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Selection of optimal U-turn locations for indirect driveway left-turn treatments on urban streets

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Abstract: The location of U-turn bays is an important consideration in indirect driveway left-turn treatments. In order to improve the performance of right-turns followed by U-turns (RTUTs), this study evaluates the impacts of the separation distances between driveway exits and downstream U-turn locations on the safety and operational performance of vehicles making RTUTs. Crash data are investigated at 179 selected roadway segments, and travel time data are measured using video cameras at 29 locations in the state of Florida, USA. Crash rate models and travel time models are developed based on data collected in the field. It is found that the separation distance between driveway exits and downstream U-turn locations significantly impacts the safety and operational performance of vehicles making right turns followed by U-turns. Based on the research results, the minimum and optimal separation distances between driveways and U-turn locations under different roadway conditions are determined to facilitate driver use of RTUTs. The results of this study can be used for future intersection improvement projects in China.

Key words: right-turns followed by U-turns (RTUT); crash data analysis; travel time analysis; separation distance

During the past decade, many transportation agencies have started using restrictive medians and directional median openings on multilane highways to manage left turn egress maneuvers from driveways or side streets. As a result of this design, a driver desiring to make a direct left-turn from a driveway onto a major-street would, instead, make a right turn followed by a U-turn (RTUT) at a downstream U-turn location. The optimal location to facilitate U-turning vehicles is a mid-block median opening in advance of a signalized intersection with a proper separation distance from the subject driveway. However, it is sometimes difficult to find an appropriate location for the mid-block U-turn median opening before a traffic signal in built-out areas due to the tight geometric conditions found there. Therefore, U-turning vehicles are also accommodated at signalized intersections, as shown in Fig. 1.

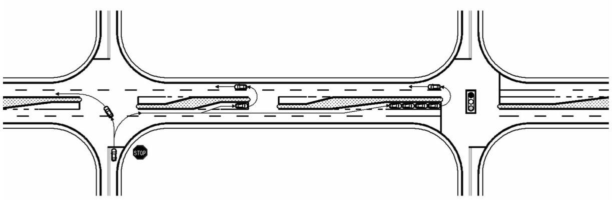

Fig. 1 Right turns followed by U-turns as alternatives to direct left-turns

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There have been considerable numbers of studies conducted concerning the safety and operational effects of U-turns. Previous studies have proved that direct left-turns result in higher traffic conflicts, crash rates and, sometimes, longer stop delays as compared with right-turns followed by U-turns; and the increased numbers of U-turning vehicles do not constitute major safety and operational concerns at signalized intersections and median openings[1-11].

Many studies have been conducted regarding the impacts of U-turns, but most of them do not focus on the effects of the separation distance between driveways and downstream U-turn locations. Only Ref. [12] concerned the selection of U-turn locations, and it developed a method for determining the optimal location of mid-block U-turn median openings on 6-lane divided roadways where the signalized intersections are coordinated. It is found that the average delay of U-turns will significantly decrease and a capacity of U-turns will increase if the U-turn median opening is located at an optimal location downstream of a driveway.

The separation distance between a driveway and a downstream U-turn location is an important consideration for a driver deciding whether to make an RTUT or a direct left-turn. If the separation distance is too short, vehicles making RTUTs do not have enough space to make a comfortable lane change; this may cause safety problems at the weaving section. On the other hand, a separation distance that is too great may result in a longer travel time and, thus, discourage drivers from making RTUTs. Currently, there are no regulations or guidelines for determining the minimum and optimal separation distance to facilitate driver use of RTUTs. The objective of this study is to evaluate how the separation distance between driveway exits and downstream U-turn locations impacts the safety and operational performance of vehicles making right-turns followed by U-turns. With such results, the optimal U-turn location can be determined so that drivers have better access to make right-turns followed by U-turns.

1 Data Collection

To achieve the research objective, crash data and travel time data were collected at 208 locations in the state of Florida, United States. The procedures for data collection are briefly discussed in this section.

1.1 Crash data

A total of 179 roadway segments are selected for crash data analysis. The roadway segment is defined as an urban or suburban arterial segment that is designed with non-traversable medians. The roadway segment begins at a driveway and continues downstream toward a median opening or a signalized intersection which accommodates U-turns. The separation distance at the selected sites varies from 22. 25 to 350. 52 m with an average of 130. 76 m.

The selected sites can be divided into four groups based on the number of through traffic lanes and the traffic control at U-turn locations (median opening or signalized intersection), as shown in Tab. 1. All of the selected sites are considered to have similar operational or design characteristics. The crash data at selected sites are obtained from the crash database of the Florida Department of Transportation (FDOT). Crash data from 2001 to 2003 are used for analysis.

Tab. 1 Selected U-turn sites for crash data analysis

Number of lanes	Median opening	Signalized intersection
4	35	24
6 or more	79	41

1. 2 Travel time data

In order to measure the travel time that drivers spent at weaving sections when making RTUTs, the research team selected 29 roadway segments with various separation distances. Among the selected sites, 13 sites are located on 4-lane divided roadways with 2 lanes in each direction, while 16 sites are located on 6- or more-lane divided roadways with at least 3 lanes in each direction. A video camera was set up in the field to record traffic data. The video camera was set up on a scaffold to achieve adequate viewing height. The separation distances were measured in the field using a measuring wheel. Vehicle travel time was measured while reviewing videotapes. Over 1 300 vehicles making RTUTs were observed at the selected sites. The average travel time that drivers spent at weaving sections while making RTUTs at each site was calculated. It should be noted that the travel time that drivers spent at weaving sections while making RTUTs does not include the stop delay at driveways or U-turn locations.

2 Crash Data Analysis Results

2. 1 Crash rates at weaving sections

If the separation distances between driveways and downstream U-turn locations are too short, vehicles making RTUTs do not have enough space to make a comfortable lane change; this may cause safety problems at weaving sections. The crashes that may occur at the roadway segments between driveways and downstream U-turn locations while vehicles making RTUTs include:

1) Angle crash/right turn crash occurs when drivers accept too small a gap in the major road through-traffic and make a direct entry into the left-turn deceleration lane. Vehicles making RTUTs in this condition will place vehicles on the major road with an increased potential of an angle crash.

2) Sideswipe crash occurs when a vehicle from the outside lane of the major road weaves to the inside lane before stopping at the U-turn location. If the separation distance is not long enough, vehicles do not have enough space to make a comfortable lane change. Some drivers in this condition may change lanes in an aggressive way, placing the major-street vehicles with an increased potential of sideswipe collisions.

3) Rear-end crash occurs when a right turning vehicle is already on the major road and begins to accelerate. If the separation distance is too short, vehicles do not have enough space to accelerate to the operating speed of through-traffic; thus, the major-street vehicles are encountered with an increased potential of rear-end collisions.

In total, there are 36 different types of crashes in the FDOT crash database. When conducting crash data analysis, it is very difficult to identify if a particular crash occurring at a selected roadway segment has an RTUT vehicle involved. Therefore, the analysis of total crashes at the selected roadway segments can provide some biased results. To overcome this problem, two steps were taken: 1) The research team selected only the roadway segments with large numbers of vehicles making RTUTs. Thus, vehicles making RTUTs had considerable effects on the safety performance of the selected roadway segments. 2) Only those crashes that may occur when vehicles making RTUTs were used for crash data analysis. These crashes include angle crash/right turn crash, sideswipe crash and rear-end crash, as explained previously.

Out of the 179 sites investigated, 39 sites do not have any crashes occurring. The crash frequency at selected roadway segments varies from 0 to 18 with an average of 2. 9 within 3 years. A total of 557 crashes were identified at the selected roadway segments. Out of these crashes, about 49% of the crashes were rear-end crashes; about 29% of the crashes were angle crashes (including right turn crashes); and about 22% crashes were sideswipe crashes. The crash rate was calculated at each selected roadway segment. The crash rate for a selected roadway segment was defined as crashes per million vehicle kilometers traveled (crashes/MVK). The crash rate can be calculated by

$$N_{CR} = \frac{10^6 A}{587.41 TVL} \tag{1}$$

where N_{CR} is the crash rate at a roadway segment, crashes/MVK; A denotes the number of reported crashes; T is the time frame of the analysis, years; V is the average ADT volume of the segment; and L denotes the length of the selected roadway segment, km.

The crash rate at the selected roadway segments varies from 0 to 1. 41 crashes/MVK with an average of 0. 24 crashes/MVK. The observed crash rate data are fitted to an exponential distribution. The parameters of the exponential distribution are estimated using the linear regression method. Based on the regression results, the distribution fitting equation for the exponential distribution is given as

$$f(x) = \lambda e^{-\lambda(x-\beta)} \tag{2}$$

where $\lambda = 2.923$ and $\beta = 0.05$.

Fig. 2 presents the frequency distribution of crash rate data and the curve for the fitted exponential distribution. The fitted curve fits the observed data well in terms of a high R^2 value (0. 99). The Chi-square test and the K-S test are performed to test the hypothesis that the crash rates are exponentially distributed. The results show that there is no evidence that the hypothesis about the exponential distribution can be rejected.

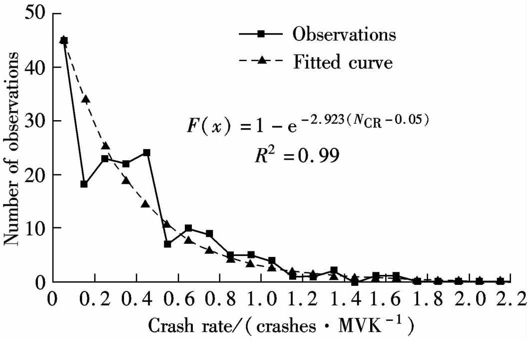

Fig. 2 Distribution of crash rate at selected roadway segments

With the fitted exponential distribution, the percentile values for crash rates can be determined. As shown in Fig. 3, the 50th and 85th percentile values of crash rates are 0.287 and 0.700 crashes/MVK, respectively. The 50th percentile is the median value of the distribution, and the 85th percentile value represents the point where 85% of all the selected roadway segments have crash rates no larger than this point's *X*-coordinate value. These two percentiles are the most commonly used in engineering analyses.

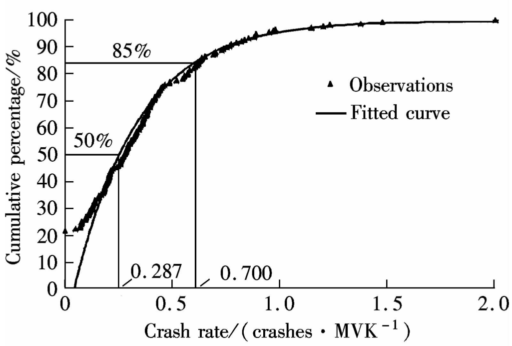

Fig. 3 The 50th and 85th percentile values of crash rates

2.2 Crash rate model

In this study, the crash rate on 4-lane divided roadways and on 6- or more-lane divided roadways are analyzed respectively. Theoretically, vehicles making RTUTs on 6- or more-lane divided roadways are more likely to be involved in an accident as compared with the conditions on 4-lane divided roadways. The linear regression method is used to identify the factors that have significant impacts on the crash rate at the selected roadway segments. The candidate independent variables include the separation distance, the traffic control at U-turn locations, the through traffic volume and the major-street speed limit.

The stepwise regression method is used to determine which variables will be incorporated into the crash rate model. It is found that the separation distance and the traffic control at U-turn locations significantly impact the crash rate at selected roadway segments. The major-street through traffic volume and the major-street speed limit are not found to be significant at a 90% confidence level; and, therefore, they are not included in the crash rate model. The crash rate models are given as follows:

$$N_{CR1} = 2.235 + 0.133 M_{TC} - 0.334 \ln(L) \qquad (3)$$

$$N_{CR2} = 2.516 + 0.192 M_{TC} - 0.364 \ln(L) \qquad (4)$$

where N_{CR1} is the crash rate at weaving sections on 4-lane divided roadways, crashes/MVK; N_{CR2} is the crash rate at weaving sections on 6- or more-lane divided roadways, crashes/MVK; M_{TC} is the binary variable, $M_{TC} = 1$ if U-turns are provided at signalized intersections, $M_{TC} = 0$ if U-turns are provided at median openings; and L is the separation distance between driveways and U-turn locations.

The R^2 values for two crash rate models are found to be 0.34 and 0.30, respectively. Based on the T-statistics, the selected independent variables are statistically significant at a 90% confidence level. From the crash rate models, it is clear that the separation distance between driveway exits and downstream U-turn locations significantly impacts the crash rate at weaving sections, and the crash rate decreases with the increase in the separation distance.

2.3 Determination of minimum separation distance

In this study, the 50th percentile value of the crash rate is used as the threshold to determine the critical value of the separation distance. The 50th percentile value of the crash rate is found to be 0.287 crashes/MVK. The critical separation distance for vehicles making RTUTs under different roadway conditions are then determined by applying the 50th percentile value of the crash rate into the regression models developed in the previous section. The idea behind this methodology is that the roadway segment with a separation distance less than the critical value will, theoretically, have a crash rate greater than that of the median level.

The critical separation distances under different roadway conditions are given in Tab. 2. Based on the critical separation distances, recommendations are given for the minimum separation distances under different roadway conditions. Based on the crash rate model, if the minimum separation distance cannot be provided, vehicles making RTUTs may cause safety problems at weaving sections.

Tab. 2 Recommended minimum separation distances

Number of lanes	Traffic control	Minimum separation distance/m	*L*/m
4	Median opening	104	107
	Signalized intersection	155	152
6 or more	Median opening	139	137
	Signalized intersection	236	229

2.4 Travel time analysis

The travel time that drivers spend at weaving sections while making RTUTs are highly correlated with the separation distances between driveways and downstream U-turn locations. If the separation distance is too long, drivers may not prefer to make an RTUT due to the increased travel time and gas consumption. The travel time that drivers spend at weaving sections while making RTUTs consists of two parts: The elapsed time from the time when a vehicle leaves the driveway until the time when it stops at the exclusive left-turn bay of a downstream U-turn location; and the elapsed time from the time when a vehicle starts making a U-turn until the time when it finishes traversing the separation distance from the U-turn location to the subject driveway at the speed of major-street through traffic.

A multiple linear regression model is developed to predict the travel time that drivers spend at weaving sections while making RTUTs. The stepwise regression method is applied to determine the independent variables that should be included in the regression model. A pre-selected F_{OUT} critical value of 0. 1 is selected as the criteria for selecting independent variables. The selected independent variables include the number of lanes of the major-street, the traffic control at U-turn locations (signalized intersection or median opening), the major-street speed limit, and the separation distance between a driveway and the downstream U-turn location. Descriptive statistics for selected independent variables and the regression results are given in Tab. 3.

Tab. 3 Regression results for travel time model

Coefficients	N	Minimum	Maximum	Mean	Standard deviation	Time	Signalized intersection
Intercept	N/A	N/A	N/A	N/A	N/A	3. 17	0. 004 2
L	29	285	1 150	608. 97	216. 66	16. 33	0. 000 0
Speed	29	40	55	46. 55	3. 56	−2. 22	0. 036 3
Lanes	29	0	1	0. 41	0. 50	−4. 30	0. 000 2
Traffic control	29	0	1	0. 55	0. 51	3. 15	0. 004 3

Note: $R^2 = 0.927$, $R^2_{\mathrm{adj}} = 0.914$.

The regression model has a fairly high R^2 value (0. 912) and an adjusted R^2 value (0. 901). The selected explanatory variables are all statistically significant at a 95% level of confidence. The regression residuals are plotted against the fitted value. It is found that the residuals are randomly distributed around the y axis, indicating the fact that the model is correctly specified and the homogeneous assumption about the error term is not violated. The correlation matrix and the variance inflation factors (VIF) are used to evaluate the extent of the multicollinearity problem between selected independent variables. It is found that there is little or no collinearity problem in the proposed travel time model. The equation of the travel time model is then given as

$$T = 22.0 + 0.032L - 3.701Q_{\mathrm{lanes}} + 2.838M_{\mathrm{TC}} - 0.296S \tag{5}$$

where T is the travel time that drivers spend at weaving sections while making RTUTs, s; Q_{lanes} is a binary variable, $Q_{\mathrm{lanes}} = 1$ on 4-lane roadways, $Q_{\mathrm{lanes}} = 0$ on 6- or more-lane roadways; and S is the major-street posted speed limit.

From the travel time model, it is clear that the separation distance between a driveway and the downstream U-turn location significantly impacts the travel time for vehicles making RTUTs. The travel time increases with the separation distance and decreases with the major-street speed limit. Vehicles making RTUTs on 6- or more-lane streets will spend around 4 s more travel time than those on 4-lane streets. Vehicles making RTUTs at signalized intersections will spend around 3 s more travel time than those making U-turns at median openings.

3 Conclusions

This study evaluates the impacts of various separation distances between driveway exits and downstream U-turn locations on the safety and operational performance of vehicles making right-turns followed by U-turns. The conclusions of this study can be made as follows:

1) The separation distances between driveway exits and downstream U-turn locations significantly impact the safety and operational performance of vehicles making right turns followed by U-turns. The crash rate at weaving sections decreases with the increase in the separation distance, and the travel time that drivers spend at weaving sections increases with the separation distance.

2) On 4-lane divided roadways with 2 lanes in each direction, if U-turns are provided at a median opening, the minimum separation distance between the driveway exit and the downstream median opening is found to be 107 m. If U-turns are provided at a signalized intersection, the minimum separation distance is found to be 152 m.

3) On 6- or more-lane divided roadways with at least 3 lanes in each direction, if U-turns are provided at a median opening, the minimum separation distance between the driveway exit and the downstream median opening is found to be 137 m. If U-turns are provided at a signalized intersection, the minimum separation distance is found to be 229 m.

It is important to note that, the separation distance defined in this study is the distance between a driveway exit and the downstream U-turn location, which also includes the transition length and the exclusively left-turn bay. This study not only examines crash data occurring at weaving sections, but also the crash data at the transition lengths and the storage lengths. This methodology follows the fact that drivers can sometimes use the transition length and the storage length to perform the weaving maneuver, as observed in the field. From a safety perspective, it is not desirable to perform a weaving maneuver at the transition length and the storage length. Thus, it is recommended that a transition length and a storage length be added to the minimum separation distance. The optimal separation distance for RTUTs should include the minimum separation distance recommended by this study, plus the transition length and the length for a left-turn storage bay.

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城市道路通过远引掉头间接左转最佳位置选取方案

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摘要:由于掉头口位置选取是城市道路远引掉头技术中的重要因素,为了提高远引掉头实施效果,从安全和运行效率 2 个方面对远引掉头口和上游支路出口之间的距离对远引掉头实施效果的影响进行了分析. 对美国佛罗里达州开展了广泛的数据采集,共得到 179 个不同路段的历史事故数据,采用录像观测法获得了 29 个不同路段的交通流运行数据. 在实测数据的基础上构建了事故率模型和车辆运行时间模型. 研究表明,掉头口和上游支路之间的间距对掉头车辆的安全性和运行效率有显著影响. 根据研究结果,提出了针对不同道路条件下设置掉头口和上游支路出口应保证的最短距离以方便司机使用掉头口. 分析研究结果可为国内交叉口改造提供借鉴.

关键词:远引掉头;事故数据分析;行驶时间分析;间距

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