COMPARISON OF THEORETICAL AND OBSERVATION BASED PROBABILITY OF CONFLICT CURVES

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ABSTRACT

This paper examines the effect of information provided to drivers through advance warning flashers (AWFs) on driver's probability of conflict at the onset of yellow at a high-speed intersection. AWFs are specifically designed to minimize the number of vehicles trapped in their respective dilemma zones at the onset of yellow (Messer et al., 2003). A probit modeling technique was used to establish dilemma zone boundaries. Based on the dilemma zone boundaries probability of a perceived conflict curves was computed and compared against actual conflicts observed at each of the studied intersections. The comparison between the actual and theoretical probability of conflict curves generated a better understanding of the risk associated with providing drivers with information prior to the onset of yellow through the use of advance warning flashers (AWFs). Results found that providing drivers with information in advance of the intersection using AWFs can potentially cause increased risk in RLRs and/or severe decelerations. Thus, caution should be used by engineers before providing drivers with information at a high speed intersection.

Keywords: Dilemma Zone, Driver's Decision Models, Traffic Conflict Technique

INTRODUCTION

According to the National Highway Traffic Safety Administration, the total cost of motor vehicle collisions in the United States was estimated at $230.6 billion in 2006 (NHTSA, 2007). The total cost of motor vehicle collisions in the State of Nebraska was projected at $2.4 billion in 2007 (State of Nebraska, 2007). Intersection and intersection-related crashes accounted for nearly 40.5 percent of all reported crashes in 2006 in the U.S (NHTSA, 2007). Intersection crashes average approximately 8,500 fatal and 900,000 injury accidents a year.

This paper reports on an empirical study modeling the impacts of advance warning flashers on driver decision making at the onset of yellow at five high speed intersections. At high speed intersections, drivers travel at high speeds with the expectation of proceeding through without stopping. A driver approaching the intersection has to decide whether to stop or go at the onset of yellow. An incorrect decision to stop when it would have been safer to proceed can lead to a severe rear-end collision. Conversely, an incorrect decision to proceed through the intersection could lead to the driver running the red light and possibly causing a right angle collision. The zone where the risk of making an erroneous decision is highest is termed the "dilemma zone" (Parsonson, 1978). The dilemma zone has been defined as the approach area where the probability of stopping on the onset of yellow is within the range of 10 to 90 percent (Herman et al., 1963; May, 1968; ITE, 1974; Zeeger, 1977).

In order to help drivers make more informed decisions at the onset of yellow, engineering countermeasures enhancing the signal display by providing advance information to motorists have been implemented. Placed upstream of high speed signalized intersections, advance warning flashers provide drivers with information regarding whether they should prepare to stop at the upcoming traffic signal or proceed through the intersection. Specifically, AWFs are designed to minimize the number of vehicles trapped in their respective dilemma zones at the onset of yellow (Messer et al., 2003).

Data was collected and compared at five high speed intersections: 4 in Lincoln, NE and 1 in Noblesville, IN. Data collected at the onset of yellow included: distance to stop line, speed, and decision of driver to stop or proceed through the intersection. The impact of AWFs on probability of stopping and probability severe conflicts was assessed by developing binary discrete choice models. The paper finally presents the dilemma zone boundaries and risk of severe conflict associated with each intersection. The intent of this paper is to document the shift in dilemma zone boundaries due to the effect or lack of information received by the driver from AWFs, and illustrate the increase in severe conflicts as a result of poorly timed yellow change intervals.

BACKGROUND

Defining Dilemma Zone

At high speed intersections, drivers travel at high speeds with the expectation of proceeding through without stopping. A driver approaching the intersection has to decide whether to stop or go at the onset of yellow phase. An incorrect decision to stop when it would have been safer to proceed can lead to a severe rear-end collision. Conversely, an incorrect decision to proceed through the intersection could lead to the driver running the red light and possibly causing a right angle collision. The zone where the risk of making an erroneous decision is highest is termed the "dilemma zone" (Parsonson, 1978). The dilemma zone was initially defined as the area where the driver can neither stop comfortably nor clear safely at the onset of yellow (Gazis, Herman and Maradudin, 1960). The dilemma zone locations were determined deterministically using perception reaction time, comfortable deceleration rate, and length of the yellow interval. However, studies have shown a wide variability in driver behavior at the onset of yellow (Williams, 1977; Sivak et al., 1982; Wortman and Matthias, 1983; Chang et al., 1985; Liu et al., 2007).

To take into account the variability in driver behavior, researchers defined a second type of dilemma zone. Also referred to as the decision dilemma zone, Type II dilemma zone, is based on a probabilistic approach of drivers' decision to the onset of yellow. The decision dilemma zone has been defined as the approach area where the probability of stopping on the onset of yellow is within the range of 10 to 90 percent (May, 1968; ITE, 1974; Zeeger, 1977; Herman et al., 1963). Researchers have attempted several approaches to characterizing the decision dilemma zone boundaries. Zeeger (1977) used a frequency-based approach of drivers stopping decisions at specified distances and speeds to develop a cumulative distribution function. Recently, researchers have used binary discrete choice models to develop probability of stopping curves and better understand the underlying human decision models (Sheffi and Mahmassani, 1981; Bonneson and Son, 2003; Gates et al., 2006; Papaioannou, 2007; Kim et al., 2008)

Effects of yellow length on driver behavior

The effects of yellow interval duration on stopping have also been studied. Lengthy yellow intervals were found to cause bad driver behavior for last-to-stop drivers at intersections (Van der Horst and Wilmink, 1986). Instead of being presented with a red indication as they approached the stop line, the drivers were stopping while the light was still yellow. Thus, persuading the driver to proceed through the intersection the next time they approached the intersection. Van der Horst and Wilmink found drivers adjusting their stopping behavior as a function of longer change intervals. The probability of stopping for drivers 4 seconds from the intersection decreased from 0.5 for a yellow length of 3 seconds to 0.34 for a yellow length of 5 seconds long. Mahalel and Prashker noted a potential increase in the indecision zone for a lengthy “end-of-phase” warning interval (Mahalel and Prashker, 1987). They observed an increase in the indecision zone from the normal zone of (2 to 5 seconds) without a flashing green interval to an indecision zone of 2 to 8 seconds for a 3-s yellow that was preceded by a 3-s flashing green. Mahalel and Prashker presented evidence of increases in the frequency of rear-end crashes due to the increase in the indecision zone. In a study of multiple intersections in Texas, Bonnenson et al. (2002) noted that drivers do adapt to an increase in yellow duration. Reductions in red light running (RLR) were found to decrease up to 50 percent for increases in yellow ranging from 0.5 to 1.5 s, as long as the yellow duration did not exceed 5.5 seconds. Contrary to the previous results, Olson and Rothery (1961) concluded that driver behavior does not change as a function of different yellow phase durations. Studies have also shown that an overly long amber could lead to greater variability in driver’s decision making and potentially increase rear-end conflicts (Van der Horst and Wilmink, 1986; May, 1968; Mahalel and Prashker, 1987).

Effects of Advance Warning Flashers

Placed upstream of high speed signalized intersections, AWFs provide drivers with information regarding whether they should prepare to stop at the upcoming traffic signal or proceed through the intersection. Specifically, AWFs are designed to minimize the number of vehicles trapped in their respective dilemma zones at the onset of yellow (Messer et al., 2003). AWFs have been found to improve dilemma zone protection in the state of Nebraska. McCoy and Pesti (2003) used advanced detection along with AWFs to develop an enhanced dilemma zone protection system. The system was found to reduce the number of max-outs, which would result in a loss of dilemma zone protection. Additionally, the Texas Transportation Institute (TTI) developed an Advanced Warning for End-of-Green System (AWEGS) that utilized a sign (text or symbolic), two amber flashers, and a pair of advanced inductive loops (Messer et al, 2003). The system capable of identifying different classifications of vehicles (car, truck) has shown to decrease delay due to stoppages at traffic signals, as well as providing extra dilemma zone protection to high-speed vehicles and trucks. Results of the study have shown a reduction in Red Light Running (RLR) by 38 to 42 percent in the first 5 seconds of red.

Gibby et al. (1992) concluded from an analysis on high-speed signalized intersections in California that advance warning flashers significantly reduce accident rates. The approaches with AWFs had lower total, left-turn, right-angle, and rear-end accident rates. Sayed et al. (1999) calculated the reduction in total and severe accidents at intersections with AWFs to be 10 and 12 percent, respectively. Farraher et al. (1999) observed red light running and vehicles speeds in Bloomington, Minnesota. Installation of advanced warning flashers resulted in reductions of 29 percent in red light running, 63 percent reduction in truck red light running, and an 18.2 percent reduction in the speed of the red light running trucks.

Although the consensus of AWFs is that the systems provide safety benefits to the users, several concerns have been raised. In their study, Farraher et al. (1999), detected car drivers running the red light entered speeds above the speed light increasing the risk of crash for opposing traffic. Pant and Huang (1992) evaluated several high-speed intersections with AWFs and detected increases in speed as the traffic signal approached the red phase. Thus, the authors discouraged the use of Prepare to Stop When Flashing (PTSWF) and Flashing Symbolic Signal Ahead (FSSA) signs along tangent intersection approaches. Further testing performed by Pant and Xie (1995) at two intersections verified the previous findings of increased speeds along roadways with a PTSWF or FSSA sign. Koll et al. (2004) compared the effects of flashing green on 10 approaches in Austria, Switzerland, and Germany. Safety impacts considered included the amount of yellow and red stop line crossings observed. A substantial increase in the number of early stops was found in Austria. A larger option zone, area where drivers can both proceed and stop safely, increased as a result. Although longer and larger option zones can lead to increases in rear end collisions, Koll et al. concluded that early stops should reduce the probability of right-angle collisions.

Traffic Conflict

Traditional surrogate measures of safety (like number of vehicles in dilemma zone) fail to quantify the risk of crash for a driver approaching an intersection. The Traffic Conflict Technique (TCT) has evolved and demonstrated its usefulness in indirectly evaluating the safety of intersections, as researchers have established direct relationships between conflicts and crashes (Baker, 1972; Spicer, 1972; Cooper, 1973; Paddock, 1974; Gettman et al., 2008). Perkins and Harris defined a conflict as “The occurrence of evasive actions, such as braking or weaving, which are forced on the driver by an impending crash situation or a traffic violation.” This paper was particularly interested in the conflict types occurring at the onset of yellow. Thus, the onset of yellow conflicts identified by Zeeger (1977) were used: red light runner, abrupt stop, swerve-to-avoid collision, vehicle skidding, acceleration through yellow, and brakes applied before passing through.

DATA COLLECTION

Nebraska Sites

Data was collected from five high-speed signalized intersections in Lincoln, NE. Individual intersection characteristics for all sites studied are shown below in Table 1. Each intersection was instrumented with three wide area detectors (WAD) recording individual vehicle information. Two SmartSensor Advance WADs, utilizing digital wave radar technology, installed on the research pole track the vehicles upstream and downstream of the pole and record their distance, speed, lane, and vehicle length up to a distance of 500 ft. A SmartSensor HD acts as the midstream sensor and records the vehicles information equidistant with the research pole. In addition to recording speed, the SmartSensor HD identifies the lane a vehicle travels in and records vehicle length. The stated accuracy of a WAD used for data collection is within 5ft. A detailed analysis on the performance of a WAD can be found in previous works (Sharma et al., 2008). Figure 1 illustrates the data collection setup used for the four sites.

Data was collected starting July 2010 to December 2010 from 8:00 AM to 5:00 PM. The data was collected for a total of 19 days during the collection period. Only clear weather days were used for calculating the dilemma zone boundaries. Additionally, only instances when a single vehicle was present in a lane were used for determination of dilemma zone boundaries.

Table 1 Site characteristics

	Saltillo	**Highway 2**	**Pioneers**	**US 34**	**US 75**	**SR 37**
Site Code	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Yellow phase	4.4 s	5.6 s	4.9 s	4.4 s	4.5 s	5.0 s
Mean speed (mph)	54.1	48.5	52.8	56.6	51.4	46.6
Posted speed limit (mph)	55	55	55	60	55	55
85th Percentile speed (mph)	64	55	58.3	63	61	55
Use of AWF	Yes	Yes	Yes	Yes	Yes	No
AWF Distance	650 ft.	563 ft.	650 ft.	650 ft.	470 ft.	-
AWF Time before yellow	7.0 s	8.0 s	8.0 s	7.0 s	6.0 s	-
Through Lanes	2	2	2	2	2	2
Right or Left turn lane	Both	Neither	Both	Both	Both	Both

Noblesville Site

In contrast to the previously studied sites, the Site 6 did not provide drivers with information prior to the intersection. Therefore, data collected by Sharma et al. (2011) at SR 37 was used for evaluation purposes. The site had a single WAD, as well as a single camera mounted on the signal mast arm. Sharma et al. (2008) provides further information on how data was collected and processed.

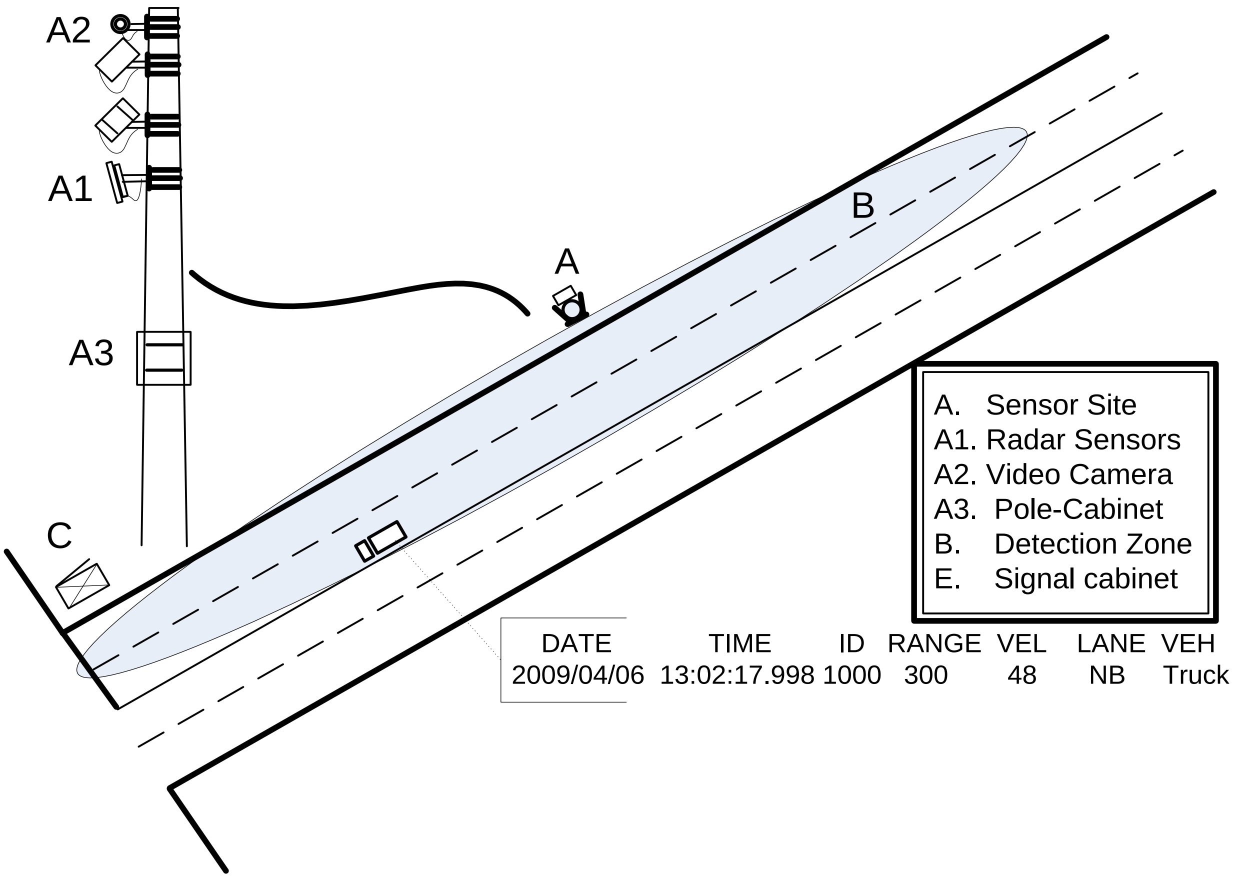


Figure 1 Lincoln data collection schematic

METHODOLOGY

Underlying theory of driver's decision

Driver behavior at the onset of yellow is essentially a binary choice process, where the driver chooses from two possible courses of action: stop or go (Sheffi and Mahmassani, 1981). Let YT_p be the yellow time perceived by a randomly chosen driver from the population. As a result of the variance in driver behavior based on several independent factors such as, perception of the distance from the stop bar, perception reaction time, perception of the yellow interval based on past experience etc., YT_p can be modeled as a normally distributed random variable, as shown below in Equation 1.

$$YT_p = YT_{req} + \xi \tag{1}$$

where:

YT_{req}: is the required yellow time to safely enter the intersection based on the vehicle's onset distance and speed

ξ : is a random variable is assumed to be normally distributed.

Similar analyses have been performed using perceived and required time to stop bar and perceived and required acceleration (Sheffi and Mahmassani, 1981; Sharma et al., 2010).

If the perceived yellow time, YT_p, is greater than the required time necessary to pass through the intersection, drivers will decide to stop, otherwise they decide to go. The perceived yellow time, converted into a distance as shown below in Figure 4, is equal to the probability of stopping value of 0.5. Two critical thresholds can be calculated for a driver approaching the intersection at the onset of yellow: distance requiring severe deceleration by the driver and the distance at which a driver would accelerate heavily or run the red light. The following calculations were performed as examples of the acceleration and deceleration threshold based off of 85th percentile acceleration and deceleration values from Sharma (2008). The distance for which a vehicle cannot proceed through the intersection without heavily accelerating or RLR is calculated as shown below:

$$Distance_{Accel} = speed \cdot yellow + \frac{1}{2}a(yellow - PRT)^2 \tag{2}$$

where:
speed: speed of the vehicle at the onset of yellow (ft/s)
yellow: is the length of yellow (s)
a: is the 85th percentile acceleration, 3.19 ft/s^2 (Sharma, 2008)
PRT: perception reaction time of 1 s

For a speed of 80.667 ft/s (55 mph) and a yellow length of 4.9s, the critical acceleration distance equals 420 ft. This distance will be referred to as the maximum passing distance throughout the remainder of this paper and represent the critical acceleration threshold. A vehicle at the onset of yellow upstream of this fixed distance choosing to proceed through the intersection will require heavy acceleration or will run the red light. Similarly, a fixed distance can be calculated where a vehicle will be require to decelerate heavily, as shown in Equation 3.

$$Distance_{decel} = \frac{Speed^2}{2 \cdot d} + speed \cdot PRT \tag{3}$$

where:
d: is the 85th percentile deceleration, 14.41 ft/s^2 (Sharma, 2008)

Again using 80.667 ft/s (55 mph) and a 4.9s yellow interval, the severe deceleration distance is computed to be 306 ft. A similar recommended severe deceleration rate of 14.76 ft/s^2 can be found in Malkhamah et al. (2005). A vehicle downstream of this distance choosing to stop will be required to decelerate heavily to stop prior to the stop bar. The two critical threshold distances previously calculated are shown in Figure 2.

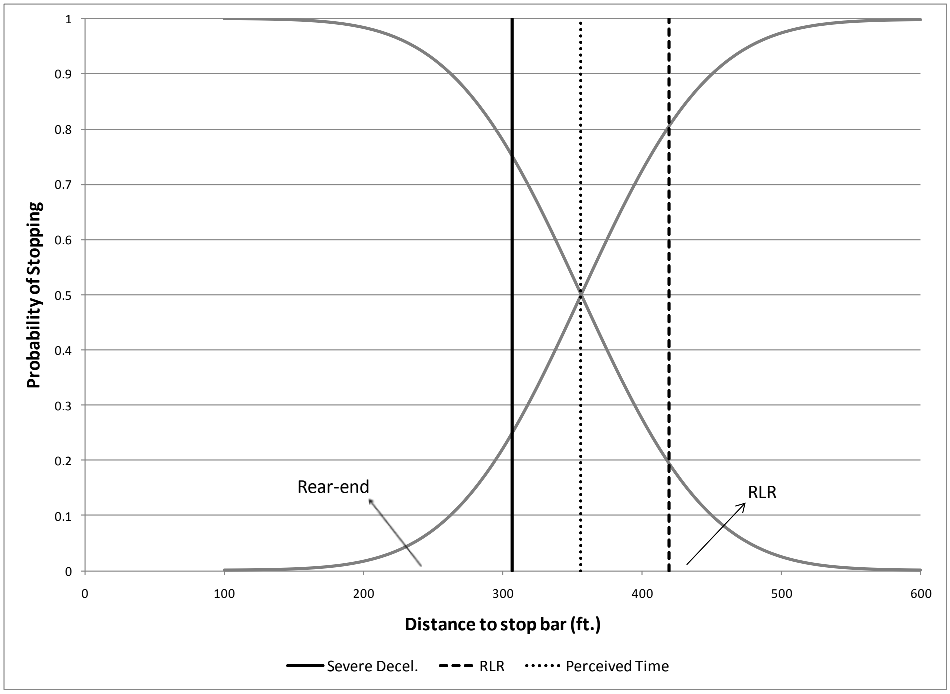


Figure 2 Critical distances along probability of stopping curve

Traffic conflicts

Drivers choosing to stop downstream of the severe deceleration distance and choosing to proceed upstream of the maximum passing distance have made an erroneous decision. The consequences of a driver making an erroneous decision at the onset of yellow can lead to a conflict and in the previously mentioned cases a severe conflict. The probability of perceived conflict can be calculated using the critical thresholds and stopping probabilities as shown below in Equation 4.

$$P_{CONFLICT} = \begin{cases} P_{STOP} & \forall D_{req} < D_t \\ P_{Go} = 1 - P_{STOP} & \forall D_{req} > D_t \end{cases} \qquad (4)$$

where:

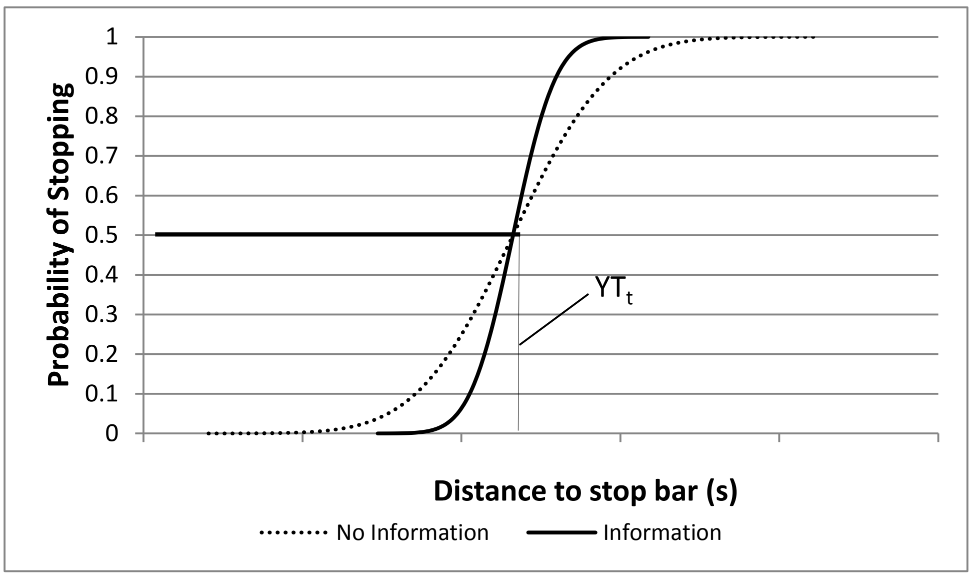
D_{req}: Required distance to perform chosen decision

D_t: critical distance threshold depended on yellow time

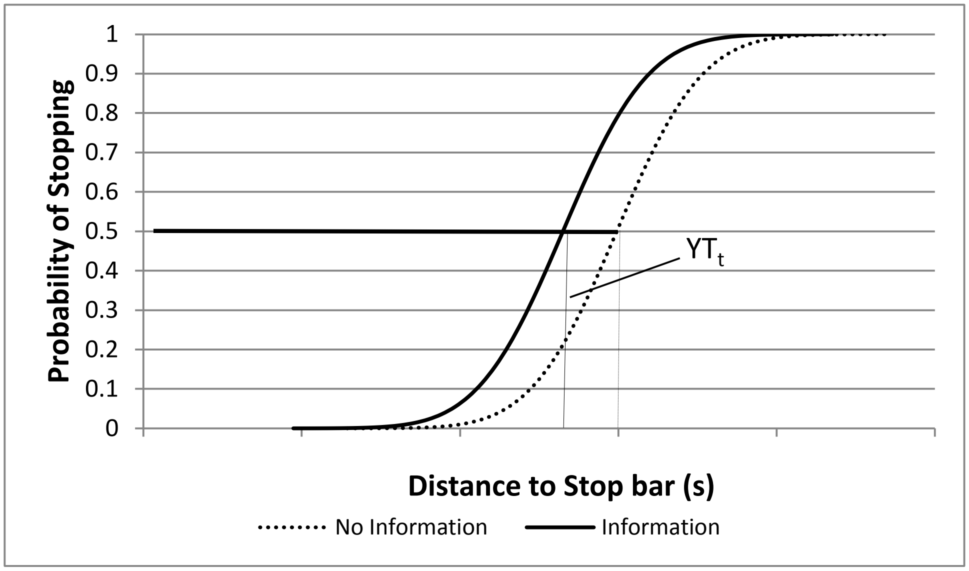
Perceived conflicts can be classified into minor and severe based on the magnitude of the acceleration or deceleration required to perform the chosen decision and the typical ranges of acceleration or deceleration used by drivers. The required acceleration or deceleration to complete the chosen action therefore can be used to determine the severity of the evasive action needed. If the required acceleration or deceleration is within the typical operating ranges, a minor traffic conflict would occur; but if the required acceleration or deceleration is greater than the thresholds of the typical ranges, a severe traffic conflict would occur. Drivers in the zone of a minor conflict are likely to have minor traffic conflicts such as an abrupt stop, applying the brakes before proceeding, or acceleration through yellow. However, the drivers in the zone of severe conflict will have severe traffic conflicts such as running a red light, swerving to avoid a collision, or vehicle skidding. For this paper, only severe conflicts were calculated.

Effect of Information

Providing drivers with information through AWFs has shown to alter the probability of stopping curves (Koll et al., 2004). Consider, the potential effect of information at an intersection on the standard error (indecision at the onset of yellow), as shown in Figure a. It can be seen that by providing information the probability of stopping curves becomes steeper due to a reduction in variability. Ideally, the slope of the probability of stopping curve would be infinity meaning every driver is making the correct decision at the onset of yellow. However, if information shifts the midpoint, the entire probability of stopping curve is shift, as shown in Figure 3b. The probability of stopping curve could be shifted closer or further away from the intersection. Recalling that probability of conflict is dependent upon probability of stopping and the two critical thresholds are fixed results in a shift in the probability of conflict curve. If the probability of stopping curve were shift closer to the intersection the probability of severe deceleration would increase. Conversely, a shift in the probability of stopping curve further away from the intersection would result in an increase in RLRs. This paper examines the effects of information on the potential shift in the midpoint as well as on the change in slope on the probability stopping curves.



a) Effect on probability of stopping



b) Effect on probability of stopping

Figure 3 Effect of information provided to drivers

DATA ANALYSIS AND RESULTS

Best Fit Model Parameters

At the onset of yellow, a driver can choose from two mutually exclusive courses of action: stop or go. The decision process thus can be modeled by binary discrete choice models. Based on the approach followed by Sheffi and Mahmassani (1981), a probit model was used to investigate the influential independent variables for driver decision at each intersection.

The independent variables tested are listed below:

- Time to stop bar
- Distance to stop bar
- Speed at onset of yellow
- Deceleration required to stop the vehicle within the stop bar
- Acceleration required by the vehicle to cross the stop bar prior to onset of red

An extensive analysis was performed, on the five variables listed previously to determine the set of instrumental variables that affect a driver's choice. Maximum likelihood estimation technique was used to obtain estimates of the parameters using NLOGIT (2007). Models were compared using Akaike's Information Criterion (AIC) (AIC, 2009). AIC takes into account both the statistical goodness of fit and the number of parameters required to obtain that goodness of fit. As the number of model parameters increase, a penalty is imposed on the model. The best or preferred model is the model that has the lowest AIC value. Results of the analysis showed the best performing model was time to stop bar and a constant, as shown in Table 3.

Table 2 Probit model results

	AIC Value	Log likelihood function
Site 1	0.43284	-32.62681
Site 2	0.51298	-110.0872
Site 3	0.44859	-35.23322
Site 4	0.42807	-28.82094
Site 5	0.52098	-62.34153
Site 6	0.28287	-386.5199

Dilemma zone boundaries and effect on stopping

The final estimated parameters were used to develop probability of stopping curves for a speed of 55 mph at each site, as shown below in Figure 3. The probability of stopping curves reveals the effect of information provided to the drivers from the AWFs. The three Nebraska Department of Roads sites (Site 1, Site 3, and Site 4) and Site 6 are relatively close, with Site 1 and Site 4 having essentially identically curves. As shown previously in Table 1, Site 1 and SITE 4 operate the same with the flashers starting 7 seconds before yellow and a yellow time of 4.4 seconds. Site 6 the only site without AWFs, has the furthest probability of stopping and largest dilemma zone. Information provided to the drivers at the Site 2 causes a drastic shift in the probability of stopping. Under the authority of the City of Lincoln, the Site 2 site is operated differently than the NDOR sites. The main distinctions of the Site 2 site from the NDOR sites are: the AWFs are 87 ft. closer to the stop bar than at the 3 NDOR sites and the sum of the yellow time and time before yellow the advance warning flashers come on is 0.7 seconds larger than at Site 3 and 2.2 seconds longer than at Site 1 and SITE 4. It appears, as illustrated in Figure 4 that the longer drivers are presented with information (yellow time and time before yellow AWFs come on) their probability of stopping earlier increases. Site 2 and Site 3 present information to drivers the longest, while Site 6 does not present drivers with information prior to the onset of yellow.

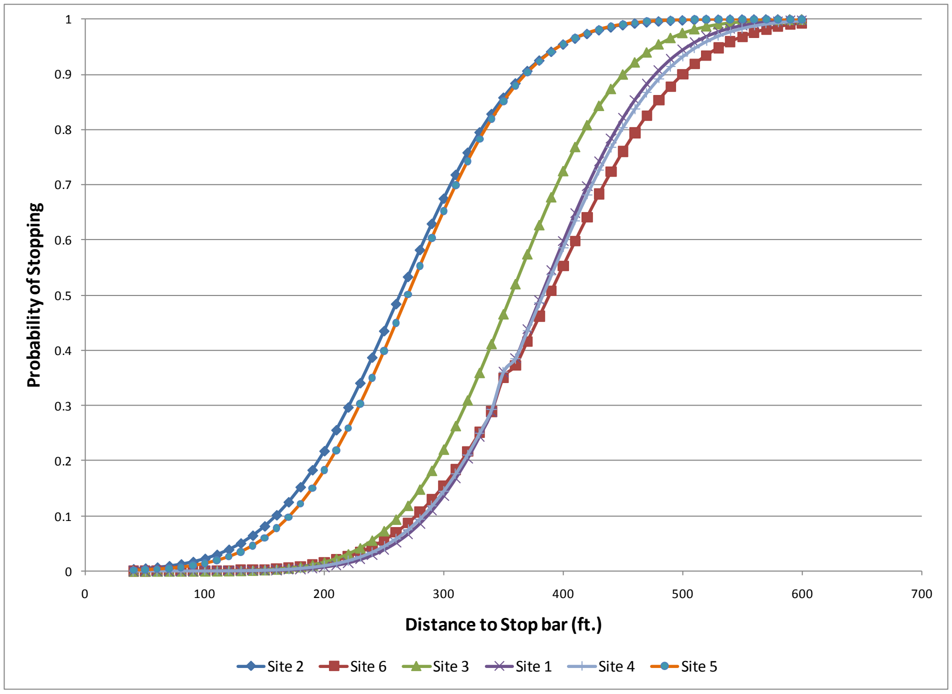


Figure 4 Probability of stopping curves

Test for transferability of model between sites

The log-likelihood ratio test was used to test the transferability of models, with Site 1 being the base model tested against. The transferability of Site 1 versus Site 4 was not tested, since the models were nearly identical. The null hypothesis tested was:

> Hypothesis: model parameters estimated from the Site 1 data and model parameters estimated from the other sites are equal.

Rejection of the hypothesis will signify that model parameters between Site 1 and the tested site are significantly different. Equation 1 was used to determine the transferability between the models:

$$X^2 = -2[LL(\beta_T) - LL(\beta_a) - LL(\beta_b)] \tag{1}$$

where:

$LL(\beta_T)$: log likelihood at convergence of the model estimated with data from both regions

$LL(\beta_a)$: log likelihood at convergence of the model using region a (Site 1)

$LL(\beta_b)$: log likelihood at convergence of the model using region b (Other sites tested)

The X^2 statistic is chi square (χ^2) distributed with degrees of freedom equal to the summation of the number of estimated parameters in both models minus the number of estimated parameters in the overall model. Results of the four transferability tests revealed a statistical significant between Site 1 and Site 2, as well as Site 1 and Site 5.

Figure 5 illustrates the dilemma zone hazard curve at Site 4. The severe deceleration and maximum passing distance are the critical thresholds for the severe conflicts. The risk of conflict increases until reaching the maximum passing distance. Figure 5 also illustrates a large percentage of drivers predicted to make erroneous decisions at the onset of yellow based on the severe deceleration and maximum passing thresholds. In particular, a sizeable percentage of drivers are predicted to either accelerate heavily or run the red light; thus, potentially causing a right angle collision.

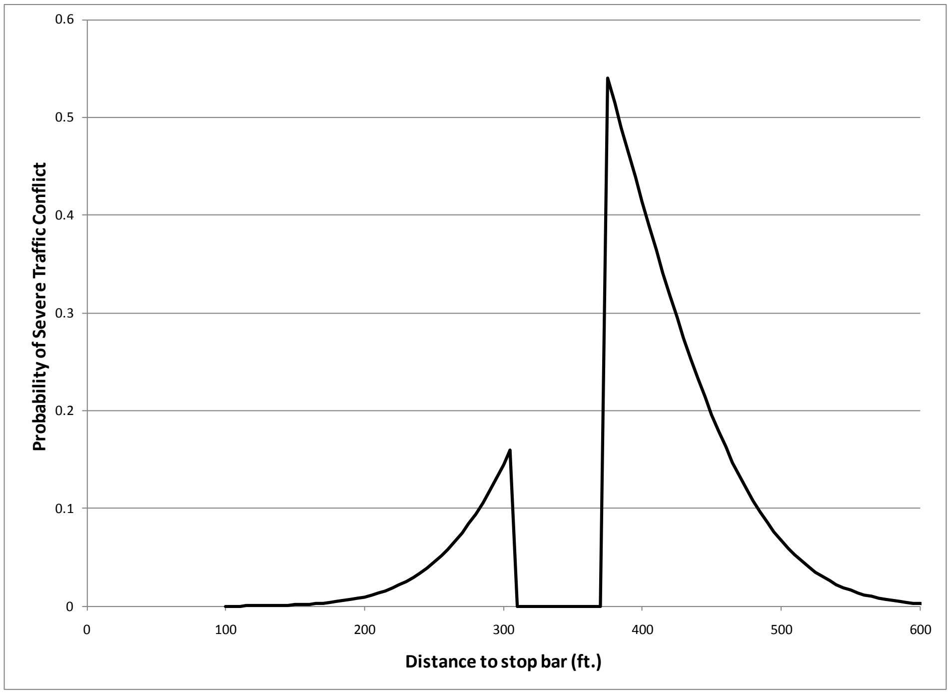


Figure 5 Probability of perceived traffic conflict at Site 4

As shown below in Figure 6, the drastic shift in probability of stopping at Site 2 causes virtually every driver approaching the intersection to potentially have a severe conflict. Based on the yellow time of 5.6 seconds and posted speed limit (55 mph), a driver traveling at the speed limit could pass through the intersection from a distance of 485 feet at the onset of yellow. While the length in yellow is significantly decreasing the possibility of a red light runner the information provided to the driver from the AWFs is telling them otherwise, resulting in significantly large predicted perceived severe conflicts, such as, abrupt stop, heavy deceleration, or vehicle skidding. The risk associated with these conflicts may lead to a severe rear-end crash. Evidence that longer yellows decrease the percentage of RLRs is also found in (Bonneson et al, 2002), while similar to Koll et al. (2004), providing drivers with information leading to early stops can increase the possibility of severe rear-end collisions.

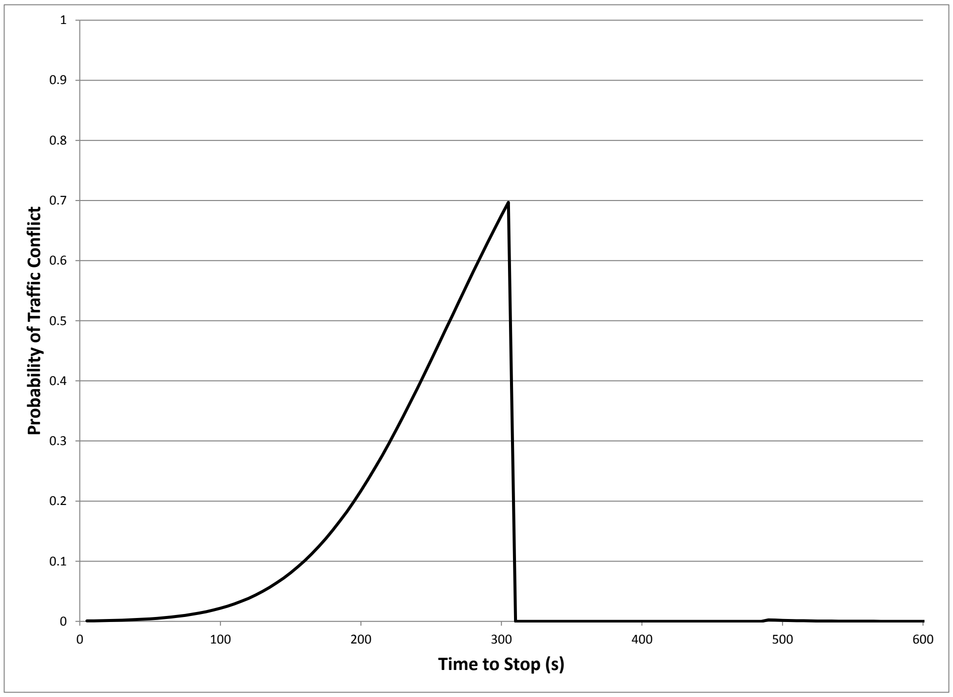


Figure 6 Probability of perceived traffic conflict at Site 2

As shown in Figure 7, if information is provided correctly, it can decrease the risk to drivers approaching the intersection. The predicted severe risk of crash at Site 3 site is significantly lower than the other studied sites.

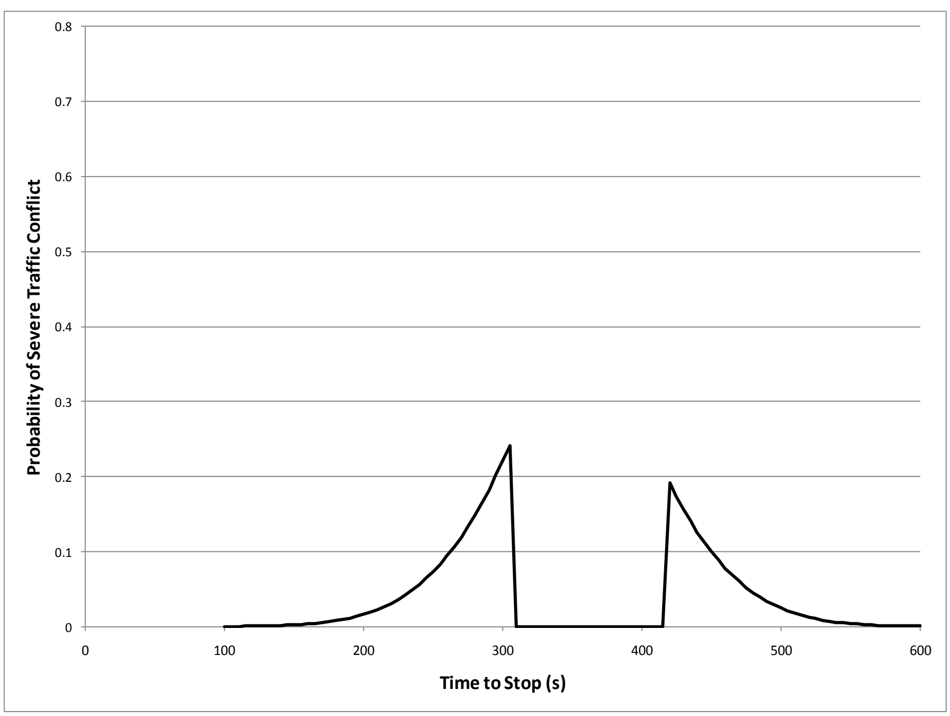


Figure 7 Probability of perceived traffic conflict at Site 3

The final estimated parameters of time to stop bar and the constant were used to develop probability of stopping curves for speeds of 35, 40, 45, 50, 55 and 60 mph at each site shown in Figure 4. Weighted risk was calculated by first integrating the area under both severe conflict thresholds. An average of the integration is computed. Lastly, the proportion of vehicles within each speed category is multiplied by the averaged integration resulting in a weighted average of risk for a driver approaching an intersection. The weighted average risk was found for both critical thresholds. Results of the risk analysis are shown in Figure 8. The effect of information is seen in that the sites seem to mitigate the probability of conflict for one of the two thresholds. As expected, Site 2 and Site 5 have the largest rear-end risk, while Site 1 and Site 4 have the largest risk of running the red light.

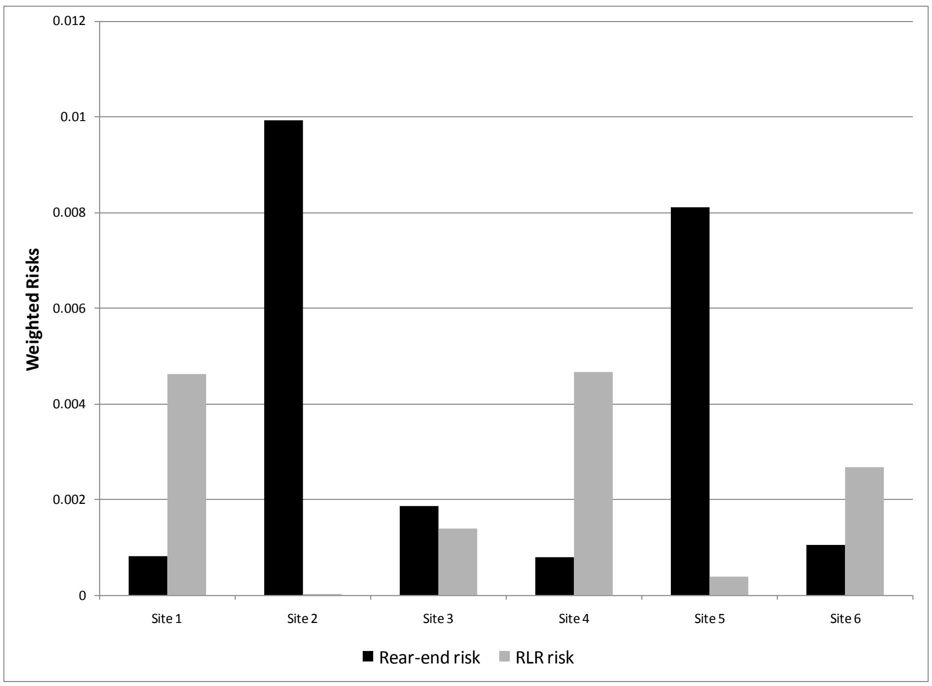


Figure 8 Calculated weighted risks

Actual severe conflicts were totaled and proportioned for each site vehicles requiring a deceleration rate of 14.41 ft/s^2 or higher and the observed RLRs. The results can be seen in Table 3, which also reports the calculated theoretical conflicts. Similar to the weighted risks, a tradeoff was found between the proportion of vehicles requiring severe deceleration and running the red light, shown in Figure 9. The proportions of risks and conflicts at Sites 1, 2, 4, and 5 were almost in complete agreement between the calculated risks and accident histories. The calculated risk and proportion of severe conflicts have a good correlation; however, at Site 3 the proportions have switched.

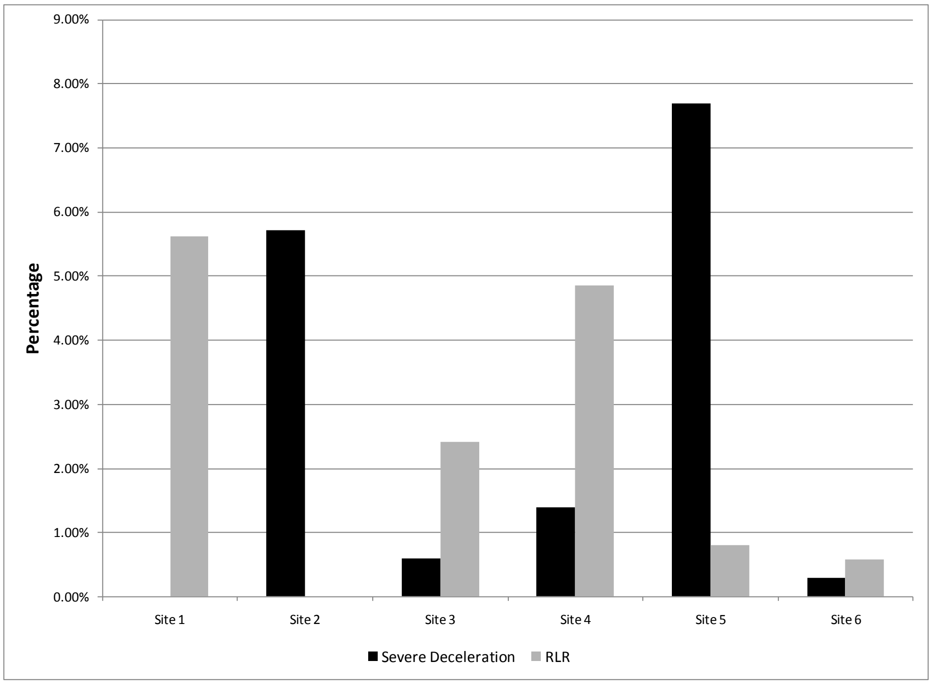


Figure 9 Proportion of vehicles performing severe deceleration or RLR

Effects of information on driving behavior

Figures 4 and 5 display the large percentage of drivers at risk of a severe conflict. Having such large percentages of drivers at risk to severe conflicts is problematic. Figure 10 illustrates the probability of stopping under four different conditions. Curves A and D represent intersections where the majority of drivers are performing erroneous decisions. Similar to the results from Site 2, drivers approaching the intersection represented by Curve A have virtually every driver at risk to a severe stopping conflict. Curve D has a significantly large percentage predicted to heavily accelerate or run the red light. The stopping curve represented by Curve C is noticeably better in providing drivers with protection from severe conflicts, as the majority of drivers are stopping between the severe deceleration and maximum passing distances. Ideally, the probability of stopping curve would appear as shown by Curve B, where the decision dilemma zone boundaries are within the thresholds of severe deceleration and maximum passing distance, thus minimizing the risk of severe conflicts at the onset of yellow.

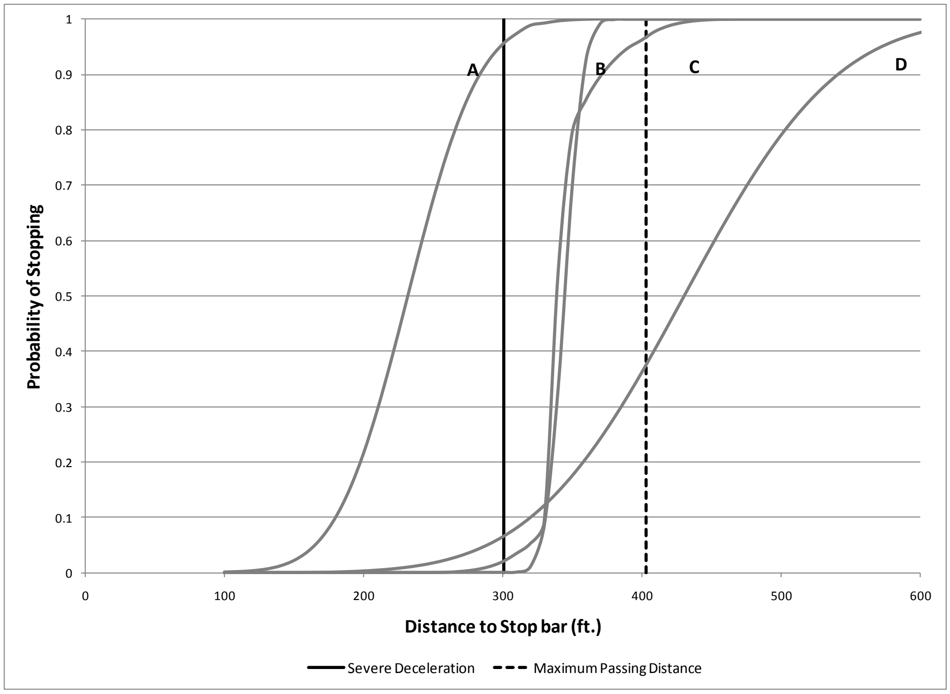


Figure 10 Ideal Probability of Stopping Curve

Finally, in comparison with previous literature (Koll et al., 2004; Elmitiny et al., 2009; Wei et al., 2009; Hurwitz, 2009) the calculated perceived yellow time length versus actual length was plotted, as shown in Figure 11. Intersections with AWFs or in the case of Koll et al. (2004) flashing green were plotted separately from intersections not providing drivers information. Four intersections were graphed from (Hurwitz, 2009); however, the perceived time and actual yellow lengths for all four intersections were four seconds. Intersections with AWFs, or, in the case of Koll et al. (2004) flashing green, were plotted separately from intersections not providing drivers' information. Based on this sample of intersections, drivers approaching intersections without being provided information correctly perceived the time threshold, while drivers inaccurately predicted the time threshold at intersections providing them information. The largest outliers from Figure 11 are points A, B, and C, which represent Site 2, Site 5, and Koll's studied sites in Austria. In addition, Figure 11 displays what type of risk is associated with being above or below the line. The three previously mentioned sites have the potential for increases rear-end risk, as these intersections all fall below the line. Conversely, any intersection above the line would have the potential for increased RLR risk. Therefore, while providing drivers with information has shown to reduce accidents and in particular RLRs (Messer et al., 2003; Gibby et al., 1992; Farraher et al., 1999), this study suggests providing information to drivers can increase their risks. In particular, the risk of stopping conflicts increases with information.

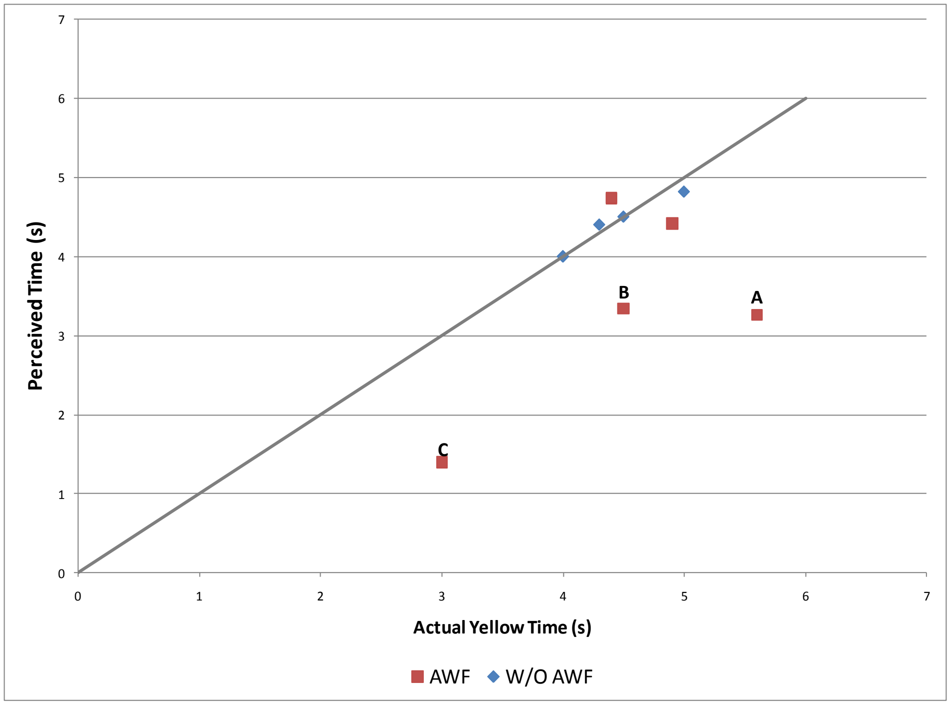


Figure 11 Comparison between actual and perceived yellow lengths

CONCLUSIONS

The effect of information was shown on both probability of stopping curves and the resulting probability of perceived conflicts. Results from Sites 2 and 5 found a shift in the probability of stopping closer to the intersection resulting in an increase in rear-end risk, while a large probability of RLR at Site 4. Site 3 site had the shortest dilemma zone, lowest predicted severe conflict risk, as well as the curve most consist with an ideal probability of stopping curve. The reason the Site 3 site performs significantly better than the other sites was not determined by the authors in this current study. The site is operated similarly to the other studied sites, yet performs better. These results contributed to increases in both rear-end and RLR risk by providing information to drivers. The effect of information on rear-end and RLR risk was shown to have an inverse relationship. As the rear-end risk increased, the RLR risk decreased as vice versa. A reasonable correlation was found between the rear-end and RLR risk and the accident histories at each site similar to previous findings on the correlation between conflicts and crashes. It is evident that providing drivers with information in advance of the intersection using AWFs can potentially cause increased risk in both RLRs and stopping as opposed to decreasing the risk of drivers approaching the intersection. Thus, caution should be used by engineers before providing drivers with information at a high speed intersection.

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