Empirical investigation of critical factors affecting driver responses during the yellow phase: A case study at six Maryland intersections

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ABSTRACT

This paper presents the investigation results of driver behavioral patterns during a yellow phase, based on field observations of 1123 drivers using a specially-designed system at six signalized intersections of high accident frequency in Maryland. By classifying drivers at each intersection into aggressive pass, conservative stop, and normal groups based on their responses (i.e., stop or pass) and their distances to the stop line when the signal turns yellow, the statistical tests with the ordered-probit model clearly indicates the impacts of some critical factors on a driver's decision. Such factors include: average traffic flow speeds, traffic volume rate, the green split, the number of through and crossing lanes in the target approach, signal coordination, the difference between individual vehicle's approaching speed and average traffic flow speeds, individual driver's gender, age, and talking over cell phone or not, individual vehicle's type and model, and etc. The analysis results offer the basis for assessing the safety conditions at hazardous intersections, and for design of contra measures.

Key words: driver behavior, yellow phase, driver classification

1. INTRODUCTION

Improving traffic safety has increasingly been regarded as one of the prority transportation issues in most states. Over the past decades, intersection related crashes constituted about 30 percent of the total accidents on Maryland state routes (e.g., 34% in 2002 and 35% in 2003). Among those, about 20 percent involved red-light-runnings, which caused either fatal rear-end or side-crash collisions *(1)*. A tremendous amount of resources have been invested in projects and programs to improve the safety and efficiency at signalized intersections. Programs such as driver education, the enforcement of seat-belt use, red-light camera deployment, and operational improvements to roadway geometry have all contributed to making drivers more aware of the potential dangers at signalized intersections. Despite the progress of those programs, significantly reduced traffic signal related crashes remain a challenging task. One of the main contributors to this dilemma is the lack of sufficient understanding on how individual factors as well as external traffic environments can ultimately have an impact on a driver's decision making process within a critical segment of signalized intersections, called the dilemma zone *(2)(3)*.

The dilemma zone problem and associated driver behaviors have been examined in the literature since its initial study by Gazis, Herman, and Maraduin *(4)*. They indicated that incompatibility frequently exists between a driver's desire to comply with the yellow-light-phase indication and his/her encountered constraints. Olson and Rothery *(5)* conducted field observations at five intersections and found that drivers tend to take advantage of the long yellow-light phase and view it as an extension of the green phase. Their research concluded that driver behavior does not seem to be affected by the yellow-light phase duration, especially since most motorists do not even know the typical phase duration. Another type of dilemma associated with a driver's decision making, termed as "Type-II Dilemma" was proposed to accommodate the problem of indecision when both stopping and passing maneuvers can be executed *(6)*. Zeeger et al. *(7)* also proposed a measuring method termed as "option zone" in which 90% vehicles stop and 10% go under various distribution of conditions. Liu et al. *(8)* presents the results of empirical study on the distribution of dilemma zones for different groups of drivers at signalized intersections using a specially designed video-based system. Their empirical results have revealed that the dilemma zone is dynamic in nature with its location varying with the driving behavior patterns, and the commonly used practice of extending the yellow phase duration recommended may not eliminate all the dilemma zones.

In researching a driver's decision-making process in response to the yellow-light phase, Horst and Wilmink *(9)* indicated that such a process is governed by a multitude of factors, including driver attitude and emotional states, the crossing ability before the red phase, consequence of stopping and passing, interactions with other drivers, and the vehicle approaching speed. Extensive numerical analyses were used to illustrate the complex decision-making process and its relations with associated factors. Their employed parameters were also adopted in later studies by Milazzo, et al. *(10)*, Koppa *(11)*, Shultz, et al. *(12)*, BMI *(13)*, and the Green Book *(14)*.

In classifying driver responses during the yellow phase and identifying potential affecting factors, Shinar and Compton *(15)* observed more than 2000 drivers over a total of 72 hours at six intersections. They concluded that male drivers are more likely than female drivers in taking aggressive actions; senior drivers, in comparison with young drivers, are less likely to manifest aggressive driving patterns during a yellow-light phase; the presence of passengers was associated with lower rates of aggressive driving; and the likelihood of taking aggressive actions increases with the driver's value of time. It has also been recognized that a driver's response to a yellow-light phase may vary with some other factors such as talking on the phone or not talking on the phone. Patten *(16)* investigated the impacts of mobile-phone usage on drivers from the perspective of cognitive workload and attention resource allocation. It reported that the reaction time of most drivers increases significantly during the use of cellular phones. Caird et al. *(17)* used a driving simulator to measure the performance of 77 participants (older and younger drivers) while approaching signalized intersections when traffic signals changed from green to yellow. Xiang, et al. *(2)* performed an extensive investigation of driver responses under different populations and vehicle characteristics. Based on the survey results, they classified driver behaviors into several distinct patterns, and found that a driver's stopping/passing behavior and vehicle speed performance were affected by multiple factors. Individual driver characteristics such as gender, age, and the use of cellular phones were found to be significant affecting factors. A very recent study by El-Shawarby et al. *(18)* characterizes driver behavior at the onset of a yellow-phase transition on high-speed signalized intersection approaches using field data gathered from 60 test subjects. The impact of age and gender factors on driver behavior and their interactions with the dilemma zone distributions were recognized.

2. RESEARCH SCOPE AND OBJECTIVE

Despite the informative results provided by the previous studies, the following issues remain to be further addressed:

- *Only the impact of individual driver related factors were investigated, however the impacts of other affecting factors such as signal control features, vehicle mechanical dynamics, intersection geometric features, and average traffic flow characteristics on driver behavior were not analyzed in a systematic way. Furthermore, the complex interactions between those factors and their collective impacts on drivers were not fully investigated.*
- *The data collection process of previous studies have either been conducted in a driving simulator or implemented through strictly controller field experiments. Driver behavior extracted from such environments could be biased and unrealistic without considering its interaction with surrounding traffic environment.*
- *Due to the constraints of the sample size and the measurement method, the results of previous studies were not sufficient for definitely identifying key factors affecting driver behavior patterns in different driving populations.*

The research presented in this paper attempts to address the above issues from the following aspects:

- *Collecting detailed information on the characteristics of drivers, roadway geometric features, congestion levels, average traffic flow speeds, vehicle dynamics, and vehicle types and performances through a specially designed video-based system with properly synchronized far-side and near-side cameras.*
- *Classifying drivers into three groups: "aggressive", "conservative", and "normal", based on the critical distance to the stop line and their stop/go decision at the onset of yellow-phase transition.*

- *Employing a multi-stage, discrete statistical test for exploring the complex interrelations between a driver's response (i.e., discrete in nature) to an intersection yellow phase, his/her individual and vehicle's performance characteristics, traffic environments, and key intersection geometric features.*
- *Proposing potential safety improvement strategies and measures for traffic safety practitioners, researchers, and authorities, grounded on a better understanding of those identified vital factors and their individual as well as collective influences on the behavior of driving populations.*

The paper is organized as follows: The data collection process is briefed in Section 3, including the data collection system design and components, surveyed intersections, and the key information collected. Section 4 classifies the driving population into three distinct groups based on the response of drivers to the yellow phase, and proposes a multi-stage statistical test procedure to identify all critical factors that may impact driver responses during the yellow phase under different traffic and environmental conditions. Test results and findings are detailed in Section 5. Potential safety improvement strategies and measures constitute the core of Section 6. Conclusions and future research needs are summarized in the last section.

3. DATA COLLECTION

The Video-based Data Collection System

Note that one of the foremost critical issues for investigating intersection safety is to design a video-based field data acquisition system. This is due to the fact that all behavioral related data, such as speed and acceleration rates, for this study need to be measured at the sufficient level of accuracy and precision. Failure to do so may render either misleading or inconclusive results even with a large sample of observations. The system described hereafter is designed as a cost-effective tool for researchers to reliably observe the complex interaction process between a driver's response during the yellow phase and a variety of contributing factors.

As shown in Figure 1, the entire system for field data collection includes the following components:

- *Two DVD video cameras located at the locations with precisely measured distances from the intersection at variable time-elapse rates of up to 30 frames per second; one camera was placed at the far side along the roadway segment to monitor the spatial evolution of each approaching vehicle trapped in a yellow phase, while the other was placed near the stop line for collecting individual vehicle-related information and intersection control features;*
- *Two or three observers stationed at the stop line, responsible for recording individual driver characteristics and activities, such as driver's gender, age, passengers in vehicle or not, talking over cell phone, vehicle's type, and vehicle's model. etc;*
- *Several rewritable DVD video disks to facilitate computer operations and to save video tape conversion time;*
- *An adjustable tripod, to allow a flexible setup of the camera orientation;*

- *Orange cones, placed at identical intervals along the roadway before the survey starts as reference points for camera calibration and video benchmarking, to obtain the vehicle speed evolution profile;*
- *A frame-by frame video editing computer program, which must be able to:*
  - a) *Read the video file directly from the video disk without any converting or capturing job;*
  - b) *Superimpose reference lines onto the video image;*
  - c) *Slice the video footage into a small set of segments (up to a frame) to facilitate future analysis;*
  - d) *Record the necessary timestamps;*
  - e) *Synchronize the far-side and near-side videos so as to match the speed evolution profile of each target vehicle with its corresponding traffic condition factors, intersection geometry factors, control features, vehicle performances, and individual driver-related characteristics (19).*

Field Collected Data

With assistance from the Office of Traffic and Safety of Maryland State Highway Administration, this study selected six intersections (MD193 at MD201-WB, MD650 at Metzerott Rd.-NB, Randolph Rd. at Glenallan Rd.-WB, MD410 at Belcrest Rd.-WB, MD410 at Adelphi Rd.-WB, and MD193 at Mission Dr.-WB) for field data collection under the proposed operational guidelines and research budget constraints. A total of 56 near-side and far-side videos were collected, from which about more than 3000 samples were extracted. To ensure the data reliability, we compared each sample from the stop-line observers, near-side videos, and far-side videos. Only after the three sources are well matched, we then included this sample in the analysis dataset. Also, for some ambiguous characteristics such as driver age, we first classified the driving population into several age groups in our laboratory experiments and trained our field observers to have consistent classifications of various sample individuals. Such pre-training enables all field observers to produce the consistent results. Through the aforementioned procedure, only 1123 individual driver responses were finally accepted for use in the analysis. The key information associated with each intersection is shown in Table 1, and all collected variables are organized into the following groups for analysis:

- ***Intersection related factors:***
  - a) *Yellow phase duration*
  - b) *Cycle length*
  - c) *Number of through lanes in the target approach*
  - d) *Number of cross lanes by the target approach*
  - e) *Green split of the target approach (the ratio of green time to the cycle length)*
  - f) *Speed limit of the target approach*
  - g) *Signal coordination or not with the next intersection*
  - h) *Visibility of the next intersection's signal*
- ***Traffic characteristics****:*
  - a) *Cycle-based average speed of the target approach*
  - b) *Cycle-based average lane flow rate of the target approach*
- ***Driver characteristics:***
  - a) *Pass or stop decision*

b) *Lane position he/she chooses, and whether in platoon or not (19)*
c) *Driver's gender*
d) *Driver's age: young, some senior or senior, and middle (judging by appearance)*
e) *Passenger in vehicle or not*
f) *Driver on cell phone or not*

- ***Vehicle characteristics:***
  a) *Vehicle's type (sedan, SUV, pick-up, sports car, van, truck, or bus)*
  b) *Vehicle's model (US, Japan, Europe, or Korea)*
- ***Vehicle dynamics:***
  a) *Distance-to-stop-line* when *drivers perceive the commencement of a yellow phase (19)*
  b) *The approaching speed of the vehicle when the yellow phase starts (initial speed)*
  c) *Expected time-to-stop-line* when *drivers perceive the commencement of a yellow phase*
  d) *Speed evolution before and after the yellow phase*
  e) *Average acceleration/deceleration rates during the yellow phase*
  f) *Average perception-reaction time of the driving population (19)*

4. METHODOLODY

This study has collected a total of 1,123 observations of individual driver responses during the yellow phase at six intersections with the aforementioned data collection system. For convenience of analysis, this study has first classified the driving population into three distinct patterns: "aggressive", "conservative", and "normal", based on their response during a yellow phase, and then evaluate the complex interrelations between different driver behavior patterns and associated factors.

Classification of response behaviors

Prior to the analysis of behavior related factors, this study needs to classify all observed driver decisions into three distinct groups: aggressive, normal, and conservative. The classification is based on the assumption that there exists a critical distance (d_c) perceived by a normal driver at each intersection when he/she notices the beginning of a yellow phase. A driver, if neither aggressive nor conservative, is most likely to take the stop action if his/her current location to the stop line (x_d) is longer than the perceived critical distance (d_c). By the same token, the driver may choose to pass the intersection during the yellow phase if his/her perceived d_c is longer than x_d. Note that such a critical distance, d_c, is not directly observable from the field data (i.e., either $x_d < d_c$, or $x_d > d_c$) and it may vary with individual driver characteristics and surrounding conditions, such as intersection geometric features and traffic volume. Hence, this study has employed a discrete choice model for estimating the average d_c for driving populations at each intersection (see Table 2 and 3). A detailed description of this estimation methodology is not the focus of this paper, and is available elsewhere *(20)(21)*. A summary of the definition for classification and the resulting distribution of driving population at each intersection are shown below:

- *Group 1: "Conservative stop" – Drivers who took the stop action even though they could have proceeded through the intersection during the yellow phase (i.e., the driver makes a stop even his/her distance to the stop line x_d is less than the critical distance, d_c);*
- *Group 2: "Normal" – Drivers who took the stop action when $x_d > d_c$ or the pass action when $x_d < d_c$;*
- *Group 3: "Aggressive pass" – Drivers who aggressively passed the intersection during the yellow phase even though they were quite far away ($x_d > d_c$).*

As shown in Table 4, at all the observed intersections, the aggressive-pass group usually executes an approaching speed about 10-20% higher than the average traffic flow speed, while the conservative-stop group averagely exhibits an approaching speed about 10-15% lower than the average traffic flow speed, which verifies the difference between different driving groups.

Notation for observed factors

To facilitate the statistical analysis, Table 5 presents the notations for all field observed factors, which will be used in the hereafter presentation.

Statistical analysis

Since the dependent variables are discrete in nature, this study has employed the ordered-probit model to investigate the impacts of associated variables on the resulting driving responses.

The core concept of an ordered-probit model for a dependent variable of three classes can be presented with the following latent regression expression *(22)*:

$$y^* = \beta' x + \varepsilon$$

Where, y^* is unobservable, its observable outcomes are:

$$y = 1 \text{ if } y^* \le 0$$
$$y = 2 \text{ if } 0 < y^* \le \mu_1$$
$$y = 3 \text{ if } \mu_1 < y^*$$

The unknown parameter μ_1, representing the boundaries between ordered responses will be estimated along with β (parameters for explanatory variables).

$$\Pr ob(y = 1) = cnorm(0 - \beta' x) - 0$$
$$\Pr ob(y = 2) = cnorm(\mu_1 - \beta' x) - cnorm(0 - \beta' x)$$
$$\Pr ob(y = 3) = 1 - cnorm(\mu_1 - \beta' x)$$

A graphic depiction of the relationship between the probability and the observed outcomes is shown in Figure 2.

The unobservable latent variable y^*, in the above model is the difference between the estimated distance to the stop line and the threshold value d_c, for a driver, the discrete dependent variable is a reflection of his/her response, which is: conservative stop, normal, or aggressive pass. The independent variables are all observable and potentially associated factors.

Multi-stage statistical tests

The statistical test with the ordered-probit model for all associated factors has been divided into three stages. The focus of Stage-I analysis is to identify critical traffic factors, which serve as the set of background variables for Stage-II and Stage-III analyses. The list of variables for Stage-I test is shown below:

- ***Stage-I:***
    - *Dependent variable – one of the following responses: "conservative stop", "normal", and "aggressive pass"*
    - *Independent variable set – AVGSPEED, VOLUME, PLATOON, SPLIT, and MIDL (Test 1)*

Based on the identified background factors, the analysis at Stage-II is to investigate the impact of the following factors on the response of drivers during the yellow phase. All tests performed at Stage-II and the included factors are also shown below:

- ***Stage-II:***
    - *Test 2 – significant background variables + yellow phase duration (YD)*
    - *Test 3 – significant background variables + cycle length (CYCLE)*
    - *Test 4 – significant background variables + number of through lanes (THRUL)*
    - *Test 5 – significant background variables + number of cross lanes (CROSSL)*
    - *Test 6 – significant background variables + speed limit sign being posted or not (POST)*
    - *Test 7 – significant background variables + speed limit value (SPL)*
    - *Test 8 – significant background variables + coordination with next intersection (COOR)*
    - *Test 9 – significant background variables + a vehicle's approaching speed when the yellow starts (I_SPEED)*
    - *Test 10 – significant background variables + the difference (in percent)between each individual driver's speed and the average traffic flow speed (PER_ABOVE)*
    - *Test 11 – significant background variables + male variable (MALE)*
    - *Test 12 – significant background variables + female variable (FEMALE)*
    - *Test 13 – significant background variables + young driver variable (YOUNG)*
    - *Test 14 – significant background variables + senior driver variable (SENIOR)*
    - *Test 15 – significant background variables + middle driver variable (MIDDLE)*
    - *Test 16 – significant background variables + variable for passengers or not (PASSENGER)*
    - *Test 17 – significant background variables + talking-on-phone variable (PHONE)*
    - *Test 18-24 – significant background variables + each of the vehicle type variables: (SEDAN, VAN, SUV, PU, SPORTCAR, TRUCK, BUS)*
    - *Test 25-28 – significant background variables + each of the vehicle made variables: (JAP, US, EUR, KOR)*

5. ANALYSIS RESULTS AND FINDINGS

The results of Test-1 in Table 6 show the impacts of Stage-I factors on a driver's decision during the yellow phase. A positive and significant coefficient for the average traffic flow speed implies that the drivers are more likely to take aggressive passing actions in response to the observed yellow phase during the high-speed traffic conditions. This seems to justify the need to place speed enforcement at high-speed intersections so as to improve traffic safety. A negative coefficient for the traffic volume and green splits indicates that drivers tend to be self-restricted or constrained during the conditions of high volume or long green times, and are less likely to take the aggressive-pass action during the yellow phase.

Tests 2-8 shown in Table 6 present the estimated impacts of intersection related factors on the response of drivers during the yellow phase. As expected, factors exhibited statistical significant signs include: the number of through and crossing lanes in the target approach, and signal coordination. A negative sign for the number of through lanes, *THRUL* (-.187), and a positive sign for the required crossing lanes, *CROSSL* (.112) imply that drivers in a major intersection approach of multiple lanes are more likely to take non-aggressive responses during a yellow phase. This may be due to the collective impacts of various factors, such as experiencing more volume (as reflected in the same estimation), having a longer green duration, and thus showing less desire to take the risk during the yellow phase. In contrast, drivers in the minor approach of a major-minor roadway intersection tend to be more aggressive to go through the intersection during the yellow phase. Also revealed is the good signal coordination (*COOR*) between adjacent intersections tends to make drivers take aggressive actions during the yellow phase. This may be due to the deficiency of traditional signal progression models to take driver behavior and safety related issues into account. Most studies on signal progression try to focus on maximizing the operational efficiency of intersections, but not to minimize the total number of vehicles trapped in the dilemma zones or to minimize the total number of potential aggressive driving maneuvers. Other factors such as the yellow phase duration, the cycle length, and posted speed limit do not exhibit any significant impact on a driver's decision making during a yellow phase among those available sample observations.

Table 7-8 reports the estimated results of individual and vehicle related factors on a driver's response during the yellow phase. Tests 9-10 are focused on investigating the impact due to an individual vehicle's approaching speed, while tests 11-15 are mainly on evaluating the response differences due to the gender and age factors. Also included in the evaluation are the impacts due to having passengers and talking over the cell-phone (through Tests 16-17), vehicle types (Tests 18-24), and vehicle made (Tests 25-28). Although the estimated relations are not consistent across all six observed intersections, their statistical indications have revealed the following interesting behavioral patterns:

- *Drivers having their approaching speeds higher than the average flow speed are more likely to behave aggressively when encountering a yellow phase (PER_ABOVE: 4.160/p-value < 0.1, see Test 10 in Table 7);*
- *Male drivers are more likely to take aggressive actions when approaching the yellow phase (MALE: .652, see Test 11 in Table 7);*
- *Female drivers tend to take conservative actions when approaching the yellow phase (FEMALE: -.652/p-value < 0.1, see Test 12 in Table 7);*
- *Young drivers tend to take aggressive actions when approaching the yellow phase (YOUNG: .925/p-value < 0.1, see Test 13 in Table 7), but senior drivers are more likely to be conservative (SENIOR: -.977/p-value < 0.1, see Test 14 in Table 7);*

- *Drivers talking on phone tend to take conservative actions when approaching the yellow phase (PHONE: -1.087/p-value < 0.1, see Test 17 in Table 7);*
- *Drivers in vans tend to take conservative actions when approaching the yellow phase (VAN: -.851/p-value < 0.1, see Test 19 in Table 8);*
- *Drivers in sports cars tend to take aggressive actions when approaching the yellow phase (SPORTCAR: 1.263/p-value < 0.1, see Test 22 in Table 8);*
- *Drivers in Japan made cars exhibited the pattern of taking aggressive decisions during the yellow phase (JAPAN: .666/p-value < 0.1, see Test 25 in Table 8);*

Stage-III analysis, shown in Table 9, is designed to explore the compound impacts of individual and vehicle related factors on a driver's behavior. It is noticeable that some factors, shown insignificant during individual tests in Stage-II, reveal significant collective impacts on a driver's response during the yellow phase. For examples, the numbers of passengers that exhibit a negative but insignificant sign when the test is based on all samples, shows different and significant relations when the samples were divided by gender. As indicated in Table 9, female drivers tend to be conservative when having passengers (*FEMALE*PASSENGER: -1.057/p-value <0.1*), but not for male drivers. Similar discrepancies also exist between young and senior drivers with passengers. Also, it is noticeable that the estimation results have revealed the following additional behavioral patterns:

- *Young male drivers tend to be more aggressive than other male drivers when approaching the yellow phase (see tests 29-31);*
- *Young female drivers tend to take aggressive actions when approaching the yellow phase, while senior and middle-age female drivers tend to take conservative actions under the same situation (see tests 45-47);*
- *Both female and senior drivers with passengers tend to take conservative actions when approaching the yellow phase (see tests 48 and 73);*
- *Female drivers talking over phone tend to take conservative actions when approaching the yellow phase, but not male drivers (see tests 33 and 49);*
- *Senior and middle-age drivers talking over phone tend to take conservative actions when approaching the yellow phase, but not young drivers (see tests 61, 74, and 87);*
- *Female van-drivers tend to take conservative actions when approaching the yellow phase, but not male drivers(see tests 35 and 51);*
- *Senior and middle-age drivers in vans tend to take conservative actions when approaching the yellow phase ,but not young drivers (see tests 63, 76, and 89);*
- *Male drivers in SUVs tend to take aggressive actions when approaching the yellow phase, but not female drivers (see tests 36 and 52);*
- *Female and young drivers in sports cars tend to take aggressive actions when approaching the yellow phase (see tests 54 and 66);*
- *Male drivers in Japan-made cars are likely to take aggressive actions when approaching the yellow phase, but not female drivers (see tests 41 and 56);*
- *Young drivers in Japan-made cars tend to take aggressive actions when approaching the yellow phase, but not senior and middle-age drivers (see tests 69, 82, and 95);*
- *Female drivers in US-made cars tend to take conservative actions when approaching the yellow phase, but not male drivers (see tests 42 and 57);*

- *Young drivers in US-made cars tend to take aggressive actions when approaching the yellow phase, but not senior and middle-age drivers (see tests 70, 83, and 96);*
- *Female drivers in European and Korean made cars tend to take conservative actions when approaching the yellow phase, but not male drivers (see tests 43-44 and 58-59);*
- *Senior and middle-age drivers in European and Korean made cars tend to take conservative actions when approaching the yellow phase, but not young drivers (see tests 71-72, 84-85, and 97-98).*

6. POTENTIAL APPLICATIONS OF THE RESEARCH RESULTS

Note that the above relations between driver responses during a yellow phase and related factors are based on more than 1000 field observations at six intersections. Some of these reported relations are likely to vary at different intersections in different regions. However, the above empirical information offers some valuable information for understanding the complex interrelations between the decision of drivers and all contribution factors. The estimation results can be used in classifying the distribution of driving populations at a target intersection, and in identifying some factors that may cause drivers to act aggressively in response to the yellow phase. More importantly, with some additional modeling work, traffic safety engineers can design effective strategies to counter dilemma zone related accidents and estimate the distribution of dilemma zones. For instance, one can:

- *Enhance traditional signal timing models for possible reduction of aggressive driving related factors identified in this study without much loss of operational efficiency;*
- *Propose driver education guidelines based on the behavioral findings in this study to depress aggressive maneuvers during the yellow phase;*
- *Develop a driver behavior classification and prediction module to support the dilemma zone protection system, as shown in Figure 3. During a yellow phase, the system will track the target driver, and the intelligent module developed with the findings from this study will concurrently predict the response of the target driver, based on measurable factors. The system will activate the warning message and extend the all-red phase to prevent any read-end collision or side-crash if the target driver is computed to be trapped in his/her dilemma zone.*
- *Construct an index of traffic safety for each intersection based on the distribution of driving populations and all critical factors identified in this study and local specific observations. Responsible traffic agencies can then apply this index to prioritize the resources for safety improvement and design effective policies.*

7. CONCLUSIONS AND RECOMMEDATIONS

This study has observed the behavior of 1123 drivers in response to an encountered yellow phase and their surrounding traffic conditions at six signalized intersections. To contend with the difficulty in measuring driver responses during the relatively short yellow phase, this study has developed a video-based system that enables users to track an individual driver's speed evolution during the yellow phase before reaching the intersection. The comprehensive field data obtained with such a reliable system offers the basis for this study to rigorously profile driver behavioral patterns and analyze the impacts of various behavioral and environmental factors.

Based on the decision of each individual driver during a yellow phase and the field observed information, this study has further classified the driving populations into aggressive, normal, and conservative groups. Using an ordered-probit model, this study employed a multi-stage statistical analysis procedure and successfully identified the underlying factors that may have significant impacts on their behavior at signalized intersections. The compound impacts of multiple factors on the behavioral pattern of drivers were also evaluated.

In summary, through extensive field observations and statistical analyses, this study has reached the following tentative conclusions:

- *Driving populations at most signalized intersections, based on their responses during the yellow phase, can be classified into three distinct groups: aggressive, normal, and conservative.*
- *A variety of factors may affect a driver's decision on taking an aggressive or a conservative action during the yellow phase. Examples of factors include: average traffic flow speed, green splits, traffic volume, signal coordination, number of approach lanes, talking on the phone or not, vehicle type, age, and gender.*
- *The speed of a vehicle approaching the intersection in comparison with the average flow speed seems to be the best indicator for identifying the aggressive level of a driver.*
- *The intersection geometric features may affect a driver's response to the encountered yellow phase. For example, drivers on the minor street are more likely to take an aggressive pass decision during a yellow phase due to the allocated short green phase.*
- *A coordinated signal system may encourage drivers to take an aggressive passing decision during the yellow phase.*
- *Multiple behavioral variables could have significant compound impact on a driver's response during the yellow phase. For example, male drivers in SUVs tend to take aggressive actions when approaching the yellow phase, but not female drivers.*
- *Understanding the distribution of different driving behavioral patterns and the critical contributing factors is essential for researchers and responsible agencies to design of improvement strategies at signalized intersections.*

It should be mentioned that all above reported findings are exploratory in nature and much remains to be extended due to the complex interactions between drivers, their experienced traffic conditions, and the large number of potentially related factors. In view of the increasing demand of improving traffic safety, further research along the followings lines will be essential:

- *Conducting comprehensive speed profile analyses with appropriate traffic sensors at all major intersections plagued by accidents so as to verify the distribution of driving populations;*
- *Performing an in-depth driving population classification for intersections experiencing a high accident frequency with the video-based approach developed in this study;*

- *Refining the set of contributing variables proposed in this study, and estimate the distribution of various driver responses to the yellow-light phase with more data from intersections of different geometric features and driving populations;*
- *Performing extensive analyses on compound impacts of multiple behavioral variables for identifying various driver behavioral patterns; and*
- *Applying all the research findings to developing a set of intersection safety evaluation models, and test their effectiveness in identifying underlying factors that degrade the quality of traffic safety at intersections of high crash frequency.*

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TABLE 1 Survey intersection characteristics

Intersections*	1	2	3	4	5	6
Cycle length (seconds)	150	150	120	150	150	150
Yellow phase duration (seconds)	4.5	5	4	4.5	5	5.5
Target approach green split	0.387 - 0.491	0.603	0.450 -0.718	0.316	0.248	0.785
Speed limit (mph)	40	40	35	35	35	45
Number of through lanes in target approach	4	3	3	2	2	3
Number of cross lanes by the target approach	3	3	2	5	5	4
Coordination with next signal	Yes	No	Yes	Yes	No	No
Next signal visibility	Yes	No	Yes	Yes	No	No
Number of observations	292	360	77	128	150	116

*Intersection indices (1-6) refer to: MD193 at MD201, MD650 at Metzerott Rd., Randolph Rd. at Glenallan Rd., MD410 at Belcrest Rd., MD410 at Adelphi Rd., and MD193 at Mission Dr respectively.

TABLE 2 The estimated average critical distance, d_c, for the driving populations at each intersection

Surveyed Intersections	Yellow Duration(sec)	Cycle Length (sec)	Critical distance d_c (ft)
193@201	4.5	150	234ft
650@Metzerott	5	150	205ft
Randolph@Glenallan	4	120	269ft
410@Belcrest	4.5	150	200ft
410@Adelphi	5	150	177ft
193@Mission	5.5	150	278ft

TABLE 3 Distribution of driving populations at each intersection

Surveyed Intersections	Total Samples	Aggressive Pass	Normal	Conservative Stop
193@201	292	4% (13)	89%(260)	7% (19)
650@Metzerott	360	8% (28)	81%(292)	11% (40)
Randolph@Glenallan	77	8% (6)	84%(65)	6% (6)
410@Belcrest	128	5% (6)	90%(115)	5% (7)
410@Adelphi	150	7% (10)	83%(125)	10% (15)
193@Mission	116	8% (9)	84%(97)	8% (10)
Summary	1123	6% (72)	85%(954)	9% (97)

TABLE 4 Speed difference analyses among driving groups

Surveyed Intersections	Group	Average Speed/Std. (mph)	Percentage Above Average Traffic	Paired-t Ratio
193@201	A-Pass*	41.05/5.03	+16.0%	6.314
	Normal	35.39/5.13	0%	0.108
	C-Stop*	32.35/3.37	-8.6%	-6.290
650@Metzrott	A-Pass	38.74/7.36	+13.5%	5.540
	Normal	34.13/6.92	0%	-0.564
	C-Stop	30.00/5.29	-12.1%	-7.644
Randolph@Glenallan	A-Pass	52.25/7.43	+13.8%	8.126
	Normal	45.91/4.59	0%	-0.728
	C-Stop	40.81/6.30	-11.1%	-8.903
410@Belcrest	A-Pass	38.09/8.44	+15.3%	9.353
	Normal	31.19/7.16	-5.6%	-3.668
	C-Stop	29.55/7.08	-10.6%	-13.679
410@Adelphi	A-Pass	38.70/6.48	+21.5%	6.014
	Normal	30.49/5.13	-4.3%	-2.990
	C-Stop	27.21/4.94	-14.6%	-8.769
193@Mission	A-Pass	54.40/6.70	+12.0%	11.396
	Normal	44.15/6.36	-9.1%	-7.402
	C-Stop	41.00/5.57	-15.6%	-7.886

* A-Pass means aggressive pass group, and C-Stop means conservative stop group.

TABLE 5 Notation for factors observed during field experiments

Traffic environment related variables	
Cycle-based average traffic flow speed	AVGSPEED (mph)
Cycle-based lane flow rate	VOLUME (veh/hr/lane)
Vehicle in platoon or not	PLATOON (1 – Yes, 0 – No)
Green split	SPLIT
Lane position of the vehicle	MIDL (1 – inner lane, 0 – not inner lane)
Intersection related variables	
Yellow phase duration	YD (seconds)
Cycle length	CYCLE (seconds)
Number of through lanes	THRUL
Number of cross lanes	CROSSL
Speed limit sign posted or not	POST (1 – Yes, 0 – No)
Speed limit value	SPL (mph)
Signal coordinated or not	COOR (1 – Yes, 0 – No)
Individual vehicle dynamics variables	
Approaching speed when the yellow phase starts	I_SPEED (mph)
Percentage of vehicles above the average traffic flow speed	PER_ABOVE
Individual driver related variables	
Driver's gender	MALE (1 – Yes, 0 – No)
Driver's age (< 26 years old – Young, > 46 years old - SENIOR)	YOUNG (1 – Yes, 0 – No) SENIOR (1 – Yes, 0 – No)
Passenger in vehicle or not	PASSENGER (1 – Yes, 0 – No)
Driver on cell phone or not	PHONE (1 – Yes, 0 – No)
Individual vehicle related variables	
Vehicle is Sedan or not	SEDAN (1 – Yes, 0 – No)
Vehicle is SUV or not	SUV (1 – Yes, 0 – No)
Vehicle is Pick-up or not	PU (1 – Yes, 0 – No)
Vehicle is Sports car or not	SPORTCAR (1 – Yes, 0 – No)
Vehicle is Van or not	VAN (1 – Yes, 0 – No)
Vehicle is Truck or not	TRUCK (1 – Yes, 0 – No)
Vehicle is Bus or not	BUS (1 – Yes, 0 – No)
Vehicle is made in US or not	US (1 – Yes, 0 – No)
Vehicle is made in Japan or not	JAP (1 – Yes, 0 – No)
Vehicle is made in Europe or not	EUR (1 – Yes, 0 – No)
Vehicle is made in Korean or not	KOR (1 – Yes, 0 – No)
Dependent variables	
Driver's response patterns	GROUP (1 – conservative stop, 2 – normal, 3 – aggressive pass)

TABLE 6 Estimation results of Test 1 - 8

Parameter Coefficient [P value] (Sample Size)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
C	3.426 [<.001]	3.779 [<.001]	4.248 [<.001]	4.889 [<.001]	4.191 [<.001]	3.432 [<.001]	4.381 [<.001]	3.470 [<.001]
AVGSPEED [+]	.0382 [<.001]	.0392 [<.001]	.0401 [<.001]	.0346 [<.001]	.0440 [<.001]	.0385 [<.001]	.0388 [<.001]	.0365 [<.001]
VOLUME[-]	-.307E-02 [<.001]	-.307E-02 [<.001]	-.309E-02 [<.001]	-.325E-02 [<.001]	-.331E-02 [<.001]	-.307E-02 [<.001]	-.311E-02 [<.001]	-.321E-02 [<.001]
SPLIT[-]	-2.199 [<.001]	-2.261 [<.001]	-2.217 [<.001]	-1.804 [<.001]	-2.226 [<.001]	-2.227 [<.001]	-2.643 [<.001]	-2.309 [<.001]
MIDL[-] (570)	-.247 [.213]							
PLATOON[-] (268)	-.521 [.408]							
YD[+]		.0725 [.643]						
CYCLE[-]			-.508-02 [.422]					
THRUL[-]				-.187 [.009]				
CROSSL[+]					.112 [.003]			
POST[-] (497)						-.0174 [.863]		
SPL[-]							-.0289 [.198]	
COOR[+] (497)								.228 [.019]

TABLE 7 Estimation results of Stage-II analysis (Test 9 - 17)

Parameter Coefficient [P value] (Sample Size)	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17
C	2.639 [<.001]	2.720 [<.001]	3.202 [<.001]	3.854 [<.001]	3.217 [<.001]	3.676 [<.001]	3.579 [<.001]	3.529 [<.001]	3.795 [<.001]
AVGSPEED[+]	.0343 [<.001]	.0348 [<.001]	.0401 [<.001]	.0401 [<.001]	.0423 [<.001]	.0394 [<.001]	.0391 [<.001]	.0376 [<.001]	.0416 [<.001]
VOLUME[-]	-.302E-02 [<.001]	-.303E-02 [<.001]	-.321E-02 [<.001]	-.321E-02 [<.001]	-.323E-02 [<.001]	-.310E-02 [<.001]	-.310E-02 [<.001]	-.307E-02 [<.001]	-.328E-02 [<.001]
SPLIT[-]	-1.672 [<.001]	-1.639 [<.001]	-2.210 [<.001]	-2.210 [<.001]	-2.435 [<.001]	-2.299 [<.001]	-2.237 [<.001]	-2.230 [<.001]	-2.326 [<.001]
I_SPEED[+]	.113 [<.001]								
PER_ABOVE[+]		4.160 [<.001]							
MALE[+] (750)			.652 [.063]						
FEMALE[-] (373)				-.652 [.063]					
YOUNG[+] (591)					.925 [.004]				
SENIOR[-] (163)						-.977 [.083]			
MIDDLE[-] (369)							-.326 [.259]		
PASSENGER[-] (192)								-.609 [.378]	
PHONE[-] (118)									-1.087 [.039]

TABLE 8 Estimation results of Stage-II analysis (Test 18 - 28)

Parameter Coefficient [P value] (Sample Size)	Test 18	Test 19	Test 20	Test 21	Test 22	Test 23	Test 24	Test 25	Test 26	Test 27	Test 28
C	3.411 [<.001]	3.587 [<.001]	3.476 [<.001]	3.390 [<.001]	3.326 [<.001]	3.437 [<.001]	3.425 [<.001]	3.214 [<.001]	3.548 [<.001]	3.512 [<.001]	3.460 [<.001]
AVGSPEED[+]	.0383 [<.001]	.0368 [<.001]	.0384 [<.001]	.0386 [<.001]	.0357 [<.001]	.0384 [<.001]	.0383 [<.001]	.0381 [<.001]	.0378 [<.001]	.0387 [<.001]	.0387 [<.001]
VOLUME[-]	-.308E-02 [<.001]	-.308E-02 [<.001]	-.308E-02 [<.001]	-.303E-02 [<.001]	-.297E-02 [<.001]	-.306E-02 [<.001]	-.307E-02 [<.001]	-.303E-02 [<.001]	-.307E-02 [<.001]	-.304E-02 [<.001]	-.304E-02 [<.001]
SPLIT[-]	-2.207 [<.001]	-2.144 [<.001]	-2.226 [<.001]	-2.195 [<.001]	-2.026 [<.001]	-2.199 [<.001]	-2.201 [<.001]	-2.183 [<.001]	-2.182 [<.001]	-2.193 [<.001]	-2.223 [<.001]
SEDAN[+] (540)	.0378 [.667]										
VAN[-] (150)		-.851 [.021]									
SUV[-] (225)			-.222 [.316]								
PU[+] (94)				.609 [.221]							
SPORTCAR[+] (81)					1.263 [.009]						
TRUCK[-] (26)						-.246 [.693]					
BUS (7)							.1123 [.855]				
JAP[+] (445)								.666 [.021]			
US[-] (559)									-.252 [.541]		
EUR[-] (80)										-.725 [.354]	
KOR[-] (39)											-.734 [.187]

TABLE 9 Estimation results of the Stage III analysis (Compound Variables)

Test #	Variables	Coef.	P-Value	Test #	Parameters	Coef.	P-Value
29	MALE*YOUNG	.787	[<.001]	64	YOUNG*SUV	.199	[.185]
30	MALE*SENIOR	-.433	[.005]	65	YOUNG*PU	.916	[<.001]
31	MALE*MIDDLE	.107	[.314]	66	YOUNG*SPORTCAR	1.551	[<.001]
32	MALE*PASSENGER	.249	[.170]	67	YOUNG*TRUCK	.509	[.426]
33	MALE*PHONE	.643	[.154]	68	YOUNG*BUS	.127	[.913]
34	MALE*SEDAN	.028	[.774]	69	YOUNG*JAP	.822	[<.001]
35	MALE*VAN	.237	[.126]	70	YOUNG*US	.361	[.001]
36	MALE*SUV	.707	[<.001]	71	YOUNG*EUR	.059	[.820]
37	MALE*PU	.613	[.035]	72	YOUNG*KOR	.046	[.904]
38	MALE*SPORTCAR	.984	[<.001]	73	SENIOR*PASSENGER	-1.023	[<.001]
39	MALE*TRUCK	-.246	[.393]	74	SENIOR*PHONE	-1.041	[<.001]
40	MALE*BUS	-.104	[.876]	75	SENIOR*SEDAN	-.424	[.018]
41	MALE*JAP	.705	[<.001]	76	SENIOR*VAN	-1.648	[<.001]
42	MALE*US	.166	[.074]	77	SENIOR*SUV	-1.469	[<.001]
43	MALE*EUR	.293	[.221]	78	SENIOR*PU	.150	[.658]
44	MALE*KOR	.610	[.369]	79	SENIOR*SPORTCAR	.207	[.730]
45	FEMALE*YOUNG	.272	[.022]	80	SENIOR*TRUCK	-.604	[.379]
46	FEMALE*SENIOR	-1.394	[<.001]	81	SENIOR*BUS	-.105	[.928]
47	FEMALE*MIDDLE	-.934	[<.001]	82	SENIOR*JAP	-.329	[.153]
48	FEMALE*PASSENGER	-1.057	[<.001]	83	SENIOR*US	-.756	[<.001]
49	FEMALE*PHONE	-1.200	[<.001]	84	SENIOR*EUR	-1.579	[<.001]
50	FEMALE*SEDAN	-.028	[.817]	85	SENIOR*KOR	-1.638	[<.001]
51	FEMALE*VAN	-1.615	[<.001]	86	MIDDLE*PASSENGER	-.318	[.050]
52	FEMALE*SUV	-1.419	[<.001]	87	MIDDLE*PHONE	-1.108	[<.001]
53	FEMALE*PU	.089	[.957]	88	MIDDLE*SEDAN	-.068	[.594]
54	FEMALE*SPORTCAR	1.343	[<.001]	89	MIDDLE*VAN	-1.097	[<.001]
55	FEMALE*BUS	-.162	[.922]	90	MIDDLE*SUV	-.14E-02	[.993]
56	FEMALE*JAP	-.169	[.182]	91	MIDDLE*PU	.129	[.676]
57	FEMALE*US	-.837	[<.001]	92	MIDDLE*SPORTCAR	-.128	[.744]
58	FEMALE*EUR	-.996	[.047]	93	MIDDLE*TRUCK	-.399	[.271]
59	FEMALE*KOR	-.780	[.004]	94	MIDDLE*BUS	-.244	[.795]
60	YOUNG*PASSENGER	-.331	[.110]	95	MIDDLE*JAP	-.180	[.203]
61	YOUNG*PHONE	.569	[.237]	96	MIDDLE*US	-.424	[<.001]
62	YOUNG*SEDAN	.233	[.024]	97	MIDDLE*EUR	-.668	[.011]
63	YOUNG*VAN	.130	[.508]	98	MIDDLE*KOR	-.599	[.087]

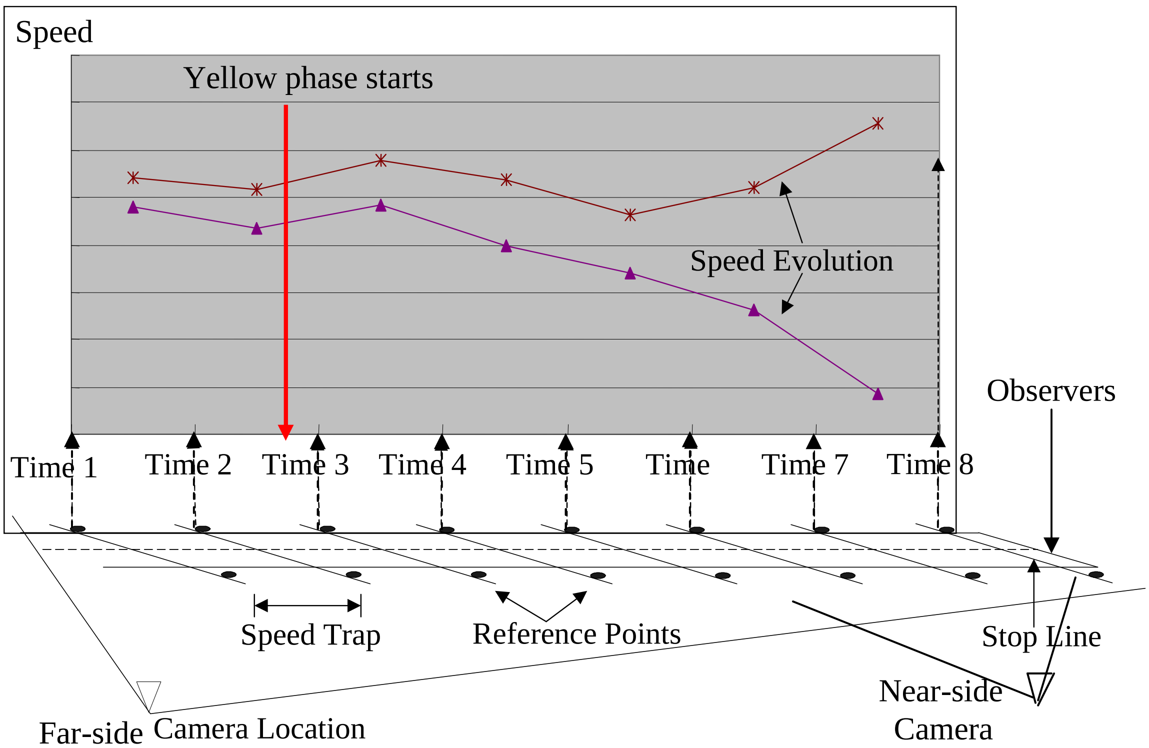

FIGURE 1 A graphic illustration of the video-based data collection system – design and components

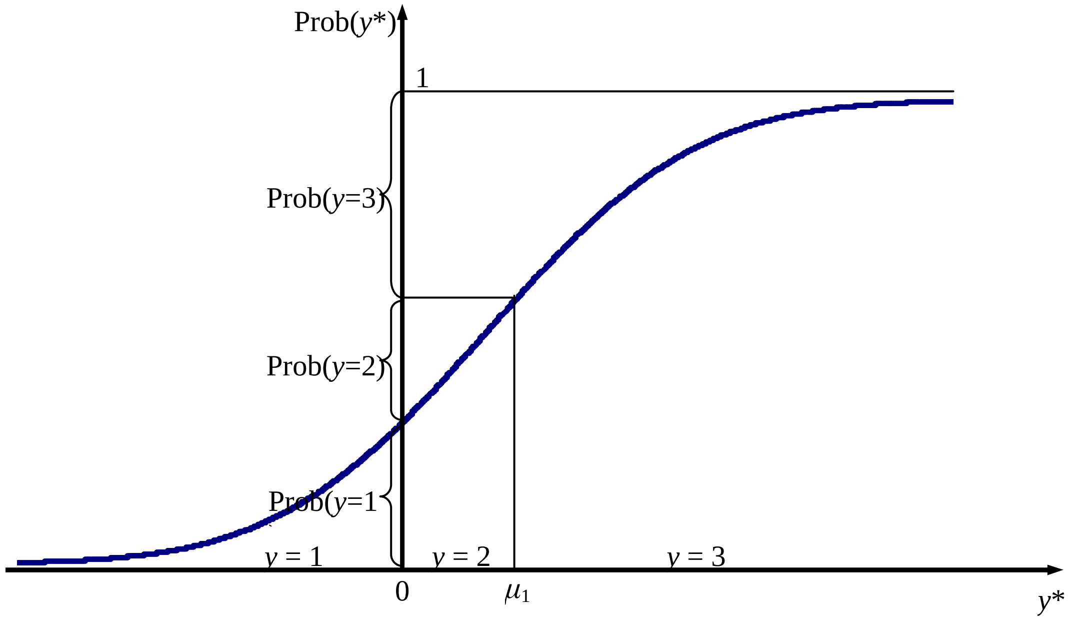

FIGURE 2 A graphical illustration of the probability distribution in an ordered-probit model.

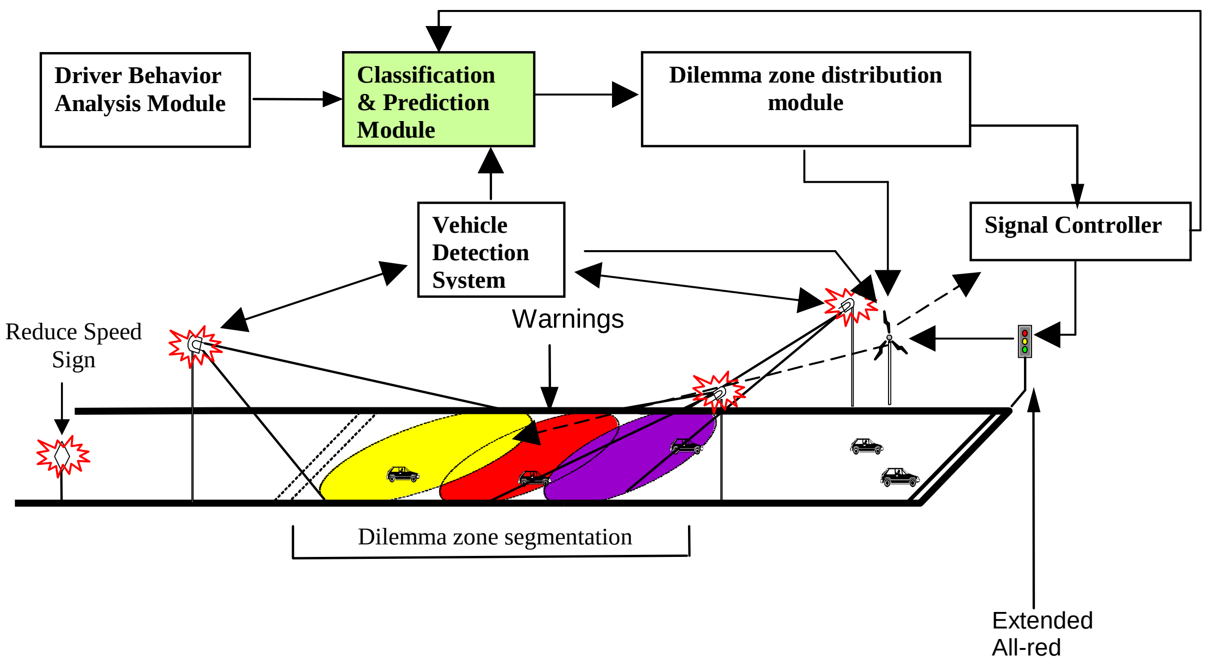

FIGURE 3 ITS-based dilemma zone protection system design