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Evaluating the Sustainable Traffic Flow Operational Features of U-turn Design with Advance Left Turn

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Abstract: Median U-turn intersection treatment (MUIT) has been considered as an alternative measure to reduce congestion and traffic conflict at intersection areas, but the required spacing between the U-turn opening and the intersection limits its applicability. In this paper, a U-turn design with Advance Left Turn (UALT) is proposed with the aim of addressing the disadvantages of insufficient intersection spacing and difficulty in the continuous vehicle lane change. UALT provides a dedicated lane to advance the turning vehicle out of the intersection and directly to the U-turn opening without interacting with through traffic. The effectiveness and traffic volume applicability of UALT was demonstrated through field data investigation, simulation and analysis with VISSIM software. The proposed design was evaluated in terms of three parameters: delay, queue length and the number of stops. The results show that when the traffic volume range of the main road is (1900, 2200) pcu/h and the traffic volume of the secondary road is more than 900 pcu/h, the optimization effect of UALT on both conventional intersections and MUIT is very significant. Taking a signal-controlled intersection in Zhengzhou City, China, as an example to build a simulation model, compared with the conventional intersection and MUIT, the delay drop is reduced by 73.48% and 41.48%, the queue length is reduced by 84.85% and 41.66%, and the operation efficiency is significantly improved.

Keywords: U-turn; intersection optimization; simulation; delay; queue length

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1. Introduction

Conflict points arise between straight ahead and left-turning vehicles in the traffic flow at a level crossing. How to correctly handle and organize left-turning vehicles is the key to ensuring smooth and safe traffic flow at the crossing. The conventional method of handling is to use a channelization design and signal control at the intersection to reduce traffic congestion and ensure traffic safety. However, these measures have also created problems such as increased intersection construction costs and increased time to cross the intersection. With the increasing number of motor vehicles in the city, traffic congestion and accidents at road intersections are becoming increasingly serious and have become a pain point of concern for the whole community.

Many researchers have proposed a series of unconventional designs for intersections to reduce such conflicts, such as Hook Turn, Tandem Intersection (TI), U-Turn (MUIT), Continuous Flow Intersection (CFI), Parallel Flow Intersection (PFI) [1–3]. These designs have a significant impact on the efficiency of the intersection. Although these designs have improved the efficiency of intersections to some extent, some drawbacks make them unpopular, e.g., Hook Turn controlled left-turn traffic affects the lateral traffic flow and leads to increased delays [4]; Almost all vehicles in TI require secondary parking and dynamic adjustments to lane assignments and phase durations, and inadequate pre-planning has a significant impact on actual usage results; CFI and PFI are both displacement left-turn intersections with relatively similar operating characteristics, and if the two lanes traveling

in opposite directions are too close to each other due to road conditions, the risk of side collisions will be greatly increased. The MUIT is used in many countries around the world due to its small engineering volume, significant optimization effect and ease of acceptance by drivers.

However, the high requirements for the median width have limited the application of the MUIT. Therefore, many scholars have studied the improvement of its geometric design, such as new double-curved U-turn intersections with different turning radii [5] and different opening widths [6], which have improved the applicability and operational efficiency of the classical MUIT. In practice, however, the distance between the intersection and the U-shaped opening is another factor affecting the suitability of the MUIT. [7,8] If the distance is too long, the vehicle travel time for the U-turn increases; if the distance is too short, the probability of continuous lane change vehicles waiting for an acceptable clearance is low, and it is difficult for vehicles changing lanes continuously to find an acceptable gap to change lanes, which reduces the success rate of vehicle U-turns and makes the act of slowing down and turning around more difficult and a safety hazard [9–11]. Based on this problem, a U-turn design with Advance Left Turn (UALT) is proposed, in which a turn-on lane is set up on the far right side of the road to allow turning vehicles to exit the intersection early and wait for the crossing gap at the U-turn through the approach lane. This design ensures safety and accessibility at turnarounds and reduces the distance required between the intersection and the turnaround.

2. Methods

The UALT consists mainly of approach lanes, left and right turn lanes and U-turn openings and is configured as shown in Figure 1. From the traffic efficiency and safety considerations, in the intersection on the right side of the road, set left turn and right turn lanes, and at a certain distance from the intersection of the road section in advance with the approach, the road will be left turn and right turn vehicle guidance to the special road. Right-turning vehicles merge directly with the main road traffic flow, while left-turning vehicles wait for the intersection gap to cross the U-turn and merge with the opposite direct traffic through the intersection to achieve the left-turning. There are two ways to connect the U-turn and the import lane: for the road with a median, the median width can be reduced to increase the efficiency of the U-turn vehicle lane; for the road without a median, the U-turn vehicle will enter the main road directly and randomly select the import lane.

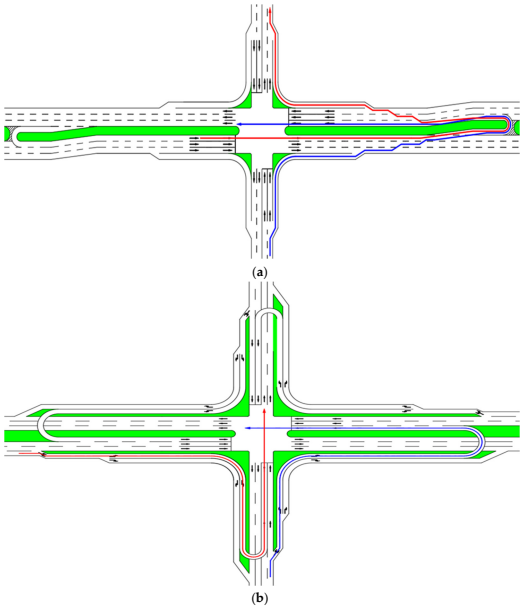

Figure 1. Schematic of the left-turn vehicle travel path. (**a**). MUIT; (**b**). UALT.

The method of diverting intersection traffic ahead of time can, on the one hand, eliminate conflicts between left-turning vehicles and straight-through traffic and improve road utilization; on the other hand, the diversion leaves only straight-through traffic at the intersection, saving the intersection's left-turning traffic signal phase, significantly reducing intersection delays and improving the level of service.

3. Model Development

The UALT proposed in this article is applicable to both new municipal roads and existing road renovations and expansions, with the necessary condition that there are at least three lanes in each direction on the main roads and at least two lanes in each direction on the secondary roads. All the studies conducted are based on the following advanced assumptions:

1. Direct left turns are prohibited at intersections.
2. The intersection arm is long enough. Roads with a median can be set in the middle of the road section U-turn openings.
3. The median, right turn lane and exit lane can meet the widening requirements of the dedicated lane, and the width of the dedicated lane can be appropriately compressed when there is insufficient space.
4. According to the "Urban Road Engineering Design Specification" (CJJ37-2012), the main road is set up with 6 lanes in both directions, the design speed is 40–60 km/h, and the intersection is widened to 8 lanes in both directions; the secondary road is set up with 4 lanes in both directions, the design speed is 30–50 km/h, and the intersection is widened to 6 lanes in both directions; the turning speed is 0.5–0.7 times the design speed, the lane width is set at 3.5 m [12].

3.1. Traffic Variables

The object of the study is a conventional crossroads with three straight lanes and two exclusive lanes on the right side of the main road and two straight lanes and two exclusive lanes on the right side of the secondary road. The specific road structure and variables are represented as shown in Figure 2. Define i as the index of the crossed arms: i = 1 for east arm, i = 2 for south arm, i = 3 for west arm and i = 4 for north arm; o indicates the index of turning target motion, o = 1 for left turn, o = 2 for through movement, o = 3 for right turn and o = 4 for U-turn; j and k indicate the lane numbers of the approach and exit lanes, respectively, counted from the innermost side of the road outwards; n_{io} indicates the total number of lanes with travel path o in the approach lane in the direction of i and m_{ik} indicates the total number of lanes in the exit lane in the direction of i.

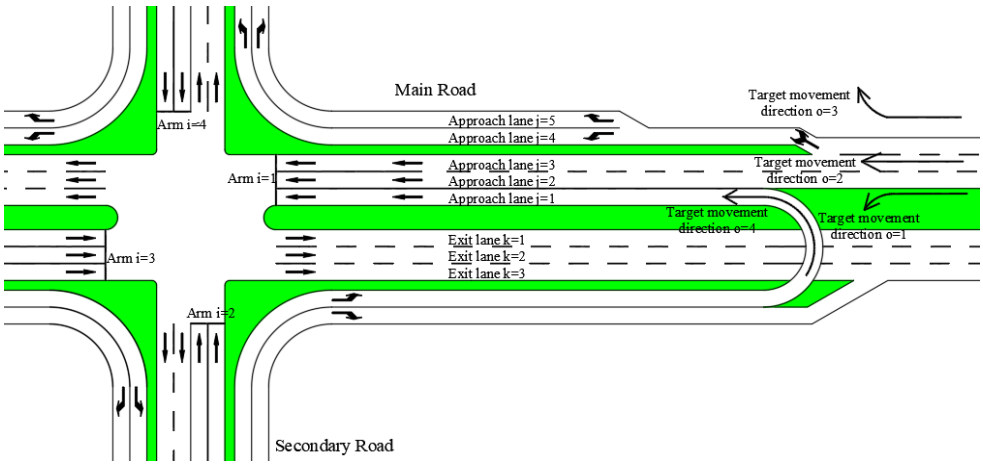

Figure 2. Schematic diagram of traffic variables.

Based on the above variables, the traffic flow on the approach lane at the intersection i direction Q_i ($i = 1, 2, 3, 4$) can be expressed as the sum of the left-turn, straight-through and right-turn traffic flows on the i direction section, i.e.,

The traffic volume Q_i ($i = 1, 2, 3, 4$) in the inlet lane of Arm i can be expressed as the sum of left-turn, through movement and right-turn traffic flows, i.e.,

$$Q_i = \sum_{o=1}^{3} Q_{io} \tag{1}$$

δ_i is the proportion of vehicles turning left in the direction i:

$$\delta_i = \frac{Q_{i1}}{Q_i} \tag{2}$$

When the road is provided with a median, the approach lane a = 1 is reserved for U-turn vehicles and the traffic volumes for each lane q_i are

$$q_i = \begin{cases} Q_{i4}, & a = 1 \\ \frac{1}{2}Q_{i2}, & a = 2, 3 \\ Q_{i1}, & a = 4 \\ Q_{i3}, & a = 5 \end{cases} \tag{3}$$

The traffic volume in each lane on a road without a median where U-turn traffic randomly enters the straight lane q_i' can be expressed as:

$$q_i' = \begin{cases} \frac{1}{2}(Q_{i4} + Q_{i2}), & a = 1, 2 \\ Q_{i1}, & a = 3 \\ Q_{i3}, & a = 4 \end{cases} \tag{4}$$

3.2. Traffic Signal Settings

Traffic signal timing is an important factor that affects the efficiency of intersections. after UALT leads the turning vehicles out earlier, only straight traffic is left at the intersection, and the original signal phase is no longer applicable, so a new signal timing scheme with two phases needs to be developed. In the study, the green phase of one intersection arm and its opposite arm are assumed to be symmetric. The Webster model is chosen for the signal timing calculation method, which is:

$$C_0 = \frac{1.5L + 5}{1 - Y} \tag{5}$$

where C_0 is the optimum signal period (s); L is the total signal loss time (s) and Y is the sum of the maximum flow ratios for each phase during the signal period.

$$L = \sum_{k=0}^{n} (l + I - A)_k \tag{6}$$

where l is the vehicle start loss time, 3 s when no data is available; I is the green light interval time, generally taken as 2–4 s, in this study, it takes 3 s; A is the yellow light time, this study takes 3 s and n is the set number of signal phases.

$$Y = \sum_{j=1}^{n} max\left[y_j, y_j', \ldots\ldots\right] = \sum_{j=1}^{n} max\left[\left(\frac{q_d}{S_d}\right)_j, \left(\frac{q_j}{S_j}\right)_j', \ldots\ldots\right]; (Y \leq 0.9) \tag{7}$$

where y_j and y'_j are the flow ratios for signal phase j; q_d is the design traffic volume in pcu/h and S_d is the design saturation flow in pcu/h.

$$G_e = C_0 - L \tag{8}$$

$$g_{ej} = G_e \frac{\max\left(y_j, y'_j, \ldots\ldots\right)}{Y} \tag{9}$$

$$g_j = g_{ej} - A_j + l_j \tag{10}$$

where G_e is the total effective green time; g_{ej} is the effective green time for phase j and g_j is the actual green time displayed for phase j.

$$g_{min} = 7 + \frac{L_p}{v_p} - I \tag{11}$$

$$G'_e = \frac{g_{\min} Y}{min\left(y_j, y'_j, \ldots\ldots\right)} \tag{12}$$

where $g_{\min}$ is the minimum green light time required for pedestrians to cross the street (s); L_p is the maximum pedestrian crossing distance (m) because the main road has a middle zone where safety islands can be set up, this study takes the width of a secondary road and a non-motorized lane of 2.5 m in both directions as the longest distance, totaling 37 m; v_p is the pedestrian crossing speed, this study takes 3.2 m/s; I is the green light interval, takes 3 s and G'_e is the adjusted optimal signal period.

3.3. Geometry

3.3.1. U-turn Openings and Intersection Spacing

For UALT, the location of the U-turn opening has a significant impact on the efficiency of the intersection. Too close to the intersection may result in queuing traffic blocking the U-turn exit; too far away reduces the efficiency of the intersection.

As shown in Figure 3, in order to prevent the U-turning vehicles from blocking the road by queuing for too long a distance, it is necessary to ensure that L_1 is greater than the length of the queue at the intersection, i.e.,

$$L_1 \geq \begin{cases} \frac{1}{3600} \frac{Q_{i4}}{n_{i4}} (C - t_{i2}) s, & i = 1, 3 \\ \frac{1}{3600} \frac{Q_{i2} + Q_{i4}}{n_{i2}} (C - t_{i2}) s, & i = 2, 4 \end{cases} \tag{13}$$

where C is the signal duration period (s); t_{i2} is the green time for the direct phase of the approach lane in direction i and s is the headway between queuing vehicles at the intersection.

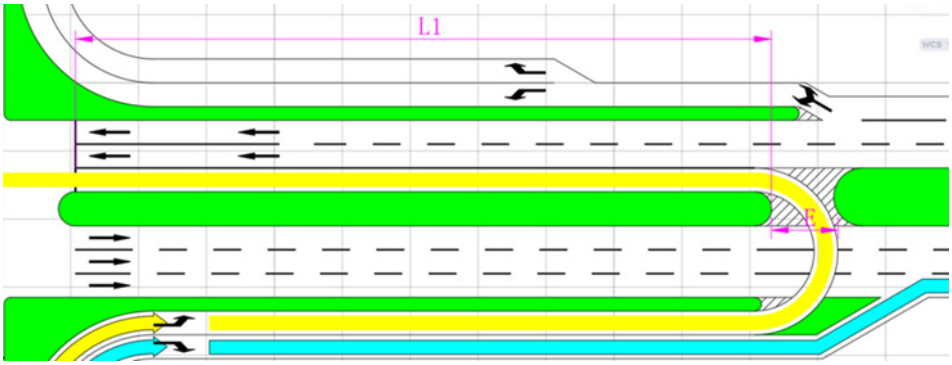

Figure 3. Schematic diagram of geometric dimensions.

The above calculation method is mainly applicable to established projects where the parameters required for the calculation are easily available. For new road intersections or intersections with unknown parameters, the method of intersection simulation is usually taken to measure the intersection queue length and thus obtains the value of L1.

The main objective of the simulation is to measure the average queue length at the intersection for different traffic combinations and select a suitable length as the initial value of L1. Then the UALT model is built with the initial value of L1, the length of L1 is adjusted in a small range, and the vehicle delays in the approach lane are then compared to obtain a determined value for L1.

1. Selection of L1 initial values. First, a simulation model was built for the conventional intersection, varying the traffic volume on the main and secondary roads, measuring the queue length of the approach lane in turn and conducting statistical analysis; the results are as follows.

From Figure 4, about 90% of the traffic combination queue length in conventional intersections is less than 110 m, while the queue length in UALT is less than conventional intersections, so the initial value of L1 taking 110 m can basically meet the length requirement.

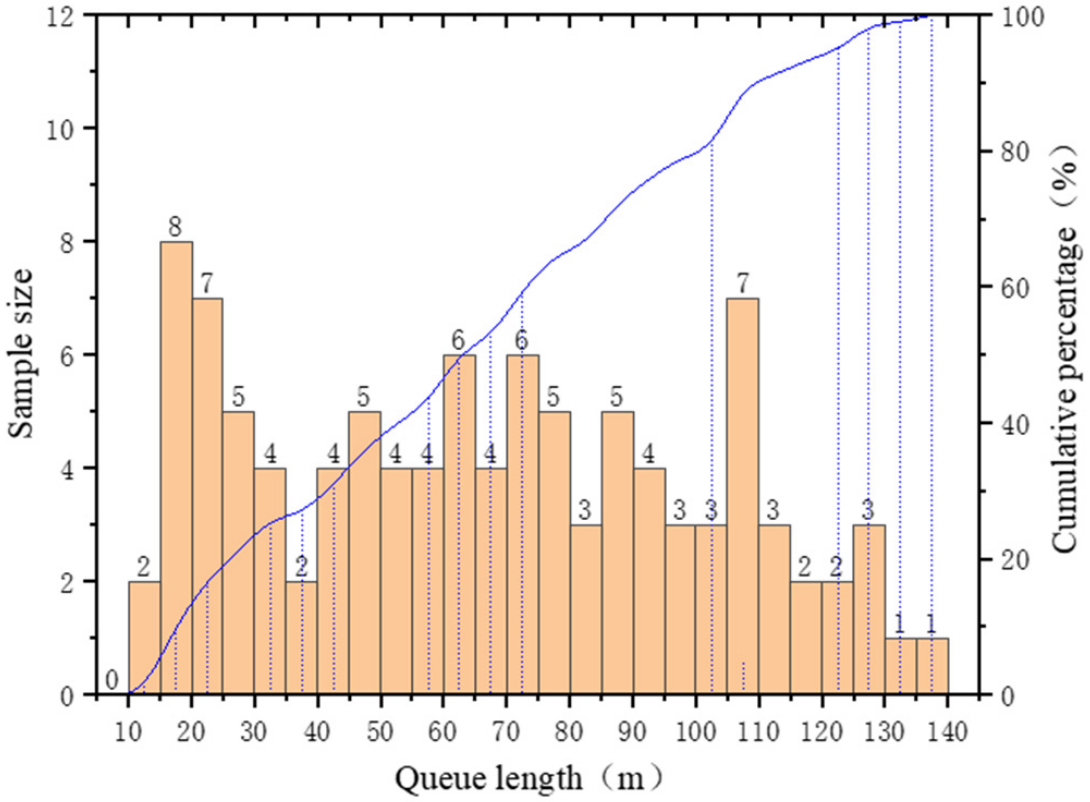

Figure 4. Statistical chart of maximum queue lengths at conventional intersections.

2. Small range adjustments of L1 values to determine the final value. Taking a single approach lane of UALT as the object, fixing the length of L1 and varying the left-turn traffic volume to detect its delay, the delay results under different lengths are obtained, and are shown in Figure 5. The results are shown below. The results show that when the spacing is fixed, the delay shows an increasing trend with the increase of traffic volume. When the left-turn traffic volume is less than 300 pcu/h, the delay gap is small for all L1 values; when the left-turn traffic volume is greater than 300 pcu/h, the delay corresponding to L1, taken as 110 m, is the smallest.

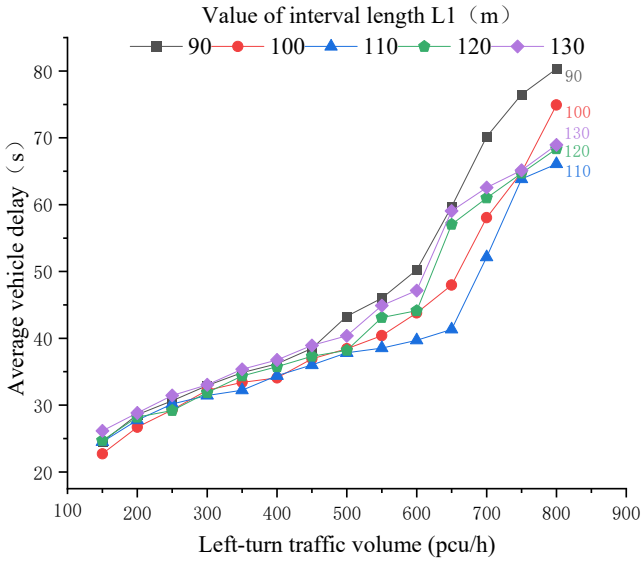

Figure 5. Plot of delay versus traffic volume for left-turning vehicles at different spacing lengths.

In summary, when L1 is less than 110 m, the probability of queuing vehicles blocking the U-turn opening at the intersection is greater; when L1 is greater than 110 m, it leads to a large increase in left-turn vehicle delays. Therefore, when L1 is set at 110 m, it not only meets the queue length requirement for about 90% of the traffic volume combinations but also reduces the left-turn vehicle delays, when UALT can play the best role.

3.3.2. Length of Central Median Opening

Refs. [13,14] showed that the length of the central median opening also has an effect on the efficiency of vehicle turning. An appropriate increase in the length of the opening not only improves the capacity of the turning vehicle but also reduces the impact of the turning vehicle on the downstream vehicles of the intertwined section and increases the safety of the traffic. As the trajectory of the turning vehicle is approximated by a semicircle (in Figure 6), the length of the opening can be calculated by the angle between the central divider and the semicircle of the trajectory of the turning vehicle.

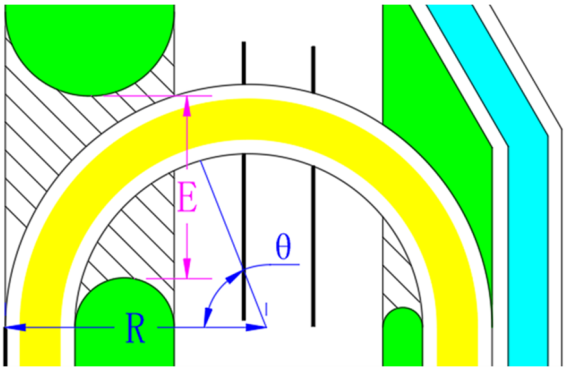

Figure 6. Length of U-turn opening.

$$R = \frac{1}{2}[(n_{ik} + 2)d + l_m + l_o] \tag{14}$$

$$E = R \cdot \sin\theta - \frac{l_m}{2} \tag{15}$$

where E is the length of the median opening (m); R is the radius of the U-turn trajectory (m); θ is the angle of the intersection of the median and the vehicle trajectory, usually in the

range of 45° to 90°, depending on the actual situation; d is the lane width, which is set to 3.5 m in this study and l_m and l_o are the widths of the median and the side divider inside the U-turn, respectively (m).

According to the Urban Road Engineering Design Specification (CJJ37-2012), the lane width of a six-lane road is usually 3.5–3.75 m, the width of the central divider is 3.0–5.0m, and the width of the side divider is 1.5–2.5 m [12]. The length of the U-turn opening is 4.07–8.56 m, by substituting the parameters into Equations (14) and (15), and the difference between the inner and outer wheelbase of the vehicle during turning is 5.3–6.4 m for small cars and 7.7–9.4 m for large cars [15]. This is similar to the results of the above calculation.

4. Development of Simulation Model

Different traffic situation combinations were specified in the VISSIM simulation model to ensure that more possible situations were covered between CI, MUIT and UALT.

When building the simulation model, some parameters need to be input into VISSIM, including: car/truck (bus) ratio, passing/turning ratio and traffic volume variation. The simulation model takes the intersection of a six-lane road and a four-lane road as the research object. The following parameters were set for the intersections after a field survey of several intersections in Zhengzhou with similar conditions:

5. The southbound and northbound intersection arms do not have a median; the width of the side median is 1.5 m; the width of the median of the eastward and westward crossing arms is 5 m and the width of the side medians is 1.5 m. All lane widths are 3.5 m;
6. According to [16], the distance from the intersection stop line at the opening of the MUIT's median is set at 350 m and the length of the opening is 9.4 m;
7. UALT's U-turn opening at the intersection is set to 110 m, the road width and putting other parameters into Equations (14) and (15), with θ equal to 60°, the calculation can be set to an opening length of 8.1m;
8. According to [17], the maximum traffic volume of urban roads with a design speed of 80 and 50 km/h corresponding to service level four is 2150 and 1250 pcu/h, respectively;
9. The results from a field survey of 12 intersections in Zhengzhou follow Figure 7. It can be seen that the proportion of vehicles turning at intersections is more concentrated, and most of the time, the proportion of left turns on secondary roads is slightly higher than on primary roads. The parameters are shown in Table 1.

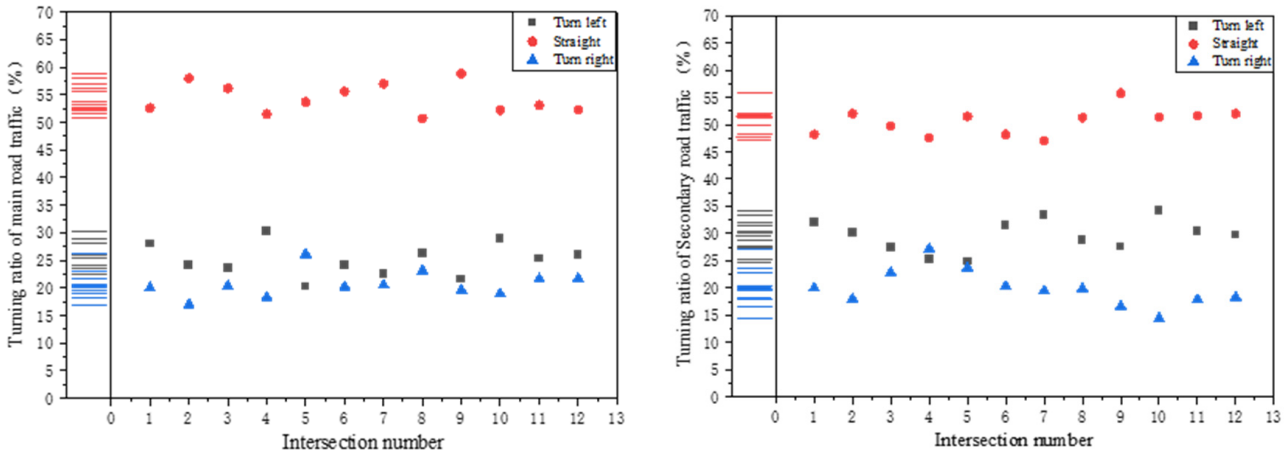

Figure 7. Field survey data on traffic turning ratios. (**a**) Main road; (**b**) Secondary road.

Table 1. Parameters input into VISSIM.

Item	Value	
Car/Truck(bus) ratio	0.97:0.03 (main road)	0.98:0.02 (secondary road)
Traffic turning ratio (Turn left: go straight: Turn right)	0.25:0.55:0.2 (main road)	0.3:0.5:0.2 (secondary road)
Main Road Volume Range	1100~2300 pcu/h	
Secondary road volume range	500~1200 pcu/h	

5. Results

5.1. Operational Features with UALT and CI

In order to demonstrate the effect of UALT on intersection operation efficiency, it is compared with conventional intersections under the same set of simulation environments. The analysis results are evaluated with three metrics: delay, queue length and the number of stops. The data need to be pre-processed before comparing them, using delay as an example, in the following way:

The delay for each approach lane in arm i of the intersection is first calculated, and then the weighted average of the network delays using the number of approach lanes in each direction as weights are found as the average network delay for that intersection. The average queue length and the average number of stops are calculated in the same way as above. The improvement ratio for each metric is calculated as shown in Equation (16).

$$Ratio = -\left(\frac{UALT - CI}{CI}\right) \times 100\% \tag{16}$$

where *UALT* and *CI* represent the same metric for different types of intersections. CI can also be replaced with MUIT, when it indicates the improvement effect of UALT on MUIT.

5.1.1. Delays

The analysis of the simulation results shows that within the set traffic volume range, the average delay range of the road network for conventional intersections is 28.99–120.84 s, while the average delay range of the road network for UALT is only 10.32–20.89 s. The average delay of the road network is reduced by 55.13–86.07%, which shows that the optimization effect of UALT on the average delay of the road network is significant.

The comparison results of delay are shown in Figure 8. The average delay reduction of UALT for conventional intersections exceeds 75% when the traffic volume on the main road is greater than 2000 pcu/h or the traffic volume on the secondary road is greater than 900 pcu/h. The reduction reaches the maximum when the combination of traffic volume on the main and secondary roads is around (1700, 1100) pcu/h; the delay reduction is lowest when the traffic volume on the secondary road is 500 pcu/h, and the traffic volume on the main road is less than 1500 pcu/h. When the traffic volume on the secondary road is 500 pcu/h, and the traffic volume on the main road is less than 1500 pcu/h, the delay reduction is the lowest, but it also reaches more than 55%.

5.1.2. Queue Lengths

The queue length improvement rate is shown in Figure 9. UALT is very effective in optimizing queue lengths and performs better than the average delay of the road network in terms of reduction and applicability. The average queue length for conventional intersections ranges from 12.61 to 136.30 m, while the queue length for UALT ranges from 3.12 to 15.68 m, reducing the average queue length by 60.66% to 94.7%. When the traffic volume on the main road is greater than 1800 pcu/h or the traffic volume on the secondary road is greater than 800 pcu/h, the reduction of queue length almost always reaches more than 85%, and the greatest reduction is achieved when the combination of main and secondary road traffic volume is around (1700, 1100) pcu/h.

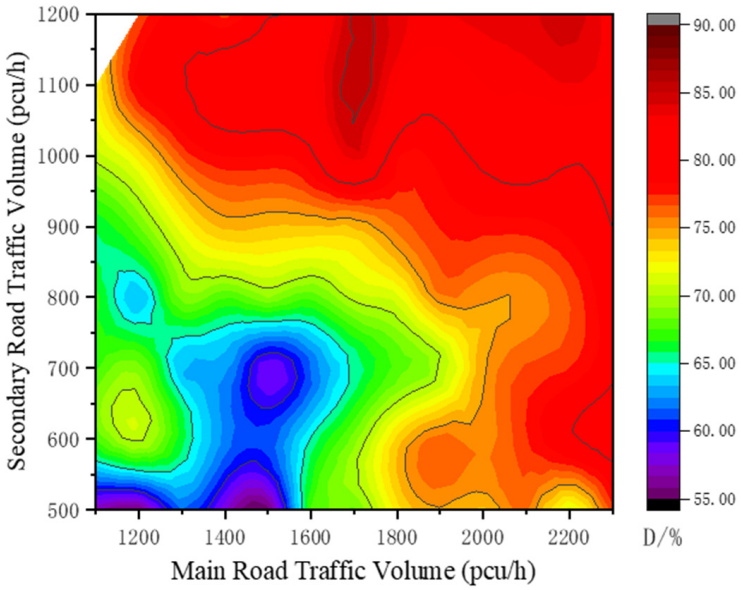

Figure 8. Delay reductions for UALT and CI.

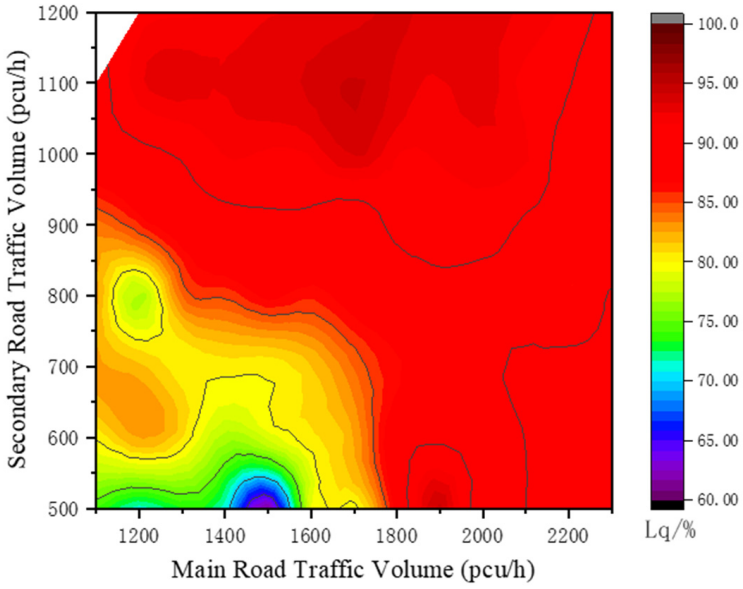

Figure 9. Queue length reductions for UALT and CI.

5.1.3. Number of Stops

The simulation results show that UALT is slightly less effective in optimizing the number of stops, with the reduction trending broadly upwards as the traffic volume on the main road increases. Within the set traffic volumes, the average number of stops at conventional intersections ranged from 0.58 to 2.56, while UALT ranged from 0.37 to 0.77.

The comparative analysis graph of the results of the improvement rate S for the number of stops is shown in Figure 10. It can be seen that when the traffic volume on the main road is greater than 2100 pcu/h or the traffic volume on the secondary road is greater than 1000 pcu/h, the reduction of the average number of stops reaches more than 65%. The best improvement was achieved when the traffic volume combination of the main and secondary roads was around (1700, 1100) pcu/h, with a reduction of 74.13%; the lowest reduction was achieved when the traffic volume combination was (1100, 500) pcu/h, with a reduction of 33.07%.

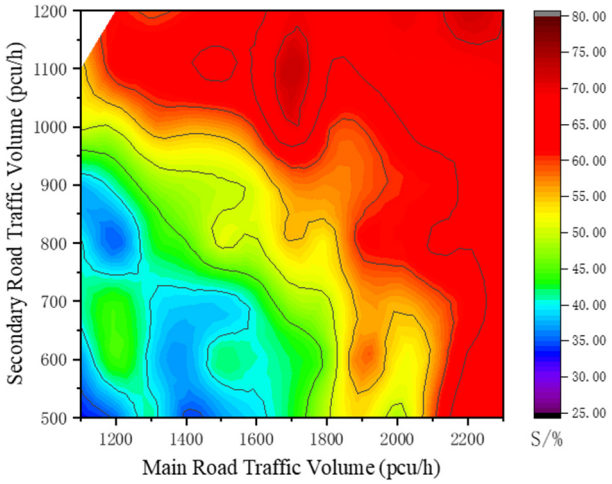

Figure 10. Stopping reductions for ULAT and CI.

In summary, UALT is effective for optimizing the level of service at conventional intersections by reducing queue length by more than 85% for over 70% of the traffic combinations; reducing average delay by more than 75% for around 50% of the combinations and reducing the average number of stops by more than 65% for one-third of the combinations. The details are shown in Figure 11.

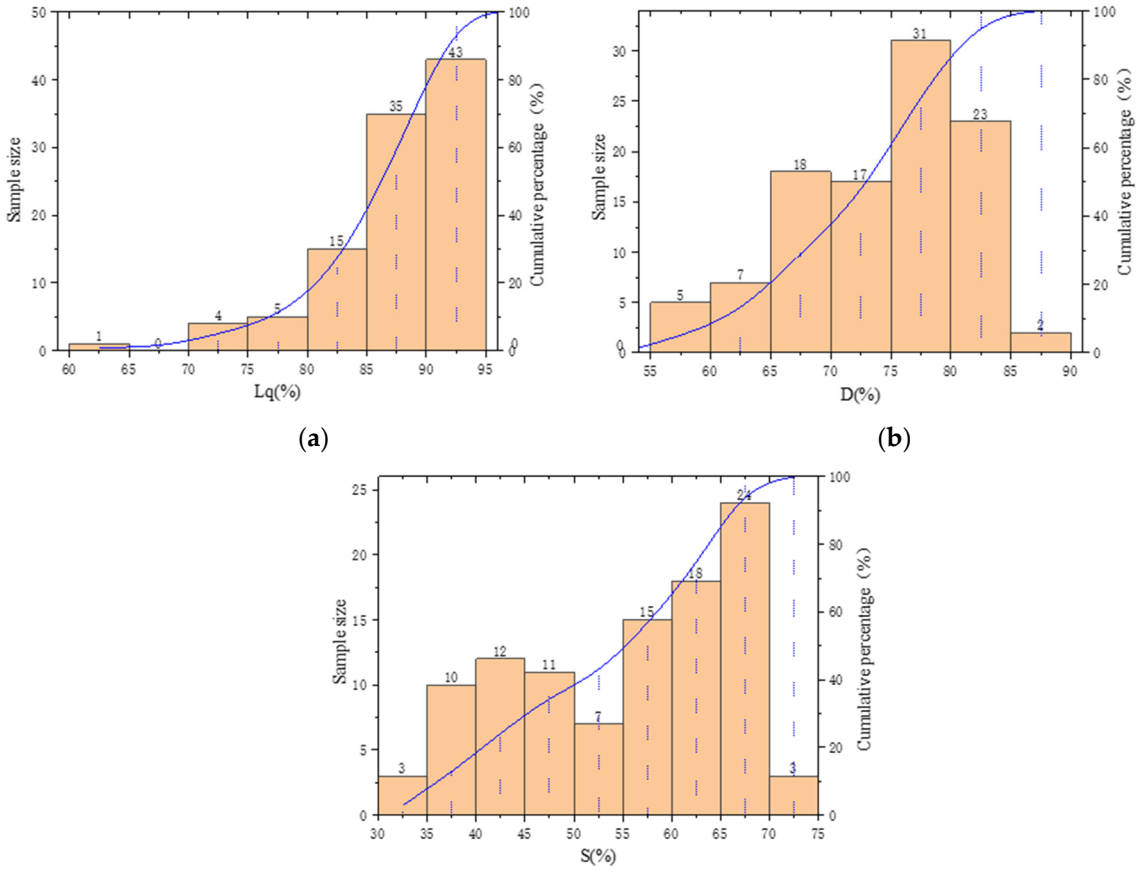

Figure 11. Statistical chart of the optimization effect of each indicator. (**a**) Queue lengths; (**b**) Delay; (**c**) Number of stops.

5.2. Operational Features with UALT and MUIT

Although UALT is very effective in improving the operational efficiency of conventional crossings, it also requires a large amount of construction work for existing crossings, which is not very cost-effective from an economic point of view. Therefore, the indicators of UALT and MUIT are also compared below, and the range of traffic volumes with higher reductions is used as the applicable range for UALT. The reduction is calculated in Equation (16).

5.2.1. Delays

The comparison of delay reduction between UALT and MUIT is shown in Figure 12. when the traffic volume on the trunk road is less than 2100 pcu/h, the delay reduction increases gradually and decreases rapidly when it exceeds 2100 pcu/h. When the main road traffic volume is between 1900 and 2200 pcu/h, UALT has the best delay improvement for MUIT, with a reduction of more than 70%.

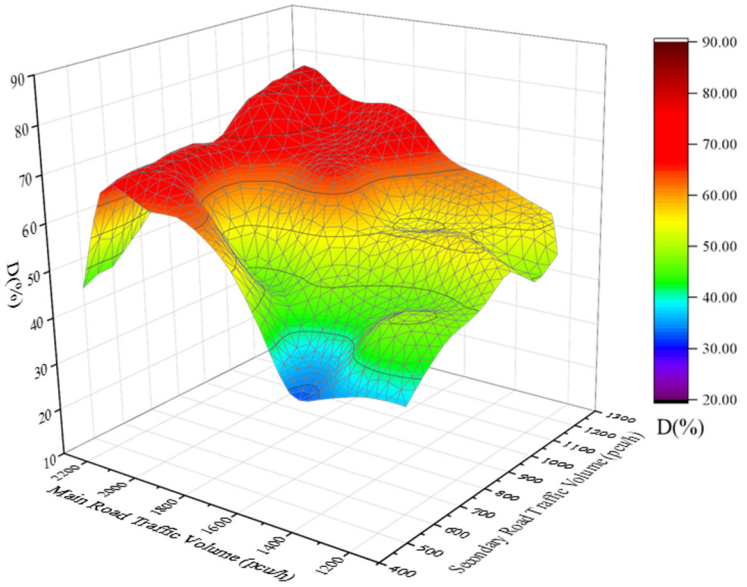

Figure 12. Delay reductions for UALT and MUIT.

5.2.2. Queue Lengths

A comparison of the queue length reductions for UALT and MUIT is shown in Figure 13. The trend of queue length improvement for UALT on MUIT is similar to the trend of delays. The queue length reduction first increases as the traffic volume on the primary road increases and then decreases above 2200 pcu/h. UALT is most applicable when the traffic volume on the main roads is between 2000 and 2200 pcu/h, and the traffic volume on the secondary roads is greater than 900 pcu/h, with an average queue length reduction greater than 70%.

5.2.3. Number of Stops

The rate of reduction in the number of stops as a function of traffic volume is shown in Figure 14. It can be seen that the reduction of the number of stops increases and then decreases with the change in the traffic volume on the main road, reaching a maximum when the traffic volume on the main road is around 2200 pcu/h. The reduction exceeds 70% when the main road traffic volume is in the range of 1900 to 2100 pcu/h. In this traffic volume range, UALT has the most significant effect on optimizing the number of stops in MUIT.

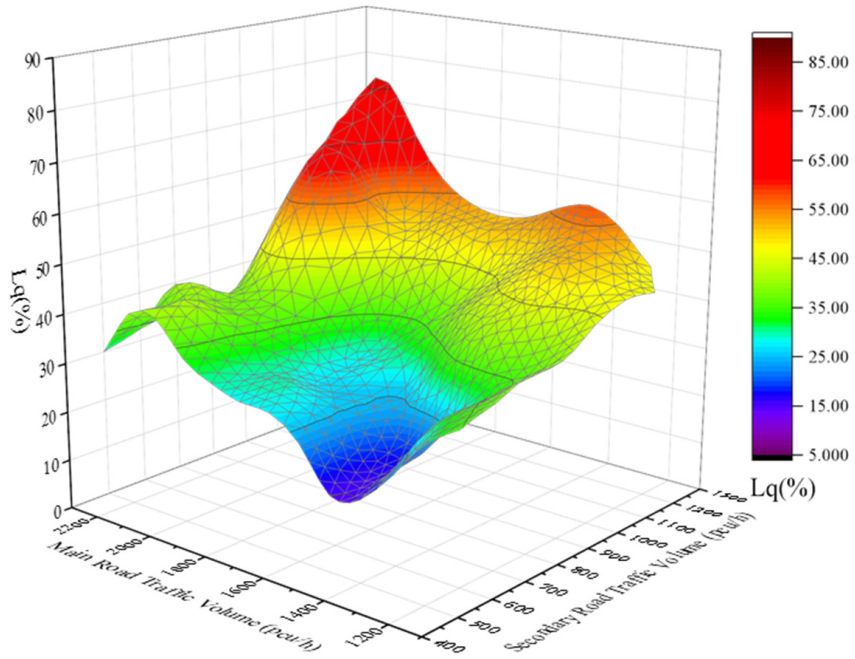

Figure 13. Queue length reductions for UALT and MUIT.

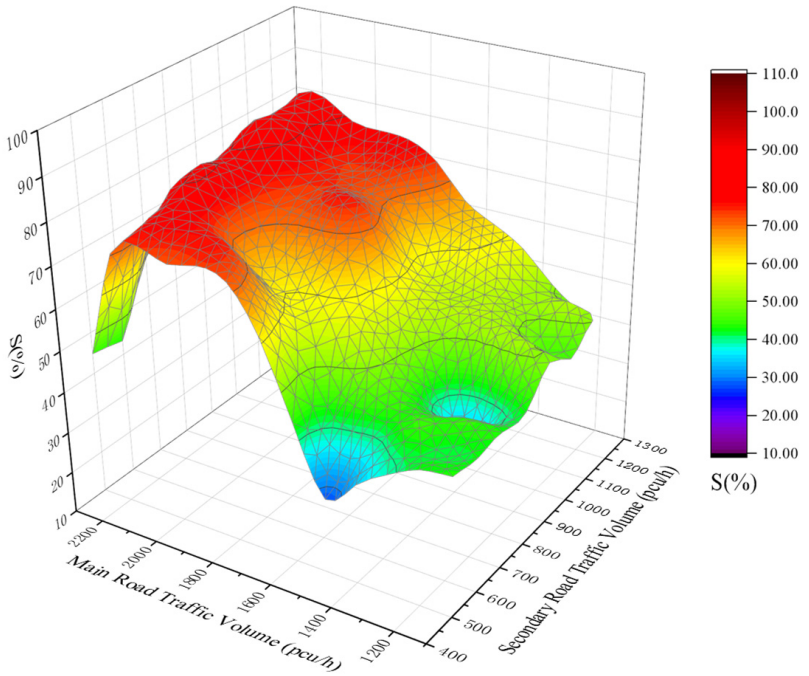

Figure 14. Stopping reductions for UALT and MUIT.

In summary, the best applicable range for UALT is 1900–2200 pcu/h. Within this range, UALT is more effective and economical for MUIT improvement, as well as for conventional intersections.

6. Project Examples

Taking a signal intersection in Zhengzhou City as an example, a simulation analysis of the setting effect of the new U-turn intersection was carried out based on field surveys to obtain traffic flow in each direction of the intersection, using queue length, capacity, delay and other indicators to comprehensively assess the setting effect of the intersection.

6.1. Data Collection

Real traffic data were collected to build and calibrate the simulation model in VISSIM. There is no specific permission required for these locations. Field data were collected at intersections in the public area of Zhengzhou, China, at the selected location at the Yan-Huang Expressway–DaHe Road intersection. Video cameras were used for data collection at the intersections. The field studies did not involve endangered or protected species. The geometric characteristics and traffic information of the intersections are shown in Tables 2 and 3.

Table 2. Basic geometric feature of selected intersections.

Direction	Number of Approach Lane			Median Width(m)	Traffic Volume (pcu/h)		
	Left Turn	Straight	Right Turn		Left Turn	Straight	Right Turn
i = 1 (East)	1	2	2	10	302	508	187
i = 2 (South)	1	3	1	5	492	1063	371
i = 3 (West)	1	2	1	10	234	577	269
i = 4 (North)	1	3	1	5	556	1172	405

Table 3. Original signal phase timing of selected intersections.

Site	Green Time	Yellow Time
Straight ahead (N–S)	45	3
Turn left (N–S)	35	3
Straight ahead (E–W)	28	3
Turn left (E–W)	20	3

6.2. Simulation Analysis

The parameters of UALT are calculated by the relevant formula above, the distance between the U-turn opening and intersection stop line is 110 m, and the width of the median opening in East–West and North–South directions are 6.93 and 7.93 m, respectively. Table 4 shows the optimized signal phase times. To eliminate the chance of the model simulation results, the random seed was changed, and each model simulation was run 20 times; the simulation results are shown in Table 5.

Table 4. Optimized signal phase timing of selected intersections.

Site	Green Time	Yellow Time
Straight ahead (N–S)	45	3
Straight ahead (E–W)	35	3

Table 5. Statistical analysis table of simulation results.

Intersection Type	Delay (s)		Queue Length (m)		Number of Stops (Times)	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
CI	37.417	10.844	27.976	11.596	0.74	0.262
MUIT	16.959	3.558	7.263	1.628	0.495	0.159
UALT	9.924	3.188	4.238	1.194	0.427	0.151

Table 5 and Figure 15 show that after converting conventional intersections to MUIT and UALT, delays are reduced by 20.458 and 27.493 s, respectively, with a reduction of 54.68% and 73.48%; queue lengths are reduced by 20.713 m and 23.738 m, respectively, with a reduction of 74.04% and 84.85%; and the number of stops is reduced from 0.74 to 0.495 and 0.428 times, with a reduction of 33.1% and 42.24%. These show that both MUIT and UALT can improve the traffic status of selected intersections.

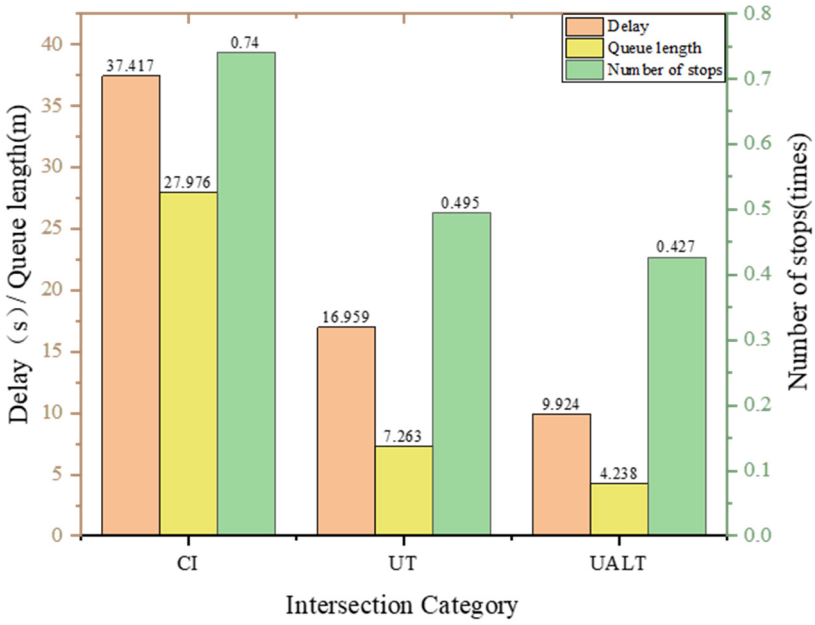

Figure 15. Analysis of simulation results for selected intersections.

Comparing the simulation results of MUIT and UALT, UALT has 7.035 s less delay than MUIT, with a reduction of 41.48%; the queue length is reduced by 3.025 m, with a reduction of 41.66%, and the intersection service level is improved more obviously. The boundary line of road width of the conventional intersection is 40 m, and the width can be kept unchanged by compressing the median when transforming to MUIT; when transforming to UALT, the lane width is compressed from 3.75 to 3.5 m, the approach width is increased to 2.5 m, the median width is compressed from 10 and 5 to 7.5 and 4.5 m, and the boundary line of roads on both sides of the road only needs to be widened by 2 m each.

As a result, for intersections with high traffic volumes, UALT only requires a small widening of the boundary line of roads, but the level of service and operational efficiency of the intersection is greatly improved.

7. Conclusions

The disadvantage of the conventional MUTI is that the turning vehicles traveling to the U-turn opening can cause traffic conflicts with the straight-ahead vehicles on the lateral road. In this study, a modified U-turn design named the U-turn design with Advance Left Turn (UALT), is proposed. The core design of the UALT is to have two turn-on lanes on the right side of the inlet lane, which provides a turnaround movement separate from the through flow. Turnaround vehicles can reach the U-turn openings directly through the dedicated lanes without disrupting the through flow. Traffic conflicts caused by turning vehicles changing lanes continuously will be greatly reduced. VISSIM simulation models were developed and calibrated to evaluate the operational characteristics of UALT intersections and to explore the applicable traffic volumes for this design. Conventional intersection design is also evaluated for comparison.

The results show that UALT is most suitable to be used when the traffic volume on the main roads is between 1900 and 2200 pcu/h, and the traffic volume on the secondary roads is greater than 900 pcu/h. Within this range, the UALT design results in a delay reduction of over 75%, queue length reduction of greater than 85% and stopping frequency reduction of over 65% at conventional intersections; compared to MUIT, the reduction in delay, queue length and stopping frequency is greater than 70%.

The findings of this study can be useful in reducing traffic conflicts (including delays, stops and potential accidents) caused by U-turning vehicles. It can be utilized as a guideline for transport policy-makers and planners to determine when and where the UALT should be used. Before the UALT is used in practical applications, some issues can be further

studied in the future: First, in this study, the intersection between the left-turn-only lane and the lateral road is considered a non-signal-controlled intersection, and the study of how to use signals that are adaptively adjusted to the lateral road traffic flow to control the turning vehicles can further improve the safety and passing efficiency of the turning vehicles. Second, this study only investigates an isolated intersection. The scope of the study can be extended to a wider range to simulate larger networks and more accurately estimate the operational effects of UALT. The authors suggest that future research could be directed in these directions.

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