Title: Recasting Dilemma Zone Design as a Marginal Costs-Benefits Problem.

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ABSTRACT

One control objective at high speed isolated intersections is to provide safe phase transition by trying to minimize the occurrence of high speed vehicles in the dilemma zone, before terminating the phase. An upper limit for extending green (maximum green time) is used to avoid an indefinite extension of the main street green. Currently, the maximum green times are chosen using engineering judgment. This approach does not explicitly consider the trade-offs between safety and delay and hence often results in both unsafe and inefficient performance at the intersection under medium to heavy traffic volumes. This paper recasts the dilemma problem as one of minimizing vehicles entering the upstream decision conflict zone (DCZ). An economic evaluation approach is proposed to maximize both safety and efficiency at the intersection by considering the problem in the terms of marginal costs and benefits. Traffic conflicts are used to estimate potential safety benefits and the induced delay cost is used to estimate the cost accrued on side street traffic that is associated with extending a competing phase. This approach allows the implementation of logic that minimizes DCZ exposure instead of the current approach of absolute protection up until maximum green time is reach, at which time no consideration is given to dilemma zone exposure when the phase is terminated. This approach handles efficiently and safely the periods of moderate demand volumes when current dilemma zone protection frequently encounters maximum green time exposure.

INTRODUCTION

The National safety council *(1)* reported motor vehicle crashes as the leading cause of unintentional injury deaths in United States for the year 2003. A death is caused by a motor vehicle crash every 12 minutes and a disabling injury occurs every 13 seconds. The cost of motor vehicle collisions in 2005 through April totaled nearly $70.8 billion *(2)*. Intersection crashes constitute a 30% of all the vehicle crashes *(3)*; they account for an average of 9,000 fatalities and 1.5 million injuries annually. Red light running (RLR) is a major cause of fatal and injury-related crashes. Also, motorists are more likely to be injured in such crashes. A survey conducted by the U.S. Department of Transportation and the American Trauma Society indicates that 63 percent of Americans witness a RLR incident more than once a week and one in three Americans knows someone who has been injured or killed because of a red-light violation.

Green extension systems are deployed at rural high speed signalized intersections to reduce the number of red light violations and rear end crashes. A primary objective of these systems is to minimize the occurrence of high speed vehicles in a dilemma zone. The green phase of the high speed approach is typically extended until there is no vehicle in the dilemma zone. An upper threshold, maximum green time, is provided for this operation to avoid excessive delays to the cross street traffic. Engineering judgment is used to determine the value of maximum green time. This approach is an all-or-nothing approach. High speed vehicles are provided complete protection against dilemma zone incursions before the maximum green is reached. However, if the maximum green is reached, the protection is completely withdrawn. Consequently, there exist no intermediate levels of protection; the signal logic either provides a 100 percent protection against dilemma zone in case of gap out or the protection drops to 0 percent in case of max out.

A new approach is proposed in this paper which explicitly considers the marginal safety benefits and delay costs to maximize the safety and efficiency of a signalized intersection.

BACKGROUND

Typically, the total number of vehicles in the dilemma zone is used as the surrogate measure for safety at rural high speed intersections. The following section provides a detailed description about the dilemma zone and its boundaries.

Defining Dilemma zone

Researchers typically characterize the decision dilemma zone as that approach area within which the probability of deciding to stop on the display of yellow is within the range of 10 to 90 percent *(4,5,6,7)*. On the onset of yellow, a high speed vehicle is confronted by decision to stop or go. The dilemma zone is typically defined as the region where more than 10 percent but less than 90 percent of the drivers decide to stop. This zone is considered to have a higher risk for rear end collisions and red light violations as the driver is not sure whether to proceed through the intersection or to attempt to stop. Figure 1 shows a hypothetical case where two vehicles are caught in the dilemma zone on the onset of yellow. If vehicle 2 decides to stop and vehicle 3 decides to proceed through the intersection, there will be an increased

probability of a rear end crash. Similarly, if a vehicle is caught in dilemma zone and incorrectly decides to cross the intersection, it can cause a red light violation.

There have been several attempts to define the dilemma zone boundaries relative to the intersection stop line (4,6,7,8,9,10,11,12). Tables 1a and 1b list some of the common dilemma zone boundaries reported by researchers. There are slight variations in the defined boundaries. This is due to the variations in the definition of dilemma zone, type of drivers, and geometric and environmental characteristics of the investigation sites.

Time can also be used instead of distance as a measure for decision dilemma zone boundaries. Based on limits given by Zeeger *(8)* and Parsonson *(4)* it can be calculated that around 90 percent of traffic stops if the passage time to stop line is 4.5 to 5 seconds or greater and only 10 percent of traffic stops if the passage time to the stop line is less than 2-2.5 seconds. Bonneson et al.*(12)* indicate that the beginning of dilemma zone is 5.0-6.0 seconds upstream and the end is about 3.0 seconds upstream.

Figure 1b to Figure 1d contrasts the present approaches with the proposed approach for the safe passage of vehicles on high speed approaches. Widely used green extension systems are all or nothing approaches. All the vehicles on the high speed approaches are cleared till the maximum green time is reached. At the end of maximum green time none of the vehicle on high speed approach is provided any protection. As shown in Figure 1b these systems do not have any metric to measure the cost of safety. The green termination systems use the number of vehicle in the dilemma zone as a surrogate measure for measuring the cost of safety. The number of vehicles is a rank ordered metric (shown in Figure 1c) where cost of one vehicle in dilemma zone is less than cost of two vehicles in dilemma zone but the cost is independent of position of vehicle in dilemma zone. Also, there has been lack of research to associate a monetary cost of safety for a dilemma zone incursion. The proposed approach proposes to use a hazard function as shown in Figure 1d to calculate the monetary cost of safety for a vehicle which is subjected to yellow indication. It is based on its location from the intersection and presence of other vehicles in the same lane.

A detailed description of vehicle detection systems is provided in the following section.

Vehicle Detection Systems

A vehicle detection system monitors a vehicle in its dilemma zone using detectors, with an objective to clear all the vehicles in their dilemma zone before changing to the next phase. Two kinds of vehicle detection systems exist: i) Green extension systems, and ii) Green termination systems.

Green extension systems are the most commonly implemented control algorithm at high speed intersections in the United States. The objective of this control mechanism is to improve the safety at the intersection by allowing the driver in the dilemma zone to proceed safely through before the phase transition. The operation of simultaneous gap out logic for green extension is illustrated using Figure 2. A hypothetical traffic signal is shown in Figure 2a. This intersection has high speed through movement running North-South. The advance detectors present on the high speed arterial mark the beginning of the dilemma zone. Both the advance detectors, on the north bound and south bound arterial, are connected in series. The northbound and southbound through phases are simultaneously extended for a pre-specified green extension time on detection of a vehicle. The green extension time is sufficient to carry

the detected vehicle through the dilemma zone. So, the green through phase for northbound and southbound movements is terminated when there is no vehicle present in the dilemma zone on either of the two approaches. Such a termination of the phase is called "gap-out". The through phase can also be terminated if traffic controller is unable to find a gap before the maximum green time has expired. Such a termination of green phase is called "max-out".

Figure 2b shows the actuation time diagram for the hypothetical traffic flow shown in Figure 2a. A green extension time of 3 seconds and maximum green time of 18 seconds are assumed. The signal is resting in green for the northbound and southbound through movements at time 0. At the arrival of first vehicle on the cross-street, the maximum green timer starts. The green phase for the through movement is extended for 3 seconds at t = 1 seconds by car *N-1*, and it is again extended by the arrival of car *S-1*. This process is continued until the last car *N-3* arrives at t = 16 seconds. The phase would have terminated as a "gap-out" at t = 19 seconds, but the maximum green time is set to be 18 seconds and hence the phase "max-out" occurs at t = 18 seconds leaving a vehicle in its dilemma zone.

This simple example illustrates a major drawback in the simultaneous gap out logic. If only the northbound traffic were present, the through phase would have gap-out at t = 4 seconds, and if only the southbound traffic were present, the phase would have gap-out at t = 12 seconds. The increase in the number of lanes decreases the probability of gap-out. This problem becomes worse when the high speed arterial carries a medium to heavy traffic volumes. The safety benefits are negated when the high speed through phase is arbitrarily terminated by max-out. A detailed analysis of this problem has been described by Sharma et al. *(13)*. It is shown that the implementation of the simultaneous gap out logic led to max-out ranging from 3.5 to 40 percent of cycles per hour during the peak traffic flow periods and around 200 dilemma zone incursions per day.

Though some advanced green extension systems (Texas Transportation Institute truck priority system *(14),* LHORVA *(15).*) exist, none to date explicitly consider the marginal trade-offs between safety and delay.

Unlike the green-extension systems described previously, green termination systems use a look-ahead window to determine the best time to end a phase. Examples of green termination systems are the intelligent detection-control system from Texas *(16)* and SOS from Sweden *(17)*. These systems try to identify an appropriate time to end the green phase by predicting the value of a performance function for the near future. This performance function is based on the number of vehicles present in the dilemma zone and the opposing queue. The cost of safety is calculated using the number of vehicles in their dilemma zone. These control systems are not widely used owing to the high technology cost.

Methodologies *(18,19)* have also been developed that dynamically vary the clearance intervals (yellow clearance and all red) to minimize dilemma zone incursions. However, they have not been widely implemented or tested.

TRAFFIC CONFLICT AS A SURROGATE MEASURE FOR SAFETY

The traffic conflict technique (TCT) was first proposed in 1967 by Perkins and Harris (20). They defined a conflict as: "The occurrence of evasive actions, such as braking or weaving, which are forced on the driver by an impending accident situation or a traffic violation." The conflicts were categorized as left-turn conflicts, weave conflicts, rear-end conflicts and cross-traffic conflicts.

This technique gained wide publicity as a surrogate for measuring traffic safety for two main reasons. First, traffic conflicts are more frequently observed than accidents, so a large amount of information about intersection safety can be collected quickly. Cooper et al. *(21)* reported that, on average, the ratio of rate of crash to rate of serious conflicts lies in the range of 1:2000, so that 10 hours of observation of conflicts at a site provides information equivalent to 2-3 years of reported accident records. Second, it provides an opportunity for traffic engineers to proactively improve the safety of a site instead of waiting for the accident history to evolve. Because of these advantages, the traffic conflict technique was used by several agencies to investigate accident potential and operational deficiencies of intersections. There were numerous research efforts to establish a direct relationship between accidents and conflicts *(22, 23)*. A review in 1980 by Glauz and Migletz *(24)* identified 33 previous studies that (at least partly) dealt with the conflict-accident relationships *(25,26,27,28,29)*.

Some concerns have been raised regarding TCT techniques *(30)* since the general approach used initially was to compare the observed crashes with the observed surrogate measure. Since both the conflict and accident are randomly distributed events it will be highly improbable to predict the exact number of accidents at a site. Glauz et al *(31)* proposed a new approach that compared the expected accident rate as predicted by conflict ratios to the expected accident rate as predicted by accident histories. This study concluded that an estimate of the expected accident rates can be computed from the data obtained from traffic conflict with nearly the same accuracy as predicted by the accident history.

Some recent studies *(21,32)* also advocate the use of traffic conflict as a surrogate measure for traffic safety in micro-simulation packages. Gettman and Head *(33)* provided a detailed use-case analysis for using traffic conflict as a surrogate measure for safety in a simulation package.

In summary, the literature review indicates a long history of development for the traffic conflict technique which suggests that it can be used effectively as a surrogate measure of traffic safety at intersections. Next, we describe our proposed methodology to use traffic conflict to estimate the safety benefits associated with decision conflict zone (DCZ) protection at high speed rural intersections.

PROPOSED MARGINAL COSTS-BENIFITS MODEL

The high speed intersection can be operated in an economically efficient manner using the following control logic:

1. A minimum green time is allotted to each phase for avoiding “short-green” dilemma. Parsonson *(34)* suggested this term for the scenario when the green is too short to violate driver’s expectancy. Minimum green time may also be governed by pedestrian safety issues.
2. Phases remain green beyond their minimum green as long as they are still discharging at or near saturation (unless the maximum green time is reached.) This is implemented using stop bar detectors *(35)*.
3. The high speed through phase is extended beyond the end of saturation discharge rate until the cost experienced by the opposing movements exceeds the estimated

safety benefits associated with extending the phase. This allows the problem to be cast as a marginal costs-benefits problem.

For implementing this logic, we must estimate the benifits associated with reducing dilemma zone incursions as well as the costs experienced by opposing movements.

Application of Decision Conflict Zone Concept

Currently, safety benefits are not explicitly calculated in any of the green extension systems. Green termination systems calculate the safety benefits by using the number of vehicles in dilemma zone.

A dilemma zone is defined using the probability of stopping as the measuring scale. Logically, traffic conflict seems to be a better indicator of the number of accidents on a specific site than the probability of stopping. Traffic conflicts has been tested in past to have a high correlation with the number of accidents occurring at the intersection. So, in this paper, a DCZ is used instead of dilemma zone. A DCZ zone is defined as the region where the driver mus make a decision regarding conflicting options of stopping or proceeding through. This region can be represented by a hazard function (Figure 3), where during heavier periods of traffic, one could seek to minimize the area under these functions—instead of trying to eliminate all conflicts. .

Safety Benefits

Green extension systems can be deployed to mitigate occurrence of vehicles in this zone. The boundaries of DCZ can be defined for a particular intersection by conducting field surveys. Here, we are only concerned with the traffic conflicts which can be affected by onset of yellow (or extension of green time). Zeeger *(6)* identified six conflicts that can be affected by green extension systems:

- Run red light: A red light violation can be defined as occurring when most of the vehicle is behind stop line on the onset of red.
- Abrupt stop: An abrupt stop occurs when a vehicle makes an unusually quick deceleration, particularly, within 100 ft of the stop bar. This conflict can be recognized by a noticeable “dipping” of the front end, and is an obvious last second decision.
- Swerve-to-avoid collision: This conflict is an erratic maneuver of the driver to swerve out of their lane to avoid hitting the vehicle that had stopped for the light in front of them.
- Vehicle skidded: This is a more severe case of abrupt halt. Vehicle skidding sound can be heard when wheels of the vehicle “lock-up” to stop during the yellow phase.
- Acceleration through yellow: This can be recognized by actually seeing or hearing a sudden acceleration.
- Brakes applied before passing through: This indicates the indecision of the driver before finally deciding to pass through the red phase. This conflict should be carefully considered as in some cases drivers brake to slow down their vehicles due to downgrades or heavy traffic.

In case, an observed conflict can be classified in more than one of the above described categories, it must be classified under the most severe group.

Modeling the Hazard Function for the DCZ

After surveying the intersection under investigation, the probability of occurrence of conflict given the location of vehicle on the onset of yellow (Pr(TC|Dist)) needs to be computed. This probability is defined as the total number of vehicles exposed to conflict divided by the total number of vehicles facing amber light at a given distance from the stop line. The probability distribution of conflicts at a given distance from the stop line will then be used as a hazard function to calculate benefits of safety. Figure 3 shows a hypothetical hazard function for a given site. It depicts a higher probability for two vehicles involved in the traffic conflict on the same approach as compared to only a single vehicle in the DCZ. This is because there are more types of conflict if more than one vehicle is present in the DCZ. For example, swerving to avoid collision can only occur when two vehicles are in their conflict zone.

The next step after developing the hazard function is to compute the benefits of preventing a particular conflict. There can be two approaches to calculate the cost of conflicts. The first is to do a survey of a representative set of drivers to obtain information on the cost they associate with each type of conflict. The second approach is to evaluate benefits by calculating the probability of accident given a particular type of conflict has occurred (Pr(Accident|Conflict)). The comprehensive cost of each accident can be then used to calculate the benefits of preventing a traffic conflict. This paper uses the latter approach for calculating the safety benefits for preventing vehicles from being in their DCZ at the onset of yellow.

Table 2 illustrates an example of calculating the benefits of preventing a single traffic conflict. For simplicity, a single probability value of a traffic conflict is used instead of hazard function. It conservatively assumes the highest value of probability of conflict throughout the DCZ. Columns 1 and 2 in Table 2 list the type of crashes and the comprehensive cost associated with them, respectively, as reported by the National Safety Council *(1)*. The weighted average cost of the accident is calculated using the current year ratios of the type of accidents. The estimated benefits of preventing traffic conflict are obtained as the product of the average accident cost and the probability of occurrence of a crash given a traffic conflict has occurred. For this example, the estimated benefit of preventing a single traffic conflict is $5.67. Multiplying the probability of the occurrence of a traffic conflict with the benefit of preventing it gives the benefits of preventing a single vehicle from entering a DCZ. For this example, it was estimated to be $0.45. These numbers can be different for different intersections and are used here only to illustrate the concept.

Cost of Delay Associated with Extension of Green Phase of the High Speed Approach

The cost of clearing a vehicle through its DCZ can be calculated using the amount of delay incurred by the queue formed on the stopped phases. Figure 4 illustrates the concept of increase in delay for extending a through green by a single vehicle extension (t_{ext}). The unshaded queue polygon in the Figure 4 is the delay experienced by the vehicles in opposing movement if the green were terminated without the green extension. The extra delay is

shown as the shaded area and this extra delay accrues to the side street if the through phase is extended by a time equal to t_{ext}. Equation (1) calculates the total area under the shaded region:

$$\Delta Delay = \frac{q_{opp}}{\left(1 - \frac{q_{opp}}{s_{opp}}\right)} \times r \times t_{ext} + \frac{q_{opp}}{2 \times \left(1 - \frac{q_{opp}}{s_{opp}}\right)} \times t_{ext}^2 \quad (1)$$

Where:

$\Delta Delay$ = Increase in the total delay for extending through green by a unit vehicle extension (veh-sec);

q_{opp} = Total volume in the opposing direction (veh/sec);

s_{opp} = Saturation flow rate for the opposing movements (veh/sec);

r = red time elapsed for the opposing movements (sec); and

t_{ext} = vehicle extension time.

The increase in the total system delay is multiplied by the cost of delay ($/veh/seconds) to obtain the cost of extending the high speed through phase by a unit vehicle extension.

Break-Even Concept

After calculating safety benefits and delay costs, the break-even points can be determined. A break-even point is the point in time when the cost of allowing *n* vehicles on *m* approaches from their DCZ equals the increase in the system delay cost associated with clearing them through. Equation (2) describes the constraint to be met at the break-even point:

$$\Delta Delay \times Cost(\$ / veh - \text{sec}) = \Pr(TC_{n,m}) \times Benefits(\$ / TC_{n,m}) \quad (2)$$

Where:

$\Delta Delay$ = Increase in system delay if the high speed through phase is extended;

$Cost(\$ / veh - \text{sec})$ = Cost of delay per unit vehicle seconds;

$\Pr(TC_{n,m})$ = Probability that *n* vehicles on *m* approaches have traffic conflicts if the green is not extended; and

$Benefits(\$ / TC_{n,m})$ = Benefits of preventing the traffic conflict.

From equation (1) and (2), we obtain break-even point as:

$$r_{n,m} = \frac{\left(1 - \frac{q_{opp}}{s_{opp}}\right)}{q_{opp} \times t_{ext}} \times \left(\frac{\Pr(TC_{n,m}) \times Benefits(\$/TC_{n,m})}{Cost(\$/veh-\sec)} - \frac{q_{opp}}{2 \times \left(1 - \frac{q_{opp}}{s_{opp}}\right)} \times t_{ext}^2 \right) \quad (3)$$

The value of $r_{n,m}$ then represents the break-even point for subjecting *n* vehicles on *m* approaches to their DCZ.

Figure 5 graphically illustrates the concept of economic evaluation of costs and benefits associated with the extension of green for the high speed through phase. Figure 5 plots the time from start of through green (seconds) for the high speed movement versus the associated value ($). The thick solid lines represent the estimated increase in the cost of system delay and the thinner solid lines represent the safety benefits. For example, for the specific case of opposing volume of 4000 vph, it can be seen that the marginal delay cost increases linearly with time. This marginal delay cost function intersects the safety benefits function for preventing one vehicle from its DCZ on a single approach at time $t_{1,4000}$. Hence, prior to this point the safety benefits of preventing a single vehicle from its DCZ is higher than the increase in system delay cost. Therefore, up to $t_{1,4000,}$ all vehicles are prevented from being subjected to their DCZ. Once the through green extends past $t_{1,4000}$, the safety benefits for saving a single vehicle become lower than the associated marginal delay cost. Beyond that point, if only one vehicle is being subjected to its DCZ the green phase should be terminated (gap-out).

Similarly, the marginal delay function intersects the safety benefits line for subjecting two vehicles on different approaches to their DCZs at time $t_{2,4000}$. Therefore, beyond this point the green phase should be terminated even if two vehicles are being subjected to their DCZ. Figure 5 also shows marginal delay cost function for the opposing volume of 3500 vph. The delay cost function at lower volume increases at lower rate. Therefore, the break-even points $t_{1,3500}$, $t_{2,3500}$, $t_{3,3500}$ are shifted towards the right of break-even points for an opposing volume of 4000vph. Not surprisingly, for a lower opposing volume, high speed through green should be extended for a longer duration before subjecting vehicles to their DCZ.

For an intersection having a set of advanced detector proposed logic can be implemented. Depending on the volume of the opposing movement break points can be computed for the specific site. Suppose the total volume of the opposing movements is 4000vph during a given time of day, full (100 percent) protection will be provided until $t_{1,4000}$ is reached. Beyond this point, controller will allow the phase to gap out even if there is one vehicle in its DCZ. Similarly, after $t_{2,4000}$ the green phase can be terminated if there exists two or less vehicles on different approaches in DCZ. So, the safety protection follows a step decent from 100 percent protection to 0 percent with points of reduction lying at every break-even point. A more refined logic can implemented if we can measure the queue lengths at the cross-streets and the speeds and position of the high speed through vehicles. Precise estimates of increment delays on the opposing traffic can be made for extending the main street green phases using the current queue profile. If the position of vehicles can be exactly determined, more precise estimate of safety cost can be obtained. The proposed technique can be implemented using

the prevalent detection system but the performance of the technique can be further enhanced by using technologically advanced detection systems.

As the through volume increases, the probability of finding a gap greater than vehicle extension time decreases, thereby decreasing the probability of realizing 100 percent safety benefits for all the high speed approaches. The important point is that as traffic volumes increase, the probability of finding concurrent gaps on all through lanes (in both directions) of a high speed approach becomes quite small.

DISCUSSION

The current green extension logic for dilemma zone protection uses an arbitrary all-or-nothing approach for signal operations. Full (100 percent) safety benefits are provided to the high speed vehicles when green phases gap out before the maximum green time is reached. In cases where the maximum green time value forces a phase termination, dilemma zone protection is completely ignored. The proposed approach proposes the use of a hazard function approach so that during periods of moderate and heavy traffic, the controller can seek to minimize DCZ exposure. This explicit reduction in dilemma zone boundaries is hypothesized to provide safer operation because some level of DCZ can be provided during periods when traditional all or nothing dilemma zone operation is overridden by maximum green time constraints. .

This DCZ methodology is formalized in an economic evaluation framework. This methodology uses traffic conflict technique for assessing safety benefits and estimates the marginal delay costs by using queue polygon technique. The technique evaluates the tradeoffs between safety and efficiency for the efficient and safe operation at high speed intersection. A further benefit of using an economic perspective is the transparency available to field practitioners in trading-off the costs and benefits.

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LIST OF TABLES AND FIGURES

TABLE 1 Dilemma Zone Boundaries

a) Beginning of Dilemma zone (probability of stopping = 0.9)

Speed (mph)	Distance of stop line, ft						
	Olson and Rothery (Ref:9)	**Webster and Ellson** (Ref:10)	**Parsonson** (Ref:5)	**Herman** (Ref:7)	**Zeeger** (Ref:8)	**Chang** (Ref:11)	**Bonneson** (Ref:12)
35	212*	170*	212*	218*	254	288	245
40	255	205	250	260	283	307	293
45	315*	252*	300	315*	325	326	343
50	375	300	350	370	350	345	396
55	-	370*	400*	-	384	364	452

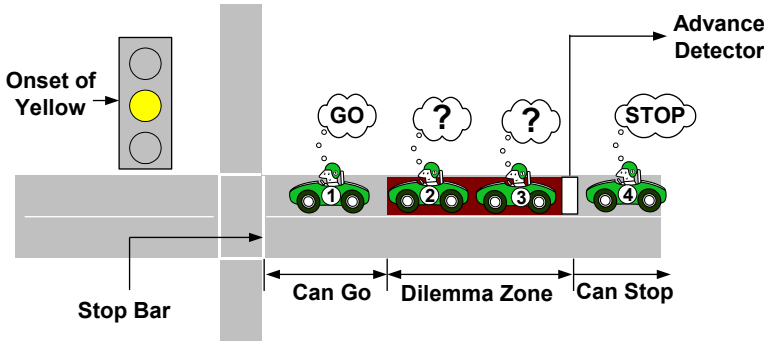
b) End of Dilemma zone (probability of stopping = 0.1)

Speed (mph)	Distance of stop line, ft						
	Olson and Rothery (Ref:9)	**Webster and Ellson** (Ref:10)	**Parsonson** (Ref:4)	**Herman** (Ref:7)	**Zeeger** (Ref:8)	**Chang** (Ref:11)	**Bonneson** (Ref:12)
35	103*	103*	105*	100*	103	128	145
40	110	125	110	110	121	147	178
45	165*	155*	165	165*	152	166	213
50	220	185	220	220	170	185	252
55	-	230*	240*	-	232	204	294

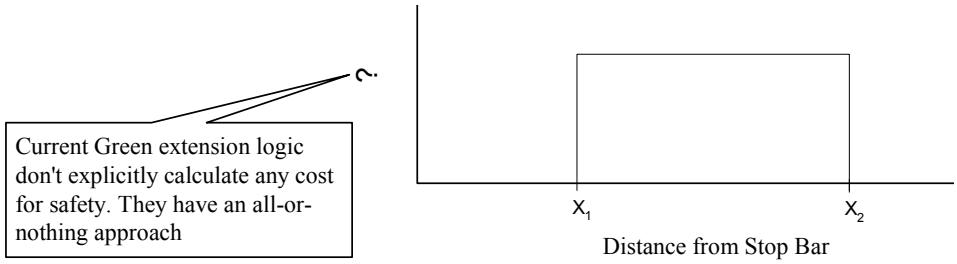
* interpolated values

TABLE 2 Estimation of Cost Associated with a Traffic Conflict

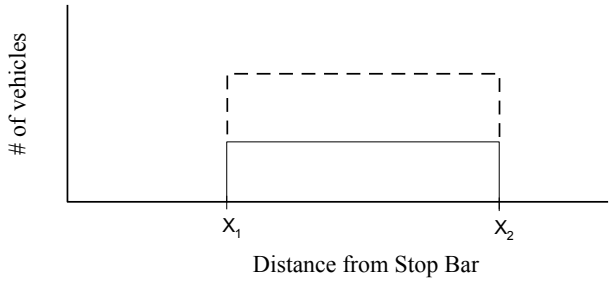
Type of Crash	**Comprehensive Cost, 2004 (Ref: 1)**	**Ratio of Each Type of Crash**	**Ratio * Cost**
Death	$ 3,760,000	1	$ 3,760,000
Incapacitating Injury	$ 188,000	100	$ 18,800,000
Non-incapacitating evident injury	$ 48,200	100	$ 4,820,000
Possible Injury	$ 22,900	100	$ 2,290,000
No Injury	$ 2,100	231	$ 484,615
Weighted average comprehensive cost per crash [*Cost($/Crash)*]			$ 56,706
Probability of getting involved in a crash given a traffic conflict [*Pr(Crash|TC)*] *(Ref:22)*			0.0001
Estimated benefits of preventing a traffic conflict [Benefits($/TC)= Cost($/Crash) X Pr(Crash|TC)]			$ 5.67
Probability of having a traffic conflict [Pr(TC)] (Ref:22)			0.08
Benefits of preventing one vehicle from its decision conflict zone *[Benefits($/incursion)=Pr(TC) X Benefits($/TC)]*			$ 0.45
Benefits of preventing two vehicles in their decision conflict zone			$ 0.91
Benefits of preventing three vehicles in their decision conflict zone			$ 1.81
Benefits of preventing four vehicles in their decision conflict zone			$ 3.63



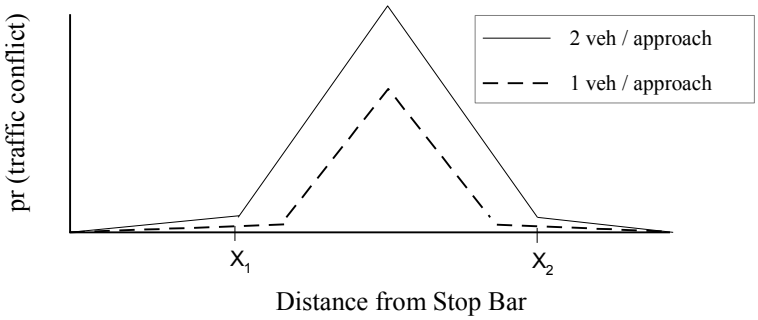
a) Illustration of dilemma zone.



b) Safety cost evaluation in current green extension systems.

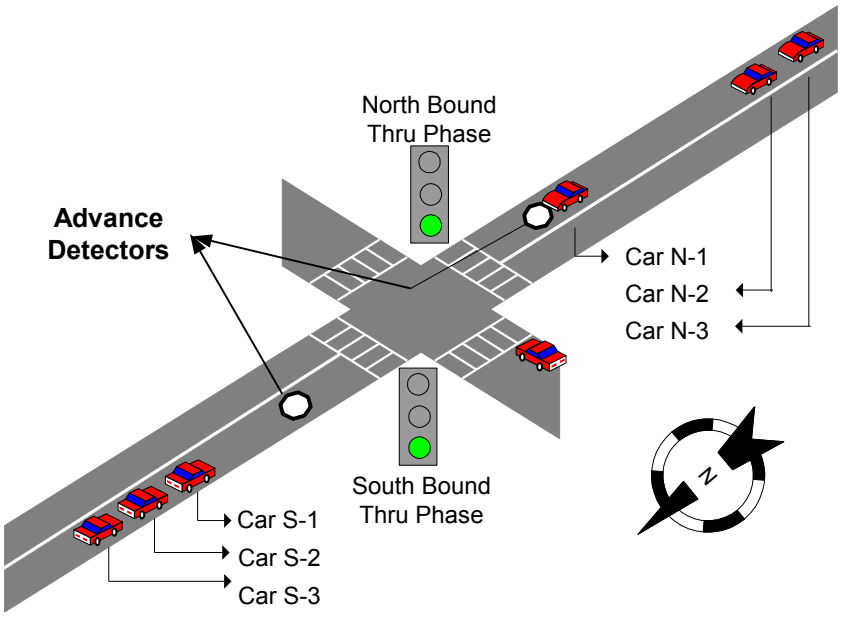


c) Safety cost evaluation in advanced green termination systems.

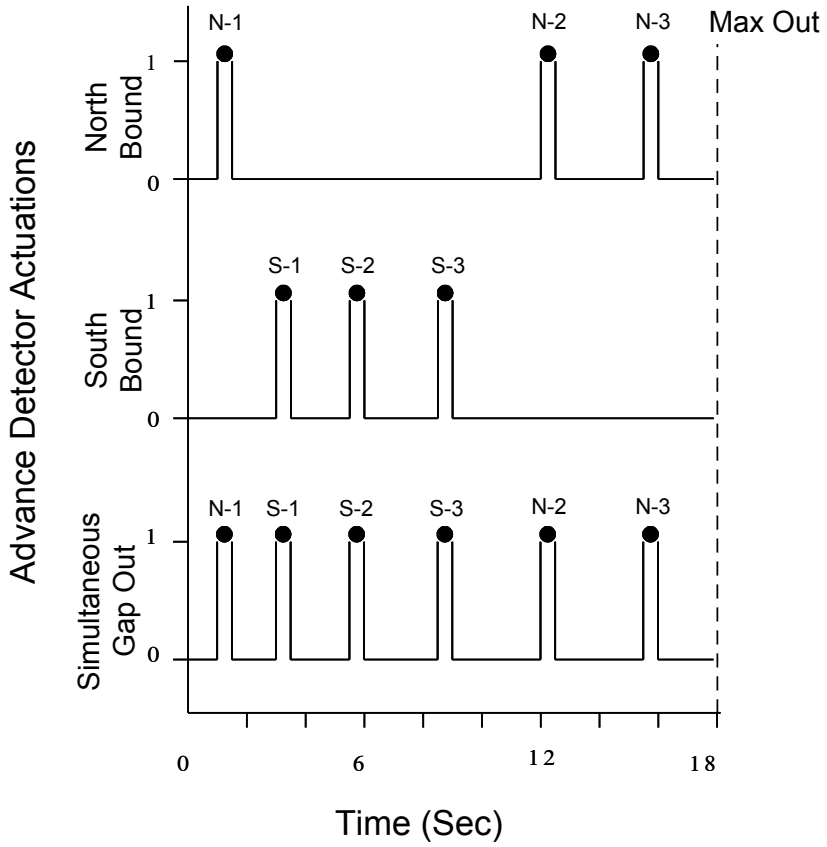


d) Proposed evaluation of safety cost.

FIGURE 1 Illustration of dilemma zone and safety cost evaluation.



a) Example intersection



b) Example detector inputs

FIGURE 2 Illustration of simultaneous gap out logic.

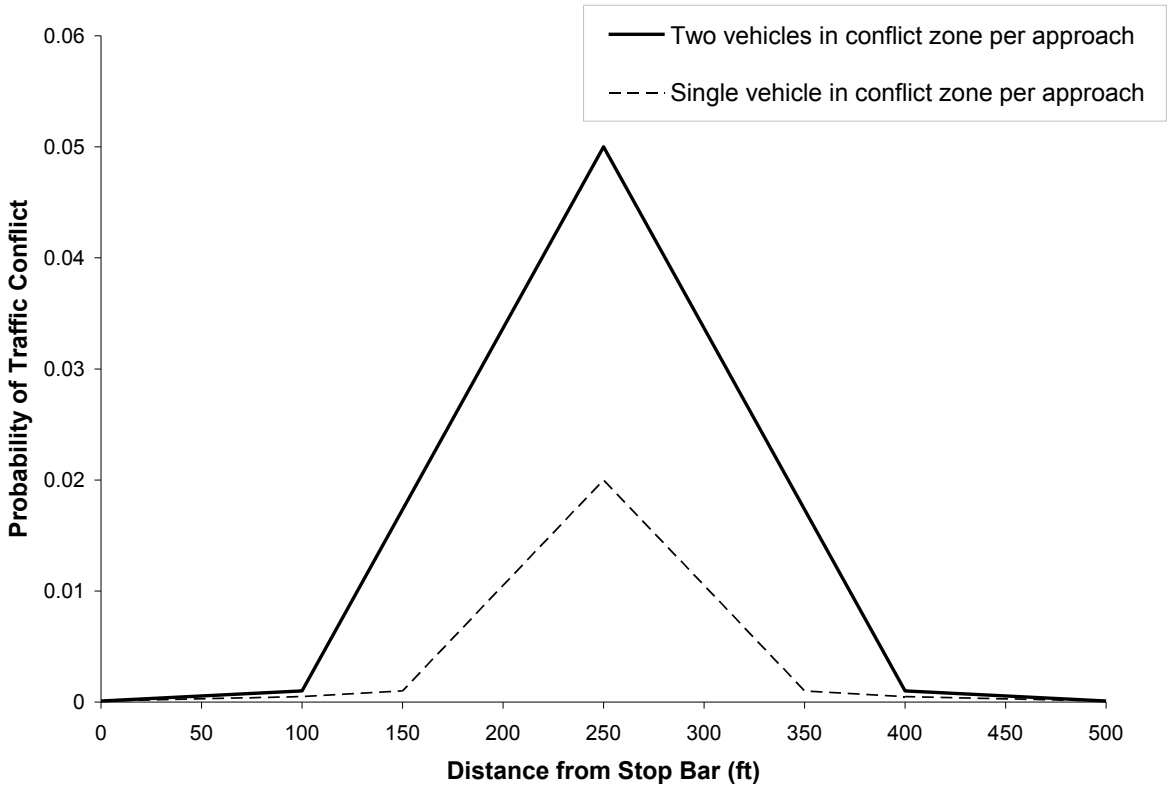


FIGURE 3 Hypothetical hazard function for an intersection.

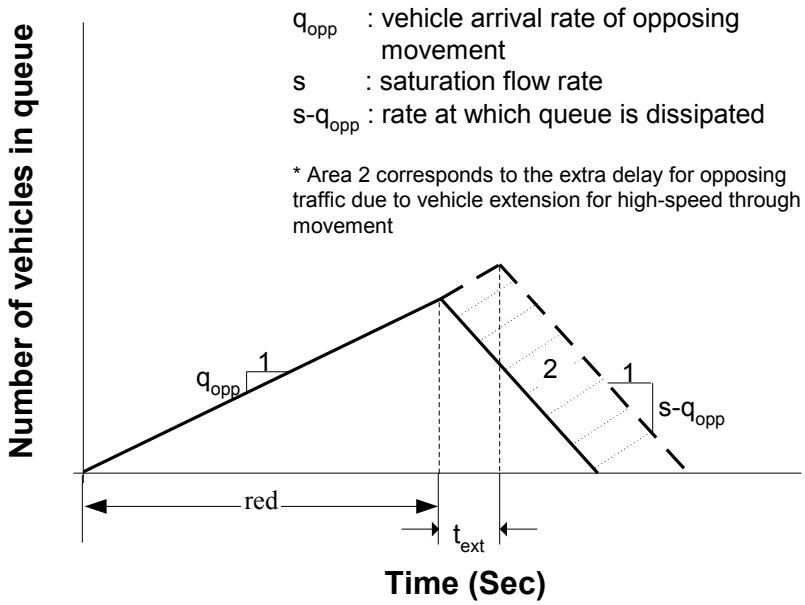


FIGURE 4 Increase in delay of the standing queue due to vehicle extension.

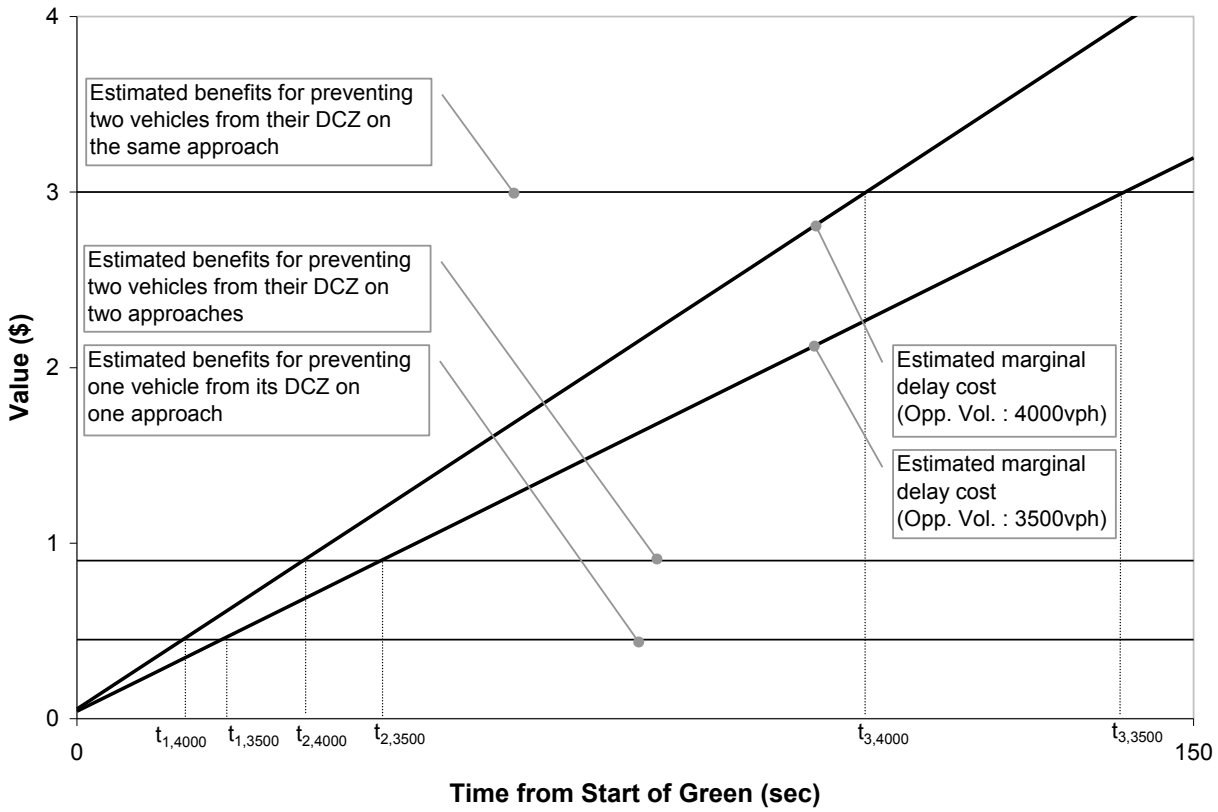


FIGURE 5 Marginal cost and benefit curves for dilemma zone incursions.