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Right Turn Split: A New Design to Alleviate the Weaving Problem on Arterial Streets

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***Abstract*—While weaving maneuvers occur on every type of roadway, most studies have focused on freeway maneuvers. Weaving occurring on non-freeway facilities, such as arterial streets, can cause significant operational and safety problems. Arterials, unlike freeways, tend to have shorter weaving lengths and lower speeds. Intensive lane changing maneuvers at weaving sections create turbulence that often leads to congestion. The Right Turn Split (RTS) design is a new design to relieve congestion and delay caused by weaving movements on arterial streets. The RTS design facilitates smoother flows with less driver delay. Pilot studies were conducted at two arterial weaving sections in Florida to demonstrate the feasibility of the approach. The intent of this paper was to study the impacts of the RTS installation based on a before-and-after study of the delay on an arterial street. To conduct the before-and-after study, the delay before and after was compared for multiple volume conditions using microscopic simulation analysis to determine how the delay of the arterial segment would differ over a wide range of volume levels.**

***Index Terms*—Weaving, arterials, right turn split**

I. INTRODUCTION

The RTS design is a new design to alleviate the delay caused by weaving movements on arterial streets (Figure 1). Arterial streets weaving typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. This type of weaving is very common on arterial streets and frontage roads especially at the off-ramps of diamond interchanges in urban areas and can cause significant safety and operational problems. Twenty-three locations have been identified only in Orlando, Florida that suffer from this type of weaving problem.

The proposed design was developed based on a real traffic problem. Pilot studies were conducted at two arterial weaving sections in Florida to demonstrate the feasibility of the approach. The first studied site was on State Road 421 between the I-95 Off-Ramp and Airport Road in Port Orange, Florida and the second site was on State Road 50 between the State Road 408 Off-Ramp and Bonneville Drive in Orlando, Florida. The two sites exist at the exit-ramps of two diamond interchanges where the side street vehicles enter the arterial street through a free-flow right turn lane, which continues as an auxiliary lane to the downstream intersection. These two sites have the following criteria: relatively short spacing between two signalized intersections that are running in coordination; moderate to heavy traffic volumes; and no driveways or median openings exist between the two signalized intersections. Both arterial segments had two through lanes. The downstream intersection for both sites had two auxiliary lanes, a left turn lane, and a right turn lane.

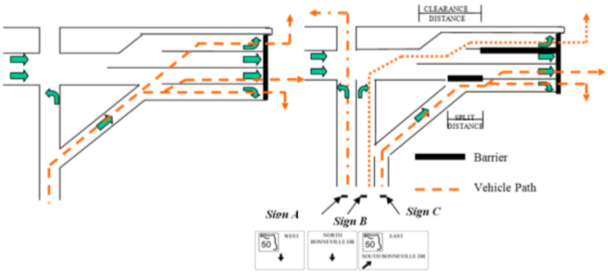

Figure 1. Before and After Applying the RTS Design

Video cameras were used to collect the data. The cameras were used for two purposes: to record the operation of weaving movements and to obtain volume counts and turning percentages along the arterials. To be able to achieve these two goals, the cameras were positioned on a high location (the Interstate 95 bridge and the State Road 408 bridge) to cover the weaving area. The weaving area was defined as the area between the gore area at the free-flow right turn to the stop bar at the downstream intersection. The cameras were zoomed in to capture the movement of each vehicle within the weaving section. In order to determine the location where the vehicle performed the weaving movement, road tubes were placed at a 100 feet spacing starting at the gore area. The tubes acted as distance meters. At each site, eight hours (7:00 a.m.-9:00 a.m., 11:00 a.m.-1:00 p.m., and

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2:00 p.m.-6:00 p.m.) of data were collected on a normal weekday using the video recording equipment.

The reduction of the field data involved observing the videotapes of each site. The videotapes were used to observe the weaving distance for each vehicle and also to obtain accurate counts and turning percentages along the arterial. The weaving distance is defined as the distance from the gore area to the location where the vehicle crossed to the desired lane. This method was used since it was difficult to observe the weaving movements and count the vehicles in real time at high volumes. Acceptable accuracy of the video data is due mainly to the fact that the viewer is able to view the videotape more than one time. Therefore, the viewer can concentrate on one single movement and, when finished, rewind the tape and observe a different movement. Data reduction sheets were created for each site so that the weaving distance and the origin-destination patterns of individual vehicles could be recorded. Videos were then watched in slow motion to verify the weaving distance, the origin-destination information, and the number of lane changes required to complete the movement. The origin-destination volumes, the weaving distances, number of lane changes were recorded in one-minute increments. By observing the videotapes of each site, the movements of 4,443 weaving vehicles were tracked.

Watching the videotapes for the two sites lead to several conclusions regarding the excessive delay occurring at the two sites. It was found that breakdown conditions, caused by the weaving movements, occurred in two cases. The first case occurred when the main street through volume was extremely heavy with moving queues observed extending into the gore area. In this case, vehicles entering from the side street at the upstream intersection could not find adequate gaps on the main street and had to come to a complete stop waiting for gaps on the main street causing observed delay on the side street.

In the second case, the left turning volume at the downstream intersection was extremely heavy and queues extended beyond the left turn lane. Although the main street volumes were moderate and adequate gaps were available, vehicles entering from the upstream side street and wanting to perform a left turn at the downstream intersection had to completely stop. The stopped vehicles blocked the free-flow right turn lane, must wait for the left turn lane to clear, and cause observed delay for the side street.

The pilot studies revealed that the worst weaving movement was the movement performed by the vehicles entering the arterial and crossing the through lanes to access the auxiliary lane at the downstream intersection. The RTS design proposed separating the vehicles performing this weaving movement from the other movements before reaching the arterial street.

II. THE DESIGN OF THE RTS CONCEPT

The RTS design proposed directing the side street right turning vehicles to two separate right turn lanes instead of one right turn lane. The additional right turn lane will be added to the side street at the stop bar. In this case, the vehicles, desiring to turn left at the downstream intersection, are directed into the additional lane then to the left turn lane at the downstream intersection through the traffic signal at the upstream intersection. Vehicles desiring to turn right or go through at the downstream are directed to the free right turn lane at the upstream intersection.

In order to force these vehicles to use the new right turn lane at the stop bar instead of the free right turn lane, two barriers were proposed at two locations along the arterial segment. The first barrier is placed at the gore area and between the free right turn lane and the outside through lane. The second barrier begins at the same location where the first barrier ends but between the inside through lane and the left turn lane. The second barrier ends at the stop bar at the downstream intersection. The two traffic barriers will prevent drivers from attempting to access the left turn lane from the free right turn lane. The proposed design will also reduce the number of conflict points along this section.

The proposed barrier can take different forms: delineators, painted striping, or raised concrete traffic separators. Delineators are retroreflective devices that can be mounted on grass, pavement, or raised concrete traffic separator to indicate a certain alignment, especially at night or in adverse weather. Raised concrete traffic separators are usually six inches height. As far as the safety concerns from introducing the barriers to the traveled way, traffic barrier between lanes is not a new idea. A similar design is commonly used between left turn and through lanes to offset opposing left turn lanes on four-lane divided roadways to improve sight distance [1]-[2].

The three proposed types of barriers offer different alternative based on the right of way availability: (1) delineators only to be used on the lane striping when it is difficult to obtain any additional right of way, (2) two feet of painted striping supplemented with delineators to be used in case of limited right of way availability, and (3) four feet of raised concrete traffic separator to be used in case of right way availability. In the last two forms, delineators should also be used as an additional indication of the barrier because they will improve the visibility and reduce the potential of vehicles crossing the barrier. A special signing arrangement should be installed to provide adequate signage for the side street approach in order to explain the new arrangement to the drivers. The special signage is illustrated in Figure 1.

A. *Split Distance*

The split distance is defined as the distance at which the first barrier ends and the second barrier begins (see Figure 1). This distance was assumed to be the distance at or over which 85% of all side street vehicles turning left at the downstream intersection performed their weaving movement. This distance was measured in the field for each site using a video camera during the pilot studies conducted at two arterial weaving sections in Florida. The cameras were zoomed in to capture the movement of each vehicle within the weaving section. In order to determine the location where the vehicle performed the weaving movement, road tubes were placed at a 100 feet spacing starting at the gore area. The tubes acted as distance meters. This distance needs to be measured at every studied site before applying the RTS design.

B. Clearance Distance

The clearance distance is defined as the minimum distance needed from the beginning of the taper for the left turn lane to the beginning of the second barrier (see Figure 1). This distance needs to provide a smooth lateral transition from the through lane to the left turn lane. The clearance distance was determined using the following formulas:

$$CD = \frac{WS^2}{60} \text{ for } S \le 45mph \tag{1}$$

$$CD = WS \text{ for } S > 45mph \tag{2}$$

where "CD" is the minimum clearance distance in feet; "W" is the width of left turn lane in feet; and "S" is the speed in miles per hour. This formula is the same formula used for lane reduction transition markings [3]. If the left turn lane needs to begin at or before the side street according to the clearance distance, the RTS design cannot be applied at this location. If possible, increasing the clearance distance will provide more distance for smoother lateral transition from the through lane to the left turn lane.

By directing vehicles performing the worst weaving movement through the new path, the RTS design is expected to decrease the number of conflict points. However, it is a challenge to demonstrate that the RTS design is actually effective and provides delay reduction. It is, therefore, the intent of this paper to study the impacts of the RTS installation based on a before-and-after study of the delay on an arterial street. To conduct the before-and-after study, the delay before and after will be compared for multiple volume conditions with microscopic simulation analysis to determine how the delay of the arterial segment differ over a wide range of volume levels. This paper presents the analysis methodology used for this research, the research results, and finally, the conclusions.

III. ANALYSIS METHODOLOGY

A. Method of Analysis

To provide a comprehensive comparison of the arterial street operations, multiple volume conditions were developed for evaluation. The geometric conditions of one of the two studied locations in the pilot study was selected for the analysis. The only geometric variable selected for this analysis was the spacing between the two intersections along the arterial segment. Microscopic simulation was selected as the method for evaluation since it provides better estimation for the operational conditions for closely spaced or interacting intersections compared to macroscopic analysis techniques. Since a wide range of volume levels will be evaluated, including near capacity and overcapacity conditions, microscopic simulation is better suited to providing reliable measures of effectiveness (MOE) under congested conditions where macroscopic analysis techniques typically breakdown and provide erroneous results. Total delay, in hours, was selected for performing the operational comparison. Total delay is defined as the travel time for all vehicles on all lanes minus the travel time it would take the vehicles with no other vehicles or traffic control devices on the arterial during one hour.

B. Analysis Tools

The analysis was conducted using SimTraffic version 6.0. SimTraffic [4], developed in 1999 by Trafficware Corporation, is one part of a software couple consisting of the coordinated models, Synchro and SimTraffic. SimTraffic is a microscopic simulation model that has the capability to simulate a wide variety of traffic controls, including a network with traffic signals operating on different cycle lengths or operating under fully-actuated conditions. Synchro is a macroscopic traffic software program that implements the Intersection Capacity Utilization method for determining intersection capacity [5]. SimTraffic 6.0 was selected as the simulation program for this study in lieu of other simulation programs because of its capability of compiling and computing vehicle movement, as well as the many features associated with intersection coding and data entry [6].

C. Calibration

To ensure meaningful and appropriate results for the study, the SimTraffic model was calibrated and validated using real traffic data for two sites in Florida that has the same geometrics used in this research. The calibration and validation procedure used the data from one site for the calibration procedure and the data from the other site for the validation procedure. The data used in the process was collected during different time periods (morning, midday, and evening) and different demand levels (peak hours and non-peak hours) during a normal weekday. The calibrated and validated model appeared to be properly effective and to replicate the existing conditions [5].

The calibrated model was used to replicate the before case. To replicate the after case, a copy of the calibrated model was modified to include the proposed RTS design. To split the right turning vehicles to two different destinations, an additional node was added at the downstream intersection. This way it was possible to create two right turn lanes at the downstream intersection, one right turn lane exist at the stop bar (stop controlled) and the other is separated from the other lanes by an island (free operation). Using the origin-destination feature in SimTraffic, the vehicles at the first right turn lane were directed to the left turn lane at the downstream intersection and the vehicles at the second right turn lane were directed to the through and right turn lanes at the downstream intersection. The animation was then viewed in SimTraffic and the new model showed that the vehicles behavior replicated the proposed RTS design. A SimTraffic snapshots for the model before and after applying the RTS design are shown in Fig. 2.

Figure 2. SimTraffic Snapshots Before and After Applying the RTS Design

D. *Base Geometric Conditions*

The goal of this research was to compare the operations of an arterial segment before and after applying the RTS design using comparable geometrics. It was important to select geometrics that were general and applicable to the real world conditions. The geometrics used were selected based on real world conditions in two sites in Florida where the RTS design will be implemented. The key geometric assumptions for the arterial street were:

- Relatively short spacing between two signalized intersections that are running in coordination;
- No driveways or median openings between the two signalized intersections;
- Two through lanes in each direction for the main street;
- A left turn lane at the downstream intersection;
- A continuous right turn lane at the downstream intersection via auxiliary lane;
- A free right turn lane for the side street at the upstream intersection.

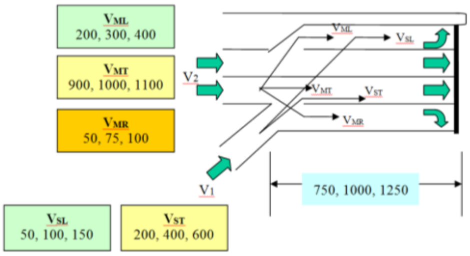

Figure 3. Variables Used in the Analysis

The spacing between the two intersections on the arterial street was the only geometric variable changed in this research due to its large impact on weaving as observed in the field as part of the pilot studies conducted at two arterial weaving sections in Florida. Three spacing levels were selected based on engineering judgment to range from very closely-spaced intersections to average spacing. The different spacing values used are shown in Figure 3.

E. *Volume Scenarios*

A range of volume conditions was developed to test the operations on the arterial street. Five movements were selected for the analysis: the through movement at the upstream intersection that will perform left (VNL), through (VNT), and right (VNR) turning movements at the downstream intersection; and the right turning movement from the side street at the upstream intersection that will perform left (VSL) and through (VST) movements at the downstream intersection. For each movement of the five movements analyzed, three volume levels were selected that ranged from light volume levels to over capacity conditions. The development of over capacity volume conditions was an iterative process in which the volumes were increased by a factor and then evaluated in SimTraffic to determine that if the arterial street is operating under breakdown conditions or not. It is important to note that during the volume development process, the signal timings was less involved since signal cycle lengths, timings, and offsets were developed using the optimization option in Synchro. Finally, having six variables, five volume related, and one for geometric related (spacing between the two intersections), and three levels for each variable, the total number of scenarios developed was 729 scenarios for the before case and 729 scenarios for the after case, totaling 1458 scenarios. All volume distributions and levels can be seen in Figure 3.

F. *Operational Assumptions*

Several operational assumptions were made when setting up the test cases. The goal was to provide a direct comparison between the two cases, before and after applying the RTS design, by minimizing the number of variables to contend with at the conclusion of the analysis. For instance, the arterial segments were analyzed under isolated conditions so the delay would not be affected by adjacent intersections other than the two intersections at the upstream and the downstream of the arterial segment.

Traffic signals were coded as fully-actuated signal control and as coordinated in SimTraffic, which was similar to the existing conditions for the two studied sites during the pilots study. Signal phases were obtained from the existing arterial segments studied in the pilot study. Signal splits and offsets and cycle lengths were optimized in Synchro after we reached capacity condition during the volume iteration process. The values obtained from the optimization step were used for all the scenarios for the existing and the proposed conditions. A geometric assumption was made that an island separates the right turn lane from the other movements at the upstream intersection and the operation of the right turn lane is free as they enter the main street. These conditions were selected since they provide the worst conditions as far as vehicles entering the main street with minimal constraints and they also replicate the two studied sites in the pilot study.

IV. DATA ANALYSIS

The six selected variables with three levels each resulted 1,458 scenarios, 729 scenarios for the before case and 729 scenarios for the after case. Because of SimTraffic's stochastic nature, twenty SimTraffic simulation runs were conducted for each scenario and the results were averaged. Each of the twenty SimTraffic runs used a different random number seed. The same random number seeds were used in each scenario (3). Delay was obtained for each scenario for the before and after cases and the difference in delay for each two similar scenarios was calculated. Out of the 729 pairs, 560 pairs (76.82%) showed improvements in total delay after applying the RTS design. The results were further investigated statistically.

A. Paired t Test

In order to statistically determine whether any improvement or no improvement exist between the before and after conditions for the 729 pairs, a paired t Test, was conducted. Using a one-tailed t-test, the null hypotheses was rejected at the 5% significance level, as the p-value is 0.000 and we conclude that, for the geometric and volume conditions tested, the proposed design provided lower delay on the arterial street than the original conditions.

B. Multivariate Analysis of Variance

The paired t-test gives a main conclusion if the variation between the two groups, before and after, is significant or not. To study the effect of the main variables and the interaction between the independent variables on the dependent variables in the before and the after cases, a statistical analysis tool known as Multivariate Analysis of Variance (MANOVA) was selected to perform the analysis. Univariate One-Way Analysis of Variance (ANOVA) could not be used since we were dealing with two dependent variables, the delay before applying the RTS design (delay-before) and the delay after applying the RTS design (delay-after) in addition to the six independent variables.

The MANOVA analysis was conducted using the SAS statistical analysis package at a level of significance of 5%. The first step in the MANOVA analysis is to test the main effect for all independent variables and interactions using the Wilks' Lambda test. If there is no significant main effect, the analysis for this specific independent variable or interaction is ended. If there is a significant main effect, the second step is to determine the significance of all independent variables and interactions on each dependent variable using the F value and the p value. If there is significance for one dependent variable and not the other, the analysis is ended. If there is significance on both dependent variables for the same independent variable or interaction, the Discriminant Function is then calculated to determine the contribution or the effect of each independent variable or interaction on each dependent variable. The results for the MANOVA analysis are shown in Table I.

TABLE I: Statistical Results of the Main Factors Influencing delay

	Main Effect	**Effect on Delay-Before**	**Effect on Delay-After**	**Discriminant Function**	
	Wilk's Lambda Significance*	**F Value p Value Significance***	**F Value p Value Significance***	**Delay-Before**	**Delay-After**
SP	0.786 Yes	31.13 <.0001 Yes	53.92 <.0001 Yes	0.00575	0.00951
ML	0.578 Yes	44.34 <.0001 Yes	185.71 <.0001 Yes	0.00433	0.01064
MT	0.501 Yes	74.74 <.0001 Yes	237.80 <.0001 Yes	0.0047	0.01035
MR	0.774 Yes	30.75 0.0047 Yes	51.17 0.0031 Yes	0.00501	0.00952
SL	0.779 Yes	19.01 <.0001 Yes	70.34 <.0001 Yes	0.00452	0.1051
ST	0.138 Yes	687.66 <.0001 Yes	1259.06 <.0001 Yes	0.00566	0.00960
SP*ML	0.992 No				
SP*MT	0.926 Yes	7.30 <.0001 Yes	10.13 <.0001 Yes	0.00493	0.00818
SP*MR	0.941 Yes	6.91 <.0001 Yes	3.11 0.0149 Yes	0.00883	0.00357
SP*SL	0.893 Yes	5.64 0.0002 Yes	1.97 0.0967 No		
SP*ST	0.898 Yes	9.19 <.0001 Yes	8.6 <.0001 Yes	0.00681	0.00951
ML*MT	0.955 Yes	7.20 <.0001 Yes	5.44 <.0001 Yes	0.00690	0.00815
ML*MR	0.991 No				
ML*SL	0.873 Yes	6.05 <.0001 Yes	1.54 0.07 No		
ML*ST	0.997 No				
MT*MR	0.932 Yes	6.10 <.0001 Yes	5.44 0.0003 Yes	0.00690361	0.00815818
MT*SL	0.972 Yes	3.05 0.0166 Yes	1.84 0.12 No		
MT*ST	0.854 Yes	4.74 0.0009 Yes	22.3 <.0001 Yes	0.00389	0.01089
MR*SL	0.929 Yes	6.05 <.0001 Yes	1.32 0.09 No		
MR*ST	0.971 Yes	4.4 0.0016 Yes	16.66 <.0001 Yes	0.00496	0.01019
SL*ST	0.864 Yes	8.6 <.0001 Yes	1.67 0.0756 No		

*Significant at the 5 percent significance level

V. CONCLUSIONS

The goal of the research presented was to introduce the RTS design and to determine if the operation of the arterial street would improve after applying the RTS design. To test the operation of the arterial street, a single geometric test case was developed for the before and after cases using geometrics that have equivalent characteristics in the two cases. Six variables, including the spacing and five volume variables, were developed with three levels each. This resulted in the development of 1,458 SimTraffic models, 729 scenarios for the before condition and 729 scenarios for the after condition. The statistical analysis conducted showed that for the geometric, volume, and the traffic control conditions tested, the RTS design provided better system operational performance than the original conditions. The arterial street had lower total delay after applying the RTS design in most cases. A more detailed analysis using the statistical analysis tool MANOVA showed that all six independent variables studied have significant influence on the delay-before and the delay-after. Studying the interactions between the independent variables, it was found that the side street vehicles making a left turn movement at the downstream intersection did not have a significant interaction with all other volume related variables and spacing after applying the RTS design.

It is important to summarize the study methods and assumptions to help the reader determine how this study can be of use to the transportation industry. The study was based on one geometric data set in which comparable geometries were defined and assumed to be equal. The SimTraffic calibration and validation was conducted using field data obtained from two sites in Florida. Existing phasing was utilized in the analysis but splits, offsets, and cycle lengths were optimized using Synchro. The arterial segment was assumed to be isolated for purpose of the analysis, meaning no median openings or driveways affecting the traffic patterns along the arterial segment. In terms of future research, it will be useful to study the after condition after implementation of the RTS design at the two studied sites.

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His research interest is traffic characteristics and traffic signal control of freeway and street intersections. Included in this area are theoretical and applied models, discrete event simulation models, and large-scale databases developed to describe traffic behavior. He was instrumental in bridging the gap between human factors researchers, computer engineers, and transportation engineers. The "Human Centered Transportation Simulation Program" that he created under CATSS auspices has been viewed as a unique and one of the leading programs in the US. He directed and co-directed close to 55 research projects totaling well over $11 million in external funded research projects. Through research and graduate advising he published more than two hundred and fifty (250) technical papers and reports and his work has been extensively cited by his peers in the US and around the world.