A PROBABILISTIC APPROACH TO CONTROL DILEMMA OCCURRENCE AT SIGNALIZED INTERSECTIONS

by

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ABSTRACT

This paper proposes a new probabilistic method of protecting drivers against Type-I dilemmas that may occur upon the display of a yellow traffic signal. At the onset of yellow, an approaching vehicle may be too close to stop but also too far away to pass the stop line before the end of yellow. The occurrence of this dilemma situation is affected by factors such as driver preference and perception-reaction time, which cannot be fully determined in real time. In this study, the dilemma likelihood function is derived and a method to identify the optimal green extension that minimizes this likelihood is proposed. A property of the likelihood function is noted and used to devise an efficient searching algorithm of the optimal green extension. In selecting an optimal extension time, the positions of all the vehicles on the approaches, the vehicle types, the speeds, and even the pavement conditions, can be considered. To evaluate the effectiveness of this method, numerical simulations are performed based on the collected field data. The method was found to reduce the frequency of Type-I dilemma occurrence significantly while the average green extension was quite short.

KEY WORDS: dilemma protection, actuated traffic signals, Type-I dilemma

WORDS COUNTS: 4,966 + 3 tables + 7 figures
INTRODUCTION

Two distinct traffic laws regulate a driver passing through a signalized intersection when arriving at an intersection right after a green signal turns yellow. The first traffic law (1) allows a vehicle to be present at and continue to clear the intersection during the red signal given that the vehicle enters the intersection during the yellow signal. In this case, the change period includes both the yellow interval and the so-called all-red interval. This case is often called the law of “permissive yellow.” The second traffic law indicates that a driver is expected to clear the intersection before the yellow signal turns red (2). In this case, the entire change period is filled with a yellow signal. The first case traffic law has become prevailing (3) and it will be considered in this study.

Two types of dilemma situations associated with the termination of the green were identified in a FHWA report in 1977 (4). The first situation, named Type-I Dilemma, was described by Gazis, Herman, and Maradudin (GHM) in 1960 (5). They pointed out that drivers approaching a signalized intersection may face a situation where obeying a red signal may be difficult if not impossible. At the beginning of a yellow signal, the driver may be both too close to the intersection to stop and too far away to pass the stop line during the remainder of the yellow interval. This situation leads to a violation of a red signal or to a rapid braking maneuver, both of which pose major safety threats. The Type-I dilemma zone is defined as the area where the driver cannot comfortably stop nor enter the intersection before a red signal.

The second dilemma or the problem of indecision, named Type-II Dilemma, arises from the inconsistent behavior of drivers when both stopping and passing maneuvers can be executed. This second criterion defines a dilemma zone as the area on the approach where 10 to 90 percent of drivers decide to stop at the intersection (6). On the basis of several empirical studies, the FHWA report (4) determines the Type-II dilemma zone as an area where the travel time to the stop bar is between two and five seconds. Several recent studies have produced slightly different travel time boundary parameters (7,8).

Since the mid-1970s, green extension systems (GES) have been used at actuated signalized intersections to deal with the issues of the dilemma zone, and significant safety improvements were reported (9,10). Excellent taxonomy and reviews can be found in reference (11). The basic idea of GES is to extend the end of the green so that the dilemma zone is free of any vehicle or until the phase is maxed-out (forced-off) (12). Some enhanced systems provide extra features such as truck priority (13-15) and consideration of delays of the crossing traffic (16).

A major disadvantage of the GES is the static dilemma zone it assumes. A fixed “Type-II dilemma” (as defined above) zone is assumed based on a single speed equal to the design speed or a speed limit. For example, for an approach with a speed of 45 mph, the dilemma zone is assumed to be between 132-331 feet to the stop line for all vehicles (4). Apparently, if a vehicle moves at a speed different than the assumed one, then it is only partially protected.
Recently, an important improvement of the GES method has been proposed, which provides protection to each vehicle at its individual speed \((11,17,18)\). Instead of choosing a typical design speed, this method uses the measured speed of a vehicle to determine its individual Type-II dilemma zone (2.5-5.5 seconds from the stop line). The green interval is extended within the allowable range such that the total number of vehicles in their own dilemma zones is minimized. Another recent study calculates the Type-I dilemma zone based on the normative values of vehicle and driver characteristics and seeks the optimal extension to minimize the number of vehicles in their Type-I dilemma zones \((19,20)\).

These methods are significant improvements over the conventional GES dilemma zone protections. They did not, however, fully recognize the probabilistic nature of the dilemma occurrence. One cannot determine with full confidence whether or not the vehicle will encounter a Type-I dilemma at the onset of yellow even if its position and speed is perfectly measured First, it is clear that the dilemma zone boundaries are affected by more factors than speed alone. These other factors include the deceleration rate and the perception-reaction time, which are affected by roadway conditions, vehicle type, and driver preferences. Excellent graphical illustration of the effects of approach speeds, perception-reaction time, and vehicle types on the spatial variations of the Type-I dilemma zones can be found in reference \((21)\). Furthermore, although the vehicle type and its position and speed can be measured, some other characteristics, such as perception-reaction time and driver preferences, cannot be fully known and therefore must be represented through their statistical distributions. In other words, rather than the dilemma occurrence being a deterministic event, it is random; and we can only estimate, at best, the likelihood of the dilemma occurrence.

In this paper, a framework to deal with the probabilistic dilemma zone problem is proposed. The probability of whether a driver is facing the dilemma is calculated based on the statistical knowledge of the dilemma factors. A method to find the optimal green extension that minimizes the aggregate likelihood of Type-I dilemma situations is proposed. A convenient property of the aggregate Type-I dilemma likelihood is noted and used to devise an efficient searching method for the extension that can be easily handled in real time by modern controllers. To test and evaluate this method, simulation experiments are performed based on collected field data.

**DILEMMA CONDITIONS**

In this paper, a level road condition is assumed. The distance between the vehicle and the stop line at the onset of the yellow signal is \(x\), the duration of yellow interval is \(Y\), and the approaching speed is \(v\). Assume that the speed is constant and the vehicle cannot enter the intersection before the end of yellow signal when moving at speed \(v\) (ft/sec) if:

\[
x > x_0 = Y \cdot v
\]  

\((1)\)
where $x_0$ is the distance in feet the vehicle travels during the yellow interval. Assuming that the driver has a perception-reaction time of $\delta$ seconds and favors deceleration rate $a$ feet per square second to stop, the driver is not able come to a complete stop before the stop line if:

$$x < x_c = v\delta + \frac{v^2}{2a}$$

in which $x_c$ is the stopping distance. As is shown in Figure 1, when $x_0 < x < x_c$, which implies that $Y < \delta + \frac{v}{2a}$, the Type-I dilemma occurs.

**FIGURE 1, Boundaries of Type-I Dilemma Zone**

To eliminate the Type-I dilemma for a vehicle with $v, a,$ and $\delta$, the yellow interval $Y$ should be set no less than:

$$Y_{\text{min}} = \delta + \frac{v}{2a}$$

Equation (3) is used to design yellow signals under the law of permissive yellow. Normative values of $\delta$, $v$, and $a$ are recommended by the ITE handbook (22). The current design manuals make a good attempt at promoting the selection of a yellow signal.
that is sufficiently long to meet the needs of drivers following the speed limit and having vehicles in reasonable mechanical condition, but not excessively long to avoid additional delays caused by long change periods.

At modern actuated controllers, a green signal is terminated because the waiting time for a next call for green exceeds the gap (gap-out), or a green signal reaches the maximum allowed value (max-out). In addition, signal coordination adds a force-off point for each actuated phase and a local zero at which typically the coordinated green signal ends. We will call the time **warranted termination time** when a green signal is warranted for termination because of gap-out, max-out, forced-off, or local zero.

Following the idea of GES protection logic, the controller is equipped with the ability to extend the green by \( \tau \) seconds beyond the warranted termination time. In contrast to the incremental green extension of actuated signals, which can be applied multiple times in one phase, this dilemma protection extension is applied only once per phase. It is not allowed to exceed a short pre-defined limit \( T \) to keep the integrity of the signal control plan. In the following sections of the paper we will present a method of searching for the optimal extension \( \tau \).

Let us assume that vehicle position \( x \), its speed \( v \), and duration of yellow signal \( Y \) are known, while the reaction time \( \delta \) and the anticipated deceleration rate \( a \) are represented through their distributions conditioned on the available information. Suppose we use advance detectors installed at setback \( L \) to measure the speed \( v \) and to determine the type of vehicle. Assuming that the speed is fixed beyond the set back detector, the vehicle position (distance to the stop bar) at the warranted termination time can be calculated as:

\[
x = L - (t + \tau) \cdot v \quad 0 \leq \tau \leq T
\]

where:
\[
\begin{align*}
v &= \text{vehicle speed (ft/sec),} \\
t &= \text{time between vehicle detection and warranted termination (sec),} \\
\tau &= \text{extension of green beyond the warranted termination time (sec),} \\
T &= \text{maximum extension of green (sec).}
\end{align*}
\]

**SINGLE VEHICLE CONSIDERATION**

We will calculate the likelihood of dilemma as a function of the extension for a single vehicle and represent the function as \( P(\tau) \). Applying (4) to (1), we find that if the yellow signal is delayed by \( \tau \) seconds, then a vehicle can reach the stop bar before the end of the yellow signal if:

\[
\tau \geq \tau_0 = \frac{L}{v} - t - Y
\]
where \( \tau_0 \) is the characteristic extension for a vehicle. In other words, when condition (5) is satisfied, then the probability of Type-I dilemma for this vehicle is 0:

\[
P(\tau) = 0, \quad \text{if } \tau \geq \tau_0
\]  
(6)

It also implies that the vehicle cannot be in the dilemma zone if \( \tau_0 \leq 0 \), because the vehicle passes the stop bar even before the warranted termination time. Please notice that all the values needed to calculate \( \tau_0 \) are deterministic.

Let us assume for now that the selected green extension \( \tau \) is less than \( \tau_0 \). It follows that the vehicle is too far away to reach the stop bar before the end of yellow. The vehicle may face the dilemma situation if at the beginning of yellow condition (2) is true. Applying (4) to (2), we find that (2) is equivalent to:

\[
\delta + \frac{v}{2a} > Y + \tau_0 - \tau
\]  
(7)

In this case, however, we cannot definitely determine if the vehicle faces the dilemma or not because the above condition includes two random variables \( \delta \) and \( a \). Therefore, the probability of dilemma is

\[
P(\tau) = Pr(\delta + \frac{v}{2a} > Y + \tau_0 - \tau), \quad \text{if } 0 \leq \tau < \tau_0
\]  
(8)

To estimate the above likelihood, let us define random variable \( d = \delta + \frac{v}{2a} \) and let \( F_D \) denote its cumulative distribution function. Then, we have

\[
P(\tau) = Pr(d > Y + \tau_0) = 1 - F_D(Y + \tau_0 - \tau) \quad \text{if } 0 \leq \tau < \tau_0
\]  
(9)

In sum, when the end of green is extended by \( \tau \), a single vehicle’s probability of experiencing Type-I dilemma is:

\[
P(\tau) = \begin{cases} 
0 & \tau \geq \tau_0 \\
1 - F_D(Y + \tau_0 - \tau) & 0 \leq \tau < \tau_0
\end{cases}
\]  
(10)

where \( \tau_0 = \frac{L}{v} - t - Y > 0 \). An example dilemma likelihood profile for a single vehicle when \( 0 < \tau_0 < T \) is shown in Figure 2.

Due to the property of the cumulative distribution function, the dilemma likelihood function \( P(\tau) \) is strictly increasing in the interval \([0, \tau_0)\) and equals to 0 in the interval \([\tau_0, T]\). For the efficiency of signal control, the shortest possible extension should be used if multiple solutions give near-minimum dilemma likelihood. The near-minimum likelihood is higher from the minimum likelihood by no more than some user-defined small amount \( \varepsilon \). For example, if 0 second of extension results in dilemma probability of
2% and 1 second of extension results in 0% dilemma probability, then 0 extension will be preferred when \( \varepsilon \) is set as more than 2%. Therefore, the optimal extension \( \tau_{opt} \) is selected as follows:

\[
\tau_{opt} = \begin{cases} 
\tau_0 & \text{if } 0 < \tau_0 \leq T \text{ and } 1 - F_D(Y + \tau_0) > \varepsilon \\
0 & \text{if otherwise}
\end{cases}
\]  

(11)

**MULTIPLE VEHICLES CONSIDERATION**

When multiple vehicles are present in the approach at the end of the green, either in the same lane or not, the sum of the likelihood values of Type-I dilemma for each vehicle is used as the objective function to minimize in terms of safety. All of the individual likelihood profiles are summed up as shown in Figure 3. It is clear that, thanks to the properties of the component likelihood functions, all the local minima occur at \( \tau_{0i} \) points and at 0. We do not have to evaluate the sum of likelihood function at every time between 0 and \( T \). This property greatly reduces the time of the searching for the solution.
The likelihood sums should be evaluated at the warranted termination time \((\tau = 0)\) and at all \(\tau_0\) s included between 0 and \(T\). The extension which has the lowest sum of dilemma likelihood is selected. If more than one extension has the lowest or the near-lowest value, then the shortest extension is selected for signal control efficiency.

\[
\sum_{i} P_i(\tau)
\]

**FIGURE 3 An example profile of sum of dilemma likelihood**

The near-lowest value is such that it is higher than the lowest by no more than a user defined small amount \(\varepsilon\).

**SEARCH FOR OPTIMAL EXTENSION**

Based on the previous discussions, the algorithm of determining the optimal green extension is described step by step:

1. For the time when green termination is warranted, identify all vehicles that are between the detector and the stop bar \((t \cdot v < L)\) and calculate their \(\tau_0\) values based on equation (5). Negative values indicate that the vehicle is able to reach the stop bar before the end of the yellow signal and the vehicle should not be further considered.
2. Based on the type of vehicle and the pavement conditions, select the proper distributions of the deceleration rate \(a\) and the perception reaction time \(\delta\) for each vehicle identified in step 1 and estimate the cumulative distribution of variable \(D\).
3. Calculate the dilemma likelihood sums for \(\tau = 0\) and all the \(\tau_0\) points between 0 and \(T\).
4. Find \(\tau_0\) with the minimum dilemma likelihood sum and identify other equivalent or near-minimum solutions. Select the shortest extension among all the identified ones.
5. Extend the green by the found value and displayed yellow signal.
Advance detectors should be installed in each lane and located a conservative distance from the stop bar. A conservative setback of the advance detector can be calculated as a braking distance with the assumption of high speed (90 percentile value), low deceleration rate (10 percentile value), and long reaction time (90 percentile value). In addition, the maximum extensible green time should also be considered in determining the setback distance in order to ensure that the vehicle that passes the detector during the extended green time does not encounter dilemma.

**APPROXIMATE DILEMMA LIKELIHOOD FUNCTION**

The proposed method holds to any distribution of \( D \) due to the non-decreasing property of cumulative distribution functions. To compare the dilemma likelihood of the candidate extensions, the distribution function of \( F_D(d) \) must be, at least approximately, determined. There is no direct statistical study on this random variable. Therefore, we must estimate it on the basis of the detected information and the known statistical properties of the factors. Better estimation will result in more precise selection of the optimal extension and thus improve the dilemma reduction performance. First, we assume that \( d = \delta + \frac{v}{2a} \) is distributed normally which means

\[
d = \delta + \frac{v}{2a} \sim \text{Normal}(\mu, \sigma^2)
\]  

(12)

where \( \mu \) and \( \sigma \) are parameters to estimate.

Since the cumulative distribution function of the normal distributed variable is not close-formed, we use the logit curve to approximate for the simplicity of calculations. After being normalized with the expected value \( \mu \) and variance \( \sigma^2 \), the distribution function \( F_D(d) \) is approximated with the logit function (23):

\[
F_D(d) \approx \frac{1}{1 + \exp[-1.7 \times \frac{d - \mu}{\sigma}]}
\]

(13)

where -1.7 is a fitted parameter. Since the number of possible \( d \) values is limited considering that the precision of the signal controllers are typically 0.1 seconds, we can use a table with the values of the logit function to avoid time-consuming evaluation of the exponential function. Applying (13) to (10), we can obtain the curve of \( P(\tau) \).
METHOD EVALUATION

For practical and legal reasons, we will evaluate the proposed method through simulation experiments. Field data were collected to provide the basis for the simulation experiment design. The approaching speeds, the braking distances, and the perception-reaction times of the first vehicles stopping during the yellow intervals were measured. The types of vehicles and pavement conditions were also recorded.

Field Study

The study focused on the first vehicles to stop after the onset of the yellow signal. High-performance surveillance cameras were used to videotape the daytime traffic at two intersections. The cameras were mounted on a mobile traffic laboratory equipped with a 40-ft mast, two computers, a multi-channel digital VCR, and the mentioned two surveillance cameras.

Two adjacent intersections in West Lafayette, Indiana, US 52 at Cumberland Avenue and at Win Hentschel Boulevard, were selected for this study. Both intersections had identical studied approaches, with a speed limit of 50 mph and a yellow signal of 4.3 seconds. The van was parked in advance of the stop bars at the distance that allowed recording the approaching vehicles and the signal displays. Traffic cones were spaced 40 feet apart, starting from the stop bar, to provide reference points for distance measurements. The last two cones from the intersection were used as a speed trap to measure the approach speeds. The field set up is illustrated in Figure 4.

Data were extracted from the video files using a Digital Time Lapse Video Cassette Recorder. For each vehicle first stopped after the beginning of the yellow interval, the following data were extracted:

1. Time when vehicle rear wheels pass the first cone of speed trap.
2. Time when vehicle rear wheels pass the second cone of speed trap.
3. Time when yellow signal starts.
4. Time when vehicle starts braking after yellow started.
5. Time when vehicle stops.
6. Distance to the stop bar when the vehicle starts braking.
7. Vehicle type.

To measure the time when the vehicle started braking, the tail lights of the vehicle were used as the indication of braking actions. Vehicles included in the study were those stopping on the approach while scheduled to pass the stop bar not later than two seconds into the red signal if continuing at the approach speed. This way, we have excluded drivers arriving late, to whom the only conceivable action was to stop the vehicle. We wanted to observe conditions as close to the dilemma situation as possible. Based on the collected data, the approach speeds, perception-reaction time, and average deceleration rates were computed for each stopping vehicle.
FIGURE 4 The field set up for data collection

TABLE 1 Driver braking characteristics during yellow signal on the studied intersection approaches (44 drivers from both intersections)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Perception-Reaction Time (sec)</th>
<th>Speed (ft/sec)</th>
<th>Deceleration Rate (ft/sec²)</th>
<th>Braking Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.13</td>
<td>66.8</td>
<td>10.9</td>
<td>213</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.365</td>
<td>15.3</td>
<td>4.52</td>
<td>36.2</td>
</tr>
</tbody>
</table>

Data for 44 passenger cars were collected in 15 hours of videotaping. The results are demonstrated in Table 1, Figures 5 and 6. It is worthwhile to note that the average values of perception-reaction and deceleration rate are close to the results of previous studies (24) and the values recommended in (5).

The Kolmogorov-Smirnov test was performed to test the random variable \( d \) against the normal distribution. At the significance level of 15%, the normal assumption is not rejected. The obtained results confirm that the normal assumption, although not perfect, is reasonable and will be used for algorithm development. The estimates of the distribution parameters are \( \mu = 4.42, \sigma = 0.77 \) and the fitted probability density function are showed in Figure 7 with the field data.

SIMULATION

We devised a simple yet sufficient simulation experiment to check the potential effectiveness of the proposed method. In one simulation run, 10 vehicles were randomly dispersed along a 1,000-ft approach section. The randomly generated vehicle positions
were applied to the warranted green extension time. These settings imply a 1,000-ft detector setback. The selected number of vehicles allowed for a frequent dilemma situation involving multiple vehicles, which is a case that puts the proposed algorithm to a challenging test. For each vehicle, we randomly assigned the speed, perception-reaction time, and deceleration rate. All of these random variables were mutually independent and normally distributed according to the parameters in Table 1.

**FIGURE 5** Histogram of the Perception-Reaction Time

**FIGURE 6** Histogram of the Approaching Speed
The search for the optimal extension utilized simplified cumulative distribution $F_D$ with distribution parameters $\mu = 4.42, \sigma = 0.77$ obtained from the collected field data. The drivers facing Type-I dilemma in two scenarios: (1) without green extension, and (2) with the optimal extension, were counted. We used the condition $x_0 < x < x_c$ to decide if a driver faces the dilemma or not at the onset of a yellow signal.

Different scenarios were tested with various settings of maximum allowed extension $T$ and yellow duration $Y$. In each scenario, the simulation was run 1,000 times. The results of the simulation experiments are summarized in Tables 2 and 3.

It is clear that the proposed green extension algorithm significantly reduces the frequency of Type-I dilemmas. For example, even if the yellow duration is only three seconds, which is far below demand, this adaptive algorithm, by extending by only 1.2 seconds the green interval on average, reduces the occurrence of dilemma to a level which is significantly lower than that of the 4.3-second fixed yellow scenario.
As expected, when the dilemma likelihood below 0.05 is considered negligible, the average extension decreases, especially when the yellow duration is long while the dilemma reduction performance also tends to drop. The trade-off between the signal efficiency and safety can be controlled by \( \varepsilon \).

The impact of yellow time on dilemma frequency is considerable, although the proposed algorithm tends to compensate for the insufficiency of yellow duration.

<table>
<thead>
<tr>
<th>Yellow (sec)</th>
<th>Max Extension (sec)</th>
<th>Average Applied Extension (sec)</th>
<th>No. of Vehicles in Dilemma Zone</th>
<th>Dilemma Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No Extension</td>
<td>After Extension</td>
</tr>
<tr>
<td>4.3</td>
<td>1</td>
<td>0.25</td>
<td>768</td>
<td>603</td>
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<tr>
<td></td>
<td>2</td>
<td>0.69</td>
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<th>Yellow (sec)</th>
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<th>Average Applied Extension (sec)</th>
<th>No. of Vehicles in Dilemma Zone</th>
<th>Dilemma Reduction</th>
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</table>
CONCLUSIONS

In this paper, the probabilistic nature of the Type-I dilemma occurrence is analyzed. The proposed method does not use the concept of dilemma zone per se, but rather the likelihood and frequency of dilemma occurrences. A framework of using advanced detectors to protect each vehicle from dilemma occurrence and of minimizing the frequency of dilemma occurrences in a signal phase is proposed. A case study is performed for two high-speed intersections and the statistical characteristics of the collected data are used as input for the numerical simulations. The results of the numerical simulations show that this method significantly reduces the number of vehicles facing Type-I dilemma at the expense of short green extensions.

It was difficult to compare the effectiveness of the proposed method with the effectiveness of the other methods reported in the literature. The D-CS system (11) tries to protect vehicles in the Type-II dilemma zone while this paper investigates the Type-I Dilemma, and the other method (19) used different simulation settings. Direct comparison should be done at some point in the future to decide which method is the most effective.

Although we have considered only light vehicles in the presented example, the method can be readily applied to other types of vehicles, such as buses and trucks, and to heterogeneous traffic with various types of vehicles. This application does not require any changes in the method. It requires, though, knowing the distribution of the reaction time and the deceleration rate for drivers of heavy vehicles.

In this study, a simplified model of dilemma likelihood is employed to show the effectiveness of the proposed method. Nonetheless, this framework can be easily refined to apply it to the Type-II dilemma zone.

REFERENCES


6. Technical Committee 18, ITE Southern Section. “Small-Area Detection at Intersection Approaches.” Traffic Engineering, Feb 1974, pp. 8-17


