they require extensive calibration of behavioral parameters like minimum gap time, car-following safety factors, and merging times. When properly calibrated, simulation models have shown capacity estimates comparable to field observations (Liu, 2008; Elsenhwy *et al.*, 2023; Zhao *et al.*, 2024).

Although gap acceptance theory and capacity estimation methods have been extensively studied internationally, limited research exists that adapts these models to Indian conditions. Most Indian studies focus on estimating critical gap values but do not evaluate the performance of complete capacity models using local data. There is also a lack of comparative studies involving empirical models, gap acceptance frameworks, and microsimulation. Furthermore, the influence of the conflicting factor (β) on capacity estimates is rarely examined, despite its role in adjusting for variations in driver assertiveness and traffic heterogeneity. This study addresses these gaps by developing and validating an empirical model based on Indian field data, comparing it with HCM-based gap acceptance estimates, and calibrating a VISSIM simulation model. The findings aim to provide practical tools for estimating U-turn capacity at midblock median openings and offer context-specific guidance for traffic engineers working in mixed traffic environments.

The remainder of this paper is structured as follows: Section 2 describes the site selection and data collection methodology. Section 3 presents the estimation of critical gap and follow-up time using regression-based techniques. Section 4 outlines the development of the empirical model for estimating U-turn capacity. Section 5 details the simulation model development using VISSIM to replicate U-turn behavior. Section 6 provides a comparative analysis of capacity estimates obtained from empirical, gap acceptance, and simulation models. Finally, Section 7 concludes the study and highlights key findings, practical implications, and directions for future research.

Site Selection and Data Collection

Two midblock median openings were selected based on carefully defined criteria to ensure that the observed sites reflected traffic and geometric characteristics of urban arterial roads in India. The selection was guided by the presence of high U-turning volumes with observable vehicle queuing during peak hours, indicating active demand and

potential capacity constraints. Each site was located at a minimum distance of 150 meters from adjacent intersections to eliminate the influence of signalized controls and ensure that U-turn behavior was not affected by intersection spillback. Both sites were situated on six-lane divided carriageways, which are typical of major urban corridors in Indian cities. Importantly, neither location featured exclusive U-turn bays or dedicated turn pockets, meaning that vehicles were required to execute U-turns by merging directly into opposing traffic streams, a condition representative of many midblock designs in India. Additional selection factors included variation in median width, the presence of pedestrian activity, and differences in road alignment, such as curvature or gradient, to capture a broad range of real-world conditions. Finally, the two sites were located within commercial and mixed-use zones, ensuring a mix of vehicular types and behavioral patterns, and enhancing the operational diversity captured in the study. A typical layout of the selected sites is illustrated in Figure 1.

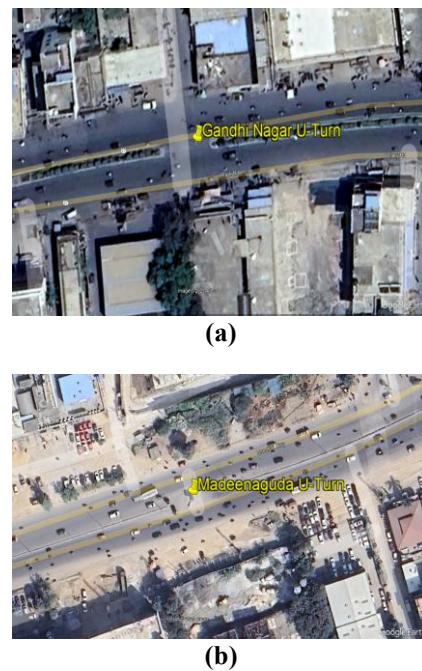


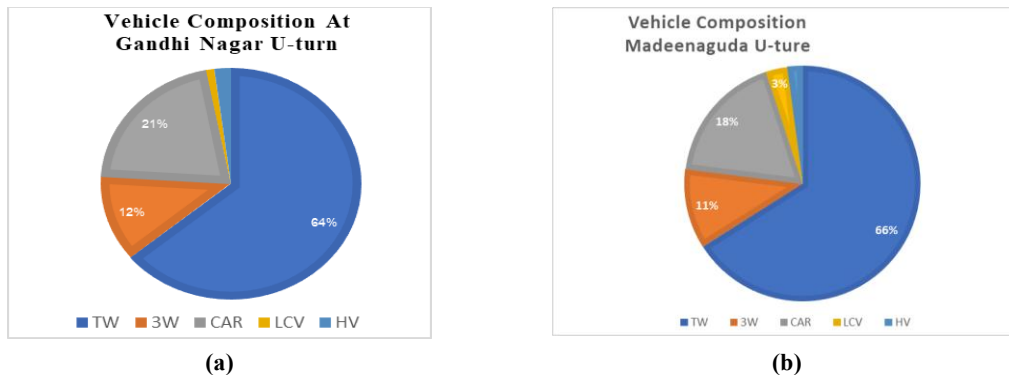
Figure 1. Google Map Images of Study Intersections (a) Gandhi Nagar U-Turn and (b) Madenaguda U-Turn

The data was collected in the present study comprise of both geometric and traffic data. Geometric data includes distance from nearest intersection, median width, median length, carriageway width, number of lanes, width of shoulder was collected from the field. Geometric details of selected study locations are presented in the Table 1.

Table 1. Geometric Details of Selected Study Locations

Site no.	Median Width (m)	Median opening length (m)	Carriageway Width (m)	No. of lanes	D1 (m)	D2 (m)
I	1.85	22.3	13.4	3	315	380
II	1.85	22.3	13.4	3	565	380

* D1, D2, denote-turns distance from upstream and downstream intersections.

**Figure 2. Traffic Composition at Study Locations (a) Gandhinagar U-Turn and (b) Madeenaguda U-Turn**

Data were collected using elevated video recording setups, such as rooftops and overbridges, allowing clear tracking of U-turning vehicles and conflicting traffic. Observations were carried out during morning (08:00-11:00) and evening (15:00-18:00) peak hours over a two-week period in the pre-monsoon summer season (April-May). The weather was consistently dry, with ambient temperatures ranging from 29°C to 36°C, and no rainfall, fog, or poor visibility occurred. The traffic conditions remained typical for weekdays, as there were no special events, festivals, construction work, or detours during the data collection period.

To maintain the accuracy and consistency of data extracted from video recordings, a standardized protocol was followed during the manual review process. The video footage was independently analyzed by two trained observers to record key parameters such as accepted and rejected gaps, U-turn discharge counts, and conflicting traffic volumes. The extracted data from both observers were cross-checked for consistency, and any discrepancies were jointly reviewed and resolved through discussion. This collaborative verification approach ensured that the extracted traffic data was both reliable and free from individual observer bias.

Although data were collected from only two sites, the number of observations obtained was analytically robust. A total of 144 usable U-turn events were recorded, capturing essential parameters such as accepted and rejected gaps, follow-up times, and conflicting traffic volumes. To assess the adequacy of this sample size, a post hoc

power analysis was conducted based on established statistical guidelines. Assuming a medium effect size ($f^2 = 0.15$), a significance level of 0.05, and employing simple linear regression, the minimum required sample size to achieve 95% statistical power is approximately 89 observations (Cohen, 1988). The study's sample of 144 observations comfortably exceeds this threshold, ensuring that the analysis is sufficiently powered to detect meaningful relationships between U-turn capacity and influencing factors. The selection of a medium effect size was based on the expectation of moderate variability between conflicting and U-turning flows, as well as driver behavior under heterogeneous traffic conditions. Despite the use of only two locations, the sample provides adequate statistical strength and represents a realistic range of operational scenarios commonly observed on Indian urban arterial roads. The recorded videos were played in laboratory to extract opposing traffic volume, field capacity and lane utilization of U-turn. The capacity was found when there is continuous arrival/stable queue of vehicles in median opening at intervals of one-minute. The gap acceptance data, accepted gap and rejected gaps, were derived from recorded videos. Moreover, for simulation model, speed of through traffic at median opening zone, and U-turning vehicles speed are obtained from recorded video files. The traffic composition at selected locations is shown in Figure 2. It is observed that more than 60% of traffic is 2W, and Three wheelers and Cars share is also high. Heavy vehicles share is too low. The vehicle compositions

Table 2. Geometric Details of Selected Study Locations

Vehicle Type	TRB (2000, 2010)	Indian Roads Congress (1994)	IRC 106-1990	Indo- HCM	Transport for London (2017)
Car	1	1	1	1	1
Truck	2	2	2.2	2.38	2.3
Bus				2.29	2
2W	-	0.5	0.5	0.48	0.4
3W	-	1	1	0.98	1

Table 3. Descriptive Statistics of Gap Acceptance Data

No. of Discharged Vehicles	Min (s)	Max (s)	Avg. Gap (s)	Std. Dev. (s)	95% Confidence Interval (s)
1	2.48	10.07	5.26	1.36	4.30 - 6.22
2	4.72	15.30	8.46	1.83	7.20 - 9.72
3	6.81	18.71	11.32	2.41	9.72 - 12.92
4	10.48	19.62	14.15	2.39	12.56 - 15.74
5	10.48	23.50	16.54	2.86	14.51 - 18.57
6	14.15	24.94	18.47	2.90	16.41 - 20.53
Rejected Gap	0.86	6.72	2.01	0.79	1.44 - 2.58

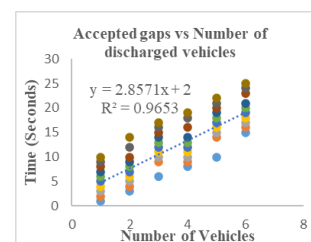
was observed and traffic converted to passenger car using passenger car equivalent factors. Table 2 provide an overview of some standards and relevant studies used for passenger car equivalent factor. From various previous literatures and proposed standards, the study considered the PCU value of heavy vehicles is 3, 1 for 3W, and 0.5 for 2W were used to convert mixed traffic to homogeneous traffic conditions.

Estimation of Critical Gap and Follow Up Time

Critical gap, follow up time and conflicting traffic are important parameters required to be calculated for local conditions in country. Descriptive statistics of gap acceptance data is tabulated in Table 3. The Maximum number of discharge U-turn vehicle using single gap in major stream was six. The minimum accepted gap for single entry vehicle found 2.48 second, while the maximum was observed 10.07 second with standard deviation of 1.36 second and an average of 5.26 second. Similarly, the minimum rejected gap observed was less than 1 second. Several factors affect critical gap such as, volume of conflicting traffic, width of median opening, carriageway width, speed of conflicting traffic, presence of opposite U-turn traffic, and driver behavior responding to offered gaps in conflicting traffic. Aggressive driving with an increase of waiting time, tends to force major stream for providing sufficient gap, which is called

gap forcing phenomena. In theory of Gap acceptance, the minor stream should not cause any delay and speed reduction to major stream, but at locations where drivers are more sensitive to waiting time are not acting ideally. This is called shared priority rather than absolute priority (Sharma *et al.*, 2017).

Different procedures of critical gap estimation have been developed over last decades. One of the most used techniques is regression technique which is used at locations where minor stream operates in capacity. The technique provides reasonable estimate of critical gap (Brilon *et al.* 1999; Liu *et al.*, 2008; Troutbeck 2014; Mohan and Chandra 2016). Therefore, in this study, Siegloch's method was used for estimation of critical gap and follow up time. In this method, plot of accepted gaps and number of discharged vehicle was made (Figure 3). Then average of accepted gaps for different number of discharged vehicles are found and regression line fitted to the average points. The coefficient of the line is the follow up time.

**Figure 3. Accepted Gaps and Number of Discharged Vehicles**

Driver behavior plays a critical role in gap acceptance, and in the Indian context, it is heavily influenced by heterogeneous traffic conditions, weaker lane discipline, and context-specific cultural attitudes toward risk and urgency. Unlike in countries with more regulated traffic environments, Indian drivers-especially two-wheeler and three-wheeler operators-tend to exhibit aggressive and opportunistic gap acceptance behavior, often accepting smaller gaps due to prolonged waiting times and impatience. This phenomenon was reflected in the present study, where the observed critical gap (4.33 seconds) was significantly lower than the TRB 2010 standard value (5.6 seconds), highlighting a more assertive merging behavior. Cultural factors such as higher tolerance for close vehicle proximity, adaptability in constrained spaces, and perceived pressure from surrounding traffic further contribute to drivers' willingness to accept shorter gaps. Moreover, informal driving norms, such as reliance on eye contact or vehicle body language instead of strict rule-based right-of-way, also influence decision-making at unsignalized U-turns. These behavioral tendencies suggest that gap acceptance models developed in Western contexts may not accurately capture Indian conditions unless calibrated with local data. Therefore, understanding these behavioral differences is essential not only for model accuracy but also for designing safer and more efficient median opening facilities in Indian cities. The estimated critical gap for U-turning vehicles was found to be 4.33 seconds, with a 95% confidence interval of [4.10, 4.56] seconds, based on regression analysis using Sieglöcher's method. This value is significantly lower than the 5.6 seconds recommended by TRB 2010 for U-turn movements on six-lane divided highways. The narrower gap reflects the more assertive and adaptive driver

behavior commonly observed under Indian urban traffic conditions, where drivers tend to accept smaller gaps due to pressure from following vehicles and the absence of dedicated U-turn lanes. From a practical perspective, this lower critical gap implies that applying HCM values without local calibration could lead to underestimating U-turn capacity, potentially resulting in overly conservative designs and unnecessary delays in planning midblock U-turn facilities.

Table 4 shows comparison of critical gap for U-turn movement on six-lane roads in other countries. As shown, the value is different for different driving behavior of each country. The follow up time computed using discharged queue model in this study was slightly higher than TRB (2010) values 2.3 second on six-lane divided roads. In India, follow up time found 2.17 second (Dash *et al.* 2017). One reason the difference of follow up time might be the difference in maneuvering speed of U-turning vehicles at median openings. Table 5 shows comparison of follow up time used in other countries.

Modelling of Capacity of U-Turn

To estimate the capacity of U-turn on six-lane divided roads using TRB (2010) gap acceptance model, the model parameters such as critical gap, follow up time and conflicting traffic flow is required. Gap acceptance data including accepted and rejected gap and lag was derived by reviewing videotapes to determine critical gap and follow up time of vehicles. As TRB (2010) defined critical gap the minimum time gap in major stream which allows entry of single vehicle in major stream (TRB, 2000, 2010), only observations with single entry or multiple streamlined entry merging vehicles was

Table 4. Comparison of Critical Gap Value for U-Turn in Other Countries

Countries	Critical gap	Method used	References
Iran	5.13	Acceptance curve	Mazaheri <i>et al.</i> (2020)
India	3.85	Mergingbehavior	Dash <i>et al.</i> (2017)
United States	5.60	Maximum Likelihood	Liu <i>et al.</i> (2008); TRB, (2010)
Thailand	4.3	Regression	Jenjiwattanakul and Sano, (2011)
Australia	6.45	N/A	Dash <i>et al.</i> (2017)

Table 5. Comparison of Follow up Time Value for U-turn in Other Countries

Countries	Follow up time	References
United States	2.30	Liu <i>et al.</i> (2008); TRB (2010)
Thailand	3.1	Jenjiwattanakul and Sano, (2011)
India	2.17	Dash <i>et al.</i> (2017)

considered, and when parallel or side by side vehicles were present, the gap data was not recorded. The time U-turn vehicle reaches stop line and the time front bumper of first vehicle in conflicting stream touches reference line was recorded as lag data. Also, the time front bumper of vehicle in conflicting traffic passes the reference line until the successive vehicle passes the reference line was recorded as gap.

Descriptive statistics of converted traffic flow in PCU are shown in Table 6 which shows total of 144 observations of U-turn capacity was derived from recorded videotapes. The observed U-turn capacity ranged from 240 pcu/h to 960 pcu/h, and the opposite U- turn traffic flow ranged from 0 pcu/hr to 420 pcu/h. The minimum observed conflicting traffic flow was 570 pcu/h, while the maximum value observed was 3420 pcu/h.

To understand factors effect capacity of the U-turn movement at median opening, correlation test was conducted to statistically evaluate relationship between U-turn capacity, opposite U-turn flow and conflicting traffic flow. The result of correlation testing Table 7 indicate a higher negative correlation of (0.926).

Table 7 presents Pearson correlation coefficients among three variables: U-turn capacity, conflicting traffic volume, and opposing U-turn flow. The correlation between U-turn capacity and conflicting traffic is strongly negative ($r = -0.926$, $p < 0.01$), indicating a statistically significant and practically meaningful relationship. This suggests that as conflicting flow increases, the availability of acceptable gaps decreases, directly reducing U-turn capacity. This strong inverse relationship is critical for capacity planning at midblock median openings, especially under mixed traffic conditions where gap

acceptance behavior is highly sensitive to opposing traffic.

The correlation between U-turn capacity and opposing U-turn flow is weak and statistically insignificant ($r = 0.092$, $p = 0.275$). This implies that, within the observed traffic conditions, opposing U-turns have a negligible impact on the capacity of U-turns in the main direction. Similarly, the correlation between conflicting traffic and opposing U-turns is weak and not significant ($r = -0.114$, $p = 0.177$), indicating minimal interaction between these streams in the current setup.

While these correlations highlight clear trends, several potential confounding factors may influence the relationships. These include median opening geometry, availability of waiting space, driver aggressiveness, presence of non-motorized traffic, and vehicle mix (e.g., high percentage of two-wheelers). Moreover, traffic enforcement, signal coordination upstream, or time-of-day effects could also affect U-turn behavior independently of traffic volume. These unmeasured factors may either inflate or suppress the true strength of correlations.

Therefore, while the statistical significance of the correlation between U-turn capacity and conflicting traffic is clear and operationally relevant, a multivariate analysis accounting for these contextual variables would further enhance the robustness and transferability of the findings.

After identifying significant variables, regression analysis performed between U-turn observed capacity and conflicting traffic flow. Tables 6 and 7 show the result of analysis. The best form of equation was found in linear form, which the model shows a strong R squared value of 0.857. The linear form was best fit for the data points with higher R squared value. The model in Equation (1)

Table 6. Descriptive Statistics of Extracted Data

	N	Minimum	Maximum	Mean	Std. Deviation
Conflicting traffic flow (pcu/hr)	144	570	3420	1853	790
U-turn capacity (pcu/h)	144	240	960	588	210
Opposite U-turn flow (pcu/hr)	144	0	420	156	116

Table 7. Result of Correlation Analysis

		U-turn	Conflict traffic	Opposite U-turn
U-turn	Pearson Correlation	1	-0.926	0.092
	Sig. (2-tailed)		0.00	0.275
Conflicting traffic	Pearson Correlation	-0.921	1	-0.114
	Sig. (2-tailed)	0.00		0.177
Opposite U-turn	Pearson Correlation	0.096	-0.114	1
	Sig. (2-tailed)	0.275	0.177	
	N	144	144	144

have an intercept of (1044) with a negative slope of (0.246).

$$C_{u-turn} = 1044 - 0.246 \times V_c \quad (1)$$

Where, C_{u-turn} is predicted capacity of U-turn in pcu/hr; V_c is total conflicting traffic flow in pcu/hr.

To quantify the uncertainty in the regression results, 95% confidence intervals were calculated for the parameter estimates of the linear model developed to predict U-turn capacity based on conflicting traffic flow. The regression equation showed that the slope (-0.246) has a 95% confidence interval of (-0.305, -0.186), indicating a statistically significant and consistently negative relationship between conflicting flow and U-turn capacity. The intercept (1044) had a 95% confidence interval of (950.13, 1137.87), representing the estimated capacity in the absence of conflicting traffic. These intervals confirm the robustness of the model parameters.

In addition, 95% prediction intervals were computed to account for uncertainty in individual capacity predictions. For example, at a conflicting flow of 790 pcu/hr, the predicted U-turn capacity was approximately 849.7 pcu/hr, with a 95% prediction interval of (670.5, 1028.8 pcu/hr). These intervals, which widen with increasing conflicting flow, offer practitioners a realistic range within which actual capacity is expected to fall, enhancing the model's reliability for real-world applications.

The exponential form of the empirical model had R squared value of 84 which is lower than linear form, but it shows strong relationship between variables. Brilon *et al.* (1999) stated for comparison purpose, exponential form of empirical model for minor stream capacity can be used; although the best form of relationship was linear.

To understand that the developed models predict reasonable estimate of capacity for median opening with the effects of U-turn movement, validation of the empirical model is required. For this purpose, site 2 was selected, recorded videotape played in laboratory and capacity of U-turn was derived. A total of 61 observations were recorded from Site 2 for the purpose of validating the developed empirical model. The initial validation, based on the full dataset, showed a Mean Absolute Percentage Error (MAPE) of 8.91% and a Root Mean Square Error (RMSE) of 55 pcu/hr, indicating strong predictive accuracy as per the threshold suggested by Liu *et al.* (2008), where $MAPE \leq 10\%$ is considered acceptable. To further assess the generalizability of the model, a holdout cross-validation was conducted by splitting the dataset into two subsets: 80% used for model training and

the remaining 20% for validation. The retrained model was applied to the validation subset, resulting in a MAPE of 8.83% and an RMSE of 54.5 pcu/hr. The closeness of these values to the original validation metrics confirms the stability and applicability of the empirical model across unseen data, reinforcing its practical relevance for estimating U-turn capacity at midblock median openings. The residual plot, shown in Figure 4, displays the residuals plotted against the fitted values of accepted gap times. The scatter shows no discernible pattern or funnel shape, and residuals are randomly distributed around the zero line, indicating that the assumptions of linearity and homoscedasticity are satisfied. To assess the normality of residuals, the Shapiro-Wilk test and Kolmogorov-Smirnov (K-S) test were performed. The Shapiro-Wilk test yielded $W = 0.8867$, $p = 0.3011$, while the K-S test returned $D = 0.2560$, $p = 0.7448$. In both cases, the p-values were greater than 0.05, indicating that the residuals do not significantly deviate from a normal distribution. Together, the graphical and statistical diagnostics confirm that the regression model meets the standard assumptions, validating its use in analyzing the relationship between accepted gap and number of discharged vehicles. Figure 5 show predicted versus observed capacity for model validation.

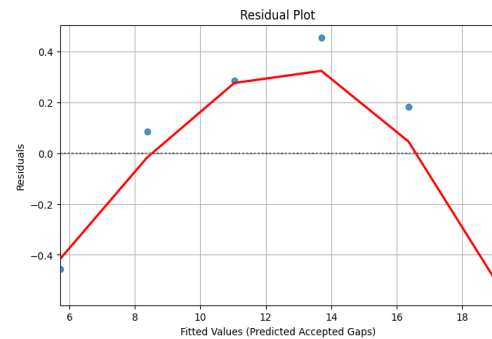


Figure 4. Residual Plot

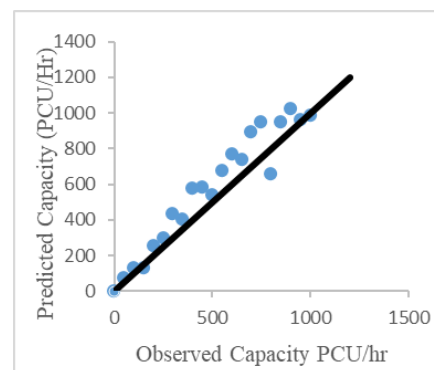


Figure 5. Empirical model validation chart

Simulation Model Development for U-Turn Capacity

Field data collected at the mid-block is provided as inputs for performing simulation analysis. The simulation runs performed with the field input data and outputs are analysed to measure the performance of selected sections. The conflicting traffic flow and capacity of U-Turn analysed and examined from the simulation output to observe operational performance of mid-block. The results from the simulation runs are verified by calibrating VISSIM results based on field. Verification of VISSIM model is performed based on field data for making traffic simulation more accurate and realistic. The final simulation analysis is performed after testing and verification of VISSIM outputs.

The simulation runs were performed with the base network prepared in VISSIM from 0 to 4200 seconds. The simulation outputs were recorded between 300 to 3900 sec. The model was run at least three times for comparing the field and simulated results to test the model output. VISSIM simulation runs are performed for 3 hours and required output data was extracted from the output file. The traffic volume and speed data was measured from the travel time output file. The RMSE and MAPE values estimated between field and simulated data are found less than 8% which indicate the traffic volume approaching to intersection resembles field traffic flow conditions. Similarly, the simulated speeds obtained for each vehicle type are compared with the field observed speeds. It is found that there is no significant difference between the field and simulated average speed of vehicle types. This file records the time taken by each vehicle type on the travel time section (60m) assigned at appropriate distance away from the point of vehicle generation and also from the stop line at approach of intersection. Simulated data such as vehicle count, vehicle type, travel time, queue length and queueing speed was obtained from the travel time output file. In this study, speed of U-turning vehicles was not observed but instead the merging time, which is the time required for U-turn vehicle starts from stop line and merge to major stream, of U- turning vehicles

was derived from recorded videotapes. This merging time was then considered as travel time for the required path a turning vehicle maneuver, and consequently the speed was determined.

The calibration test has been performed on the driver behavior model parameters to check whether the default values of parameters in VISSIM are able to replicate the field performance. The average queue length values as observed at intersection approaches are used as threshold for calibration of driver behavior model. The all-driver behavior parameter values as given in the VISSIM model (Wiedemann 74) are kept default for the test run. The simulation runs were performed for given duration and data from the output files are extracted. The calibration process started with running simulation with default gap time for priority rule and car following model multiplicative part of safety parameter. The first comparison is using default values of minimum gap time and car following model.

Table 8 shows the difference in error between observed and simulated capacity with respect to changes in multiplicative part of safety. A decrease in the value increased intercept of capacity. This is similar to findings of previous studies on roundabout capacity analysis (MassDOT, 2020). Figure 6 shows simulated capacity curves. The best form of simulated capacity was found to be exponential, while there was slight difference in terms of MAPE between exponential and linear form. It is similar to the findings of (Liu *et al.*, 2008) which was found to be simulated capacity using VISSIM follows exponential form.

Comparison of Capacity Models

To understand the difference between empirical and HCM gap acceptance model, two statistical tools, MAPE and RMSE, are used. The HCM model has three main parameters, critical gap, follow up time and conflicting traffic. All three parameters have been found for study area.

Since there was a slight difference in the linear and exponential form of empirical model, a separate comparison between gap acceptance and empirical was made.

Table 8. VISSIM Calibration Result

Min gap time for priority rule	Wiedemann 74			RMSE	MAPE
	Average Standstill distance	Additive part of safety	Multiplicative part of safety		
Default (3)			3	138	24.33
2.8	Default (2)	Default (2)	3	115	19.64
2.8			2	81	13.5

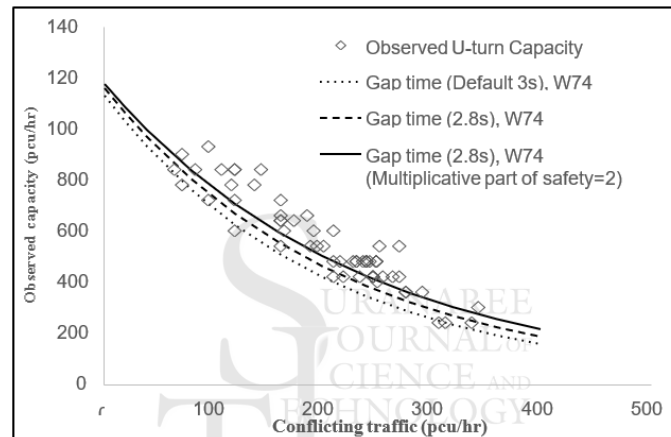


Figure 6. Simulated Capacity for Different Calibrated Parameters

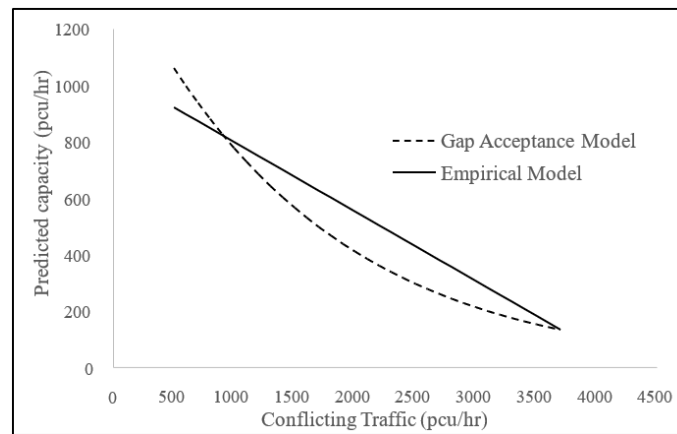


Figure 7. Predicted Capacity using Empirical and Harders Model

Figure 7 shows predicted capacity using empirical (linear form) and gap acceptance model. It can be observed that gap acceptance overestimate capacity at lower conflicting traffic. This finding is similar to (Al-Masaeid 1999; Liu *et al.*, 2008). Moreover, at conflicting traffics between 1500-2800 pcu/hr, the gap acceptance model underestimate U-turn capacity significantly. To assess the influence of the conflicting factor (β) on the performance of the gap acceptance model, a sensitivity analysis was conducted by varying β within the range of 0.71 to 0.73 in 0.01 increments. The analysis revealed that as β increased, the predicted U-turn capacity decreased. At a conflicting traffic volume of 2000 pcu/hr, the estimated capacities were 420 pcu/hr ($\beta = 0.71$), 414 pcu/hr ($\beta = 0.72$), and 408 pcu/hr ($\beta = 0.73$). Correspondingly, the Mean Absolute Percentage Error (MAPE) increased from 19.81% ($\beta = 0.71$) to 21.2% ($\beta = 0.72$) and 22.1% ($\beta = 0.73$). Similarly, the Root Mean Square Error (RMSE) increased from 102.2 pcu/hr to 106.3 pcu/hr and 110.73 pcu/hr, respectively. These results clearly

indicate that the gap acceptance model is sensitive to small changes in the conflicting factor, and its prediction accuracy is impacted accordingly.

At a conflicting flow of 2000 pcu/hr, the gap acceptance model (with $\beta = 0.73$) estimated a capacity of 408 pcu/hr, whereas the empirical model estimated 552 pcu/hr, indicating a 26% underestimation. However, the difference corresponds to 1.81 times the standard error, suggesting that the gap acceptance model can still reasonably predict U-turn capacity if its parameters, particularly the conflicting factor, are properly calibrated. Although the p-value ($0.9375 > 0.05$) from the statistical comparison of MAPE values for $\beta = 0.71$ and $\beta = 0.73$ indicates no significant difference between the two, the lower error metrics at $\beta = 0.71$ demonstrate better alignment with field-observed capacities. Thus, the sensitivity analysis reinforces the importance of local calibration of the conflicting factor to improve the reliability and applicability of the gap acceptance model under mixed traffic conditions. Table 9 presents a

Table 9. Comparison Results of Gap Acceptance and Empirical Model Capacity

No.	Model	$(\beta = 0.71)$		$(\beta = 0.73)$	
		MAPE	RMSE	MAPE	RMSE
1	Gap acceptance and Empirical	19.81	102.2	22.1	110.73

comparison of capacity estimates between the empirical and gap acceptance models.

In addition to performance metrics such as MAPE and RMSE, a paired t-test was conducted to assess whether the difference in capacity estimates between the empirical and gap acceptance models is statistically significant. The test yielded a p-value of 0.041, indicating that the difference is significant at the 5% level. This confirms that the gap acceptance model systematically underestimates U-turn capacity compared to the empirical model under prevailing mixed traffic conditions. The findings reinforce the importance of local calibration and support the empirical model's suitability for operational planning.

A t-test between the two mean MAPE, resulted from using different conflicting factors, performed with sample size of 34 and mean MAPE of 19.81 and 22.1, respectively. The result shows the observed difference of 3.40 % was lower than estimated difference 4.36%, which indicate the difference was not statistically significant at 95 percent confidence level. Also, the result of chi-square test with degree of freedom 33.

The observed Mean Absolute Percentage Error (MAPE) difference of 19.81% between the gap acceptance and empirical models highlights a notable deviation in predicted U-turn capacities. From a practical standpoint, this difference is significant for traffic engineers and planners, as it may lead to underestimation of capacity when relying solely on traditional gap acceptance models, particularly in high-conflict, mixed-traffic environments. The empirical model, calibrated using local traffic data, captures context-specific driver behavior, such as aggressive merging and smaller gap acceptance, more accurately than theoretical models based on standard assumptions.

For practitioners, the empirical model is more suitable for operational assessments, especially when detailed local data are available or when working in environments with unstructured, heterogeneous traffic. Conversely, the gap acceptance model may still be appropriate for preliminary design, sensitivity analysis, or signalized conditions where gap distributions are more consistent and behavioral variation is lower. However, users should be cautious and consider local calibration of critical input parameters (e.g.,

critical gap, follow-up time, and conflicting factor β) to improve its accuracy. The results suggest that applying uncalibrated theoretical models in diverse urban contexts could lead to conservative and potentially inefficient designs.

Comparison of VISSIM calibrated model and HCM gap acceptance model shows in Figure 8. For estimation of capacity using gap acceptance model, conflicting factor of 0.713 used. It can be observed that there is a slight difference between simulated and gap acceptance capacity at low conflicting traffic. Gap acceptance model overestimate U-turn capacity when theoretically there is no conflicting traffic, while it underestimates the U-turn capacity at higher conflicting traffic. To understand difference between simulated and gap acceptance model, the MAPE statistics was found 15.72 %. The error is high and indicate that even if the parameters of gap acceptance model is calibrated for local condition, it systematically underestimate and overestimate the U-turn movement capacity at midblock median openings. One reason might be the assumptions of absolute priority and consistent drivers made in developing gap acceptance model. The result is satisfactory comparing to previous study on U-turn capacity at unsignalized intersection on multilane in the United States which found 17.5 % (Liu *et al.*, 2008). But, that study did not calibrate car following model, instead the author used parameters like speed of U-turn, lane distribution of U-turn, and minimum gap time for priority rule for calibration. As per literatures, a MAPE of less or equal to 10 % is acceptable. At the other hand, the mean absolute percentage error between empirical and simulation model capacity after simulation found 10.41 %. Although the error is more than 10 %, the calibrated simulation model has close agreement with empirical model capacity. In conclusion, simulation models can be used reasonably for prediction of midblock median openings U-turn capacity on six-lane roads after calibration of model with field data. The calibrated simulation model can produce accurate capacity for U-turn movement. The simulated capacity has less difference with empirical model, and have slight difference in terms of form with gap acceptance model. The empirical model is easy for practical purposes, since it does not require multiple parameters determination, while gap acceptance

model requires determination of several parameters like critical gap, follow up time, and conflicting factor.

Discussion

The results of this study provide significant insights into the behavior of U-turning vehicles at mid-block median openings under mixed traffic conditions in Indian cities. One of the most prominent findings was the strong negative correlation ($r = -0.926$) between U-turn capacity and conflicting traffic flow, a result that supports earlier work by Liu *et al.* (2008) and Main Roads Western Australia (2013), who similarly observed that U-turn capacity diminishes with increasing opposing volume. However, the magnitude of the observed correlation in the present study is higher, suggesting that the influence of conflicting flow may be more pronounced in the Indian context, where lane discipline is weak and traffic interactions are less regulated.

The estimated critical gap (4.33 seconds) and follow-up time (2.50 seconds) were notably lower than the TRB 2010 values (5.6 s and 2.3 s, respectively) for six-lane divided arterials. This aligns with Indian studies such as Dash *et al.* (2017), who reported lower gap thresholds due to driver aggressiveness and informal yielding behavior. The lower values suggest that drivers under mixed traffic conditions are more willing to accept smaller gaps to complete U-turns, a behavioral trait that has practical implications for simulation and design. This divergence from international standards underscores the necessity for localized calibration of behavioral parameters when applying capacity models in Indian cities.

From a modeling perspective, the empirical linear model demonstrated superior performance compared to both the gap acceptance model and the uncalibrated simulation outputs. The linear form, with $R^2 = 0.87$, provided a straightforward yet reliable estimation of U-turn capacity, especially when conflicting traffic was the dominant influence. The MAPE of 8.91% and RMSE of 59.16 pcu/hr achieved by the empirical model are within acceptable limits for field-based transportation modeling, and compare favorably with studies conducted in similar contexts such as China and Vietnam.

On the other hand, the gap acceptance model, when applied using the TRB 2010 conflicting factor ($\beta = 0.73$), significantly underestimated capacity, producing a MAPE of 22.1%. This finding aligns with observations made by Yousif and Saba (2001), who emphasized the limitations of traditional gap

acceptance models in heterogeneous traffic environments. However, when the conflicting factor was locally calibrated to 0.713, the MAPE improved to 19.81%, indicating that modest calibration can partially correct model bias but may still fall short in accurately representing complex field conditions. These results reinforce the recommendation that gap acceptance models should not be applied in their default form without site-specific adjustment in Indian conditions.

The use of VISSIM microsimulation, with calibrated priority rule settings and behavioral parameters from Wiedemann 74, further validated the empirical model. The default minimum gap time of 3 seconds and other driver behavior parameters led to underestimation, which was corrected by setting the minimum gap to 2.8 seconds and adjusting the multiplicative safety factor to 2. The calibrated model showed a MAPE of 13.5%, and its comparison with the empirical model yielded a MAPE of 10.4%, demonstrating strong alignment. These findings are consistent with those reported by Cao *et al.* (2020), who noted that VISSIM accuracy is highly sensitive to local behavior calibration, particularly in unsignalized, mixed traffic scenarios.

Theoretically, this study adds to the growing body of literature emphasizing the importance of contextual behavioral modeling in transportation engineering. The significantly lower critical gap and follow-up time values observed confirm that conventional assumptions in global standards may not capture the nuances of driving behavior in developing countries. From a methodological standpoint, combining empirical, theoretical, and simulation approaches provided a triangulated validation strategy, enhancing the robustness of findings.

Practically, the study delivers a set of calibrated parameters and a validated empirical model that traffic engineers and urban planners can directly use in designing median openings, evaluating U-turn feasibility, and performing corridor-level access management analysis. The results serve as evidence that reliance on default international standards like those in TRB 2010, without local adaptation, may lead to overconservative designs and inefficient use of road space in Indian cities.

Conclusions

This study examined the capacity of U-turn movements at midblock median openings under Indian mixed traffic conditions using a combination of field data analysis, empirical modeling, and microsimulation techniques. A strong negative

correlation of -0.926 was found between U-turn capacity and conflicting traffic flow, reinforcing the operational understanding that increased opposing volumes significantly restrict the availability of acceptable gaps for U-turn maneuvers. In contrast, the effect of opposite-direction U-turn flows was statistically insignificant, suggesting that bidirectional U-turns may not interfere under specific urban traffic environments. An empirical model was developed using conflicting traffic volume as the independent variable, and a linear form was found most suitable with an R^2 value of 0.87, outperforming the exponential form ($R^2 = 0.84$). The model showed strong performance upon validation, achieving a MAPE of 8.91% and RMSE of 59.16 pcu/hr, confirming its suitability for practical application.

Key behavioral parameters were also quantified in the analysis. The critical gap was found to be 4.33 seconds, which is notably lower than TRB 2010 recommendations, reflecting the assertive and opportunistic driving style common in Indian traffic. The follow-up time was estimated at 2.50 seconds, and observed accepted gaps for single-entry vehicles ranged from 2.48 to 10.07 seconds, while rejected gaps ranged between 0.86 and 5.71 seconds. These values confirm that drivers frequently accept smaller and riskier gaps in congested conditions, particularly in the absence of dedicated U-turn infrastructure. When comparing capacity estimates from the empirical and gap acceptance models, a significant discrepancy was observed. Using a conflicting factor of 0.713, the gap acceptance model produced a MAPE range of 1.1-35.0%, with an average of 19.81%, while the RMSE reached 102 pcu/hr. The default conflicting factor used in TRB (2010) further increased the MAPE to 22.1% and RMSE to 111 pcu/hr, highlighting the risk of overgeneralization when using non-calibrated international models.

To better capture driver behavior in simulation, a VISSIM model was calibrated using local field data. The default minimum gap time of 3 seconds in the priority rule led to underestimation of capacity, which was corrected by reducing the value to 2.8 seconds, and calibrating the Wiedemann 74 parameters—most notably the multiplicative part of safety, adjusted from the default 3 to 2. The calibrated simulation produced a MAPE of 13.5% and RMSE of 81 pcu/hr compared to observed data. When compared with the empirical model, the simulation model yielded a MAPE of 10.4%, indicating close alignment. Despite slightly exceeding the 10% threshold, the model

performance is deemed acceptable considering the real-world variability and limitations in data availability for simulation calibration.

From a practical perspective, this study offers several important contributions for traffic engineers and urban planners in India. It is strongly recommended that Indian highway design guidelines be revised to incorporate locally calibrated behavioral parameters—specifically a critical gap of 4.33 seconds and follow-up time of 2.50 seconds—instead of adopting default values from HCM or other international standards. The empirical model developed herein is suitable for use in urban access management, corridor-level capacity estimation, and median opening design, particularly under uncontrolled, mixed-traffic conditions. For advanced applications such as design evaluation or scenario simulation, calibrated microsimulation using VISSIM can be used, provided that key behavior parameters are localized based on observed data.

Despite the robustness of the results, this study is not without limitations. The data were collected from a limited number of urban corridors, which may constrain the generalizability of the model to other cities or regions with distinct traffic patterns, vehicle mixes, or enforcement regimes. Furthermore, manual video-based data extraction, though cross-verified, may introduce human error or bias. The study did not explicitly model the effects of median width, presence of deceleration or acceleration lanes, or pedestrian movements, all of which can significantly influence U-turn capacity. In addition, the sample was dominated by light vehicles, with less than 2% heavy vehicles and approximately 12% three-wheelers, limiting the application of findings in heavy commercial traffic environments.

Future research should focus on expanding the data collection effort to include a broader range of urban settings and geometric configurations, including signalized and multi-lane median openings. There is also a need to examine the influence of pedestrian activity, bicycle traffic, and vehicle heterogeneity on U-turn operations. The use of automated video analysis tools could improve data reliability and processing efficiency. Additionally, integrating behavioral studies into simulation tools will further enhance their fidelity. Ultimately, the models developed in this study offer a solid foundation for evidence-based design guidance, and with further refinement, can support a more context-sensitive and efficient approach to urban median design in India.

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References

- Al-Masaeid, H.R. (1999). Capacity of U-turn at median openings. *Institute of Transportation Engineers Journal*, 69(6):28-34.
- Amin, H.J., and Maurya, A.K. (2015). A review of critical gap estimation approaches at uncontrolled intersection in case of heterogeneous traffic conditions. *Journal of Transport Literature*, 9(3):5-9. <https://doi.org/10.1590/2238-1031.jtl.v9n3a1>
- Ashworth, R. (1968). A note on the selection of gap acceptance criteria for traffic simulation studies. *Transportation Research*, 2(2):171-175. [https://doi.org/10.1016/0041-1647\(68\)90060-9](https://doi.org/10.1016/0041-1647(68)90060-9)
- Brilon, W., Koenig, R., and Troutbeck, R.J. (1999). Useful estimation procedures for critical gaps. *Transportation Research Part A: Policy and Practice*, 33(3-4):161-186. [https://doi.org/10.1016/S0965-8564\(98\)00048-2](https://doi.org/10.1016/S0965-8564(98)00048-2)
- Cao, B., Liu, P., and Qu, X. (2020). Calibration and validation of VISSIM driving behaviour parameters for signalized and unsignalized intersections in Bangalore City. *GI Science Journal*, 7(11):929-932.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.
- Dash, S., Mohaptra, S.S., and Dey, P.P. (2017). Estimation of critical gap of U-turns at uncontrolled median openings. *Transportation Letters*, 11(5):229-240. <https://doi.org/10.1080/19427867.2017.1288890>
- Elsenhwy, M., Bakry, H., and Ramadan, I.M. (2023). Development of a methodology for estimating U-turn capacity at median opening on Egyptian roads. *Engineering Research Journal*, 52(1):46-53. <https://doi.org/10.21608/erjsh.2022.153020.1069>
- Indian Roads Congress. (1994). *Guidelines for design of at-grade intersections in rural and urban areas* (IRC SP:41). Indian Roads Congress.
- Jenjiwattanukul, T., and Sano, K. (2011). Effect of waiting time on the gap acceptance behaviour of U-turning vehicles at mid-block median openings. *Journal of the Eastern Asia Society for Transportation Studies*, 9:1601-1613.
- Kimber, R.M. (1989). Gap-acceptance and empiricism in capacity prediction. *Transportation Science*, 23(2):100-110. <https://doi.org/10.1287/trsc.23.2.100>
- Liu, P., Lu, J. J., Hu, F., and Sokolow, G. (2008). Capacity of U-turn movement at median openings on multilane highways. *Journal of Transportation Engineering*, 134(4):147-154. [https://doi.org/10.1061/\(ASCE\)0733-947X\(2008\)134:4\(147\)](https://doi.org/10.1061/(ASCE)0733-947X(2008)134:4(147))
- Main Roads Western Australia. (2013). *Annual report*.
- Massdot (2020). *MassDOT roundabout guidance*. American Council of Engineering Companies of Massachusetts. Retrieved from <https://www.mass.gov/doc/guidelines-for-the-planning-and-design-of-roundabouts/download>
- Mazaheri, A., Akbarzadeh, A., Rahimi, A.M., and Akbarzadeh, M. (2020). Estimation of critical gap of U-turns at uncontrolled median openings considering Iran's driver behaviour. *Transportation Letters*, 14(6):1-13. <https://doi.org/10.1080/19427867.2020.1805680>
- Mohan, M., and Chandra, S. (2016). Review and assessment of techniques for estimating critical gap at two-way stop-controlled intersections. *European Transport*, 61:1-18.
- Sadek, A., Akib, R.S.M., Ashraful, I., and Yousuf, H. (2021). Study on the effects on traffic performance of newly constructed U-turn from Mohakhali to Uttara road [Undergraduate thesis, Stamford University, Bangladesh]. Stamford University Institutional Repository. <http://182.160.117.219:8080/xmlui/handle/123456789/242>
- Sharma, V.K., Mondal, S., and Gupta, A. (2017). Analysis of U-turning behaviour of vehicles at mid-block median opening in six-lane urban road: A case study. *International Journal for Traffic and Transport Engineering*, 7(2):243-255. [https://doi.org/10.7708/ijtte.2017.7\(2\).08](https://doi.org/10.7708/ijtte.2017.7(2).08)
- Transport for London. (2017). *Traffic modelling guidelines* (4th ed.). Transport for London.
- Transportation Research Board. (2000). *Highway capacity manual* (TRB Special Report 209). National Research Council.
- Transportation Research Board. (2010). *Highway capacity manual* (5th ed.).
- Troutbeck, R.J. (2014). Estimating the Mean Critical Gap. *Transportation Research Record: Journal of the Transportation Research Board*, 2461(1):76-84. <https://doi.org/10.3141/2461-10>
- Yousif, M.A., and Saba, T. (2000). A decision model for gap acceptance and capacity at intersections. *Transportation Research Part B: Methodological*, 36(7):649-663. [https://doi.org/10.1016/S0191-2615\(01\)00024-8](https://doi.org/10.1016/S0191-2615(01)00024-8)
- Zhao, C., Liu, X., Wu, T., and Zhang, W. (2024). Median U-turn intersection critical parameter research and operational performance evaluation. *Applied Science*, 14(23):11445-11456. <https://doi.org/10.3390/app142311445>