Journal of Traffic and Transportation Engineering 11 (2023) 15-28
doi: 10.17265/2328-2142/2023.01.002

Evaluation of Dilemma Zone Protection on High-Speed Arterials with Signal Coordination

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Abstract: In the U.S. and worldwide, driver behavior within an area close to high-speed signalized intersections – the dilemma zone, can be a major safety concern especially for heavy trucks. A variety of mechanisms are available as countermeasures for the dilemma zone problem. In Nebraska, the Department of Roads has developed and implemented an Actuated Advance Warning dilemma zone protection system. The system has been effective at improving traffic safety in isolated applications. However, the system is yet to be used at signalized intersections operating in the coordinated mode. This paper presents results from a simulation study that assessed the potential deployment of the system on arterials where the signals are closely spaced and operate in a coordinated mode. The analysis indicated that, on average, there were 30%, 7% and 30% reductions in the number of rear-end, lane change and crossing conflicts. The system also improved relative productivity by processing more vehicles.

Key words: Dilemma zone, advance warning, simulation, safety.

1. Introduction

Driver behavior within the dilemma zone can be a major safety concern at high-speed signalized intersections, especially for heavy trucks. As a signal indication changes from green to yellow, drivers must decide whether to stop or proceed through the intersection. The section of roadway upstream of the intersection in which neither decision is satisfactory is known as the dilemma zone. In the dilemma zone, some drivers might stop abruptly, thereby increasing the risk of rear-end collisions; others might proceed through the intersection and thus increase the risks of red light running and right-angle collisions with vehicles entering the intersection from the cross road. Common mitigation strategies have involved the three complementary techniques of signal timing, vehicle detection, and advance warning.

A number of state transportation agencies use advance detection and warning systems at isolated intersections. These systems provide information (via flashing signal heads and a warning sign) to drivers regarding whether they should be prepared to stop as they approach a traffic signal. The decision on whether to provide information to the drivers is a function of a number of parameters including the presence of vehicles on the roadway (identified via an upstream detector), the phase sequence, and where in the cycle the current signal timing plan is operating.

However, the Nebraska Department of Roads (NDOR) has developed and implemented an actuated advance warning (AAW) dilemma zone protection system. The AAW system is different in that the operating algorithm is unique to Nebraska. The system continually monitors traffic at an upstream detector as well as at stop-line detectors to predict the onset of the yellow indication and provides information to drivers (via flashing signal heads and a warning sign) regarding

Corresponding author: Bhaven Naik, research fields: traffic microsimualtion modelling, highway safety and human factors research, traffic signal system design and optimization.

whether they should be prepared to stop as they approach a traffic signal. The benefits of the AAW system at improving intersection safety at isolated signalized intersections operating in the fully-actuated mode have been documented [1, 2]. However, the system is yet to be deployed at closely-spaced high-speed signalized intersections operating in the coordinated mode.

While it is common practice in traffic control not to combine dilemma zone protection and signal coordination (because the fixed time of coordinated signals typically overrides any detectors providing dilemma zone protection), the reality is that this often occurs as a city grows. One objective of this research was to develop a mechanistic procedure for testing the feasibility of deploying the AAW system on coordinated arterials. The proposed approach involves emulating traffic operations on a selected arterial using the VISSIM microscopic traffic simulation software. The simulation model provides simulated vehicle tracking data (trajectories) that can be conveniently analyzed in a fast, inexpensive, and risk-free manner. The vehicle trajectories can later be analyzed using the Surrogate Safety Assessment Model (SSAM). The integration of microsimulation and surrogate safety performance measures allows for the assessment of the potential benefits (safety and operational) in-lieu of observed traffic and crash data.

2. Background

2.1 Dilemma Zone Concept

At high speed signalized intersections, there exists an area upstream of the intersection – a dilemma zone, inside which the potential for vehicle crashes is high. The dilemma zone often poses a problem for drivers in stopping safely during the yellow interval or in proceeding through the intersection before the beginning of the red interval. Therefore, a driver is exposed to a potentially hazardous scenario in which a rear-end crash may occur if an abrupt stop is made during the yellow interval or an angle crash may occur if an attempt to proceed through the intersection is made at the onset of the red interval. The dilemma zone can be defined generally by either of two definitions (i.e. Type I and Type II).

The Type I dilemma zone is more traditional and is defined as the area in which, at the onset of yellow, a driver has neither sufficient distance to bring his/her vehicle to a comfortable stop nor sufficient intergreen time to proceed safely through the intersection before the signal indication changes to red [3]. In comparison, the Type II dilemma zone, was formally identified in a technical report by the Southern Section of the Institute of Transportation Engineers [4]. The Type II dilemma zone is defined as the region which begins at the point on the roadway upstream of the signalized intersection where most drivers choose to stop the vehicle when presented with the yellow indication and ends at the point where most drivers choose to continue through the intersection. Strict definitions of the boundaries for the Type II dilemma zone are difficult to define especially that they are dynamic in nature and directly influenced by driver decision making. Several researchers have provided methods to quantify the location of the Type II dilemma zone [1, 5, 6].

2.2 Dilemma Zone Protection

In theory, it is possible to eliminate the dilemma zone through proper timing of the traffic signal. However, the stochastic nature of driving means that some drivers will invariably find themselves in the dilemma zone. For example, they may misjudge the distances involved and elect to stop when they should proceed, they may have slower perception/reaction times than the design driver, or their vehicles may lack the necessary braking power required. Because drivers exhibit distinct differences in their desire or ability to stop when they are in the dilemma zone at the onset of the amber indication, they are potentially at risk of being in a crash. In other words, some drivers may stop abruptly, therefore increasing the risk of a rear-end collision and other drivers might proceed through the intersection which increases the risk of red-light running and the possibility of a right-angle collisions with vehicles entering the intersection from the cross road. The potentially negative impact of dilemma zones on the operational capacity and safety of signalized intersections, especially at high-speed locations, has prompted a great deal of effort focused on the mitigation of the dilemma zone issue.

The common methods of providing dilemma zone protection at high-speed signalized intersections are the use of either 1) advanced detection [6, 7], 2) advance warning flashers [8], or 3) a combination of both advance detection and advance warning flashers [1, 9]. Table 1 provides a list of research and findings that have evaluated different dilemma zone protection systems.

2.3 Background Summary

Driver behavior within the dilemma zone can be a major safety concern at high-speed signalized intersections. The common methods to mitigate the potential risks of the dilemma zone are the use of either, 1) advanced detection, 2) advance warning flashers, or 3) a combination of both advance detection and advance warning flashers. The literature indicates that these systems have been effective in reducing the number of vehicles caught in the dilemma zone and as such there is a reduction in the number of vehicle crashes. There is also evidence of these systems having a positive effect on driver behavior – reduced approach speeds and reduced red-light running. Most applications of the dilemma zone protection systems discussed above have been in the context of isolated intersections. That is, the dilemma zone protection systems have been deployed (and evaluated) at locations outside of city limits where the approach speeds are greater than 40mph [64.3 kph].

However, not all intersections are isolated. As cities grow, these systems that were initially deployed at isolated locations can become part of arterials where the signals are closely spaced and operate in a coordinated mode. In a coordinated setting, while it is not an option to provide green extension(s) using advance detection the use of advance warning flashers (or a combination of both) remains an option however, there can be a significant difference between driver behavior in isolated versus coordinated settings. Therefore, there is need to assess the potential effectiveness of dilemma zone protections systems when deployed in a coordinated environment.

Table 1 Summary of research studies evaluating dilemma zone protection systems

Research Study	Key Findings from Research
ADVANCE DETECTION	
Pant et al., 2005	Reduction in driver speeds
Zimmerman, 2007	58% reduction in red-light-running, 39% reduction in severe crashes, 14% reduction in delay, 9% reduction in stop frequency
ADVANCE WARNING FLASHERS	
Eck and Sabra, 1985	Lower Left-Turn, Right-Angle, and Rear-End crashes
Gibby et al., 1992	Significantly lower total, Left-Turn, Right-Angle, and Rear-End crashes Lower night-time crashes
Klugman et al., 1992	Effectiviely reduced Right-Angle and Rear-End crashes under certain situations
Agent and Pigman, 1994	Lower Left-Turn, Right-Angle, and Rear-End crashes Use should be limited to locations with an existing (or potential for a) high number of angle crashes
Pant and Xie, 1995	Increase in driver speeds
Sayed et al., 1999	Lower Left-Turn, Right-Angle, and Rear-End crashes 10% fewer total crashes and 12% fewer severe crashes
Farraher et al., 1999	29% reduction in total red-light-running, 63% reduction in truck red-light-running and 18.2% speed reduction for trucks
Knodler and Hurwitz, 2009	Use should be limited to locations with an existing (or potential for a) high number of angle crashes
ADVANCE DETECTION + ADVANCE WARNING FLASHERS	
Sunkari et al., 2005	38-42% reduction in red-light-running, less delay, extra dilemma zone protection for trucks and passenger vehicles
Appiah et al., 2011	0.5% less heavy vehicle crashes, 1.2% less Rear-End crashes, 43.6% less Right-Angle crashes, 11.3% less injury crashes and 8.2% less total crashes Reducing delay on minor approaches

3. Methodology

An evaluation of the sort desired for this research can essentially be achieved by performing a "before and after" study. That is, compare a selected set of MOE's from a period when the AAW is not in place with a period when the AAW is in place. However, at the time of this research, there were no known coordinated corridors on which the NDOR had deployed their AAW system. Because it would be difficult to obtain any "real" data to conduct a before-after study, it was intended that this research will make use of a mechanistic approach. The basis of such a mechanistic approach lies in the use of traffic microsimulation tools.

The use of traffic microsimulation models in traffic operations, transportation design, and transportation planning has become widespread across the United States because of: (i) rapidly increasing computer power which is required for complex micro-simulations; (ii) the development of sophisticated traffic microsimulation tools; and (iii) the need by transportation engineers to solve complex problems which do not lend themselves to traditional analysis techniques. Microscopic traffic simulation models mimic closely the stochastic and dynamic nature of both the vehicle-to-vehicle and vehicle-to-traffic interactions that occur within the transportation system. Thus, once developed, simulation models provide simulated vehicle tracking data (trajectories) that can be conveniently analyzed in a fast, inexpensive, and risk-free manner.

The vehicle trajectories can later be analyzed using tools such as the Surrogate Safety Assessment Model (SSAM) developed by the FHWA [10]. The integration of microsimulation and surrogate safety performance measures allows for the assessment of the benefits (safety and operational) in-lieu of observed traffic and crash data.

3.1 Traffic Microsimulation: VISSIM

VISSIM is a discrete, stochastic, time step based microscopic traffic simulation model with driver-vehicle-units modeled as single entities. It was developed by Planung Transport Verkehr in Germany [11]. The model consists internally of two distinct components that communicate through an interface – first, a traffic simulator that simulates the movement of vehicles and generates the corresponding output and second, a signal state generator that determines and updates the signal status using detector information from the traffic simulator on a discrete time step basis. The input data required for VISSIM include network geometry, traffic demands, phase assignments, signal control timing plans, vehicle speed distributions, and the acceleration and deceleration characteristics of vehicles. VISSIM allows the user to model traffic signals using different control types such as: pre-timed, RBC standard signal control emulator (which can operate in fully actuated, coordinated, or semi-actuated coordinated modes), and vehicle actuated programming (VAP). The model is also capable of producing measures of effectiveness commonly used in the traffic engineering profession such as average delay, queue lengths, and fuel emissions [12].

VISSIM incorporates Wiedemann's psycho-physical car following models for longitudinal movement and a rule-based algorithm for lateral movements. The basic idea of the Wiedemann models is the assumption that a driver can be in one of four driving states as he travels along a highway section. These states are the free-driving, approaching, following, and braking [11]. The acceleration of an individual vehicle in a given state is described as a result of speed, speed difference, distance, and individual characteristics of the driver. The driver switches from one state to another as soon as he reaches a certain threshold defined as a combination of speed difference and distance [13].

In VISSIM, a rule-based algorithm is used to model lateral movements on multi-lane highways. A driver is motivated to change lanes if the preceding vehicle predictably hinders his movement or it is necessary to stay within a predefined route such as an upcoming exit with a deceleration lane. Before executing a lane change, the driver checks whether the intended change will improve the present condition (speed and position). The driver checks if he will benefit from the intended lane change by considering the speeds and positions of the vehicle directly ahead of him as well as those of the leading and following vehicles in the intended destination lane [14].

To ensure the validity and reliability of results from microsimulation models, the parameters that govern the underlying car-following, lane-changing, and gap-acceptance models are calibrated and validated against observed traffic data. While the authors acknowledge that it is an important step to calibrate and validate a microsimulation model, the model(s) developed for this particular project were not calibrated and validated. Because the research objective was primarily to assess output from simulated alternatives, it was determined that using default parameter values would not affect the results.

3.2 Surrogate Safety Assessment Model

The Surrogate Safety Assessment Model (SSAM) is a product that was developed by the Federal Highway Administration (FHWA) to perform conflict analysis for traffic facilities. SSAM automates the conflict analysis process by directly processing vehicle trajectory data. Essentially, vehicle trajectories from VISSIM, and other traffic microsimulation models such as AIMSUN and Paramics, are post-processed with SSAM to identify and classify conflict events [15]. For each event SSAM also calculates several surrogate safety measures including: (i) post-encroachment time (PET) that is, the elapsed time between the departure of an encroaching vehicle and the actual arrival of a trailing vehicle at the same position [16], a value of zero indicating an actual collision; and (ii) time-to-collision (TTC), namely, the projected time for two vehicles to collide if they continued at their present speed and stayed on the same path [17, 18]. These proximal safety measures are considered "valid and credible precursors of actual crashes" [19].

3.3 Simulated Test Bed

The objective of this research study was to evaluate the use of Active Advance Warning Systems in conditions where the signalized intersections operate in a coordinated mode. Therefore, it was important that the corridor to serve as a test bed had signals operating in coordination. The Highway 2 corridor shown in Fig. 1 (from 56th street to 14th street) in Lincoln, Nebraska was identified as the test bed for this study. This section of Highway 2 has two lanes in both directions of travel with posted speed limit of 45 mph, traffic signals are coordinated, and the traffic volumes are relatively high. In addition, this corridor section is a major conduit for both passenger vehicles and heavy vehicles (trucks). The entire corridor is approximately 3.5 miles [5.6 kilometers] long with six signalized intersections spaced at an average distance of 0.5 miles [0.8 kilometers] apart.

The majority of the supply input data was obtained from engineering drawings and signal timing plans provided by the public works department of the city of Lincoln. More specifically, was the signal control information which included phase assignments, maximum and minimum green times, detector lengths and locations, passage times, and detector call options. The traffic detection type (video or loop) information at each intersection was obtained from intersection blueprints and coded accordingly. The traffic controllers were coded accordingly in VISSIM using the Vehicle Actuated Programming (VAP). Other supply data sources included background images downloaded from Google Earth. These were used to trace the network in VISSIM and also extract data such as number, length, width and other distinguishing features related to the geometry of the road network.

The demand data were extracted from SYNCHRO files obtained from the public works department of the city of Lincoln. This demand data was imputed into the VISSIM model as aggregated peak hour volumes with vehicles being routed or directed by using turning ratios at intersections. In terms of vehicle classification, the "Car," and the "HGV" vehicle types were used. Default performance attributes for these vehicle types were utilized [11]. A traffic composition of 90% passenger cars and 10% heavy vehicles was adopted.

3.4 Actuated Advance Warning System

The Actuated Advance Warning (AAW) system developed by the NDOR combines advance detection and advance warning flasher systems with the legend "PREPARE TO STOP WHEN FLASHING". The system has one advance detector in each approach lane as well as an advance warning flasher assembly positioned on either side of the roadway approach downstream of the advance detector. In addition, stop line detection is also provided in the through lanes and left-turn bays. The range of stop-line detection is 30 to 40 feet [9.1 to 12.1 meters] in the left-turn bays. The advance detector operates in the pulse mode, which means that each vehicle crossing the detector transmits a single pulse to the controller, regardless of the time that the vehicle spends in the detection area. The stop line detectors operate in the presence mode (a continuous call is transmitted to the controller as long as a vehicle is within the detection area) but are not active during the extendible portion of the green interval [1]. Specific details on the operation of the AAW system are available in the literature [1].

In general, the design algorithm combines the functionality of advance detection and advance warning; and uses a shorter maximum allowable headway to extend the green [20].

3.5 Simulation Runs

Two VISSIM models were developed: 1) a base model (signals operate in coordination and there are no AAW systems), and 2) an alternate model (signals are coordinated and AAW systems are present). Each model was simulated for two hours, with the first hour

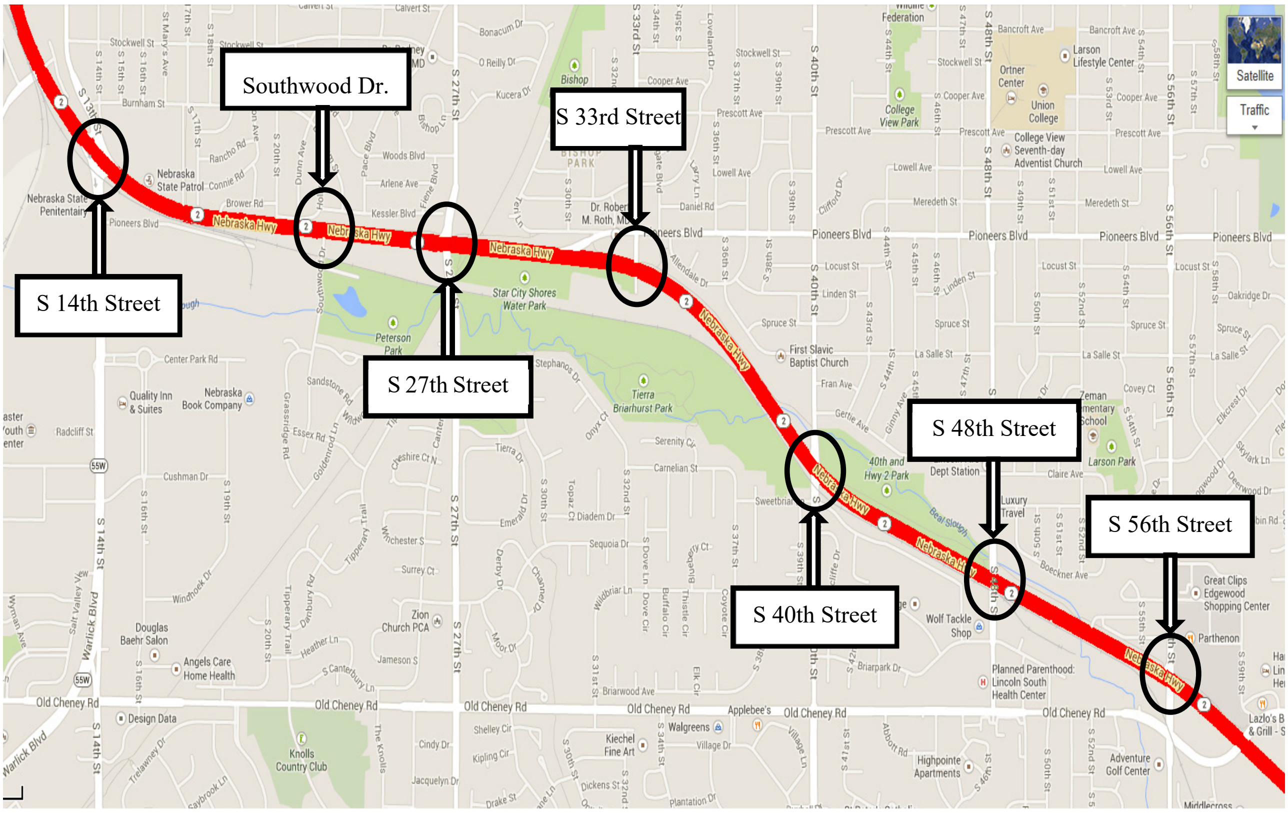

Fig. 1 Simulated test bed: Nebraska Hwy/Highway 2 (Lincoln, Nebraska).

serving as a warm-up period during which traffic was loaded onto the network and the system was allowed to reach equilibrium.

By their nature, microsimulation models are deterministic – will provide the same output given the same input. However, by using different random seeds, stochastic variation in the input arrival flow patterns is generated. Consequently, the results of each simulation run will usually be close to the average of all runs; but each run will be slightly different from the other [21]. In this research, the same 20 random seeds were used to model each alternative. Thus, each alternative was modeled with the same arrival flow pattern and a direct comparison could be made between alternatives. Vehicle trajectory files from the simulation runs were exported to FHWA's SSAM software for conflict analysis. Results of the 20 replications were then averaged to obtain the desired measures of performance.

4. Analysis and Results

This section primarily presents detail into the results of the mechanistic approach used in this study and presented earlier. The effects of adopting the AAW system on coordinated arterials was evaluated on the basis of three measures: i) conflicts, ii) throughput, and iii) travel times

4.1 Conflict Analysis

It is a common practice in highway safety research to rely on actual crash statistics when addressing safety related concerns, such as evaluating the effects of a safety countermeasure (or program), identifying hazardous locations (black spots), and remedying irresponsible driver behaviors. However, while crash data has proven to be useful, there are serious limitations to their availability. To overcome this shortcoming, forms of non-accident information such as traffic conflicts have been employed. Traffic conflicts have long been employed by highway engineers when they exercised 'engineering judgment' in identifying hazardous locations on the highways [22]. By definition, a traffic conflict is "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remained unchanged" [17].

For this study, a conflict analysis was conducted by comparing the SSAM surrogate safety measures obtained from a base microsimulation model with those measures obtained from an alternate model. The specific measures that were compared include: (i) post-encroachment time (PET), and (ii) time-to-collision (TTC). Both the PET and TTC are considered "indicators of crash propensity with smaller minimum values indicating a greater likelihood of a crash occurring" [23]. Conflicts from the two simulation models (base and alternate) were compared for the signalized intersections at Southwood Drive, 27th Street, 33rd Street, and 40th Street.

4.2 Distributions of Time to Collision (TTC) and Post-Encroachment Time (PET)

The potential benefits of using the AAW system in coordinated arterials can been shown by comparing counts of potentially hazardous situations (conflicts) as will be seen in the next section. However, by establishing statistical distributions of the vehicle-vehicle interactions, the proportion of critical situations (conflicts) is not merely counted but derived mathematically [23].

Time-to-collision is the projected time for two vehicles to collide if they continued at their present speed and stayed on the same path. VISSIM vehicle trajectory files were processed in SSAM to yield conflicts using a user defined maximum threshold TTC value. Conflict data and surrogate safety measures for only those vehicle-to-vehicle interactions less than the user defined threshold were output. Based on the relationship between conflict speed, time-to-accident, and conflict severity developed by Hyden [17], a TTC threshold of 3 seconds was used to identify serious conflicts.

The frequency distributions for the TTC were developed as shown in Figure 2. Each figure depicts both the frequency and cumulative frequency for both the base and alternate models. Figure 2 compares the distributions of the base and alternate models. For all the intersections (27th St., Southwood Dr., 33rd St., and 40th St.) it can be observed that the shape of cumulative distributions is similar for both models. However, the frequency distribution indicates that there are fewer conflicts in the alternate model than the base model. This is an indication that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer.

Additionally, the TTC distributional characteristics (i.e., mean, standard deviation, 15th percentile, and 85th percentile) for both models were compared. The TTC distributional characteristics were found to be similar.

Post-encroachment time is defined as the elapsed time between the departure of an encroaching vehicle and the actual arrival of a trailing vehicle at the same position. The default SSAM maximum threshold value of five seconds was used for this study. The frequency distributions for the PET were developed as shown in Figure 3. Each figure depicts both the frequency and cumulative frequency for both the base and alternate models.

As with the TTC, Figure 3 shows that the shape of the cumulative distribution of all conflicts is similar for both models. For 27th St. and Southwood Dr., the cumulative frequency distribution curve for the base model is above that of the alternate model whereas for 33rd St. and 40th St., the cumulative frequency distribution curves for the two models run relatively close to each other. Overall, this is indicating that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. The PET distributional characteristics (mean, standard deviation, 15th percentile, and 85th percentile) were compared and found to be similar.

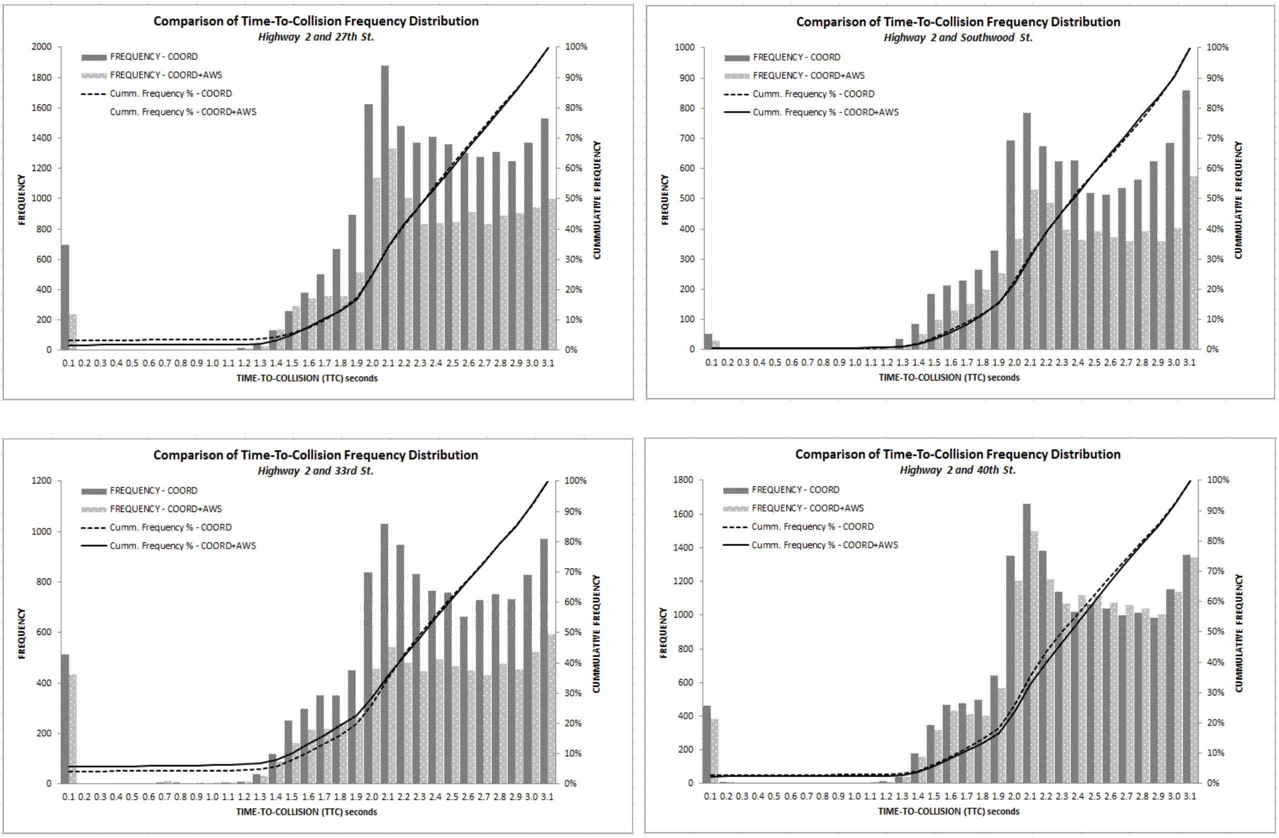

Fig. 2 Time to collision frequency distributions.

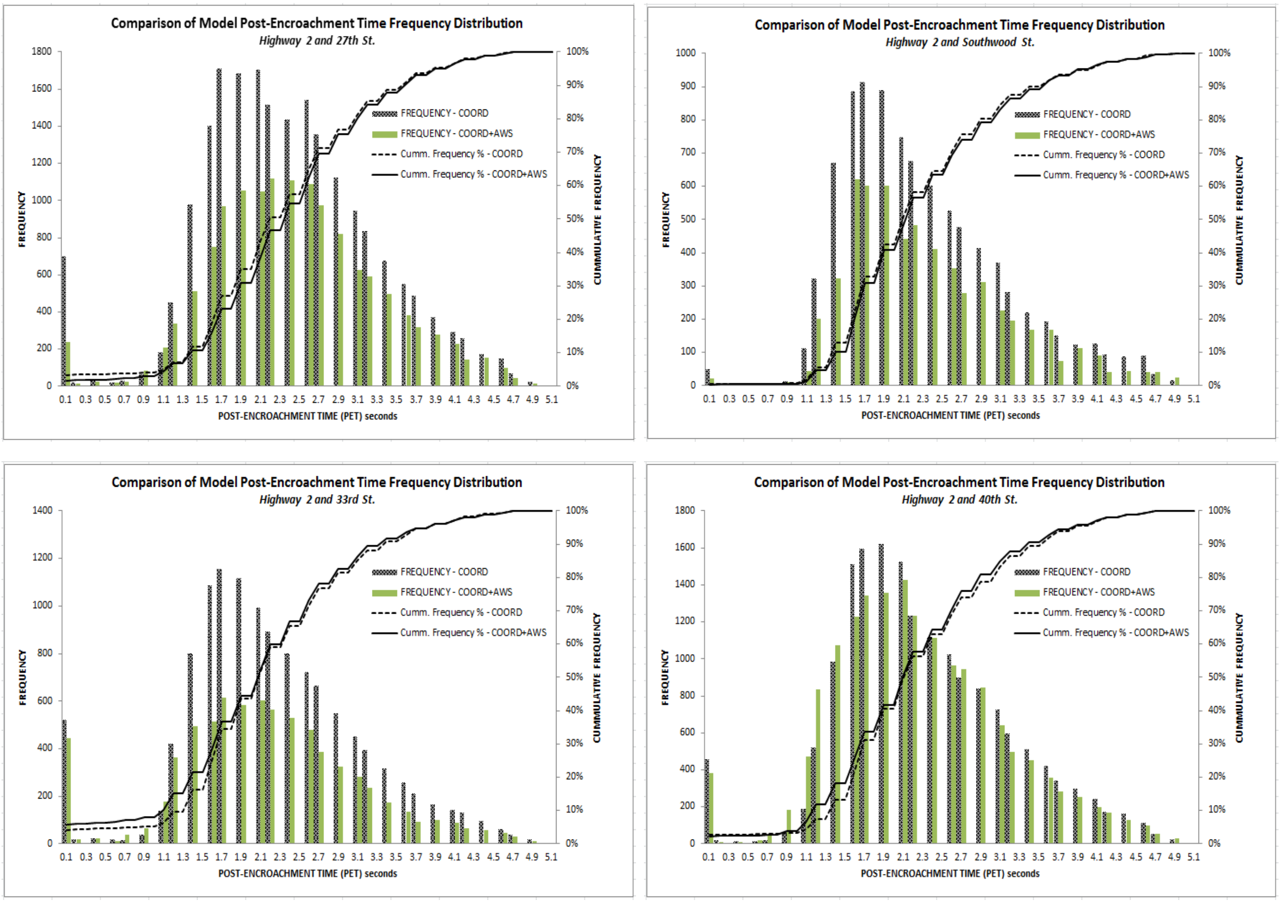

Fig. 3 Post encroachment time frequency distributions.

4.3 Number of Conflicts

Based on the TTC and PET values, the conflicts are classified within SSAM into 3 types – rear-end, lane change and crossing as presented in Table 2. Overall, it can be observed that, for all 20 simulation runs, there was a reduction in all three conflict types when the AAW system was being used in addition to the signals being in coordination mode. On average there were 30%, 7% and 30% reduction in rear-end, lane change and crossing conflicts, respectively, across all four intersections.

Based on the overall results shown in Table 2, it was hypothesized that the placement of the AAW system would reduce the number of conflicts. T-tests were performed to check if there were statistically significant differences in the number of conflicts between the models. The tests were performed using the JMP software package. The hypotheses can be stated mathematically as:

Ho: number of conflicts from base model = number of conflicts from alternate model

Ha: number of conflicts from base model $\neq$ number of conflicts from alternate model

and

Ho: number of conflicts from base model $\geq$ number of conflicts from alternate model

Ha: number of conflicts from base model < number of conflicts from alternate model

where: conflicts = rear-end, lane change, crossing, and also the total of all three conflicts types.

In terms of all conflict types, for all intersections (27th St., South Dr., 33rd St., and 40th St.) at the 95% significance level there was enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models were not equal. In addition, the result indicates that the numbers of conflicts in the base model were greater than from the alternate model.

With regard to rear-end conflicts, the t-test indicated that at the 95% significance level there was enough evidence to reject the null hypothesis and conclude that the rear-end conflicts between the base and alternate models were not the same. In fact, for the 27th St. intersection there was a decrease in the number of rear-end conflicts when the AAW system was used in addition to signal coordination. This was not the case for the Southwood Dr., 33rd St., and 40th St. intersections. The mixed results seem to suggest that drivers could/could not be responding positively to the AAW system by slowing down as they approach the intersection.

As for lane change conflicts, there was enough evidence to reject the null hypothesis and conclude that the lane change conflicts are not the same for both the base and alternate models. The results, indicated that for the 27th St., Southwood Dr., and 40th St. intersections, there was a statistically significant decrease in lane change conflicts when the AAW system was used in addition to signal coordination on a corridor.

With respect to crossing conflicts, there was enough evidence to reject the null hypothesis at all intersections. Crossing conflicts are those conflicts that occur inside the intersection and are likely caused by vehicles entering the intersection at the onset of the amber indication or during the amber phase. At all intersections, the results of the T-test suggest that there was a lower number of crossing conflicts in the alternate model. This could be an indication of drivers responding to the AAW system, slowing down and eventually coming to a safe stop.

In summary, statistically significant differences were observed between the conflicts observed from the base and alternate models. In fact, for all four intersections, the results also indicate that conflicts actually reduced with the alternate model.

4.2 Throughput Analysis

Throughput is defined as "an indicator of the relative productivity of the system [24]". It makes the analyst aware of the number of vehicles that were processed by the system during a specified analysis period. The throughput is compared for different alternatives to determine the relative productivity of each alternative. Higher values are desired. For this study, the number of vehicles that passed through each intersection during one hour was computed. Table 3 presents the throughput comparisons at each intersection. The throughput was computed as the 5-minute average of the 20 simulations and also as the total of the 20 simulations. Values of both the 5-minute average and total for the major approaches only (Eastbound and Westbound) are presented.

Table 2 Comparison of conflict frequencies.

COORDINATED ONLY								
All Conflict Types	Southwood Drive		27th Street		33rd Street		40th Street	
All Conflicts	9109	**(455)**	20796	**(1040)**	12279	**(614)**	17429	**(871)**
Rear-End Conflicts	8577	**(429)**	18380	**(919)**	11028	**(551)**	15315	**(766)**
Lane Change Conflicts	475	**(24)**	2158	**(108)**	931	**(47)**	1855	**(93)**
Crossing Conflicts	57	**(3)**	258	**(13)**	320	**(16)**	259	**(13)**

AAW + COORDINATION								
All Conflict Types	Southwood Drive		27th Street		33rd Street		40th Street	
All Conflicts	5938	**(297)**	13779	**(689)**	7541	**(377)**	16637	**(832)**
Rear-End Conflicts	5396	**(270)**	11892	**(595)**	6497	**(325)**	14556	**(728)**
Lane Change Conflicts	492	**(25)**	1822	**(91)**	790	**(40)**	1856	**(93)**
Crossing Conflicts	50	**(3)**	65	**(3)**	254	**(13)**	225	**(11)**

Table 3 Comparison of throughput.

Model	MOE's	WestBound			
		Southwood Dr.	27th St.	33rd St.	40th St.
Base Model (COORD)	5-min Average (20 sims)	108	86	100	83
	Total (20 sims)	1292	1027	1201	1001
Alternate (COORD+AWS)	5-min Average (20 sims)	107	86	100	83
	Total (20 sims)	1287	1028	1199	999

Model	MOE's	EastBound			
		Southwood Dr.	27th St.	33rd St.	40th St.
Base Model (COORD)	5-min Average (20 sims)	65	57	87	78
	Total (20 sims)	776	686	1039	932
Alternate (COORD+AWS)	5-min Average (20 sims)	57	47	78	71
	Total (20 sims)	682	561	937	848

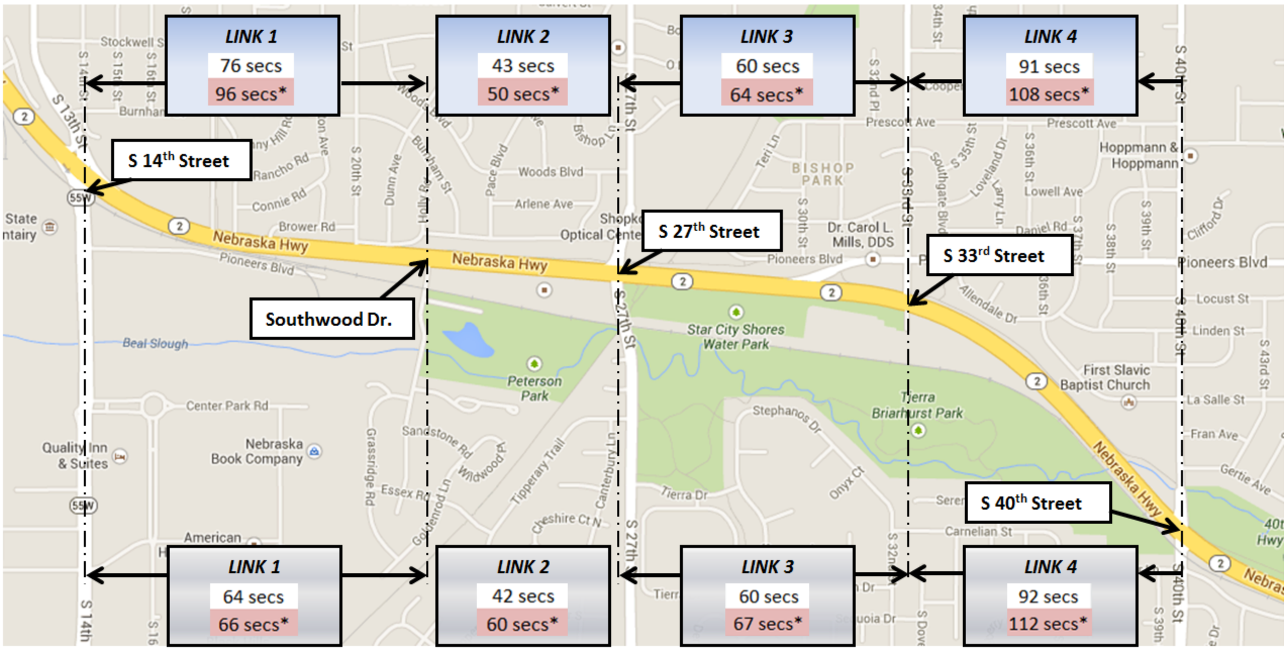

Fig. 4 Comparison of link travel times

From Table 3 it can be observed that the throughputs in the westbound direction are very similar at each intersection. However, in the eastbound direction, the throughputs are slightly lower when the AAW system is in place (alternate model). To check if the differences in eastbound direction throughput values were statistically significant, T-tests were performed on the 5-minute average throughput. The results suggested that there was a statistically significant (95% level) decrease in throughput when the AAW system was used in addition to signal coordination on a corridor.

4.4 Travel Time Analysis

The final MOE that was compared to provide insights into the use of the AAW system in a coordinated corridor was travel time. For each of the 20 simulation runs, link travel times (aggregated at 5-minutes) were collected for a period of one hour. These 5-min travel times were compared from both the base and alternate models. Figure 4 depicts the 5-min travel time (average of 20 runs) for each link on the corridor. The values shown at the top of Figure 4 are for the westbound direction while those values shown at the bottom are for the westbound direction.

It can be seen from Figure 4 that the link travel times from the alternate model are slightly higher than values from the base model. This is expected given that drivers reduce their speeds when the AAW system is operational.

5. Conclusions and Recommendations

This study assessed the potential deployment of the AAW system (developed by the Nebraska Department of Roads) on arterials where the signals are closely spaced and operate in a coordinated mode. A mechanistic approach – integration of traffic microsimulation and surrogate safety performance measures was utilized to assess the potential benefits (safety and operational) in-lieu of observed traffic and crash data.

The analysis on conflicts indicated that, on average, there were 30%, 7% and 30% reductions in the number of rear-end, lane change and crossing conflicts when the AAW system was used. Additional statistical t-tests confirmed that not only were there significant differences in the number of conflicts between the two models but also the conflicts from the base model were higher than those from the alternate model. This suggests that having the AAW system in place with signal coordination does improve the safety.

A comparison of the relative productivity of the system – the number of vehicles that were processed by the system during a specified analysis period revealed that there were generally more vehicles processed by the base model than the alternate model. The throughput in the westbound direction was very similar however, in the eastbound direction the throughput was slightly lower when the AAW system is in place (alternate model). The throughput was computed as the 5-minute average of the 20 simulations and also as the total of the 20 simulations. A t-test performed on the 5-minute average throughput in the eastbound direction indicated that the throughput was not the same for both the base and alternate models. Furthermore, there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on a corridor.

Finally, aggregated 5-minute travel times from all links between intersections were compared for the two models. Overall, the link travel times from the alternate model were slightly higher than values from the base model. Therefore, it took drivers in the alternate model longer to traverse between intersections and also the entire corridor altogether. This is expected given that drivers reduce their speeds when the AAW system is operational.

Based on the results of this research, the following recommendations are made with regard to the use of AAW devices:

From the perspective of safety effectiveness, the AAW system is worth considering for dilemma zone protection on arterials that have closely spaced signalized intersections operating in a coordinated mode. The system appears to reduce vehicle conflicts.

In terms of operational benefits, the AAW system is not worth considering for dilemma zone protection on arterials that have closely spaced signalized intersections operating in coordination. There were fewer cars processed through the intersections and link travel times were higher.

Overall, the decision to employ AAW devices on coordinated arterials would have to be based on which of either safety or operations is a priority. It should be noted that this research was fully mechanistic. A field evaluation of the AAW system involving real data is recommended.

Acknowledgements

The authors would like to acknowledge the contributions of numerous individuals and organizations that made the successful completion of this study possible. We are especially grateful to the Federal Highway Administration for making the Surrogate Safety Assessment Module available to us; and the business team at the Mid-America Transportation Center who provided technical support.

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