International Journal of Business, Human and Social Sciences
ISSN: 2517-9411
Vol:3, No:6, 2009

Travel Time Evaluation of an Innovative U-Turn Facility on Urban Arterial Roadways

Ali Pirdavani, Tom Brijs, Tom Bellemans, Geert Wets, and Koen Vanhoof

***Abstract*—**Signalized intersections on high-volume arterials are often congested during peak hours, causing a decrease in through movement efficiency on the arterial. Much of the vehicle delay incurred at conventional intersections is caused by high left-turn demand. Unconventional intersection designs attempt to reduce intersection delay and travel time by rerouting left-turns away from the main intersection and replacing it with right-turn followed by U-turn. The proposed new type of U-turn intersection is geometrically designed with a raised island which provides a protected U-turn movement. In this study several scenarios based on different distances between U-turn and main intersection, traffic volume of major/minor approaches and percentage of left-turn volumes were simulated by use of AIMSUN, a type of traffic microsimulation software. Subsequently some models are proposed in order to compute travel time of each movement. Eventually by correlating these equations to some in-field collected data of some implemented U-turn facilities, the reliability of the proposed models are approved. With these models it would be possible to calculate travel time of each movement under any kind of geometric and traffic condition. By comparing travel time of a conventional signalized intersection with U-turn intersection travel time, it would be possible to decide on converting signalized intersections into this new kind of U-turn facility or not. However comparison of travel time is not part of the scope of this research. In this paper only travel time of this innovative U-turn facility would be predicted. According to some before and after study about the traffic performance of some executed U-turn facilities, it is found that commonly, this new type of U-turn facility produces lower travel time. Thus, evaluation of using this type of unconventional intersection should be seriously considered.

***Keywords*—**Innovative U-turn facility, Microsimulation, Travel time, Unconventional intersection design.

I. Introduction

ONE of the most important factors that significantly impact the performance of signalized conventional intersections is the existence of heavy left-turn volumes. High left-turn demand at 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, and reduce the available green time for through movement phases. Some of the recommended alternatives such as widening roads or changing intersections to interchanges are quite expensive, so some low-cost solutions should be considered. As a result, there has been considerable interest in alternative measures for dealing with left-turns at intersections to improve performance, some of which have been unconventional schemes. Unconventional 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 phases. Different types of unconventional intersection designs are known that have been or may be applied to reduce intersection delay and travel times. In these type of unconventional intersections, mainly direct left-turn (DLT) is replaced by right turn plus U-turn (RTUT). Little documentation is available on the operational effects of providing U-turns as an alternative to DLT from driveways. However, due to the widespread use of various indirect left-turn treatments, increased attention has been given to evaluating the safety and operational effects of U-turn movements. For instance, Liu et al. studied the effects of U-turns on capacity of signalized and unsignalized intersections [1], [2]. In another research by Carter et al. operational and safety effects of U-turns at signalized intersection were studied [3]. Liu et al. evaluated some characteristics of U-turns such as capacity or gap acceptance on 4-lane divided roadways and multilane highways [4], [5]. In another study about the operational effects of indirect driveway left-turn treatments, Liu et al. compared delay and travel time for three different driveway left-turn alternatives [6]. They are: (1) direct left-turns at driveways, (2) right-turns plus U-turns at downstream median openings, and (3) right-turns plus U-turns at signalized intersections. Guo et al. proposed a procedure for evaluating the impacts of indirect driveway left-turn treatments on traffic operations at signalized intersections. The major task of their study was to develop a model to relate the number of vehicles making U-turns at a signalized intersection during peak periods to various explanatory variables such as roadway traffic conditions and geometric characteristics [7]. Tabernero and Sayed introduced the Upstream Signalized Crossover (USC) intersection with a brief comparison to the conventional intersection. Their analysis showed that the USC has the potential for accommodating heavy left-turn movements while maintaining an acceptable performance level for through traffic [8]. Sayed et al. further investigated and compared the performance of the USC to a similar

Ali Pirdavani is with Transportation Research Institute (IMOB) Hasselt University, Science Park – Building 5, B-3590 Diepenbeek, Belgium (e-mail: ali.pirdavani@uhasselt.be; phone: +32-11-26.91.39; fax: +32-11-26.91.99).

Tom Brijs, Tom Bellemans, Geert Wets and Koen Vanhoof are with Transportation Research Institute (IMOB), Hasselt University, Science Park – Building 5, B-3590 Diepenbeek, Belgium (e-mail: {tom.brijs, tom.bellemans, geert.wets and koen.vanhoof} @uhasselt.be).

conventional scheme under different volume scenarios [9]. El Esawey and Sayed compared the performance of the USC intersection to that of the conventional and the Crossover Displaced Left-Turn (XDL) intersections [10]. A study by Stover analyzed the operational issues associated with these two movements and established a procedure to calculate the delay and travel time in relation to upstream and downstream signal effects using queuing analysis [11]. In *NCHRP Report 420: Impacts of Access Management Techniques,* an analytical model was developed and calibrated to estimate the travel-time savings (or loss) in suburban and rural environments where there are no nearby traffic lights [12]. A case study by Long and Helms showed that limiting access at unsignalized intersections can reduce turning volumes, increase arterial operating speeds, and improve safety [13]. A study by Al-Masaeid developed an empirical model to estimate the capacity and average total delay of U-turns at median openings [14].

Studies about system wide travel time savings of the unconventional left-turn alternatives have also been conducted by computer simulation [15]. Reid and Hummer used CORSIM to compare traffic operations along an arterial, that has five signalized intersections, for the conventional Two-Way Left-Turn Lane (TWLTL) design and two alternative unconventional designs; the Median U-Turn Crossover design (MUT) and the Super-Street Median Crossover design (SSM) [16]. Reid and Hummer also used CORSIM to conduct travel time comparisons between seven isolated unconventional intersection schemes and a similar conventional intersection. Their simulation results showed that at least one unconventional scheme outperformed the conventional intersection in at least one volume scenario. In general, the analysis was in favor of the Quadrant and the Median U-turn intersections for most volume scenarios [17]. Jagannathan and Bared used VISSIM to compare three different XDL configurations to their conventional counterparts. The analysis 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 intersection was found [18]. Kim et al. used VISSIM to obtain performance of the superstreet designs and its comparable conventional alternatives. The superstreet design is similar to the median U-turn design but has some additional features that allow for perfect progression of through traffic on the major road in both directions by preventing the minor road traffic from crossing the major road [19].

In this study a new type of U-turn is proposed which has some crucial differences to the other types of median openings. These developed U-turn facilities are built on main roads, both sides of the intersection, and used as a complete replacement of signalized intersections. It means that all the movements on the intersection will be done by U-turn and the signalized intersection is fully blocked; while all types of U-turn facilities reviewed in the literature were used just for left-turns. This type of U-turn is geometrically designed, has channelizing and splitting islands and provides protected U-turn movements. Channelizing island with a convex section helps drivers to keep track on their desired trajectories even if they want to use the U-turn facility or go straight on the main road. This convex section affords an opportunity for a through driver to pass to the right of a slower moving or stopped vehicle on the deceleration lane preparing to use the U-turn. By the use of a splitting island, a safe divergence at the entrance of U-turn facility and a safe and protected convergence operation at the exit of U-turn are provided. An acceleration lane is also provided for a safe merging of U-turn vehicles with through movement of the main road. Different sections of a developed U-turn facility which are depicted in Fig. 1 are defined as:

A: Channelizing island
B: Deceleration lane
C: U-turn raised island
D: Acceleration lane
E: Major road
F: Minor road
G: Blocked intersection

Fig. 1 just shows one side of the intersection. The left side is the same as right side and has the similar sections.

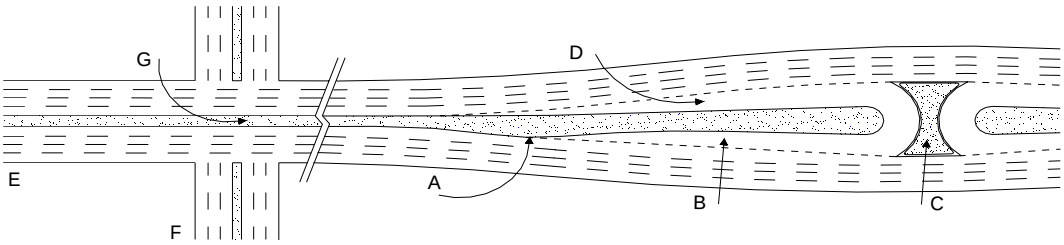

Fig. 1 Different parts of the developed U-turn facility

The purpose of this research was just to conduct a travel time evaluation of the developed U-turn facility which is proposed as an alternative of the signalized intersection. Along with the results of this research, engineers and designers would be able to implement a side-by-side comparison of this new type of traffic facility to the conventional design of signalized intersection. The outcome of these comparisons at different volume levels will provide them 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 would be meaningful to consider of implementing this type of facility instead of traditional signalized intersection.

Several limitations were imposed on the scope of this research. The most important restriction is that this paper studies just a single U-turn facility (isolated intersection and U-turn), not a network or corridor. Another limitation of this study is the exclusive focus on travel time and other traffic engineering related results. Safety, driver expectations, cost, and many other factors may feed into the decision making process behind an intersection design, but this paper focuses only on travel time and related operational measures.

The structure of the paper is as follows. Initially, a U-turn facility is geometrically defined in the simulation and different traffic characteristics are loaded. 5000 scenarios would be applied to result travel time prediction model for different movements. Consequently, the extracted models out of 4500 scenarios are tested with the other 500 scenarios. Correlation of the models with observed data of some implemented U-turn facilities are also presented to show if the models fit the field data well or not. Finally, concluding remarks can be found at the end of the article.

II. Construction of the Travel Time Prediction Model

A. Simulation Model

The GETRAM (Generic Environment for Traffic Analysis and Modeling) modeling tool was used to build the U-turn facility and to obtain travel times for developed type of U-turn. 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 API or Application Programming Interface).

There are several parameters which affect the operational measures (c.q. travel time), principally divided into two categories; geometric and traffic parameters. Arguably, traffic performance is influenced by the number of lanes, lane width, weaving length and traffic volume [20]. Accordingly, all relative parameters were taken into account to model the U-turn facility with the simulator and compute travel time consequently.

Some prerequisites and uniform design assumptions included the following:

- 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.
- U-turn width is designed such that two side-by-side vehicles are able to turn simultaneously.
- Speed limit on the roadways is proposed to be 70 km/h [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 don't affect the traffic situation.

For a comprehensive investigation, different scenarios were implemented to calculate travel time in different traffic and geometric situations. Besides, to simplify the simulation procedure and make it as real as possible, the alternative's input values are categorized as follows:

1. 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 direction of travel.

2. Distance between intersection and U-turn facility

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 suggested to be 600 m. The model is constructed independently for different distances, from 200 m to 600 m by intervals of 100 m.

3. Traffic volume on the major road

According to field observations, the traffic volume on the major road is suggested to vary from 1500 veh/h up to 3500 veh/h by steps of 500 veh/h.

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 would be 20%, 40%, 60% or 80% of the major approach's traffic volume.

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.

6. Left-turn volume

The left-turn traffic volume for each approach is supposed to vary from 5% to 25% of that approach by intervals of 5%.

The combination of all parameters mentioned above produces 5000 different traffic and geometric situations to

obtain a wide-ranging simulation. Based on the analyses, it was found that the correlation coefficient between the number of lanes and total traffic volume of the major and minor roadways was high which means that these two variables should not be used together. On the other hand, the number of lanes has a great influence on the capacity of roadways, subsequently travel time of vehicles. Thus, a combined use of these parameters was proposed by taking the number of lanes into account (i.e. traffic volumes are mentioned in terms of vehicles per hour per lane instead of vehicles per hour). The following variables were considered for developing the U-turn travel time evaluation model:

1. Distance between the U-turn raised island and the middle of the intersection (m)
2. Total traffic volume on the major roadway (veh/hr/lane)
3. Left-turn traffic volume on the major roadway (veh/hr)
4. Total traffic volume on the minor roadway (veh/hr/lane)
5. Left-turn traffic volume on the minor roadway (veh/hr)

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 movements within approaches. Segmenting the travel time evaluation into different movements is significant and useful. Firstly, because of different characteristics of different movements, they should be considered separately (i.e. through traffic on the major roadway has less conflicts with the other movements and does not use the U-turn facility while through movement on the minor roadway should cross the major traffic two times and use the U-turn facility). Secondly, independently deliberation of different movements would be ended to a more comprehensive travel time evaluation. In other words, designers would be able to decide on blocking the intersection, prohibiting all movements and transfer them to the U-turn facility, or just use the U-turn facility for left-turn movements. This type of U-turn facility would be interpreted as an uninterrupted-flow facility, so it was assumed that right-turn movements would be carried out without any kind of conflict with other movements at the free flow speed range. Accordingly, just through movement and left-turn on both the major and minor roadways were taken into account to implement 4 different travel time evaluation models. Another important aspect which should be considered is defining the simulated network boundaries to calculate travel time. Borders of the network should be delineated in order to encompass all movement interactions perfectly. Thus, borders on the major roadways are just after the U-turn facility and on the minor roadways they are assumed to be 50 meters far from the intersection.

B. Model Specification

In this study, different U-turn prediction models were developed for estimating travel time of different movements. Data obtained from 4500 different geometric and traffic simulations were used as a training sample to develop the models. Model specification started from a traditional linear regression model. The best linear regression model however did not fit the data well and thus was not found appropriate for modeling U-turn travel time. A Generalized Linear Model (GLM) was therefore considered. For a GLM model structure, the Poisson model was tested and was found to fit the data adequately. The equations of the final models are given as follows:

$$TT_{Th-Maj} = \exp(0.000974X_1 + 0.0000235X_2 + 0.000109X_3 + 0.0000182X_4 + 3.645) \quad (1)$$

$$TT_{LT-Maj} = \exp(0.00134X_1 + 0.0000964X_2 + 0.000182X_3 + 0.0000177X_4 + 0.00018X_5 + 3.771) \quad (2)$$

$$TT_{Th-Min} = \exp(0.00159X_1 + 0.000116X_2 + 0.000176X_3 - 0.0000208X_4 + 0.000293X_5 + 3.62) \quad (3)$$

$$TT_{LT-Min} = \exp(0.0014X_1 + 0.000093X_2 + 0.000128X_3 - 0.0000443X_4 + 0.000256X_5 + 3.78) \quad (4)$$

Where;
TT_{Th-Maj} = Estimated Travel Time of Through movement on the major road (sec)
TT_{LT-Maj} = Estimated Travel Time of Left-turn on the major road (sec)
TT_{Th-Min} = Estimated Travel Time of Through movement on the minor road (sec)
TT_{LT-Min} = Estimated Travel Time of Left-turn on the minor road (sec)
X_1 = Distance between the U-turn raised island and the middle of the intersection (m)
X_2 = Total traffic volume on the major roadway (veh/hr/lane)
X_3 = Total traffic volume on the minor roadway (veh/hr/lane)
X_4 = Left-turn traffic volume on the major roadway (veh/hr)
X_5 = Left-turn traffic volume on the minor roadway (veh/hr)

C. Model Validation

The extracted models are validated with the rest of simulation data as a testing sample which contains 500 scenarios. The comparison shows a significant correlation between the predicted values and simulated travel times. It would be interpreted that the simulation data are adequately fitted within the predictive models. Spearman's correlation coefficient for each model is shown in Table I.

TABLE I
SPEARMAN'S CORRELATION COEFFICIENTS OF PREDICTED AND SIMULATED TRAVEL TIMES

Movement	Spearman's correlation coefficient
Through movement on the major road	0.984
Left-turn on the major road	0.987
Through movement on the minor road	0.986
Left-turn on the minor road	0.993

On the other hand, observed travel times which were collected for different movements on 50 different traffic and geometric situations of some implemented U-turn facilities, compared with the model outputs to verify if the models are suitable for the observation data or not. Observed travel times and values calculated by the models for 4 different movements are depicted in Fig. 2 to Fig. 5.

The comparisons show a considerable correlation between the predicted values and observed travel times. It means that the observed data also fitted well in predictive models. Spearman's correlation coefficients of predicted and observed travel times are shown in Table II.

TABLE II
SPEARMAN'S CORRELATION COEFFICIENTS OF PREDICTED AND OBSERVED TRAVEL TIMES

Movement	Spearman's correlation coefficient
Through movement on the major road	0.951
Left-turn on the major road	0.990
Through movement on the minor road	0.987
Left-turn on the minor road	0.989

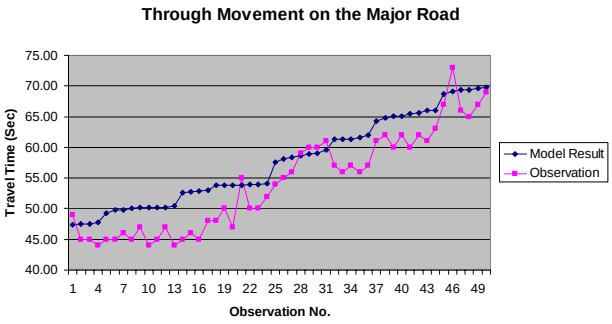

Fig. 2 Observed and modeled travel time of through movement on the major road

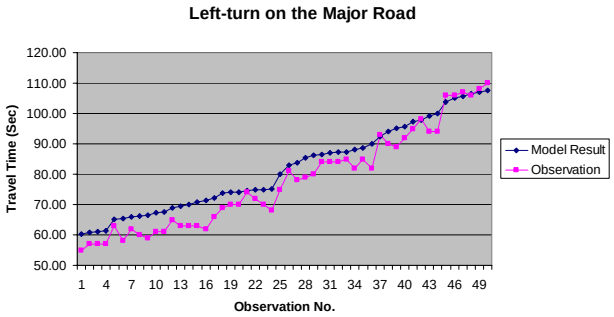

Fig. 3 Observed and modeled travel time of left-turn on the major road

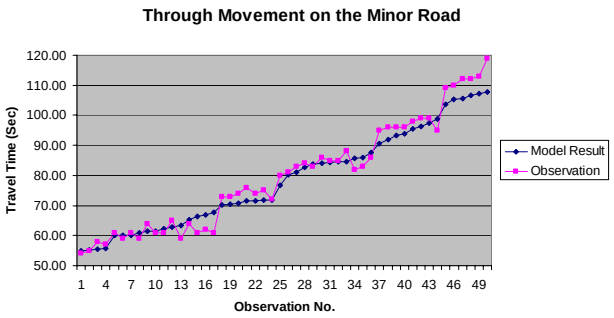

Fig. 4 Observed and modeled travel time of through movement on the minor road

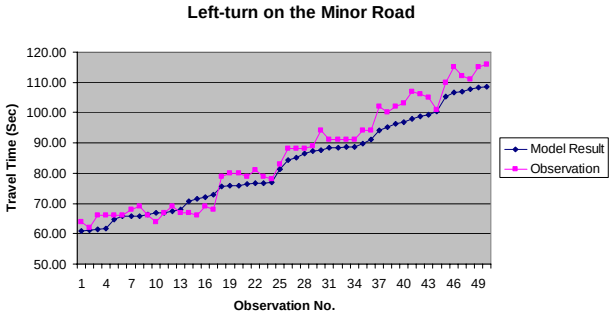

Fig. 5 Observed and modeled travel time of left-turn on the minor road

Although the significant correlation values indicate that the models can be used to predict travel time very well, but because of collecting the field data under different circumstances such as weather condition, there are always some uncertainty and differences in observed values. The same patterns which are depicted in Fig. 2 to Fig. 5, allow the designers to use the proposed models undoubtedly. Nonetheless, taking into account of an error value of ±5% for predicted travel times should be well thought-out.

III. CONCLUSION AND DISCUSSIONS

As an overview on the simulations' results, for most of the scenarios it was discovered that the proposed U-turn facility has the potential to improve system travel time over conventional designs. Explicitly, reduction of travel time for

vehicles on the major approaches was notable. Also it was found that for high volume arterials it would be better to build the U-turn facility farther from the intersection and vice versa; although the proposed models empower the designers to find the best place to build the U-turn facility. Additionally, studying travel time of different movements individually enables the designers to compare the future and present traffic situation for each movement accurately, i.e. they would be able to decide about blocking the intersection or just use the U-turn facility for left-turn movements on minor approaches and control the through movements by a signalized intersection. Overall, the proposed type of U-turn design should receive strong consideration, wherever agencies can reasonably procure the extra right-of-way they need. Unconventional design alternatives such as the proposed U-turn facility that showed improvement over the conventional intersection do not necessitate that an unconventional design is always the best or that it should necessarily replace any existing design. The intent of this research was to evaluate travel time at different geometric and volume conditions while right-of-way, 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 time after the unconventional design is implemented and drivers gain familiarity with turning patterns, particularly if the design is an isolated application.

Many future research questions remain regarding this unconventional intersection design. For instance, it requires wider rights-of-way, where the U-turn facility is going to be built, compared with a conventional intersection design, and ways to reduce these needs should be explored. Although several numbers of this type of unconventional intersection are implemented and drivers have become accustomed to alternative left-turn patterns, questions remain about driver expectations. As a recommendation, it would be useful to correlate the proposed models with other field data at different geometric and volume conditions to make the travel time prediction models as accurate as possible. Also a study could determine the most 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 another suggestion, a comparison in terms of travel time between this unconventional intersection and a signalized intersection would be done using microsimulation tools.

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