# TRAVEL TIME EVALUATION OF A U-TURN FACILITY AND ITS COMPARISON WITH A CONVENTIONAL SIGNALIZED INTERSECTION

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## ABSTRACT

2 Signalized intersections on high-volume arterials are often congested during peak hours, causing 3 a decrease in through movement efficiency on the arterial. Much of the vehicle delay incurred at 4 conventional intersections is caused by high left-turn demand. Unconventional intersection 5 designs attempt to reduce intersection delay and travel time by rerouting left-turns away from the 6 main intersection and replacing it with "right-turn followed by U-turn". The proposed new type 7 of U-turn intersection is geometrically designed with a raised island which provides a protected 8 U-turn movement. In this study several scenarios based on different distances between U-turn 9 facility and present intersection, traffic volume on major/minor approaches and percentage of 10 left-turn volumes were simulated using AIMSUN; a microscopic traffic simulation software. Subsequently some models are proposed in order to predict travel time of each movement at the 11 intersection. Eventually by correlating these models to some in-field collected data of some real-12 13 life implemented U-turn facilities, the reliability of the proposed models is approved. With these 14 models it would be possible to calculate travel time of each movement under any kind of 15 geometric features and traffic conditions. By comparing travel time of a conventional signalized intersection with U-turn facility, it is possible to decide on converting signalized intersections 16 17 into this new kind of U-turn facility or not. In this paper only travel time of this U-turn facility 18 will be modeled. According to some before and after study about the traffic performance of some 19 selected U-turn facilities, it is found that commonly, this new type of U-turn facility produces 20 lower travel time. Thus, evaluation of using this type of unconventional intersection should be 21 seriously considered.

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#### INTRODUCTION

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3 One of the most important factors that significantly impact the performance of signalized 4 conventional intersections is the existence of heavy left-turn volumes. High left-turn demand at 5 major intersections and high arterial design speeds justify protected left-turn phasing. Protected left-turn phases however add more phases to the signal cycle, increase lost time between phases, 6 7 and reduce the available green time for through movement phases. Some of the recommended 8 alternatives such as widening roads or changing intersections to interchanges are quite 9 expensive, so some low-cost solutions should be considered. As a result, there has been 10 considerable interest in alternative measures for dealing with left-turns at intersections to 11 improve performance, some of which have been unconventional schemes. Unconventional 12 arterial intersection designs attempt to reduce intersection delay and travel times by diverting left-turns from crossing through the main intersection, therefore reducing the number of signal 13 phases. Different types of unconventional intersection designs are known that have been or may 14 15 be applied to reduce intersection delay and travel times. In these types of unconventional 16 intersections, mainly direct left-turn (DLT) is replaced by right turn plus U-turn (RTUT). Due to 17 the widespread use of various indirect left-turn treatments, increased attention has been given to 18 evaluating the safety and operational effects of U-turn movements.

19 Many studies were carried out to assess the impacts U-turn movement itself on the 20 capacity of signalized and unsignalized intersections (1-4) while some other researchers were 21 interested in evaluating some characteristics of U-turn maneuver (5, 6). Some other studies 22 focused on U-turns at median openings. A study by Al-Masaeid developed an empirical model to 23 estimate the capacity and average total delay of U-turns at median openings (7). In one of the 24 initiative studies, the operational issues associated with DLTs and RTUTs were analyzed and a 25 procedure to calculate the delay and travel time in relation to upstream and downstream signal effects was established (8). In NCHRP Report 420: Impacts of Access Management Techniques, 26 27 an analytical model was developed and calibrated to estimate the travel-time savings (or loss) in 28 suburban and rural areas. Findings indicated that DLT vehicles would suffer longer delays than 29 RTUT vehicles when the volumes on the major road are relatively high and the DLT volume 30 exceeds 50 vph (9). NCHRP Report 524 presents guidelines for locating and designing 31 unsignalized median openings. In this report a methodology is included for comparing the 32 relative safety performance of different designs (10).

33 On the other hand, alternative unconventional designs got engineers attention in order to 34 carry out indirect left turns. The unconventional alternatives share two major principles. First, the emphasis is on reducing delay to through vehicles. Serving through vehicles is the main purpose 35 36 of the "arterial" functional class. Second, the unconventional alternatives try to reduce the 37 number of conflict points at intersections and separate the conflict points that remain. By their 38 nature as unconventional solutions, and by rerouting certain movements, the alternatives 39 presented here all have the potential to cause more driver confusion than conventional arterials. 40 However, newness is not a sufficient reason to ignore an otherwise superior alternative. Hummer 41 described different unconventional alternatives that engineers may wish to consider for their 42 urban and suburban arterials (11). In another study about the operational effects of indirect 43 driveway left-turn treatments, Liu et al. compared delay and travel time for three different 44 driveway left-turn alternatives. They are: (i) DLTs at driveways, (ii) RTUTs at downstream 45 median openings, and (iii) RTUTs at signalized intersections. It was found that vehicles making 46 RTUT at a downstream median opening before a signalized intersection have comparable total

travel time as compared with those making DLT at a driveway; and the percentage of drivers selecting RTUT increases with the upstream through traffic volume, left-turn volume from major road into the driveway, and the total left-turn traffic demand at a driveway (*12*).

4 Performance of unconventional designs was further investigated by other researchers. 5 Tabernero and Sayed introduced the Upstream Signalized Crossover (USC) intersection with a 6 brief comparison to the conventional intersection. Their analysis showed that the USC has the 7 potential for accommodating heavy left-turn movements while maintaining an acceptable 8 performance level for through traffic (13). Sayed et al. further investigated and compared the 9 performance of the USC to a similar conventional scheme under different volume scenarios (14). 10 El Esawey and Sayed compared the performance of the USC intersection and Crossover Displaced Left-Turn (XDL) intersections to conventional intersection (15). Their analysis 11 12 revealed that both unconventional designs exhibited lower delay and higher capacity than 13 conventional intersection design.

14 Studies about system wide travel time savings of the unconventional left-turn alternatives have also been conducted by computer simulation. Reid and Hummer used CORSIM to compare 15 16 traffic operations along an arterial that has five signalized intersections, for the conventional Two-Way Left-Turn Lane design and two alternative unconventional designs; the Median U-turn 17 Crossover design and the Super-Street Median Crossover design (16). Reid and Hummer also 18 19 used CORSIM to conduct travel time comparisons between seven isolated unconventional 20 intersection schemes and a similar conventional intersection. Their simulation results showed 21 that at least one unconventional scheme outperformed the conventional intersection in at least 22 one volume scenario. In general, the analysis was in favor of the Quadrant and the Median U-23 turn intersections for most volume scenarios (17). Jagannathan and Bared used VISSIM to 24 compare three different XDL configurations to their conventional counterparts. The analysis 25 showed considerable savings in average control delays for all volume conditions (low, medium, and high). Furthermore, a significant increase of 15% to 30% in the overall capacity of the XDL 26 27 intersection was found (18). Kim et al. used VISSIM to obtain performance of the superstreet 28 designs and its comparable conventional alternatives. The superstreet design is similar to the 29 median U-turn design but has some additional features that allow for perfect progression of 30 through traffic on the major road in both directions by preventing the minor road traffic from crossing the major road (19). In another research Cheong et al. compared the operational 31 performance of three unconventional intersections: Continuous Flow Intersection, Parallel Flow 32 Intersection and Upstream Signalized Crossover. To do this, a variety of experimental designs, 33 34 including traffic conditions, geometric features and signal plans, were set and the average delays 35 were compared for movements of through-only traffic and left-turn-only traffic. From the results, all three unconventional intersections outperformed the conventional one (20). 36

In this study a different type of U-turn facility is proposed which has some crucial 37 38 differences to the other types of median openings and has been widely used in Middle East, 39 specifically in Iran and Egypt. As far as we know, this particular type of U-turn design has not 40 been studied yet. These developed U-turn facilities are built on main roads with moderate or high level of traffic, at both sides of the intersection, and used as a complete replacement of signalized 41 intersections. This means that through and left-turn movements of minor roads and left-turn of 42 major road will use the U-turn facility and median on the major road at the former intersection is 43 44 blocked (see part G in Figure 1). This is different from other typical U-turn facilities (median 45 openings) reviewed in the literature which were only used as a replacement of left-turns. There are no signals at points C and G; thus, this facility can be characterized as an uninterrupted flow 46

1 facility. This type of U-turn is geometrically designed, has channelizing and splitting islands and 2 provides protected U-turn movements. Channelizing island with a convex section helps drivers 3 to keep track on their desired trajectories either if they want to use the U-turn facility or go 4 straight on the main road. This convex section affords an opportunity for a through driver to pass 5 to the right of a slower moving or stopped vehicle on the deceleration lane preparing to use the 6 U-turn. By the use of a splitting island, a safe divergence at the entrance of the U-turn facility 7 and a safe and protected convergence operation at the exit of the U-turn are provided. An 8 acceleration lane is also provided for a safe merging of U-turn vehicles with the traffic on the 9 main road. Different parts of this U-turn facility which are schematically depicted in Figure 1

- 10 are defined as:
- 11 A: Channelizing island
- 12 B: Deceleration lane
- 13 C: U-turn raised island
- 14 D: Acceleration lane
- 15 E: Major road
- 16 F: Minor road
- 17 G: Blocked median
- 18 H: Network's boundaries



19		
20	FIGURE 1 Different parts of the developed U-turn facility.	
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22	Figure 1 just shows one side of the intersection. Actually, the left side is the same as right	
23	side and has similar sections. To have a better idea, the geometric characteristics of some	
24	implemented U-turn facilities in Iran are presented below:	
25	<ul> <li>Turning inside radius varies from 2m to 5.5m</li> </ul>	
26	<ul> <li>Design turning radius varies from 10m to 20m</li> </ul>	
27	• Turning area width varies from 12m to 16m	
28	• U-turn island width varies from 13m to 25m	
29	<ul> <li>Median width varies from 4m to 10m</li> </ul>	
30	<ul> <li>Deceleration lane length varies from 80m to 130m</li> </ul>	
31	<ul> <li>Acceleration lane length varies from 80m to 150m</li> </ul>	
32	• Deceleration lane width varies from 3.7m to 9m	
33	<ul> <li>Acceleration lane width varies from 4m to 9m</li> </ul>	

- Deceleration lane number varies from 1 lane to 2 lanes
- Acceleration lane number varies from 1 lane to 2 lanes

It is essential to mention that the geometric design of this U-turn facility depends on different traffic conditions and right of way restrictions which vary from case to case. Implemented facilities were designed based on the standards of the manual "A Policy on Geometric Design of Highways and Streets" (21).

7 The purpose of this research is to conduct a travel time evaluation of the developed U-8 turn facility which is proposed as an alternative of the traditional signalized intersection. Along 9 with the results of this research, engineers and designers would be able to implement a side-byside comparison of this new type of traffic facility to the conventional design of signalized 10 intersections. The outcome of these comparisons at different volume levels will provide them 11 12 with more firm guidance on which type of alternatives they should consider. For instance, if the comparison shows a reduction of travel time by using this U-turn facility, it could be meaningful 13 14 to consider implementing this type of facility instead of a traditional signalized intersection.

Before elaborating on the analysis and results of this study, it is however important to elaborate on the scope (and limitations) of this study. First of all, this paper only studies a single U-turn facility (isolated intersection and U-turn), not a network or corridor. Moreover, the study focuses on the traffic performance evaluation only. Obviously, safety, driver expectations, costs, and many other factors may feed into the decision making process behind an intersection design.

20 The structure of the paper is as follows. Initially, a U-turn facility is geometrically 21 defined in the simulation and different traffic conditions are loaded. 800 scenarios will be 22 applied to create travel time prediction models for different movements. Subsequently, the extracted models are tested with the other 200 scenarios. Correlation of the models with 23 24 observed data of some implemented U-turn facilities in real-life are also presented to show if the 25 models fit the field data well or not. Then the results of the predictive models are compared to the operational performance of a conventional signalized intersection. This comparison will 26 27 show how much the U-turn facility outperforms the traditional signalized intersection. Finally, 28 concluding remarks can be found at the end of the article.

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## 30 CONSTRUCTION OF THE TRAVEL TIME PREDICTION MODELS

## 31 Simulation Model

The GETRAM (Generic Environment for Traffic Analysis and Modeling) modeling tool was used to simulate the U-turn facility and to obtain travel times. GETRAM is a simulation environment comprising TEDI (traffic network graphical editor), AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks), AIMSUN 3D, a network database, a module for storing results, and the GETRAM Extensions (an Application Programming Interface).

There are several parameters which affect the operational measures (c.q. travel time), principally divided into two categories: geometric features and traffic conditions. Arguably, traffic performance is influenced by the number of lanes, lane width, weaving length and traffic volume (22). Accordingly, most of the relative parameters were taken into account to model the U-turn facility with the simulator and to compute travel times consequently. Some prerequisites and uniform design assumptions included the following:

44 • The U-turn facility is supposed to be built in urban arterial streets.

• Curbside parking and any type of stopping such as bus stops are prohibited in the U-turn influence area and between the intersection and the U-turn.

- All grades are supposed to be 0%.
- Roadways on divided arterials should be designed with lanes 3.6 m wide (21). All lane widths are supposed to be 3.6 m.
- Acceleration/Deceleration lanes' width, turning area's width and turning radiuses are designed based on traffic demand and the standards of the manual "A Policy on Geometric Design of Highways and Streets" (21) which also enables trucks and buses an easy turn.
- The speed limit on the roadways is proposed to be 70 km/h while turning speed is limited to 20km/hr (21).
- Provision for deceleration clear of the through-traffic lanes is a desirable objective on arterial roads and should be incorporated into the design whenever practical. The approximate total lengths needed for a comfortable deceleration to a stop from the full design speed of the highway and vice versa for the acceleration lane, for a design speed of 70 km/h is 130 m (21).
  - Pavement, drainage and other physical conditions are supposed to be perfect and thus not affecting the traffic situation.
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To do a comprehensive investigation, different scenarios were implemented to calculate travel time under different traffic conditions and geometric configurations. Besides, to simplify the simulation procedure and make it as real as possible, the alternative's input values are categorized. An overview of the configurations that are considered is given by describing all parameters and their values. The scenarios follow from combining all ranges of parameter values below.

- Number of Lanes: The number of lanes varies, depending on the traffic demand and availability of the right-of-way, but the normal range for urban arterial streets is four to eight lanes in both directions of travel combined (21). Thus, the model is built separately with both 3 and 4 lanes for each traffic direction.
- Distance between minor roadway and the U-turn opening: The location of the U-turn facility varies depending on the desired weaving length which is itself based on traffic volume and speed. The minimum desired weaving length is proposed to be 200 m, while the maximum weaving length which is assumed to keep travel time at an acceptable range is considered to be 600 m. The model is constructed independently for different distances, from 200 m to 600 m by intervals of 100 m.
- 36 3. Traffic volume on the major road: According to field observations, the traffic volume on
   37 the major road is considered to vary from 1500 veh/h up to 3500 veh/h in 500 veh/h
   38 increments.
- 4. Traffic volume on the minor road: Traffic volume on the minor approach is defined in terms of a percentage of the major road's traffic volume. It is assumed that the minor road's traffic volume will be 20%, 40%, 60% or 80% of the major approach's traffic 42 volume.
- 43 5. Right turn volume: To simplify the simulation, the right turn traffic volume of each approach is assumed to be always 10% of the whole traffic volume of that approach.
- 45 6. Left-turn volume: The left-turn traffic volume for each approach is considered to vary
  46 from 5% to 25% of that approach by intervals of 5%.

1 The combination of all parameters mentioned above produces 1000 different traffic and 2 geometric situations to obtain a wide-ranging simulation. 800 cases are chosen as the training 3 sample and the rest 200 cases are chosen as test sample. It is necessary to mention that the cases 4 in which traffic congestion was experienced were left out from the database. It has been done to 5 avoid any type of bias caused by extreme values of travel time in traffic congestion situations.

6 Based on the analyses, a very low correlation is found between all movements' travel 7 times and two explanatory variables; "number of lanes" and "Left-turn traffic volume on the 8 major roadway", respectively less than 0.033 and 0.062. On the other hand the correlation values 9 between travel times and the other independent variables are quite significant. Thus, the 10 following variables were considered for developing the U-turn travel time prediction models: 11

- 1. Distance between the U-turn opening and the minor roadway (m)
- 2. Average traffic volume on the major approaches (veh/hr)
- 3. Average traffic volume on the minor approaches (veh/hr)
- 4. Average Left-turn traffic volume on the minor approaches (veh/hr)
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16 The proposed methodology for computing travel time of the U-turn facility is disaggregate; that is, it is designed to consider individual major/minor approaches and individual 17 movements within approaches. Segmenting the travel time evaluation into different movements 18 19 is significant and useful. Firstly, because of different characteristics of different movements, they 20 should be considered separately (i.e. through traffic on the major roadway has less conflicts with 21 the other movements and does not use the U-turn facility while through movement on the minor 22 roadway should cross the major traffic two times and use the U-turn facility). Secondly, 23 independent assessment of different movements results in a more comprehensive detailed travel 24 time evaluation. The travel time for whole facility can be computed as the weighted average of 25 the travel time for each movement using volume of these movements. Therefore, it is possible to determine the overall performance of this facility compared to signalized intersection. 26

27 This type of U-turn facility would be interpreted as an uninterrupted-flow facility, so it was assumed that right-turn movements from major roadways are carried out without any kind of 28 29 conflict with other movements at the ordinary operational speed range. According to the 30 geometric design, right-turn movements from minor roads are also protected using exclusive right turn lanes followed by an acceleration lane on an on-ramp and have the least friction with 31 32 the traffic on the major roadway. Thus, it is presumed that right-turn movements are now functioning better than the conventional interrupted-flow signalized intersection. Accordingly, 33 34 just through movements and left-turns on both the major and minor roadways were taken into 35 account to implement 4 different travel time prediction models. It is essential to indicate that the traffic from the minor roads use the exclusive right turn lanes followed by an acceleration lane 36 37 on an on-ramp to merge with the major road traffic without having to stop or to cross the major 38 road's flow. Another important aspect which should be considered is defining the simulated 39 network boundaries to calculate travel time. Boundaries of the network should be delineated in 40 order to encompass all movement interactions perfectly. These boundaries should not be too wide because the model will lose its sensitivity, neither too small because effects of the U-turn 41 facility on travel time might not be counted properly. Thus, boundaries on the major roadways 42 are just after the U-turn facility and on the minor roadways are assumed to be 50 meters far from 43 44 the intersection (see Figure 1). These assumptions were also used for field observation. This 45 means that the observed travel times for all different movements were counted all the way through the proposed boundaries. 46

#### 1 Model Specification

In this study, 4 different U-turn travel time prediction models were developed for estimating
 travel time of different movements. Data obtained from traffic simulations of 800 different cases

4 were used as a training sample to develop the models. While dependent variable - "travel time" -5 is a continuous parameter, model specification started from a traditional linear regression model.

6 To construct the regression models, stepwise method is chosen. In this method, at each step, the

7 independent variable not in the equation that has the smallest probability of F is entered, if that

8 probability is sufficiently small. Variables already in the regression equation are removed if their

9 probability of F becomes sufficiently large. The method terminates when no more variables are 10 eligible for inclusion or removal. From the results of analysis, the linear regression models were

found to fit the training data adequately (i.e. all coefficients are significant at the p=0.01 level).

12 The final travel time prediction models are given below:

13 
$$TT_{Th-Maj} = 32.957 + 0.058X_1 + 0.001X_2 + 0.002X_3 + 0.003X_4$$
, Adjusted  $R^2 = 0.968$  (1)

14 
$$TT_{LT-Maj} = 25.698 + 0.115X_1 + 0.004X_2 + 0.006X_3 + 0.015X_4$$
, Adjusted  $R^2 = 0.907$  (2)

15 
$$TT_{Th-Min} = 11.299 + 0.134X_1 + 0.005X_2 + 0.008X_3 + 0.016X_4$$
, Adjusted  $R^2 = 0.899$  (3)

16 
$$TT_{LT-Min} = 25.443 + 0.123X_1 + 0.003X_2 + 0.006X_3 + 0.012X_4$$
, Adjusted  $R^2 = 0.906$  (4)  
17

- 18 Where;
- 19  $TT_{Th-Maj}$  = Estimated Travel Time of Through movement on the major approach (sec)

20  $TT_{LT-Mai}$  = Estimated Travel Time of Left-turn on the major approach (sec)

21  $TT_{Th-Min}$  = Estimated Travel Time of Through movement on the minor approach (sec)

22  $TT_{LT-Min}$  = Estimated Travel Time of Left-turn on the minor approach (sec)

- 23  $X_1$  = Distance between the U-turn opening and the minor roadway (m)
- 24  $X_2$  = Average traffic volume on the major approaches (veh/hr)
- 25  $X_3$  = Average traffic volume on the minor approaches (veh/hr)
- 26  $X_4$  = Average Left-turn traffic volume on the minor approaches (veh/hr)

27 The analysis of standardized coefficients indicated that the distance between the U-turn 28 opening and the minor roadway has the greatest impact on travel time compared to other 29 independent variables for all prediction models. This variable has the most effect on the travel 30 time of through movement on minor road, while has the least influence on the travel time of 31 through movement on major road. Increasing total traffic volume on the major roadway will 32 increase the friction between this traffic and through movement of minor road. Thus, traffic volume on the major road has the most influence on the travel time of through movement on 33 34 minor roads which can be seen by  $X_2$  coefficient in the proposed models. The minor roadway's 35 traffic volume has the least impact on the major roadway through movement's travel time because they conflict only one time, but minor roadway's traffic has considerable friction with 36 37 other movements in 2 different weaving areas before and after the U-turn facility. Arguably, left 38 turn traffic volume on the minor road has also the least impact on the major roadway through 39 movement's travel time. Adjusted R square values for all models indicate that these models fit 40 the data properly. All of four explanatory variables are significantly correlated to travel times 41 while correlations between themselves are trivial. This approves the veracity of the chosen 42 variables to predict traffic performance of this U-turn facility appropriately.

## 1 Model Validation

The extracted models are validated with the rest of the simulation data as a test sample which contains the 200 remaining scenarios that were not used to build the prediction models. The comparison shows a significant correlation between the predicted values and the simulated travel times. It can be concluded that the simulation data are adequately fitted within the predictive models. The Pearson correlation coefficient for each model is shown in Table 1.

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 TABLE 1 Pearson Correlation Coefficients of Predicted ~ Simulated Travel Times

 and Predicted ~ Observed Travel Times

Pearson Correlation Coefficients of Predicted and Simulated Travel Times		
Movement	Pearson correlation coefficient	
Through movement on the major road	0.984	
Left-turn on the major road	0.953	
Through movement on the minor road	0.949	
Left-turn on the minor road	0.952	
Pearson Correlation Coefficients of Predicted and Observed Travel Times		
Movement	Pearson correlation coefficient	
Through movement on the major road	0.951	
Left-turn on the major road	0.983	
Through movement on the minor road	0.979	
Left-turn on the minor road	0.981	

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On the other hand, observed travel times in real-life, which were collected from 50 11 12 different geometric and traffic conditions of some implemented U-turn facilities in Iran, were 13 compared with the model outputs to verify if the models are able to predict the real observed 14 travel time data or not. These 50 cases were observed on 8 different sites at different times of the 15 day. This means that both peak and nonpeak hours were taken into account. These 50 cases were also chosen in a way to cover a good variety of variable values. They consist of major roads with 16 17 3 or 4 lanes and the distance between minor roadway and the U-turn opening varies from 200m 18 to 550m. Ranges for traffic on major and minor roads are respectively 1050 to 3265 and 450 to 1540 vph. Left turn volume on the major and minor roads are varied from 90 to 550 and 35 to 19 20 220 respectively. Thus, all geometric and traffic characteristics of the observed cases are within 21 the ranges of 1000 simulated situations. Observed travel times and values calculated by models 22 for 4 different movements are depicted in Figure 2. The comparisons show a considerable 23 correlation between the predicted and the observed travel times. It means that the observed data 24 were also predicted well by the predictive models. Pearson correlation coefficients of predicted 25 and observed travel times are shown in Table 1.

Because the field data were collected under different circumstances such as weather conditions, there are always some uncertainty and differences between observed values and predictions. However, the significant correlation values indicate that the models can be used to predict travel time very well. The same patterns which are depicted in Figure 2, allow the designers to use the proposed models with confidence.



FIGURE 2 Observed and modeled travel times of four different maneuvers under U-turn design.

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# COMPARATIVE ANALYSIS OF INTERSECTION TRAFFIC PERFORMANCE

3 To compare traffic operations of a U-turn facility design to an equivalent conventional signalized 4 intersection, a signalized intersection simulation model was also created. The design included 5 different traffic and geometric conditions corresponding to our 50 U-turn cases studied in real 6 life. Signal-timing design for conventional signalized intersections is generated using 7 Trafficware's Synchro modeling program. The Synchro model has been chosen for its ability to optimize timings. Optimized signal timings are important for equitable design comparison to 8 9 eliminate signal timing as bias. Therefore optimum cycle lengths and signal timings became 10 available for each of 50 cases as an input variable for signalized intersection simulation models. 11 Comparisons between the travel times of the four major maneuvers under signalized and U-turn designs are shown in Figure 3. These cases are ranked according to travel time of the 12 conventional signalized intersection design in ascending order. The results of the simulation for 13 14 signalized intersections shows that in most of the cases, the unconventional U-turn facility 15 outperforms the conventional signalized intersection (i.e. lower travel time).

16 As it is shown in Figure 3, travel time of the through maneuver on major roadway is 17 always less for the U-turn design compared to the signalized intersection in all of the 50 case 18 studies. Through movement vehicles on the major roadways are travelling the same distance in 19 both designs. On the other hand, the U-turn design is considered as an uninterrupted flow 20 facility; thus, travel times of this movement are naturally expected to be lower under the U-turn 21 design. For through movements, the travel time difference between conventional and 22 unconventional designs becomes more significant if traffic flow on the major road is more than 23 2000 veh/hr.

For left turn movements on the major road, in almost half of the cases with smaller traffic flow, travel time is slightly more under the U-turn design. It is due to the fact that vehicles which want to turn left, should travel all the way to the U-turn facility and then come back to the intersection. For other cases with higher amount of traffic flow and left turn percentage, traffic performance is much better under U-turn design (Figure 3).

Through movements on minor roads also have to go on the U-turn facility and come back to the intersection. This causes a slightly higher travel time (average of 5 seconds) for half of the cases with lower traffic flow using U-turn design (Figure 3). Similar to other movements, through maneuvers on the minor road are carried out much faster under the U-turn design if the traffic flow is more than 1000 veh/hr on minor roads.

Usually, left turn movements at signalized intersection face or cause delays. Through movements usually have the priority in signal design and left turns are performed either permitted, experiencing delay because of conflicting with opposing traffic which has priority, or done protected which in fact increase cycle length and delay. Results of the analysis show that travel time of left turns on minor roads are less in almost all of the case studies under the U-turn design compared to the signalized intersection (Figure 3).

40 Based on these comparisons, it is fair to conclude that the U-turn facility is performing 41 better than the conventional signalized intersection. As it is depicted in Figure 3, this dominance 42 is more noteworthy for through movements on major roads and left turns on minor roads and 43 more specifically at higher levels of traffic flow.

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FIGURE 3 Travel times of four different maneuvers under signalized and U-turn designs.

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# CONCLUSIONS AND DISCUSSION

3 To summarize the simulations results, for most of the scenarios it turns out that the proposed U-4 turn facility has the potential to improve system travel time over conventional designs. 5 Explicitly, reduction of travel time for vehicles on the major approaches was notable. In general 6 because of replacing an interrupted flow facility (conventional signalized intersection) with an 7 uninterrupted flow facility (proposed U-turn facility) traffic performance will be improved. For 8 movements on the major roads, mainly through movements which don't need to stop at the 9 traffic signal, the U-turn facility is considerably favorable. On the other hand the major problem 10 of conventional intersections - the crossing conflict between through movements and left turns which cause delays at intersections will also be replaced by weaving maneuvers. For all 11 12 movements, the U-turn facility clearly outperforms the signalized intersection if traffic flow is 13 relatively high. It was also found that for high volume arterials it would be better to build the U-14 turn facility farther from the intersection and vice versa. Additionally, studying travel time of 15 different movements individually enables the designers to compare the present and future traffic performance for each movement accurately, i.e. they would be able to decide about blocking the 16 17 median or just use the U-turn facility for left-turn movements on minor approaches and control 18 the through movements by a traffic light. Overall, the proposed type of U-turn design should 19 receive strong consideration; wherever the extra needed right-of-way can reasonably be obtained. 20 Unconventional design alternatives such as proposed U-turn facility studied in this research, that 21 showed improvement over the conventional intersection in terms of travel times, do not 22 necessarily imply that an unconventional design is always the best and that it should replace the 23 existing design by default. Like other studies' results, outcome of this research enables designers 24 to compare different available designs in the field.

The intent of this research was to evaluate travel time at different geometric and traffic conditions while right-of-way, traffic safety, signing, marking, pedestrian facilities and access, which were not part of the scope of this paper, must be considered in addition.

The AIMSUN model and analysis results do not reflect driver unfamiliarity with the unconventional design alternative. Reductions in intersection travel time likely would not reach full potential until some times after the unconventional design is implemented and drivers gain familiarity with turning patterns, particularly if the design is an isolated application.

32 Many future research questions therefore remain regarding this unconventional 33 intersection design. For instance, it requires wider rights-of-way, where the U-turn facility is 34 going to be built, compared with a conventional intersection design, and ways to reduce these 35 needs should be explored. Although several numbers of this type of unconventional intersection 36 are implemented and drivers have become accustomed to alternative left-turn patterns, questions 37 remain about driver's expectations. As a recommendation, it would be useful to correlate the 38 proposed models with other field data at different geometric and traffic conditions to make the 39 travel time prediction models as accurate as possible. Also a study could determine the most 40 efficient distance of the U-turn facility from the intersection for each category of traffic volume to prepare a more practical overview of using this type of unconventional intersection. As 41 42 another suggestion, a comparison in terms of travel time between this unconventional design and 43 other unconventional intersections should be carried out. 44

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