Supervisory Control Intelligent Adaptive Module (SCIAM)

Theoretical Background and VISSIM Test-bed Development

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Supervisory Control Intelligent Adaptive Module (SCIAM)—Theoretical Background and VISSIM Test-bed Development

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### Abstract
Supervisory Control Intelligent Adaptive Module (SCIAM) system is intended to be a next generation of smart traffic signal control system that consists of four modules: smart vehicle trajectory predicting system, intelligent control logic decision subsystem, innovative phase transiting logic and intelligent self-learning and self-calibrating subsystem.

In the past phase of the project, the research team completed:

- Smart vehicle trajectory predicting system’s literature review and functional design;
- The kernel model, stochastic dilemma hazard model, for intelligent control logic decision subsystem, which forms the basis of a paper accepted at AATT (2008) conference. This model is to be applied to the optimal green extension system design.
- Preliminary study of intelligent self-learning and self-calibrating subsystem based on reinforcement-learning knowledge, based on which one paper will be submitted for TRB 2009.
- Established a VISSIM-based Simulation Environment via VISSIM COM, VISSM VAP, Database ADO and VISSIM external APIs, which will implement innovative real-time extension and be used as the test-bed for SCIAM system.

In the coming year, we are planning to:

- Set up vehicle trajectory predicting algorithm based on traffic flow models and car-following models.
- Intelligent signal control logic decision-subsystem which could determine dynamic timing plans according to efficiency as well as safety.
- Innovative phase transiting logic, which will monitor traffic on each approach during green time as well as red time, identify platoon and determine timing plan dynamically.
- Contingent on progress, we also have plans of deploying more advanced applications with the test-bed, such as hardware-in-the-loop, cabinet-in-the-loop traffic simulation for the purpose of system testing.
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1. Executive Summary:

1.0 Introduction

Supervisory Control Intelligent Adaptive Module (SCIAM) system is the acronym for one of the next generation smart traffic signal control systems and it basically has four modules: smart vehicle trajectory predicting module, intelligent control logic decision module, innovative phase transiting logic module and intelligent self-learning and self-calibrating subsystem. The intent of this project is to develop an innovative signal control system that is capable of increasing traffic efficiency as well as safety at signalized intersections with the state-of-art technical and research achievements. The significance of SCIAM is twofold: (1) SCIAM will bridge the gap between efficiency studies and safety studies from signal control perspective and (2) SCIAM will borrow latest research achievements in other fields, such as artificial intelligence, to determine dynamic timing plan such that it could keep a continuous self-learning-and-calibrating process in the running process. As a result, many prevailing issues in signal control operations, such as obsolete timing plans, could be significantly improved.

Figure 1-1: Structure of SCIAM systems

There are 5 chapters in this report:

Chapter 1 is the executive summary of work last phase. Its intent is to provide a basic idea for the readers. It also provides a brief introduction of SCIAM’s objective and overall proposed structure in efforts of providing an understanding.

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Chapter 2 is about the detailed explanation of kernel model, dilemma hazard model (essentially a traffic conflict measure), developed in this project. The corresponding paper was accepted in a peer-reviewed conference proceeding, AATT (2008) to be held in Greece.

Chapter 3 is about an application of the model described in chapter 2. Green extension system (GES) is one of well-known dilemma zone protection systems. With multiple advance detectors, it protects the vehicles in the dilemma zone until they are safe by extending the green time. Although the prevailing detector designs for GES could provide effective protection, it is somehow dependent on engineering experience when traffic engineers determine the detector settings. Consequently, there is no guarantee that currently used detectors designs provide the best dilemma zone protection. A simple simulation engine was developed in order to test the hourly dilemma cost plus delay cost under different detector settings.

Preliminary studies with this user-defined GES simulation engine show that this optimization problem is not convex. In the meanwhile, experiments with simplified enumeration show that there exist better detector settings than prevailing ones so as to lower the overall cost further.

The work for this paper is still in development; optimization algorithms are currently being developed and tested.

Chapter 4 is a brief introduction of VISSIM-based simulation test-bed for innovative signal control systems research. Future research is described in Chapter 5.

1.1 What was done?

In the last phase of the project, we have finished the following associated with this project:

- smart vehicle trajectory predicting system’s literature review and functional design;
- The kernel model, stochastic dilemma hazard model, for intelligent control logic decision subsystem. This model comprises the basis of a paper that was submitted to AATT (2008) conference. The model will be applied to the optimal green extension system design.
- Preliminary study of intelligent self-learning and self-calibrating subsystem based on reinforcement learning knowledge, based on which one paper will be submitted to TRB 2009.
- Set up a VISSIM-based Simulation Environment via VISSIM COM, VISSM VAP, Database ADO and VISSIM external APIs, which will implement innovative real-time extension and be used as the test bed for SCIAM system.

1.2 Recommendations for next phase

In the coming years, we are planning to:

- Set up vehicle trajectory predicting algorithm based on traffic flow models and car-following models;
• Intelligent signal control logic decision subsystem which could determine dynamic timing plans according to efficiency as well as safety;
• Innovative phase transiting logic, which will monitor traffic on each approach during green time as well as red time, identify platoon and determine timing plan dynamically;
• More investigation of intelligent self-learning and self-calibrating subsystem with reinforcement learning and machine learning knowledge; and
• Contingent on progress, we also have plans of deploying more advanced applications with the test-bed, such as hardware-in-the-loop, cabinet-in-the-loop traffic simulation for the purpose of system testing;
2. A New Look into Dilemma-Zone-Associated Dilemma Hazard and Crash Potential

This chapter explains one of the kernel models: the dilemma hazard function model that is intended for use in the intelligent control logic decision module in SCIAM. The signal control system design will expand the feasible space of dilemma zone protection measurement from traditional integer space (the average number of vehicles in the dilemma zone) to the continuous non-negative real number space (the average dilemma hazard of vehicles in the dilemma zone).

Dilemma zone is a leading cause for accidents at signalized intersections. Generally, the dilemma zone protection systems detect the number of vehicles in the dilemma zone to decide when to end the green time. This mechanism implies each vehicle in the dilemma zone is evenly hazardous with weight 1, regardless of its speed or location. However, nowadays many researchers agree a vehicle's dilemma hazard varies with its position in the dilemma zone and speed. This paper addresses this issue by presenting a dilemma hazard model to reflect the variable feature of vehicles’ dilemma hazard. With the collected field data and a simple but sufficient Monte-Carlo numerical simulation method, this paper ascertains that a vehicle’s dilemma hazard will increase then decrease while approaching an intersection and primarily decided by the remaining time to stop line and speed limit.

2.0 INTRODUCTION

A survey by the US National Safety Council (2007) reported that crashes related with the signalized intersection constituted up to 30 percent of all crashes. Besides drivers' recklessness, the indecisiveness in the dilemma zone (DZ) is also a leading cause of accidents, especially at high-speed intersections. Consequently, protecting vehicles from being trapped in dilemma zone has witnessed an increasing interest. Researchers typically classify dilemma zone into two types: D. Gazis et al.(1960) defined the type I dilemma zone as a region where drivers can neither stop completely nor pass the intersection at the onset of yellow indication. It is also known as "GHM model". Type II dilemma zone was first defined by Parsonson. P.S et al.(1974) as an indecision zone, where 90% of drivers would stop at the upper boundary from stop line whereas only 10% would stop at the lower boundary.

2.1 SIGNIFICANCE OF RESEARCH

There is a gap between the two DZ definitions: Few studies considered both types of DZs when addressing dilemma zone issues. For instance, the prevailing designing method for yellow interval and all-red clearance provided by ITE (1985) is based on the type I DZ definition only, and it assumes that all the drivers will uniformly stop whenever they can. Alternatively, if drivers cannot stop, they will keep their speed constant until they clear the intersection. This method is incapable of dealing with the observed randomness of driver behaviors when vehicles are trapped in the DZ. On the other hand, when engineers design the dilemma zone protection systems (DZP) with the type II DZ definition, the yellow interval and all-red clearance are usually considered as constants having no influence on dilemma zone protection. This paper bridges this gap in DZ definitions with
a new dilemma hazard model. The proposed dilemma hazard model is capable of calculating the DZ-related accidents probability for the trapped vehicles, according to their initial speeds, locations, as well as the intersection geometry, controller settings, and traffic volumes.

The speculation underlying this new model is that, at the onset of yellow indication, the vehicles in the DZ will have to make two sequential decisions: (1) they first have to decide to stop or clear the intersection, and (2) they have to choose the sufficient deceleration/acceleration rates to safely stop or clear. Because drivers have different perceptions and judgments, it is very likely that some drivers will make wrong decisions that might lead to accidents.

Two types of accidents could possibly be related to DZ: (1) right-angle collision, caused by vehicles' failure to stop or clear; (2) rear-end collision, caused when the lead vehicle of two consecutive trapped vehicles decides to stop but the following vehicle decides to go.

The random sources addressed in this paper include: (1) decision of stopping or clearing when vehicles are trapped in the type II DZ; and (2) selection of acceleration/deceleration rates considered as sufficient by the drivers. The related driver behavior issues include: (1) probability of stopping when vehicles are presented in yellow; (2) approaching speed distribution at intersections; (3) acceleration rate if clearing decision is made and deceleration rate if stopping decision is made; and (4) the perception-reaction time by drivers (drivers "time-lag"). Detailed reviews on all related driver behavior studies are in the "Literature Review" section.

Based on the speculation above and the knowledge of driver behavior, the dilemma hazard of single-vehicle is comprehensively modeled first. Then this model is extended to the more general multi-vehicle scenario. Monte-Carlo simulation is implemented to test the dilemma hazard's sensitivity to all the influential factors. Finally, with the most influential factors included, design graph under typical values of the influential values is provided for practitioners.

### 2.2 Dilemma zone definitions

As mentioned above, there are two definitions for dilemma zones. The following paragraph describes the models used for each definition.

#### 2.2.1 Type I Dilemma Zone

GHM type I dilemma zone model defines the dilemma zone based on the longest distance from stop line for vehicles to completely stop ($x_c$) and the shortest distance ($x_0$) for them to clear the intersection after the onset of yellow interval, shown in figure 1. These two critical distances are calculated as:

\[ x_0 = v_0\tau_0 + \frac{1}{2}a_i\left(\tau_0 - \delta\right)^2 - L - w \]  \hspace{1cm} (1)

and

\[ x_c = v_0\delta + \frac{v_0^2}{2a_i} \]  \hspace{1cm} (2)

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Where: $v_0$ is the initial speed when the yellow interval begins;

$d^i$: the maximal acceleration/deceleration rate;

$\delta^i$: the Perception-Reaction (P-R) time;

$i$: the index, 1 for acceleration and 2 for deceleration;

$L$: the vehicle length;

$w$: the width of intersection and

$\tau^0$: the yellow duration.

\[ \tau^0 = \delta + \frac{v_0}{2a_i^1} + \frac{L + w}{v_0} \]

FIGURE 2-1: Demonstration of GHM dilemma zone model

When $x_c$ is greater than $x_0$, type I DZ exists with length $(x_c-x_0)$. The dilemma zone could be removed by adjusting inter-green duration as to make $(x_c-x_0)$ zero.

Researchers typically divide $\tau^0$ into permissive "yellow interval" $(\tau = \delta + \frac{v_0}{2a_i^1})$ and "all-red clearance" $(\tau = \frac{L + w}{v_0})$.

The terms of $\tau^0$ and $\tau$ used in this paper should be distinguished. This method was adopted by ITE(1985) as yellow interval and all-red clearance designing method. Liu Ch et al.(1996), extended GHM model by counting for the decreasing relationship between acceleration and instantaneous speed. Other revised calculations were provided by Olson P.L et al.(1961); Crawford. A et al.(1961); Williams. W. L(1977); Chang M. S et al.(1985); Lin F. B(1986).

The GHM model and its extensions are kinematics models and assume that all the vehicles will uniformly stop if they can at the onset of yellow indication. However, Olson P.L et al.(1961) observed that some vehicles took advantages of yellow interval as the green extension; May A. D(1968) concluded that some vehicles accelerated/decelerated sufficiently to high/low speeds so to escape the dilemma zone; Liu Y et al.(2007) observed that driver behaviors were significantly different from theoretical assumptions. These conclusions imply that the approaching speeds and
driver aggressiveness have distributions with wide ranges. Incapability of dealing with the randomness among vehicles is the primary disadvantage of the type I DZ definition. The prevailing designing method of yellow interval and all-red clearance is only based on certain typical values, such as 85th percentile approaching speed.

Easa S. M(1993) followed a different approach by proposing a stochastic model, attempting to reflect the randomness residing among drivers. Easa model assumed the type I DZ length was normally distributed and derived a solution capable of lowering DZ length to a low significance level \((\alpha = 10\%)\). Although Easa’s model is theoretically more correct than the GHM model, the recommended yellow time by Easa’s model is significantly longer than that by the GHM model, possibly impairing its efficiency. Meanwhile, the consideration of randomness does not include drivers’ decision randomness. As a result, its application has been limited.

2.2.2 Type II Dilemma Zone

Parsonson. P.S et al.(1974) defined the other probability-based decision zone, known as type II DZ definition, by defining an area where 90% vehicles will stop at its upper boundary from stop line whereas only 10% will stop at its lower boundary at the yellow onset. In the light of type II DZ definition, many studies attempted to ascertain the type II DZ boundaries in different areas. For example, 2.5s~5.0s were recommended by Zegeer C.V(1977); 2.0s~4.5s by Chang M.S et al.(1985); 3.0s~5.0/6.0s by Bonneson J.A et al.(1994); 3.3s~5.3s by and 1.7s~4.7s by Papaioannou P(2007).

Type II DZ definition is widely used in dilemma zone protection systems (DZP), such as the green extension systems (GES) by Zegeer C.V(1977); advanced GES by Peterson A(1986) and Zimmerman K.H(2007); green termination systems by Kronborg P(1997) and by Crabtree M.R et al.(2006); detection control systems by Bonneson J et al.(2002); Platoon Identification and Accommodation System by Chaudhary N. A. et al.(2003), etc.

2.2.3 Driver Behaviors Studies Review

Driver behaviors are a physic-psychological problem. It could be partially represented by speed distribution, perception-reaction time, probability of stopping at the onset of yellow indication, and selected acceleration/deceleration rates in different road geometries and signal controller settings. Given that there is wide behavior diversity among drivers, some studies divided driving populations into separate groups.

Studies on approaching speed distribution

It is commonly accepted that the approaching speed is normally distributed. ITE (1985) concluded that a pace with 10 mph contains the largest fraction of the speeds. 85th percentile approaching speed, with 5 mph faster than speed limit, is used for yellow interval design. Although some observations provided different conclusion, such as Papaioannou P(2007), the ITE method is used in most cases nowadays.

Studies on the probability of stopping after the onset of yellow indication

As mentioned before, type II dilemma zone is defined according to vehicle’s stopping probability after they encounter an onset of yellow indication. The probability of stopping will decrease while
vehicles are moving from the upper boundary of type II DZ to the lower. With the available dataset, Yosef S et al.(1981) used probit model to present the relationship between the remaining time \( t = \frac{d}{v_0} \) or distance \( d \) to stop line and stop decision. Two types of models were set up, which are:

1. speed \((v_0)\)-independent model, \( P_{spt}(t) = \Phi \left[ \frac{t - 3.40}{0.96} \right] \)

2. speed-dependent model, \( P_{spt}(d) = \Phi \left[ \frac{d/v_0 - 3.90 - 0.28*v_0}{\sqrt{2.40}} \right] \).

Other studies by Chang M. S et al.(1985), Papaioannou P(2007) and Gate T.J et al.(2007) used logistic regression model and concluded that the stopping probability has an increasing relationship with distance to stop line whereas a decreasing one with the vehicles' initial speed.

Studies on the deceleration after vehicles decide to stop

Vehicles' deceleration rates are dependent on the initial speeds, the remaining time to stop line, road geometries and drivers' knowledge of controller settings. D. Gazis et al.(1960) recommended to use 0.3g~0.5g as maximal deceleration; ITE.(1985) uses 10feet/s\(^2\) and AASHTO(2004) uses 11.2 feet/s\(^2\). Other reported maximal deceleration rates for 85\(^{th}\) percentile vehicle include: 14 feet/s\(^2\) by Williams. W. L(1977); 10.5 feet/s\(^2\) by Chang M.S et al.(1985); 12.9 feet/s\(^2\) by Gate T.J et al.(2007) and 10.7 feet/s\(^2\) by Ihab E et al.(2007).

Studies on the acceleration after vehicles decide to go through

D. Gazis et al.(1960) provided a constant acceleration model according to vehicles' initial speed, and suggested 0.5g~0.8g ft/s\(^2\) as maximal rates. Liu. Ch et al.(1996) used a linearly decreasing model between acceleration and instantaneous speed to calculate the yellow and all-red interval. Other field observations, such as McCoy P.T(2003) and Liu Y et al.(2007), showed some vehicles accelerated while clearing intersections. Nevertheless, these studies did not reach a common conclusion with a prevailing assumption that drivers do not know the controller settings and that they will have the same behavior regardless of the controller settings. As a result, most studies assumed that vehicles will clear the intersection at constant speeds, and failed to address the issue of vehicles accelerating at the onset of yellow to clear the intersection. For example, Olson. Paul. L et al.(1961) concluded the controller settings did not significantly affect the drivers behaviors and the possible reason was that drivers did not to know the yellow and all-red duration so they would not attempt to accelerating to clear the intersection. Most of the later studies followed on Olson's assumption.

Studies on the perception-reaction time to the onset of yellow interval

P-R time is also a physi-psychological term and an indicator of drivers' aggressiveness. Bonsall P et al.(2005) defined the driver's risky aggressive driving as: overtaking, heavy braking, low headways, large speed differentials, reckless movement and near misses. It is commonly concluded that the more aggressive a driver is, the faster speed, the heavier acceleration/deceleration rate and the shorter P-R time he could have. Some reported value are 1.0s by ITE(1985); 1.9s by Chang M.S et
2.3 PROPOSED DILEMMA HAZARD MODEL

The objective of the proposed dilemma hazard model is to ascertain the relationship between the probability of DZ-associated accidents and influential factors. Specifically, the new dilemma hazard model will be capable of reflecting the changing tendency of DZ-associated accidents probability when influential factors are changed. Sharma A et al. (2007) proposed a hypothetical dilemma hazard function from economics perspective, stating that the dilemma hazard will reach maximum in the middle of dilemma zone. There is no explanation how Sharma’s model was formed.

2.3.1 New Dilemma Hazard Measure: The Probability of DZ-Associated Accidents

A new dilemma hazard measure, named “dilemma hazard”, is defined in this paper as the probability of accidents associated with DZ. The DZ-associated accidents occur when vehicles in the DZ choose insufficient deceleration or acceleration rates or when consecutive vehicles take incompatible actions (lead vehicle brakes, but the following vehicle accelerates). As mentioned before, two types of accidents could occur at the signalized intersection: right-angle collision due to red-light running and rear-end collision due to incompatible behaviors between two consecutive vehicles. According to the traffic laws in most countries, red-light runners and following vehicles are liable for these accidents. Consequently right-angle and rear-end collision accidents are considered to belong to the red-light runner and the following vehicles only.

Unlike most of the previous studies, in this paper the drivers are assumed to be aware of yellow and all-red durations. Under this assumption, the drivers will make appropriate decisions to stop or clear and choose sufficient acceleration/deceleration to clear the intersection or stop. However, due to different perceptions of remaining inter-green time, vehicles will not uniformly choose the acceleration/deceleration rates as calculated in the kinematics models. Instead, their selections will be random, making the vehicle maneuvers either safe or not. When a vehicle fails to clear or stop completely, it becomes a red-light runner and generates a dilemma hazard. In multi-vehicle cases, if the lead vehicle decides to stop but the following vehicle decides to go through, an additional DZ-associated rear-end collision will occur.

Given that the mainstream signal controllers cannot adjust the inter-green time in a real-time manner, the new dilemma hazard model follows the ITE’ prevailing design method to guarantee the consistency between the dilemma hazard model and signal controllers. The formulas are:

\[ r = \delta + \frac{v_0^{15}}{2a + (64.4 \times 0.01)} \]  \hspace{1cm} \text{Yellow interval:}

\[ r = \frac{w + L}{v_0^{15}} \]  \hspace{1cm} \text{all-red clearance:}

Where:

\[ \delta = \text{driver reaction time (usually 1 second)}; \]

\[ v_0^{15}, v_0^{15} = 85\text{th and 15\text{th percentile speed of approaching vehicles(ft/s)}}; \]
\( a = \text{maximal deceleration rate of vehicles (ft/s}^2) \);

G = grade of approach; \( w = \text{intersection width (feet)} \); and

\( L = \text{length of a standard vehicle (feet)} \).

The yellow and all-red durations affect the vehicles’ responses to the onset of yellow indication. In special cases, the vehicles in the DZ will ignore the yellow indication if they know the inter-green is long enough for them to clear. However, they will be more likely to stop than to clear the intersection if they know the yellow and all-red time is very short.

Based on the above analysis, the dilemma hazard model could be set up in two different scenarios: (1) single trapped vehicle scenario and its extension, (2) multiple trapped vehicles scenario.

2.3.2 Single Trapped Vehicle Scenario

In this scenario, only one trapped vehicle is considered, so only the right-angle collision is possible. A subject vehicle will make two sequential decisions after the onset of yellow indication:

1. Decide to go or to stop; and
2. Choose acceleration rate to clear or the deceleration rate to stop

Probability of stopping: an application of the probit model proposed by Yosef and Mahmassani’s is used in this paper. The stopping probability is assumed to decrease following the cumulative normal distribution curve while vehicles are approaching intersections.

Drivers are assumed to choose the acceleration or deceleration rate based on their judgments. However, due to different perceptions, each driver will adopt a unique rate considered as sufficient. As a result, the acceleration/deceleration rates are considered to be random variants. This could be expressed as \( \alpha = \alpha^* + \varepsilon \), where \( \alpha^* \) is the critical acceleration/deceleration rate derived from kinematics model; \( \varepsilon \) is a random term associated with the randomness residing in the drivers.

When the subject vehicle decides to clear the intersection, it will become a red-light runner and generate a dilemma hazard if

\[
\frac{v_0(t + r + \frac{1}{2} a(t + r - \delta)^2)}{a_1} + d + w + L \leq \frac{v_0 (t + r + \frac{1}{2} a(t + r - \delta)^2)}{a_1} + d + w + L
\]

\[
\frac{v_0 (t + r + \frac{1}{2} a(t + r - \delta)^2)}{a_1} + d + w + L \leq \frac{v_0 (t + r + \frac{1}{2} a(t + r - \delta)^2)}{a_1} + d + w + L
\]

When the subject vehicle decides to stop, it will become a red-light runner and generate a dilemma hazard if

\[
\frac{v_0 (t + r + \frac{1}{2} a(t + r - \delta)^2)}{a_1} > d
\]

where \( \alpha \) is the chosen deceleration rate by the driver’s judgment and the other terms are the same as previously defined,
The probability of accidents occurrence is:

$$P_z \left\{ v_0 \tau - \frac{1}{2} a z (\tau - \delta)^2 > d \right\}$$  \hspace{1cm} (5)$$

The phenomenon of “negative acceleration” should be noticed. In this paper it implies $a_i$ could be negative. Latest study by Liu Y et al. (2007) showed some drivers tended to brake slightly even though they decided to clear the intersection. Additionally, speed limit is often violated in practice so acceleration is assumed to continue even after the vehicle reaches speed limit, but it cannot exceed maximal accelerate rate yet to comply with the physical law. On the other hand, deceleration $a_d$ has to be positive but constrained by physical laws. ITE recommended $10 \text{ft/s}^2$ as the maximal “comfortable” decelerating rate. This is conservative since drivers could adopt very heavy (thus uncomfortable) braking in emergency.

In summary, the proposed dilemma hazard for single vehicle scenario proposed is shown in the following equation:

$$H_s = P_1 \ast P\{\text{clearing decision}\} + P_2 \ast P\{\text{stopping decision}\},$$

Where $P_1$ and $P_2$ are defined in equation (2) and (3), $P\{\text{clearance decision}\}$ and $P\{\text{stopping decision}\}$ are the probability of clearing and stopping after the onset of yellow indication.

### 2.3.2 Multiple Trapped Vehicles Scenario

May A. D (1990) concluded that headway between vehicles is exponentially distributed in the light or moderate traffic, whereas normal distribution in the heavy traffic. There is a minimum headway requirement for safety. However, this requirement is often violated by aggressive drivers. As a result, the number of vehicles in the dilemma zone could be 2, 3 or even more. When multiple vehicles are in the dilemma zone, another type of DZ-associated accidents, rear-end collision, can possibly occur due to incompatible behavior between two consecutive vehicles. Assuming a vehicle’s decision will not be affected by its adjacent vehicles. A rule-based dilemma hazards analyzing algorithm for a subject vehicle could be set up as in Figure 2.
Step 1: The first step is to ascertain whether there is a lead vehicle in the dilemma zone. If not, its dilemma hazard ($P_1$ in fig.2) is the same as that in single vehicle scenario. Otherwise go to next step.

Step 2: If the subject vehicle decides to stop, then only braking right-angle collision is possible ($P_2$ in fig.2), which could be calculated with equation (3) in single vehicle scenario. If it decides to go, go to next step.

Step 3: If the lead vehicle decides to go, both vehicles will go and only acceleration right-angle collision ($P_4$ in fig.2) is possible, which could be calculated with equation (2). If the lead vehicle decides to stop but the subject vehicle decides to go, a rear-end collision will happen ($P_3$ in fig.2)

The total dilemma hazard for a vehicle in the dilemma zone could then be calculated as

$$H_D = P_1 + P_2 + P_3 + P_4$$

### 2.3.4 Hazard Dilemma Calculation

The total dilemma hazard can be calculated by accumulating each of the probabilities below:

- **$P_1$:** (right-angle collision dilemma hazard)

  When subject vehicle is $t$ seconds from stop line, the remaining travel time in the dilemma zone is $(t-DZ_d)$ seconds, where $DZ_d$ is the lower boundary of type II dilemma zone. If the headway between the subject vehicle and its lead vehicle is shorter than $(t-DZ_d)$, it means the lead vehicle is also in the dilemma zone. The probability that the lead vehicle exists in the dilemma zone could be calculated as:

  $$P_1 = H_s * \left(1 - P\{lead\ \text{exist}\}\right) = H_s * \left(1 - P\{headway \leq (t-DZ_d)\}\right),$$

  where $H_s$ is the dilemma hazard calculated in single vehicle scenario.
$P_2$: (Probability of braking right-angle collision)

When a subject vehicle decides to stop, the lead vehicle will have no influence on its dilemma hazard, which is the same as that in equation (3).

$$P_2 = P\{\text{braking right-angle collision}\mid \text{stopping decision}\} \times P\{\text{stopping decision}\mid \text{lead exist}\} \times P\{\text{lead exist}\}$$

$P_3$: (Probability of rear-end collision)

This kind of accidents can occur when the subject vehicle decides to go, but the lead vehicle, if exists, decides to stop. The conditional probability that lead vehicle decides to go is:

$$P\{\text{lead go}\} = \int_0^{t-DZ_2} P\{\text{lead go}\mid \text{headway} = x\} f(x) dx$$

where $x$ is the headway between the subject vehicle and the lead vehicle; $t$ is the remaining time of the subject vehicle from stop line; $DZ_2$ is the downstream boundary of type II dilemma zone. $P_3$ will not happen unless the lead vehicle exists, meaning the headway has to be less than $(t-DZ_2)$.

$$P_3 = P\{\text{subject go}\mid \text{lead stop}\} \times P\{\text{lead stop}\mid \text{lead exist}\} \times P\{\text{lead exist}\}$$

$P_4$: (Probability of acceleration right-angle collision)

On condition that both subject vehicle and lead vehicle decide to go, the dilemma hazard of the subject vehicle could be calculated with equation (2).

$$P_4 = P\{\text{acceleration right-angle collision}\mid \text{both subject and lead vehicle go}\} \times P\{\text{both subject and lead vehicle go}\mid \text{lead exist}\} \times P\{\text{lead exist}\}$$

Due to the dilemma hazard model’s complexity, it is hard to directly derive close-form formulas to reflect the relationship between the dilemma hazard and the influential factors. As an alternative, statistical simulation techniques are utilized to ascertain the dilemma hazard’s changing tendency while the influential factors changes.

### 2.4 Estimating DILEMMA Hazard Using monte-Carlo SIMULATION

The objective of this task is to calculate vehicles’ dilemma hazard in different scenarios. It is hard to derive a close-form model to obtain dilemma hazard. Therefore, as an alternative, a simple but sufficient numerical simulation program was developed in using Microsoft Office Excel functions and Visual Basic for Application.

#### 2.4.1 Numerical Simulation Model:
The intersection in figure 3 is an isolated high-speed intersection with four approaches, a typical layout in the rural area of US. Some priori settings are set up as:

- Average vehicle length: 14 feet;
- Dilemma zone boundaries: three sets of dilemma zone boundaries will be used.
- P-R time: 1.0s (ITE value);
- Maximum acceleration rate: 15 ft/s² (0.5g, D.Gazis, et al. (1996));
- Maximum deceleration rate: -15 ft/s² (which is greater than ITE value, but still reasonably complies with physical laws);
- Individual acceleration/deceleration rates $\alpha_i = \alpha^* + \epsilon$. Three sets of coefficient of variance will be used;
- Probability of stopping decision: adjusted speed-independent probit model, which will be consistent with type II dilemma zone boundaries to be used later $P_{\text{stop}}(t) = \Phi\left(\frac{t - 3.3}{0.94}\right)$ to be consistent with the 2.1s~4.5s type II dilemma zone used in this paper);

The changeable influential factors are:

- Speed limit: 35 mph, 40 mph, 45 mph, 50 mph, and 55 mph;
- Design speed used for inter-green design: 80th, 85th, 90th, 95th percentile speed;
- Traffic flow: 400 vphpl (vehicles per hour per lane), 800 vphpl and 1200 vphpl and;
- Intersection width: 34 feet, 58 feet and 70 feet;

Only intersections with 35 miles per hour (mph) speed limit or higher are considered in this paper, where dilemma zone issue is a leading cause for accidents; Four typical design speed percentile for inter-green interval are tested; three traffic volumes represent light and moderate traffic with exponentially distributed headway and heavy traffic with normally distributed headway; The selected intersection widths represent three typical widths of conflicting approaches: 2 lanes and buffer width (34 feet); 4 lanes and buffer width (58 feet) and 4 lanes with one left-turn lane and buffer width (70 feet). The combinations of speed limits, design speed percentiles, traffic volumes and intersection widths compose of all the possible configurations. In each scenario, simulation is implemented according to the vehicle’s remaining time (t) to intersection.

In each simulation run, totally 2000 independent vehicles within the type II dilemma zone are simulated. Each vehicle is randomly assigned an initial speed, decision of clearing or going, acceleration or deceleration rate and headway from its lead vehicle. With all these information,
each vehicle could be decided whether it could be involved in the dilemma-zone-associated accidents. The ratio of the vehicles with possible accidents to all 2000 vehicles is the probability of dilemma-zone-associated accidents, defined as the "dilemma hazard" in this paper.

2.4.2 Experiment Design:

Three types of dilemma hazard models are designed:

- Model I: General model with ITE dilemma zone boundary for green extension systems;
- Model II: Calibrated model with field data (without P-R time) and;
- Model III: Calibrated model with field data (with 1 second P-R time);

Field data was used to provide the basis for the model II and model III designs. With a high performance data acquisition system (DAS), Virginia Tech Transportation Institute (VTTI) collected the data at the four-leg Peppers Ferry intersection in Christiansburg of Virginia. The data was choreographed and recorded by a custom hardware package. Parametric data was stored at 20 HZ to a binary file. The sensing system is composed of radar, signal sniffer and video subsystems. At each intersection, signal phase are correlated with one or more lanes on a given approach. At the same time, signal sniffer provided the current light status and timing information for up to eight different signal phases.

With three days of field data collected at Peppers Ferry Intersection shown in figure 4, the study attempts include: identify the type II dilemma zone boundaries; calibrate probability of stopping model; calibrate acceleration/deceleration randomness of the vehicles in dilemma zone.

![FIGURE 2-4: The sensing network at Peppers Ferry Intersection (Cited from VTTI internal report)](image)

<table>
<thead>
<tr>
<th>Item</th>
<th>Model I: General Model with ITE boundary</th>
<th>Model II: Calibrated Model without P-R time</th>
<th>Model III: Calibrated Model with P-R time</th>
<th>Unite</th>
</tr>
</thead>
</table>

Virginia Tech
M. M. Abbas and Pengfei Li
<table>
<thead>
<tr>
<th>Percentage</th>
<th>Stopping Boundary</th>
<th>Time to Intersection</th>
<th>90%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>10%</td>
<td></td>
<td></td>
<td>5.0</td>
<td>5.9</td>
</tr>
<tr>
<td>Coefficient of Variance of Acceleration ($a_1$)</td>
<td>1.00</td>
<td>0.75</td>
<td>0.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Coefficient of Variance of Deceleration ($a_2$)</td>
<td>1.00</td>
<td>0.93</td>
<td>0.75</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Probability of Stopping Model

$$P_{stop}(t) = \Phi \left( \frac{t - 3.5}{1.17} \right)$$

$$P_{stop}(t) = \Phi \left( \frac{t - 4.05}{1.43} \right)$$

$$P_{stop}(t) = \Phi \left( \frac{t - 3.3}{0.94} \right)$$

FIGURE 2-5: Stopping probability with respect to time to intersection

### 2.4.3 Output Analysis:

Each simulation run outputs a dilemma hazard and totally 6840 dilemma hazards are generated. It is clear that all the influential factors do not evenly contribute to the dilemma hazard. Thus the first attempt is to ascertain the best-fit decision subsets for the dilemma hazard. The best subsets are enlisted in table 2.

**TABLE 2-A**

<table>
<thead>
<tr>
<th>Best Decision Variable Subsets for Model I</th>
<th>$R^2$(%)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Volume</td>
<td>Speed Limit</td>
<td>Speed Percentile for Inter-green Design</td>
</tr>
</tbody>
</table>
According to Table 2, the most influential factors are the remaining time to the stop line and speed limit in all three models. The other three factors are negligible. Consequently, it is reasonable to consider the remaining time to intersection and local speed limit only in calculating the dilemma hazard.
a: Model I:

b: Model II
FIGURE 2-6 Demonstration of dilemma hazard and primary decision variables

From figure 6, cube polynomial regression models could be set up based on the simulation outputs.

Model I:

\[ H = -1.93 + 0.00693v_0 + 2.02t - 0.566t^2 + 0.0477t^3 \]
\[ (R^2 = 91.3\%, \ S = 0.041) \] (6-a)

Model II:

\[ H = -0.666 + 0.00596v_0 + 0.865t - 0.225t^2 + 0.0159t^3 \]
\[ (R^2 = 94\%, \ S = 0.04) \] (6-b)

Model III:

\[ H = -2.73 + 0.00910v_0 + 2.59t - 0.706t^2 + 0.0575t^3 \]
\[ (R^2 = 88.2\%, \ S = 0.05) \] (6-c)

Where:

- \( H \): dilemma hazard;
- \( v_0 \): the speed limit (mph); and
- \( t \): the subject vehicle's remaining time to intersection (second).

From figure 6, three models unanimously conclude that a vehicle's dilemma hazard increases first then decrease while it is approaching a signalized intersection. The dilemma hazard is primarily decided by local speed limit and remaining time to intersection.
2.5 CONCLUSION

The dilemma hazard function modeled in this paper bridges the gaps between the two types of dilemma zone definitions. A new dilemma hazard measure is defined in this paper in terms of probability of dilemma-zone-associated accidents occurrence. This new measure overcomes the shortcomings of the prevailing but controversial assumption that all the vehicles in the dilemma zone are independent and equally hazardous. In the light of this new model, vehicles’ dilemma hazard is comprehensively decided by vehicles approaching speeds, remaining time to intersection, vehicle length and road geometries, as well as the yellow and all-red durations. The dilemma hazard will first increase, then decrease, while vehicles are moving in the dilemma zone toward intersections. The hazard function is primarily decided by the local speed limits and the subject vehicle's time to intersection at the onset of yellow indication.

There are wide potential applications with the model designed in this paper: (1) since most state-of-art dilemma zone protection systems use the number of vehicles in the type II dilemma zone as the safety measure, it is estimated the dilemma zone protection performance will be significantly increased when the safety measure is replaced with the more precise dilemma hazard measure; and (2) the dilemma model could be easily calibrated with field data to be consistent with various dilemma zone studies' conclusions, by replacing the type II dilemma zone boundaries, P-R time and other influential factors.

REFERENCES


3. OPTIMAL DETECTORS DESIGN FOR THE GREEN EXTENSION SYSTEM AT HIGH-SPEED SIGNALIZED INTERsections

Dilemma zone is an area where drivers face indecisiveness when the yellow time is presented and it is the leading cause for crashes at high-speed signalized intersections. The green extension system (GES) is the most widely used dilemma zone protection system, which extends the green phase through single or multiple advance detectors until all the vehicles in the dilemma zone are cleared. This paper presents a simulation-based GES model and a comprehensive analysis how to design advance detectors. Based on a new safety measure, dilemma hazard, this paper provides optimal designs for the most desirable traffic scenarios. The results show the optimal design could provide better dilemma zone protection than traditional designs.

3.0 Introduction:

Dilemma zone (DZ) at the signalized intersections is an area where the drivers face an indecisiveness of comfortable stopping or safety going through after the onset of yellow indication. It is the leading cause for traffic crashes and injuries at intersections (National Safety Council 2007).

Generally two types of dilemma zone exists: Gazis defined the first dilemma zone, type I DZ (D. Gazis et al. 1960), as an area where vehicles could neither stop comfortably or go through safely; type II DZ is also called "option zone" and generally defined as an area where the stopping probability decreases from 90% to 10% vehicles when yellow indication is presented. Many literatures have addressed the issue of type II dilemma zone boundaries, such as, 2.5s~5.0s (Zegeer C.V 1977); 2.0s~4.5s (Chang M.S et al. 1985); 3.0s~5.0/6.0s (J.A. Bonneson et al. 1994); 3.3s~5.3s (J.A. Bonneson and P.T. McCoy 1996) and 1.7s~4.7s (Papaioannou P 2007).

Type II DZ definition is commonly used in the design of DZ protection studies, such as, in detector-control system (J. Bonneson et al. 2002), truck priority system (Zimmerman K.H 2007), Gate Operating study at crossing of highway and railway (Moon and Coleman Iii 2003), in-vehicle dilemma zone warning system (Moon et al. 2003), Platoon identifying Algorithm (N. A. Chaudhary et al. 2003).

The green extension system (GES) is the most common dilemma zone protection system. Its mechanism is to extend the current green phase until either there are no vehicles in the dilemma zone (gap-out), or maximal green time is recalled (max-out). When max-out occurs, GES provides no protection for vehicles so max-out is hazardous and should be avoided.

3.1 Literature review:

Several detector configurations for GES were developed in the last decades. The simplest form is single-detector configuration. The 6 x 6 feet² advance detector is placed in the beginning of type II DZ. The main disadvantage is that there is no consideration of slow approaching vehicles so when gap-out occurs, slow vehicle might possibly be still in the dilemma zone. As a result, its application is very limited.
Sackman H.B et al developed another famous detector configuration (Sackman H.B et al. 1977) . They used multiple presence-mode detectors with one-second passage time throughout the DZ. The detectors placements are decided based on the safe stopping distance to the stop line. Consequently, the first detector is placed where the vehicle with design speed could stop safely; the second detector is placed where the vehicle with 10 mph less than design speed could stop safely and so on, until the last one is sufficiently close to the stop line or out of dilemma zone. Later on, TxDOT modified this method with the stopping distance criteria by AASHTO (American Association of State Highway and Transportation Officials).

Southern Section ITE ((Parsonson. P.S et al. 1974), (Southern Section ITE 1976)) also developed multi-detector configuration for GES. The controller operates in a non-locking mode and with uniform detector extension, the advance detectors are placed to ensure the slow vehicles do not enter the dilemma zone when gap out is triggered. SSITE recommended two-detector design for the green extension systems. According to the design speed, the outmost detector is placed approximately five seconds away from the stop line with 3 seconds extension time; the second detector is placed at 2.5 seconds away from the stop line with 2 second extension time.

The most prevailing GES detector configuration nowadays was developed by J.A.Bonneson(J.A.Bonneson et al. 1994), (J.A.Bonneson and P.T.McCoy 1996). Its main features include different protecting vehicle ranges and protection goals. The number of the required advance detectors is decided by the vehicle protecting vehicle range (2-detector for 70% protection and 3-detector for 95% protection). The first detector should be placed where the fastest vehicles ($V_0$) enter their dilemma zone and the second and third (optional) detectors are designed in two methods:

**Constant-speed method:** detectors locations are first decided. The second detector is placed where the vehicles, with 10 mph less than $V_0$, enter their dilemma zone. When the protecting ratio is 95%, the third detector becomes necessary and should be placed where the slower vehicles, with 20 mph less than $V_0$, enter their dilemma zone. After that, the passage time for each advance detector could be calculated according their positions and dilemma zone boundary as

$$t_i = (x_i - x_{i+1} - L_d - L_v) / v_i$$

Where

- $t_i$ is the detector $i$'s extension time;
- $x_i$ is the distance from the detector $i$'s leading edge to the stop line;
- $L_d$: average detector length;
- $L_v$: average vehicle length;
- $v_i$: speed to decide the location of detector $i+1$;

**Constant-time method:** As in the constant-speed method, the first detector is placed where the fastest vehicles enter their dilemma zone. With a uniform passage time, typically 2 seconds, the second detector's location could be obtained. Similarly, the third detector's
location could be decided and its passage time is calculated with its location and the end of dilemma zone.

Different detector designs described so far are based on various type II dilemma zone boundary studies. For comparison reason, those designs were adjusted to ensure that the same dilemma zone is used among different detector settings. Figure 3-1 shows the detector configurations in one of the most desirable traffic scenarios.

![Diagram of detector configurations](image)

**FIGURE 3-1 Different detector settings for the green extension system in one traffic scenario**

### 3.2 Problem statement:

Previous studies showed GES could effectively reduce the dilemma-zone-related accidents. Previous literature also concluded there was no absolutely best design among the prevailing methods for all traffic scenarios, but Bonneson’s method could provide the best dilemma zone protection in the most desirable scenarios (Si Jianwen et al. 2007) Nevertheless, there are no sufficient studies yet concluding the commonly-used detector methods could provide the best dilemma zone protection. Consequently, it is sensible to raise the following questions:

- Are the current detector configurations providing the optimized solutions for the green extension systems or not?
- If not, how could we exploit the potential and provide a better detector design for the green extension systems? How much could we improve?
The current mechanism of the green extension system is to extend the green time until all the vehicles in the dilemma zone are cleared. This is essentially an all-or-nothing protecting method because gap-out provides full vehicle protection but max-out provides no vehicle protection. Therefore the max-out probability is the primary measure of GES safety performance. The lower the max-out probability is, the better safety performance a GES provides.

Obviously, this objective is founded on the assumption that the vehicles in the dilemma zone are evenly hazardous, regardless of their locations and speeds. However, more and more researchers agree that vehicles’ hazardous level, when they are in the dilemma zone, is not fixed, instead, is dependent on their positions and speeds. Sharma et al proposed a hypothetical model assuming the vehicle has the largest dilemma hazard when they are in the middle of dilemma zone(Sharma A et al. 2007), but here are no explanations in that paper how they drew that conclusion.

In the authors’ option, the dilemma hazard is associated with various driving behaviors and traffic flow studies, including approaching speed distribution, stopping probability after the onset of yellow interval and the corresponding acceleration/deceleration and driver’s perception-reaction time. The drivers in the dilemma zone will have to make two sequential decisions: stop or not; the acceleration/deceleration rate considered as sufficient. Due to different perceptions of inter-green time by drivers, two types of dilemma-zone-related accidents could happen when yellow is presented: right-angle and rear-end collisions. With Monte-Carlo simulating method, the authors developed a dilemma hazard model and prove the dilemma hazard is primarily dominated by the vehicle’s approaching speed and the remaining time to the stop line.

The dilemma hazard function showed in figure 3-2 forms the foundation of this paper and it is essentially the trapped vehicles’ hazardous weight, when yellow is presented, with respect to their locations and speeds at intersections. Readers are advised to notice the property that the dilemma hazard reaches the maximum when the vehicles are in the middle of the dilemma zone.

$$HZ = -1.93 + 0.00693v_0 + 2.02t - 0.566t^2 + 0.0477t^3$$

$$(R^2 = 91.3\%, \ S = 0.04)$$

**FIGURE 3-2 Dilemma Hazard function for vehicles in the dilemma zone**
In the light of the dilemma hazard concept, the “accumulated hourly dilemma hazard” is used as a new safety measure, which stands for the weighted number of vehicles in the dilemma zone per hour. It could be generated at max-out as well as gap-out. Compared with the traditional no-gap-out-dilemma-hazard objective, a new philosophy for GES systems is proposed, allowing for vehicle’s existence in the dilemma zone at gap-outs. In this way, gap-outs occur more likely before max-outs, generating gap-out hazard. On the other hand, however, the new method could also decrease the max-out probability therefore max-out hazard. The argument is, if the detectors are designed in a way that the reduced max-out probability and therefore hazard is more than the created gap-out hazard. The new detector design will provide better dilemma zone protection for vehicles.

Following this new philosophy, the “optimal” detector configuration for the GES systems will be designed so that the least hourly dilemma hazard is generated. Obviously, in this context, the traditional design methods become special cases in which only max-out hazard is generated.

3.3 Proposed method:
On certain speed and volume condition, different detector configurations will generate different hourly dilemma hazards. A detector configuration could be considered as optimal if it generates the least dilemma zone. Mathematically the optimal detector design for GES could be modeled as an optimization problem:

\[
\min HZ = f(n,t_1,t_2,...,t_n, x_1,x_2,...,x_n)
\]

where,

HZ: average dilemma hazard per hour
n: the number of detectors;
t_i: the detector i’s passage time;
x_i: the detector i’s location;
i: the detector's number counting from upstream

\( (n,t_1,t_2,...,t_n, x_1,x_2,...,x_n \) are subject to the contraints)  \(  \) \( (1) \)

PRIORI INPUTS:
The new philosophy shares many definitions with the traditional designs and, as a result, many priori inputs also have to be addressed before optimization is deployed. The associated issues include:

- What's the protecting range of vehicles?
- What is dilemma zone protection goal?
- The coverage of protected area?
- What is Maximum Allowable Headway?
- Traffic volume?
- Approaching speed?

Protecting range of vehicles: it decides how many vehicles should be considered. Typically, 70% of vehicles’ speeds could fall into the 10 mph speed fraction around speed limit. And 95% vehicles’
speeds could fall into 20 mph speed fraction. Consequently, 85th percentile and 15th percentile speed are considered as fastest and slowest for 70% protecting range; 97.5th ratio and 2.5th percentile speeds for 95% protecting range.

Protecting goals: There are two kinds of protection goals for GES. Goal 1 is to extend green until the vehicle moves out of dilemma zone; goal 2 is to extend green until the vehicle arriving at the stop line. Nowadays, goal 2 is used more often than goal 1.

The coverage of protected area: Once the protecting range and goal are decided, the protected area is decided, too. The spatial area begins where the fast vehicles enter the dilemma zone and ends where the slowest vehicles leave the dilemma zone for goal 1 or arrive at the stop line for goal 2.

Maximum Allowable Headway (MAH): MAH is an important parameter for GES’s operation. Specifically, the longer MAH is, the more likely max-out occurs. MAH is traditionally calculated as the time that a vehicle with average speed takes to go through the protected area. However, the new design philosophy would possibly shorten the MAH and so reduce the max-out probability because, instead of clearing vehicles, new philosophy could end the current green time even there are vehicles in the dilemma zone.

Traffic volume: Higher traffic volume means shorter headways between vehicles. The higher volume is, the more likely max-out occurs. The most desirable volume for the green extension system is light or moderate.

Approaching speed: Driver dilemma problem become significant when vehicle speed is fast. Although not totally agreed, those signalized intersections with 40 or higher mph speed limits are considered as high-speed.

**DECISION VARIABLES FOR OPTIMIZATION:**

The decision variables include the number of detectors, detectors’ locations, and their extension times.

The number of advance detectors could be 1, 2, 3 or even more. However, besides the general rules, the number of advance detector is subject to some constraints, which is described in later section.

Besides the common agreement that the first detector should always be placed where the fastest vehicles enter dilemma zone. The other variables include: detectors’ locations their extensions. Each combination of those variables composes of a set of detector configuration and will generate different accumulated hourly dilemma hazard

**VARIABLES CONSTRAINTS:**

Not all the detector configurations are practically applicable since the function of advance detectors of GES is to screen certain slow vehicles but still allow certain fast vehicles to reach the next detector, or move out of dilemma zone. Consequently, constraints have to be applied to ensure detectors’ functionality.
The first intuitive constraint is that the Maximum Allowable Headway is supposed to be less than the time needed for the slowest vehicle to go through the protected area, otherwise unnecessarily long MAH might rule out appropriate gap-out opportunities before max-out is recalled. The mathematical expression is:

\[
MAH_{max} \leq \frac{BU - BL}{VL} (\text{Goal 1}) \quad \text{or} \quad MAH_{max} \leq \frac{BU}{VL} (\text{Goal 2})
\]

where,

- MAH: Maximum Allowable Headway (second);
- BU: Upper boundary of protected area (feet);
- BL: Lower boundary of protected area (feet);
- VL: the slowest speed of protected vehicles (feet per second);

\section*{Critical Speed:}

A new concept, the “critical speed” between two consecutive detectors, is introduced and defined as “The minimal speed \(v_{0(i)}\) required for a vehicle to hold green when it passes from \(D_i\) to \(D_{i+1}\)”. Mathematically, the critical speed is:

\[
v_{0(i)} = \frac{x_i - x_{i+1} - L_{Di} - L_v}{t_i}
\]

Where:

- \(x_i\): the distance of \(D_i\) to stop line
- \(x_i - x_{i+1}\): the distance between \(D_i\) to \(D_{i+1}\);
- \(t_i\): \(D_i\)’s passage time;
- \(L_{Di}\): The length of advance detector \(D_i\);
- \(L_v\): The length of average vehicle;

\section*{Basic Constraints to Critical Speed:}

The function of intermediate detectors is to gap out certain slow vehicles before they arrive at the next detector but still allow certain fast vehicles to hold green. As a result, the critical speed between two consecutive detectors should be less than the fastest speed \(V_U\), otherwise all the vehicles will trigger gap-out when they are between these two detectors, impairing the efficiency.

On the other hand, the critical speed should also be greater than the slowest speed \(V_L\), otherwise, no vehicles will be gapped out between these two detectors. Mathematically, it could be expressed as:
\[ V_L \leq v_{0(i)} = \frac{X_i - X_{i+1}}{t_i} \leq V_U \]  

(4)

**ADDITIONAL CONSTRAINTS WHEN A HIGH NUMBER OF DETECTORS ARE USED:**

Besides the basic constraints, more constraints are necessary if the number of advance detector is equal to or greater than three, multiple critical speeds exist.

As shown in figure 3-3, if \( v_{0(i)} \geq v_{0(i+1)} \), once a vehicle reaches detector \( D_{i+1} \), it means its speed \( v \) must be greater than \( v_{0(i)} \). It is obvious that this vehicle could also reach the \( D_{i+2} \) since its speed is also greater than \( v_{0(i+1)} \). No gap-out will occur. On the other hand, if the vehicle speed is lower than \( v_{0(i)} \), it will trigger gap-out before it reaches \( D_{i+1} \). As a result, no vehicles will be gapped out between \( D_{i+1} \) and \( D_{i+2} \) and the \( D_{i+2} \) is not practically functional and could be replaced by extending its immediate upstream detector’s passage time.

![FIGURE 3-3: Concept of additional constraint in three or more advance detector settings](image)

Consequently, \( v_{0(i+1)} \) has to be greater than \( v_{0(i)} \). This constraint could be mathematically expressed as:

\[ v_{0(i)} = \frac{X_i - X_{i+1}}{t_i} \leq \frac{X_{i+1} - X_{i+2}}{t_{i+1}} = v_{0(i+1)} \quad (i = 1, 2, ..., n - 2) \]

(5)

where

- \( i \): the detector number;
- \( n \): total numbers of advance detector

**CONSTRAINT TO THE LAST ADVANCE DETECTOR:**

Depending on the protection goals, the last advance detector’s passage time and location should satisfy:

\[ d_s \leq V_L \cdot t_s \text{ (Goal 1)} \quad \text{or} \quad x_0 \leq V_L \cdot t_s \text{ (Goal 2)} \]

(6)

Where,

- \( d_s \): the distance from the leading edge of last advance detector to the end of protected area;
- \( x_0 \): the distance from \( D_s \)’s leading edge to the stop line;
- \( t_s \) and \( V_L \): \( D_s \)’s passage time and lower limit of speed distribution respectively.
3.4 Objective function: a stochastic simulation-based GES Model:
It is hard to derive a close-form analytical model for the hourly dilemma hazard under different detector configurations. A simplified, simulation-based model is developed in this paper instead. This model is developed for typical major-minor high-speed intersections with two phases in one cycle. Phase 1 is for major approaches and gap out simultaneously; phase 2 is for minor approaches and recalled by maximum green only. Obviously, this simple two-phase controller timing could be easily expended to standard NEMA eight phases. It is shown in figure 3-4.

FIGURE 3-4: Hypothetical intersection fit for the simulation model

In GES model, as shown in figure 3-5, there are three modules, the VEHICLE GENERATOR, PHASE TERMINATOR, and HAZARD CALCULATOR. Figure 3-5 is for one cycle calculation.
VEHICLE GENERATOR: This module is to generate vehicles on the GES-enabled approaches. Two random parameters need to be generated for each vehicle, the speed, and its headway from the lead vehicle. The average headway between vehicles could be calculated according to the traffic volume and the headway is exponentially distributed in light or moderate traffic. On the other hand, the speeds of the approaching vehicles are normally distributed and the 85th percentile speed is 5 mph higher than the average speed. From the field and simulation observations, in light or moderate traffic, fast vehicles could keep their desired speeds by changing lanes if their lead vehicles are slow. In acknowledge of these information, vehicles that arrive at the first detector between minimum green and maximum green are generated lane-by-lane.

PHASE TERMINATOR: Under certain detector configuration and during the time between minimal green and maximal green, each vehicle call could extend the green time. With simultaneous gap-out strategy, vehicles could actually assist the slow vehicles in other lanes to reach the next detector. For an example, in the phase terminator of figure 3, with the assistance of v2, the slow vehicle v1, which will be otherwise gapped out, could reach the next detector, and place a second extension call. However, if all the vehicle extensions expire at certain time point, gap-out is triggered. If vehicle extension keeps being called until maximum green is recalled, then max-out is triggered.
HAZARD CALCULATOR: When gap-out or max-out is triggered, each generated vehicle will be inspected whether it is in the dilemma zone and, if so; its dilemma hazard is calculated and accumulated.

After hazard calculator module, one cycle is finished. Then the model is reset and run again. This process will repeat until the total simulation time reach an hour. The accumulated hourly dilemma hazard is calculated accordingly.

After the GES-enabled phase duration is identified, the cycle length could be calculated by appending the other green phase, which is recalled by maximum green only, and inter-green time.

3.5 Work being done for this paper

Preliminary studies with the developed simulation model show that this problem is not convex and there really exist better designs capable of reducing dilemma hazard further in the feasible space than traditional method. In the light of these findings, an effective and fast optimizing algorithm is being designed and globally optimal detector designs with confidence level of “α” will be suggested according to existing traffic conditions.

REFERENCES:


Si Jianwen, Urbanik, T., and Han, L. "Effectiveness of Alternative Detector Configurations for Option Zone Protection on High-Speed Approaches to Traffic Signals." Transportation Research Board 86th Annual Meeting, Washington, D.C (CD-ROM).


4. VISSIM simulation test bed for innovative signal control systems

A VISSIM-based simulation test bed for innovative signal control systems has been developed. The test bed is designed such that it could generate and automatically implement multiple traffic scenarios with different control logic, and collect data from output database after each simulation run.

At the next stage, more advanced features will be developed, such as optimizing module with VISSIM simulation engine, hardware-in-the-loop simulation and cabinet-in-the-loop simulation, etc. The conceptual illustration of the VISSIM test bed is shown in Figure 4-1.

![FIGURE 4-1 Conceptual Illustration of VISSIM Test Bed]
5. Future SCIAM Work

5.1 Smart vehicle trajectory predicting algorithm
Based on the literature review and the statement of prevailing problems, new short-term vehicle trajectory algorithm based on real-time microscopic detector data will be developed. It will combine the research efforts in driving behavior, traffic flow and signal control system studies.

5.2 Innovative phase transiting logic
Prevailing signal control systems only monitor traffic when the corresponding phase is green, the proposed logic will monitor traffic on the phase of interest through the whole cycle. It will be able to extend the current phase beyond the maximum green to avoid cutting off approaching platoon; end current red indication dynamically to allow for a platoon’s clearance and provide dilemma zone protection for the vehicles at the same time.

5.3 Automatic calibrating signal control systems with reinforcement learning
Calibration is crucial to ensure the signal control system’s performance. In the meanwhile, with time elapsing, traffic pattern will change, which cannot be automatically ascertained by systems. As a result, the state-of-practice method is to calibrate signal systems as a timing-demanding routine job. The objective of next generation signal control system is to develop a signal control system such that it is able to learn the changing driving behavior and traffic pattern via artificial intelligence knowledge and tune the controller settings accordingly.

5.4 Advanced features of VISSIM test bed for innovative signal control systems
At the next stage, more advanced features will be developed, such as fast optimizing module with VISSIM simulation engine, hardware-in-the-loop simulation and cabinet-in-the-loop simulation, etc.