Empirical observations of dynamic dilemma zones at signalized intersections

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ABSTRACT

In this paper the author presents the results of our empirical study on the distribution of dilemma zones for different groups of drivers at signalized intersections. Using a specially designed video-based system, this study has conducted extensive field observations of 1123 drivers' responses to a yellow phase at six intersections of high accident frequency, including all critical data such as the speed evolution during the yellow phase, the acceleration/deceleration rates, and the approximate reaction time to an encountered yellow phase. Our empirical results have revealed that the dilemma zone is dynamic in nature with its location varying with the driving populations, and the commonly used practice of extending the yellow phase duration recommended may not eliminate all the dilemma zones. Two types of strategies which can effectively eliminate the dynamic dilemma zones are also designed to improve intersection safety.

Key words: yellow phase, dilemma zone, driver grouping

1. INTRODUCTION

Over the past several decades, traffic signal-related crashes constituted about 30 percent of the total accidents on Maryland state routes (e.g., 33% in 2002 and 34% in 2003). Among those, about 20 percent involved red-light-runnings, which caused either fatal rear-end or side-crash collisions *(1)*. Despite the significant progress of safety improvement programs implemented by responsible agencies over the recent years, traffic signal related crashes have not been significantly reduced. In Maryland and many other states, one of the main contributors to signal-related accidents is the existence of a dilemma zone at signalized intersections. Thus, understanding the dynamic nature of intersection dilemma zones so as to design counter measures has emerged as one of the imperative research issues in the traffic safety community *(2)*.

As defined in the ITE handbook *(3)*, a dilemma zone is a range, in which a vehicle approaching the intersection during the yellow phase can neither safely clear the intersection, nor stop comfortably at the stop-line (see Figure 1). The existing practice *(3)* for computing the dilemma zone is based on the following kinematics equation:

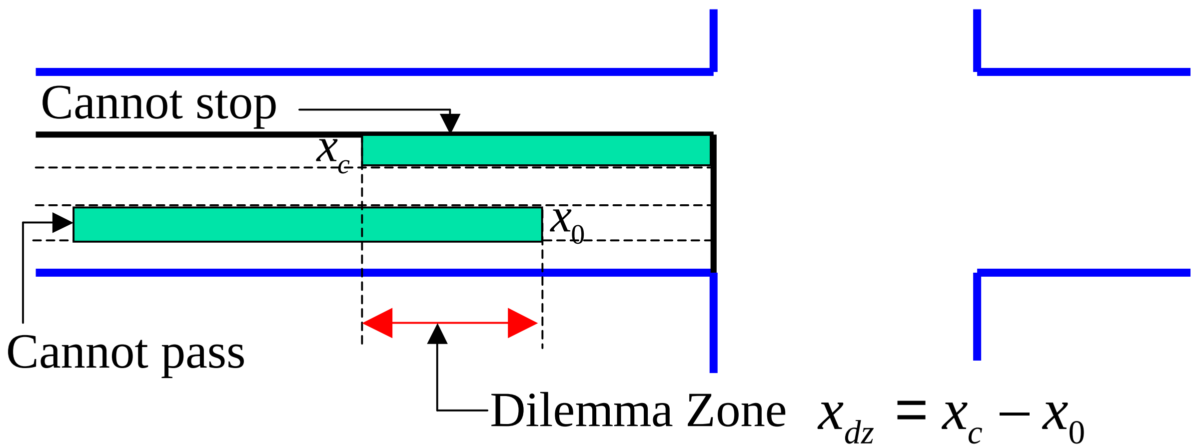


FIGURE 1 A graphical illustration of the dilemma zone at signalized intersections

$$x_{dz} = x_c - x_0 = v_0\delta_2 + \frac{v_0^2}{2a_2^*} - v_0\tau + (w + L) - \frac{1}{2}a_1^*(\tau - \delta_1)^2 \quad (1)$$

where:

x_c = the critical distance for a smooth “stop” under the maximum deceleration rate;

x_0 = the critical distance for “pass” under the maximum acceleration rate;

τ = duration of the yellow phase (*sec*);

δ_1 = reaction time-lag of the driver-vehicle complex (*sec*);

δ_2 = decision-making time of a driver (*sec*);

v_0 = approaching speed of vehicles (*ft/sec*);

a_1 = average vehicle acceleration rate (ft/s^2);

a_1^* = maximum acceleration rate of the approaching vehicles (ft/s^2);

a_2 = average vehicle deceleration rate (ft/s^2);

$a_2^* =$ maximum deceleration rate of the approaching vehicles (ft/s^2);
$w =$ intersection width (*ft*); and
$L =$ average vehicle length (*ft*).

Note that both the length and the location of a dilemma zone may vary with the speed of the approaching vehicles, driver reaction times, and vehicle acceleration/deceleration rates. Under the same condition, one can use a longer yellow phase to eliminate the dilemma zone if both the reaction time and vehicle acceleration/deceleration rates are identical among the driving populations. However, in reality the parameters, δ_1 and δ_2, which represent the perception and reaction times may vary significantly among driving populations. The maximum acceleration/deceleration rates (denoted as a_1^* and a_2^*), and the approaching speed (v_0) may also be distributed in a wide range among different driver and vehicle groups. For example, young and aggressive drivers tend to exercise a higher speed and have a shorter perception-reaction time than older and/or conservative drivers when approaching the intersection. The acceleration/deceleration rates of sport cars are certainly different from those of family sedans *(4)*. Hence, the actual dilemma zone at an intersection is more likely to be a distribution rather than a constant as computed in existing practices. Thus, an increase in the yellow duration alone may not be sufficient for eliminating all such dilemma zones for different driving populations.

In review of the literature, it is evident that the first intersection dilemma zone model, also termed as “Type-I Dilemma” was developed by Gazis, Herman, and Maraduin *(5)* in their land-marking paper, called *The GHM Model*. They also indicated that incompatibility frequently exists between a driver’s desire to comply with the yellow-light-phase indication and his/her encountered constraints. Inspired by the pioneering GHM model, Olson and Rothery *(6)* 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. The other dilemma, termed as “Type-II Dilemma” was proposed to accommodate the problem of indecision when both stopping and passing maneuvers can be executed. It defines the dilemma zone as the range in which 10 to 90 percent drivers decide to stop *(7)*. Zeeger et al. *(8)* also proposed a measuring method termed as "option zone" in which 90% vehicles stop and 10% go under the condition of stochastic traffic distribution.

Since the 1970s, dilemma zone protection systems have been deployed at the actuated intersections to mitigate the safety problems of dilemma zones. An excellent review of the related work was provided by Bonneson et al. *(9)*. However, a major drawback of those dilemma zone protection systems is the assumed static dilemma zones.

Transportation researchers in recent years began to realize that both the location and length of dilemma zones are dynamic in nature, and may vary with the complex interactions between the response of drivers, yellow phase duration, vehicle mechanical performances, intersection geometric features, and average traffic flow characteristics. For instance, Moon and Coleman *(10)* proposed a strategy to minimize the gate delay by adjusting rail-gate closing actions, based on the length and locations of dilemma zones on highway-rail intersections. McCoy and Pesti *(11)* designed a set of detection/warning strategies for safety improvements at high-speed intersections in response to the dynamic distribution of dilemma zones. For signalized intersections, several improvements of the dilemma zone protection system have been proposed *(9, 12).* Instead of using an assumed desired speed, those approaches use the measured speed of a vehicle to determine its individual dilemma zone. However, those improvements did not fully address the probabilistic nature of the dilemma zone due to the measure error and driver preferences. A recent study by Tarko, et al. *(13)* proposed a framework to deal with the probabilistic dilemma zone problem by introducing the dilemma zone likelihood function as well as a method to optimize the green extension time. Xiang, et al. *(2)* performed an extensive numerical investigation of the dilemma zone dynamics under different driving populations and vehicle characteristics. Based on the survey results, they also classified driver behavior into several distinct patterns, and identified the potential key factors that may affect a driver's decision-making process during the yellow phase. However, due to the constraints of the sample size and the measurement method, their results are informative, but not sufficient for computing the dilemma zone distribution under different driving populations.

Along the same line of research, this study will focus on the following critical subjects:

- *Design of a reliable video-based measurement system to capture the critical data needed for driver classification and analysis of dilemma zones dynamics;*
- *Classification of drivers based on their responses to the yellow phase;*
- *Analysis of different dilemma zones for different driver groups at a target intersection;*
- *Recommendations of some strategies to address the safety issues associated with the distribution of dilemma zones.*

The paper is organized as follows: The data collection system for field observations is introduced in Section 2, including the key information to collect, observation and system validation procedures and results. Section 3 classifies the driving population into three distinct groups based on the response of drivers to the yellow phase, and extracts key characteristics associated with dilemma zone computation at each target intersection. Empirical results of the dynamic dilemma zone under different driver groups and yellow phase durations are presented in Section 4. Two safety improvement designs for eliminating the dilemma zones are briefly introduced in Section 5. Conclusions and future research needs are summarized in the last section.

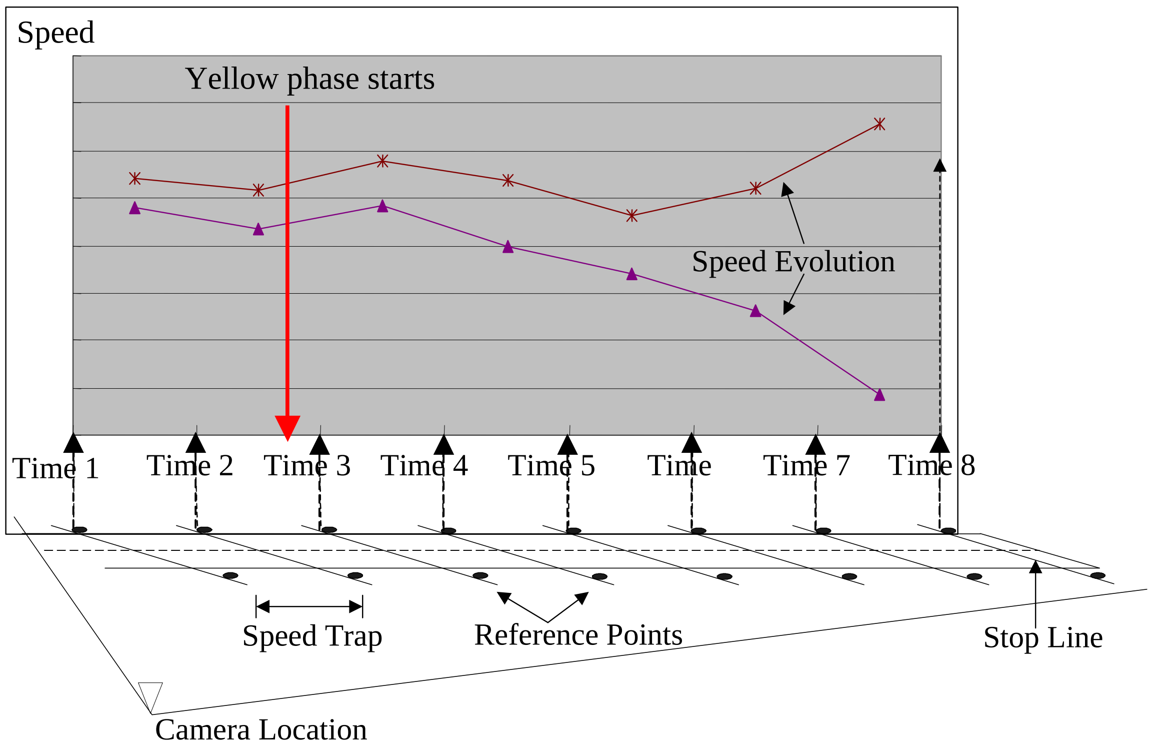
2. DATA COLLECTION SYSTEM

To capture the distribution of dilemma zones, this study has conducted field surveys at 6 typical signalized intersections in Maryland, and focused on collecting the following key information:

- *Acceleration/deceleration rates of drivers before and after a yellow phase;*
- *Distance and expected time to the stop-line when drivers perceive the commencement of a yellow phase;*
- *The speed distribution of different driving populations in response to a yellow phase.*

In order to measure the above information reliably, this study has developed a video-based data collection system, as shown in Figure 2, which has the following functions:

- *Precisely tracking each individual vehicle trapped in the yellow phase;*
- *Computing the exact distance and time for a vehicle to reach the stop-line from the start of a yellow phase;*



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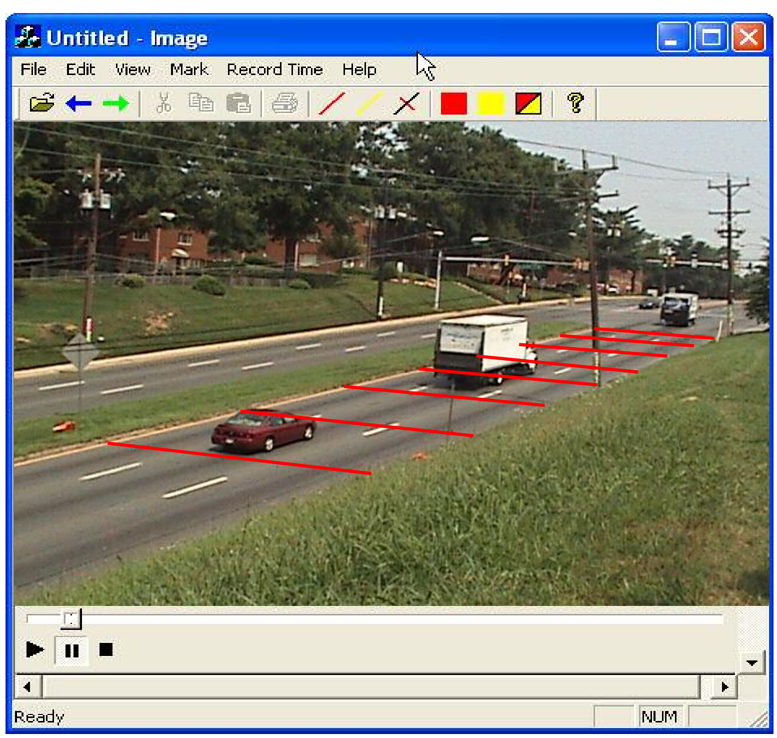


(b)

FIGURE 2 A video-based data collection system

- *Measuring the speed evolution without influencing the behavior of drivers during a yellow phase;*

The key idea of the proposed system is to superimpose reference lines over the video image and measure a vehicle's travel times between these lines sequentially to obtain the speed evolution profile. The distance between two adjacent reference lines (i.e., speed trap length) has been optimized to minimize the potential measurement errors under given operational conditions *(14)*. One can superimpose reference lines over the video image through a specially-designed computer program. The time when vehicles reach the reference line and the starting time of a yellow phase are also recorded by the program for extraction of the speed evolution profile before-and-after a yellow phase. Figure 3 illustrates the entire observation procedure with the proposed measuring system.

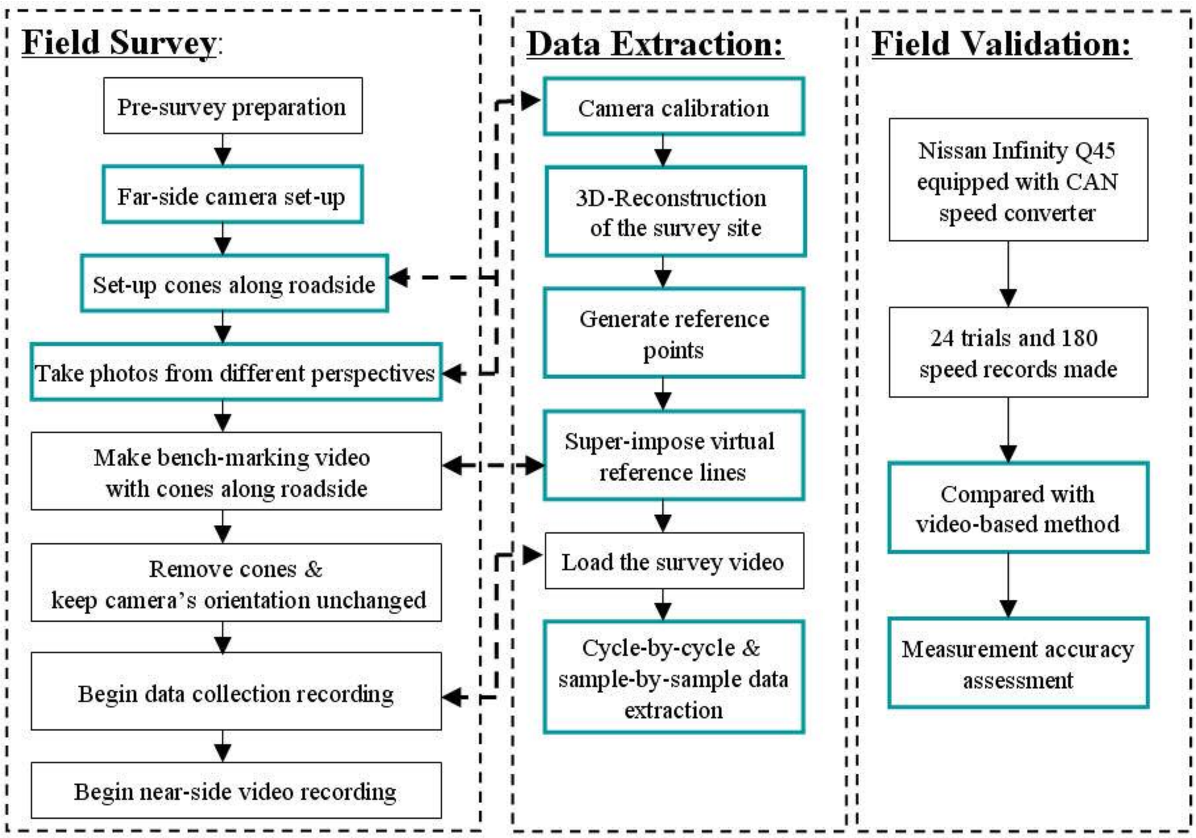
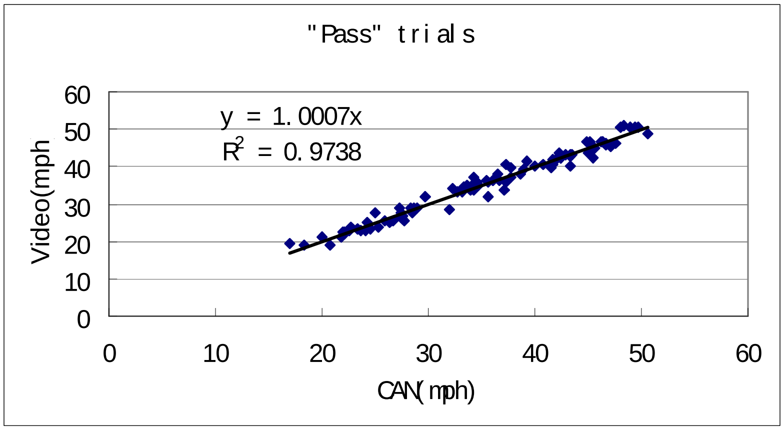


FIGURE 3 Observation procedures of the video-based measuring system

To evaluate the accuracy of the proposed system for speed measurements, this study has also conducted a field test at the intersection of MD 650 and Metzerott Road with a Nissan Infinity Q45 instrumented with a CAN message converter. The CAN message converter is a measuring device which can convert the actual speed to the precision of ±0.0001 mph, and one can connect it to a laptop computer via a serial cable to display the speed of the experimental vehicle in a time frame of every 0.01 second. The speed data from the CAN message converter are deemed as the "true" speed, and used as the basis for evaluating the accuracy of the data collected from the proposed video-based system.

The field validation consists of 24 trials over the test site with six different entry speeds (20-25, 25-30, 30-35, 35-40, 40-45, 45-50 mph), and 4 trials (2 for pass, 2 for stop) for each speed level. There are a total of 180 speed records (“pass” plus “stop” records) for the system validation. As shown in Figure 4, there exists a high correlation between the measured speeds and the actual speeds (by CAN), which indicates a high accuracy of those speeds measured with the developed video-based method.



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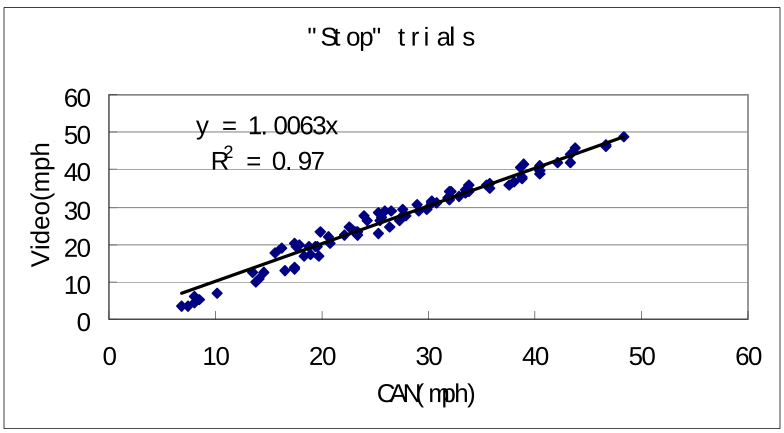

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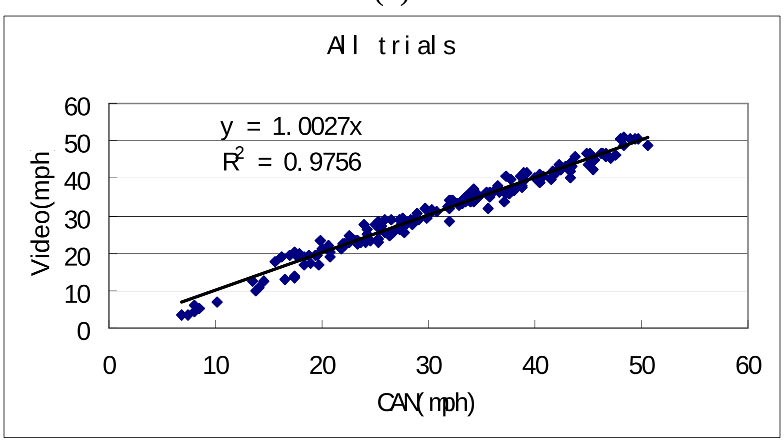


(c)

FIGURE 4 Speed measurements by video versus the CAN converter

3. CLASSIFICATION OF DRIVING POPULATION

This study has collected a total of 1,123 observations of individual driver responses over the yellow phase with the aforementioned video-based measuring system. As stated previously, driver behavior and characteristics at signalized intersections are not uniformly distributed, which will definitely affect the distribution of the dilemma zones. For convenience of analysis, this study has first classified the driving population at each sample intersection into three distinct groups: "aggressive", "conservative", and "normal", based on their response to a yellow phase, and then measuring their key characteristics, such as the approaching speed and distance to stop-line when the yellow phase starts, average acceleration/deceleration rates after the yellow phase, and their approximate perception-reaction times.

Classification of Driver Behavior

In this study, all drivers observed at each intersection are classified into the following 3 groups:

- *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-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 ($x_d > d_c$).*

The critical value d_c for driver classification can be estimated through a binary logit procedure *(15)* for each surveyed intersection based on the observations of each driver's distance-to-stop-line and response when the yellow starts.

The classification results for all the six surveyed intersections as well as the critical distances are summarized in Table 1. It is noticeable that for all surveyed intersections, the driving population is not uniform and can be classified into different groups. The above classifications will be further used as the basis for estimating the dilemma zone for each driving group.

TABLE 1 Driver classification results

(a) Critical distance-to-stop-line

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@Glennian	4	120	269ft
410@Belcrest	4.5	150	200ft
410@Adelphi	5	150	177ft
193@Mission	5.5	150	278ft

(b) Classification Results

Surveyed Intersections	Total Samples	Aggressive Pass	Normal	Conservative Stop
193@201	292	13	260	19
650@Metzerott	360	28	292	40
Randolph@Glennian	77	6	65	6
410@Belcrest	128	6	115	7
410@Adelphi	150	10	125	15
193@Mission	116	9	97	10
Summary	1123	72	954	97

TABLE 2 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@Glennian	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.

Key Characteristics Associated with Driving Groups

Based on the classification results, this study has compared the following key characteristics among driving groups:

- *Approaching speed – the speed of a vehicle when the yellow phase starts;*
- *Average acceleration/deceleration rates after the yellow phase;*
- *Perception-reaction time to the yellow phase.*

As shown in Table 2, 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. The speed difference between different groups has been verified with the pair-t test.

The mean values as well as the standard deviations of the acceleration/deceleration rates during the yellow phase for each driving group are summarized in Table 3. These empirically observed values, rather than the maximum theoretical values, can reflect the actual acceleration/deceleration maneuvers of vehicles among different driving groups after the yellow phase, and offer the basis for computing the actual dilemma zone distribution.

A driver's perception-reaction time in response to YELLOW is also a critical factor that affects the dilemma zone distribution at signalized intersections. Unfortunately, the perception-reaction time of most drivers is quite short and difficult to observe. The proposed measuring system offers a convenient way to approximate a driver's response time with his/her speed profile *(14)*, which is approximately equal to a theoretical perception-reaction time. The perception-reaction time analysis was made based on the entire sample size, and the mean values as well as the standard deviations are also summarized in Table 3.

4. DEMONSTRATION OF DYNAMIC DILEMMA ZONES

Note that with the above analyses one can effectively obtain the approaching speed, acceleration/deceleration rates, and response time of drivers at a target intersection. These critical data are essential behavioral information for estimating the dilemma zone of each target driving group.

In this paper, the dilemma zone distributions for different driving groups are estimated with Eq. (1) at each of those six intersections under the following three scenarios:

- *Estimation using the set of parameters with theoretical values (see Table 4a) recommended by the ITE handbook (3) and with the actual yellow duration from the field observation;*
- *Estimation using the set of parameters measured from field studies (see Table 4b) with the proposed video-based system and the actual yellow duration;*
- *Estimation using the set of parameters measured from field studies (see Table 4b) with the proposed video-based system and an extended yellow duration.*

Those parameter values used for estimating the dilemma zones at all observed intersections are summarized in Table 4, and the results of the dilemma zone distributions are shown in Figure 5-7. Note that in Figure 5, all six observed intersections exist no dilemma zones (denoted as the dark bar in the figure) if the existing practice and the theoretical values for all key parameters (e.g., theoretical acceleration/deceleration rates and reaction times of normal drivers) are used in the computation.

TABLE 3 Field measured acceleration/deceleration rates and drivers' response times

(a) Field measured acceleration/deceleration rates

Surveyed Intersections	a/c rates after yellow	A-Pass ($ft/\sec^2$)	Normal ($ft/\sec^2$)	C-Stop ($ft/\sec^2$)
193@201	acceleration Mean/Std	0.39/1.63	0.20/1.51	0.20/1.51*
	deceleration Mean/Std	-4.93/1.29*	-4.93/1.29	-6.46/1.67
650@Metzrott	acceleration Mean/Std	0.80/1.79	1.10/2.23	1.10/2.23*
	deceleration Mean/Std	-5.10/1.20*	-5.10/1.20	-5.20/1.42
Randolph@Glennian	acceleration Mean/Std	0.92/2.05	-0.82/3.25	-0.82/3.25*
	deceleration Mean/Std	-6.94/1.59*	-6.94/1.59	-7.61/1.55
410@Belcrest	acceleration Mean/Std	2.66/0.99	1.10/2.04	1.10/2.04*
	deceleration Mean/Std	-4.17/1.31*	-4.17/1.31	-4.22/1.94
410@Adelphi	acceleration Mean/Std	0.69/0.83	-0.28/1.46	-0.28/1.46*
	deceleration Mean/Std	-4.30/1.24*	-4.30/1.24	-5.40/1.43
193@Mission	acceleration Mean/Std	1.33/2.77	1.00/2.46	1.00/2.46*
	deceleration Mean/Std	-5.87/1.48*	-5.87/1.48	-8.24/1.78

* Use the same values as the "Normal" group.

(b) Field measured drivers' response to YELLOW

Driving Group	Applicable Sample Size	Reaction time	
Aggressive Pass	64	Mean	1.86s
		Std.	1.26s
Normal	538	Mean	1.86s
		Std.	0.72s
Conservative Stop	78	Mean	2.32s
		Std.	1.15s

TABLE 4 Parameter values applied in the computation of dilemma zones

(a) Theoretical parameter values by the ITE manual

Surveyed Intersections	Group	a_1 (ft/sec^2)	a_2 (ft/sec^2)	v_0 (mph)	τ (sec)	w (ft)	L (ft)	δ_1 (sec)	δ_2 (sec)
193@201	A-Pass	16.0	-11.2	41.05			12	1.14	1.14
	Normal	16.0	-11.2	35.39	4.5	42	12	1.14	1.14
	C-Stop	16.0	-11.2	32.35			12	1.14	1.14
650@Metzrott	A-Pass	16.0	-11.2	38.74			12	1.14	1.14
	Normal	16.0	-11.2	34.13	5	40	12	1.14	1.14
	C-Stop	16.0	-11.2	30.00			12	1.14	1.14
Randolph@Glennian	A-Pass	16.0	-11.2	52.25			12	1.14	1.14
	Normal	16.0	-11.2	45.91	4	30	12	1.14	1.14
	C-Stop	16.0	-11.2	40.81			12	1.14	1.14
410@Belcrest	A-Pass	16.0	-11.2	38.09			12	1.14	1.14
	Normal	16.0	-11.2	31.19	4.5	84	12	1.14	1.14
	C-Stop	16.0	-11.2	29.55			12	1.14	1.14
410@Adelphi	A-Pass	16.0	-11.2	38.70			12	1.14	1.14
	Normal	16.0	-11.2	30.49	5	87	12	1.14	1.14
	C-Stop	16.0	-11.2	27.21			12	1.14	1.14
193@Mission	A-Pass	16.0	-11.2	54.40			12	1.14	1.14
	Normal	16.0	-11.2	44.15	5.5	56	12	1.14	1.14
	C-Stop	16.0	-11.2	41.00			12	1.14	1.14

(b) Field measured values

Surveyed Intersections	Group	a_1 (ft/sec^2)	a_2 (ft/sec^2)	v_0 (mph)	τ (sec)	w (ft)	L (ft)	δ_1 (sec)	δ_2 (sec)
193@201	A-Pass	0.39	-4.93	41.05			12	0.93	0.93
	Normal	0.20	-4.93	35.39	4.5	42	12	0.93	0.93
	C-Stop	0.20	-6.46	32.35			12	1.16	1.16
650@Metzrott	A-Pass	0.80	-5.10	38.74			12	0.93	0.93
	Normal	1.10	-5.10	34.13	5	40	12	0.93	0.93
	C-Stop	1.10	-5.20	30.00			12	1.16	1.16
Randolph@Glennian	A-Pass	0.92	-6.94	52.25			12	0.93	0.93
	Normal	-0.82	-6.94	45.91	4	30	12	0.93	0.93
	C-Stop	-0.82	-7.61	40.81			12	1.16	1.16
410@Belcrest	A-Pass	2.66	-4.17	38.09			12	0.93	0.93
	Normal	1.10	-4.17	31.19	4.5	84	12	0.93	0.93
	C-Stop	1.10	-4.22	29.55			12	1.16	1.16
410@Adelphi	A-Pass	0.69	-4.30	38.70			12	0.93	0.93
	Normal	-0.28	-4.30	30.49	5	87	12	0.93	0.93
	C-Stop	-0.28	-5.40	27.21			12	1.16	1.16
193@Mission	A-Pass	1.33	-5.87	54.40			12	0.93	0.93
	Normal	1.00	-5.87	44.15	5.5	56	12	0.93	0.93
	C-Stop	1.00	-8.24	41.00			12	1.16	1.16

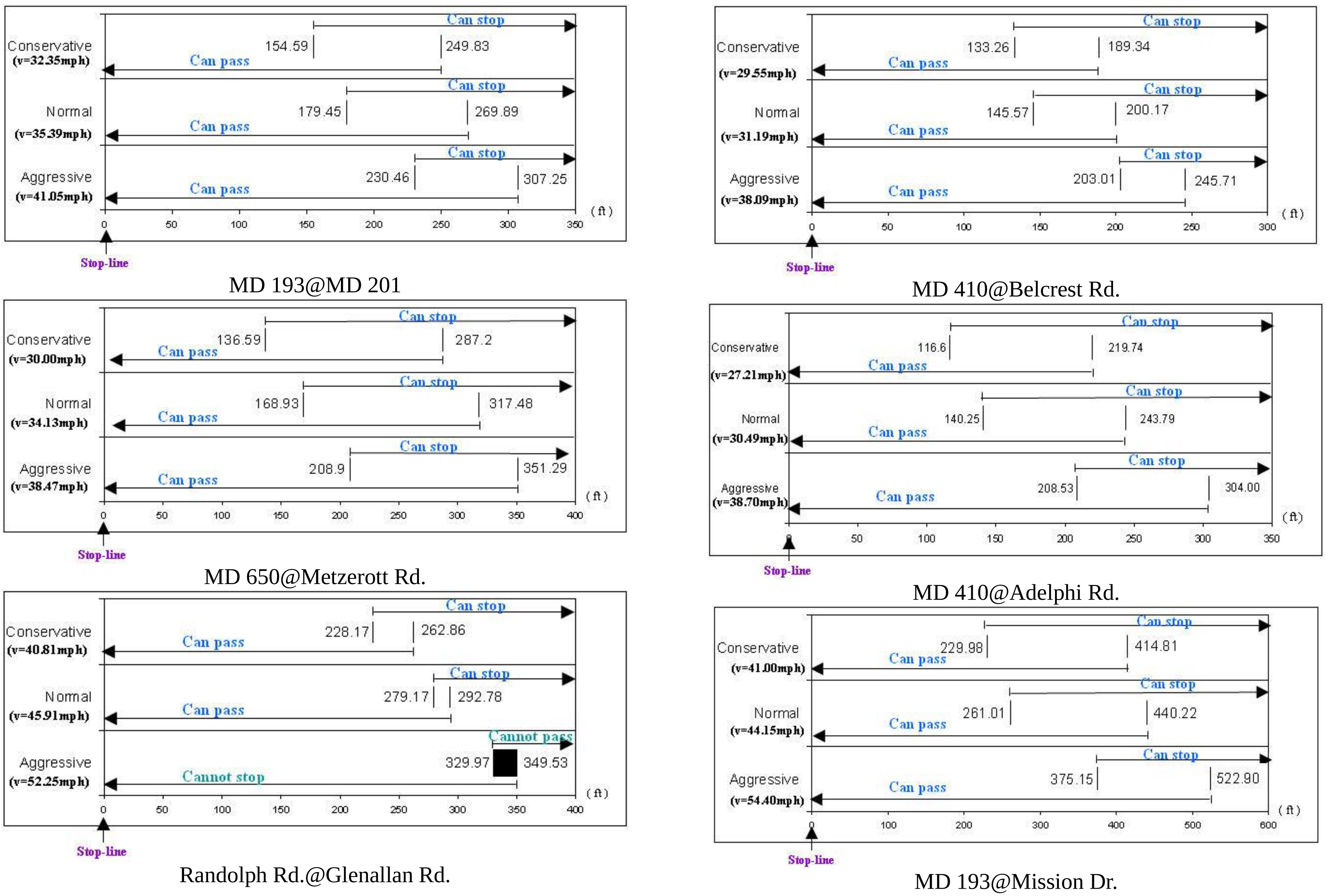
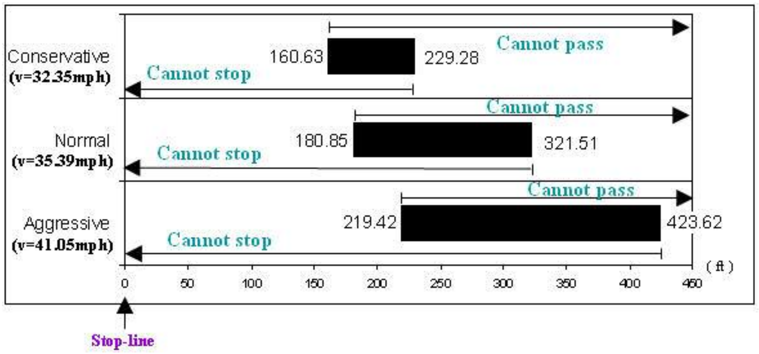


FIGURE 5 Dilemma zone estimation using theoretical parameter values



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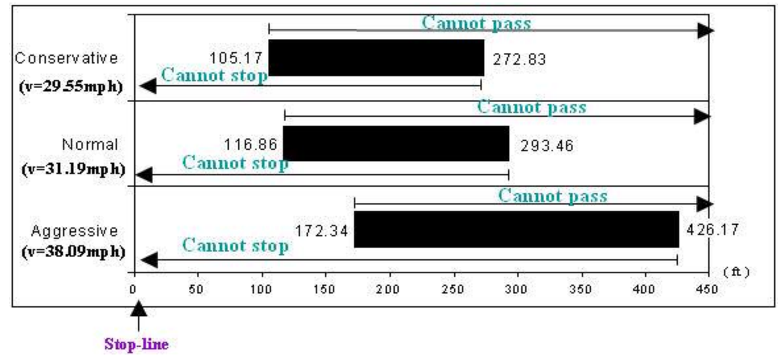

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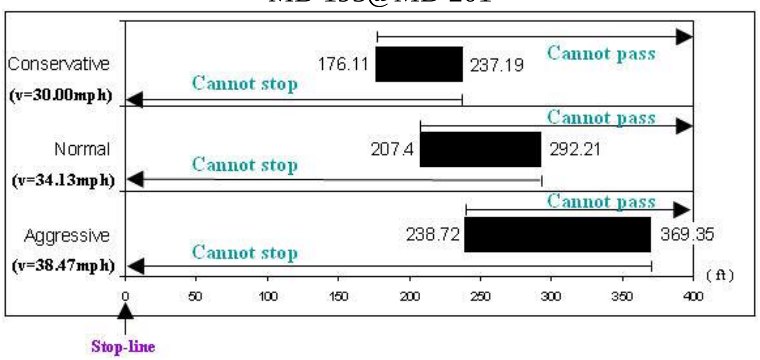

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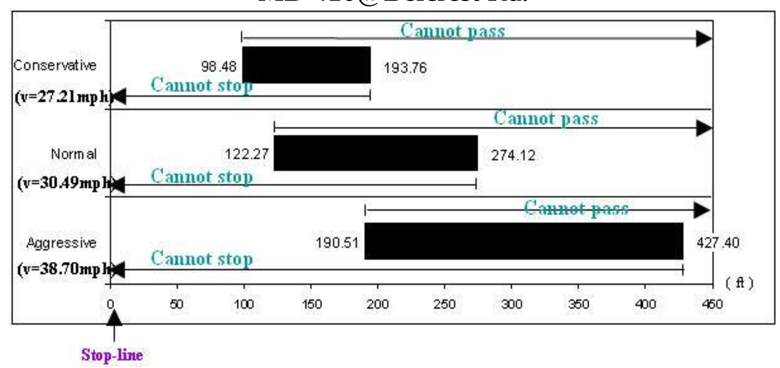

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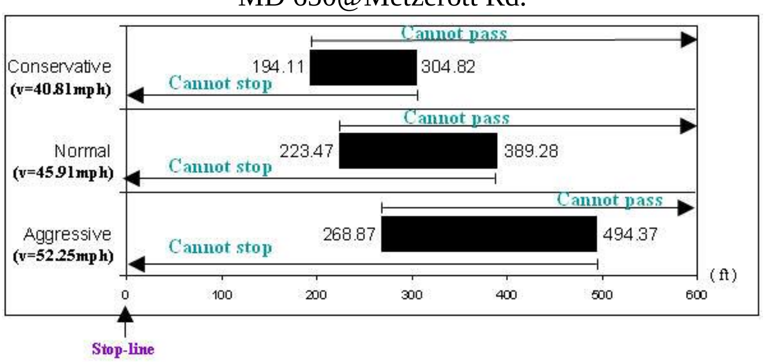
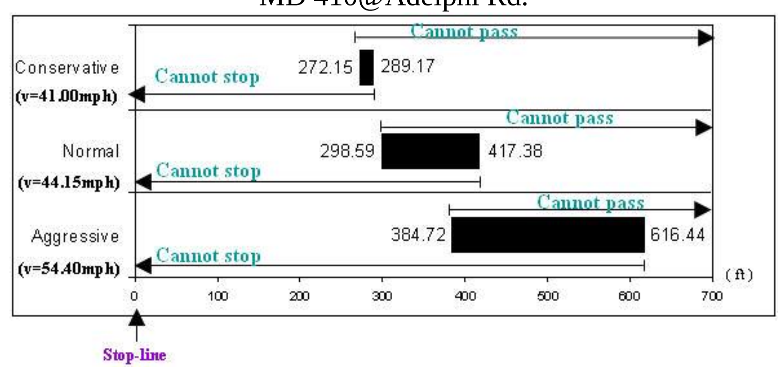
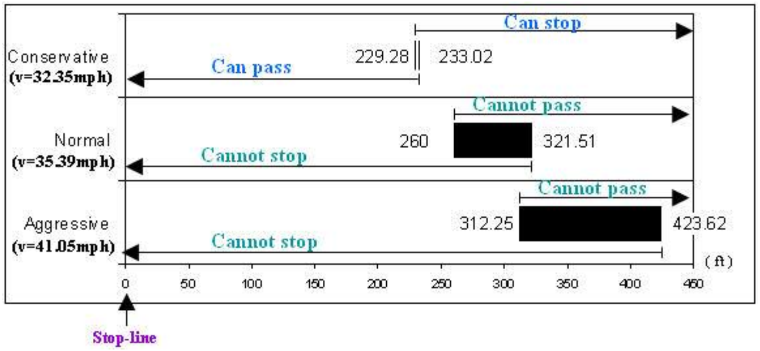


Randolph Rd.@Glenallan Rd.



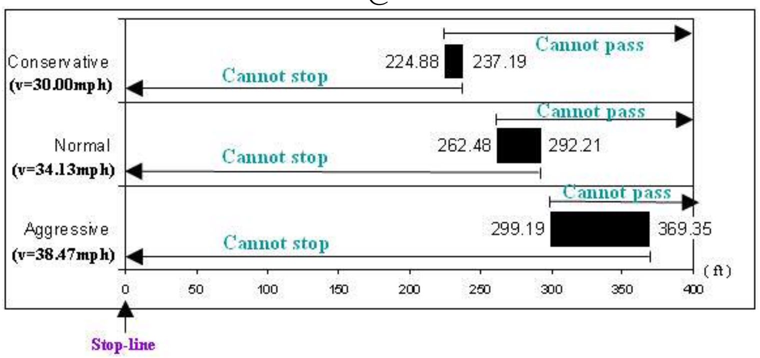
MD 193@Mission Dr.

FIGURE 6 Dilemma zone estimation using field measured parameters

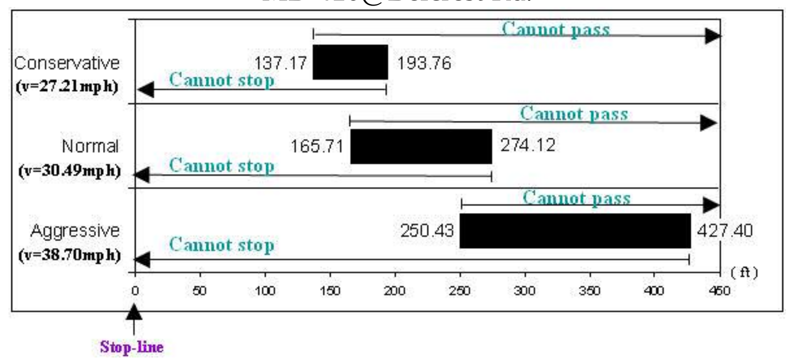


MD 193@MD 201

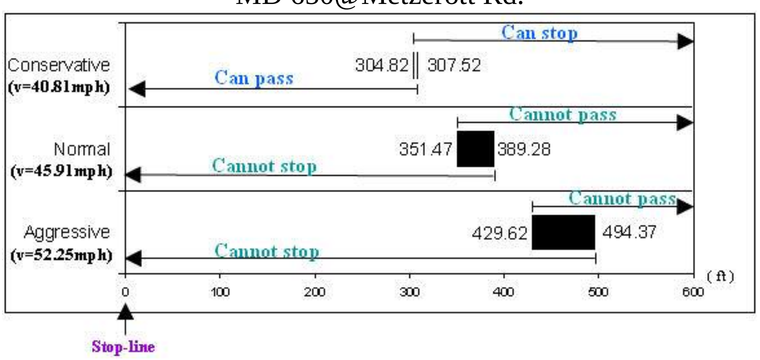
MD 410@Belcrest Rd.



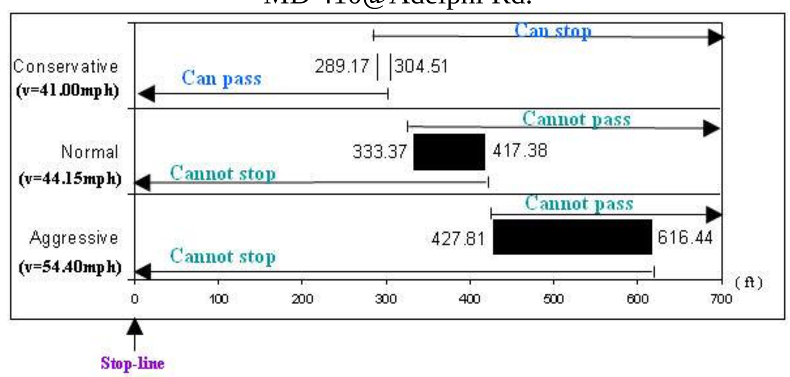
MD 650@Metzerott Rd.



MD 410@Adelphi Rd.



Randolph Rd.@Glenallan Rd.



MD 193@Mission Dr.

FIGURE 7 Dilemma zone distribution under the impact of extended yellow phase

In contrast, as shown in Figure 6, dilemma zones exist at all observed intersections if field measured parameter values are applied in the computation. For instance, at the intersection of MD193@MD201, the dilemma zone for the conservative driver group is distributed from 160.63ft to 229.28ft to the stop-line with a range of 68.65ft, while the dilemma zone for the aggressive driver group has a wider and upstream range from 219.42ft to 423.62ft to the stop-line with a length of 204.2ft. Even for the normal group, there exists the dilemma zone actually of 140.66ft (321.51ft-180.85ft). Similarly, at all other five intersections, the dilemma zone actually exists and varies with different driving populations. In general, aggressive drivers tend to encounter a wider dilemma zone with a location near the upstream of the approach than other driver groups, while conservative drivers are more easily trapped in the dilemma zone located at the downstream part of the approach.

This study has also evaluated the impact of an extended yellow duration on reducing or eliminating the dilemma zones at signalized intersections. In this case, the yellow phases at all intersection are extended to 6 seconds to see their impact on the distribution of dilemma zones. As shown in Figure 7, although the dilemma zones for all driving groups are reduced or eliminated significantly, there are still some driving groups who will encounter a dilemma zone even with the yellow duration of 6 seconds. For example, at the intersection of MD193@MD201, after extending the yellow phase from the current 4.5 seconds to 6 seconds, the dilemma zone for the conservative driver group disappears. However the dilemma zones for the normal and aggressive driver groups still exist, although significantly reduced from 140.66ft and 204.2ft to 61.51ft and 111.37ft, respectively. The same impact exists at the intersections of Randolph Rd.@Glenallan Rd. and MD193@Mission Dr. after extending their current yellow durations to 6 seconds. For the intersections of MD650@Metzerott Rd., MD410@Belcrest Rd., and MD410@Adelphi Rd., their dilemma zone distributions for all driver groups are not eliminated after the extension of the yellow phase.

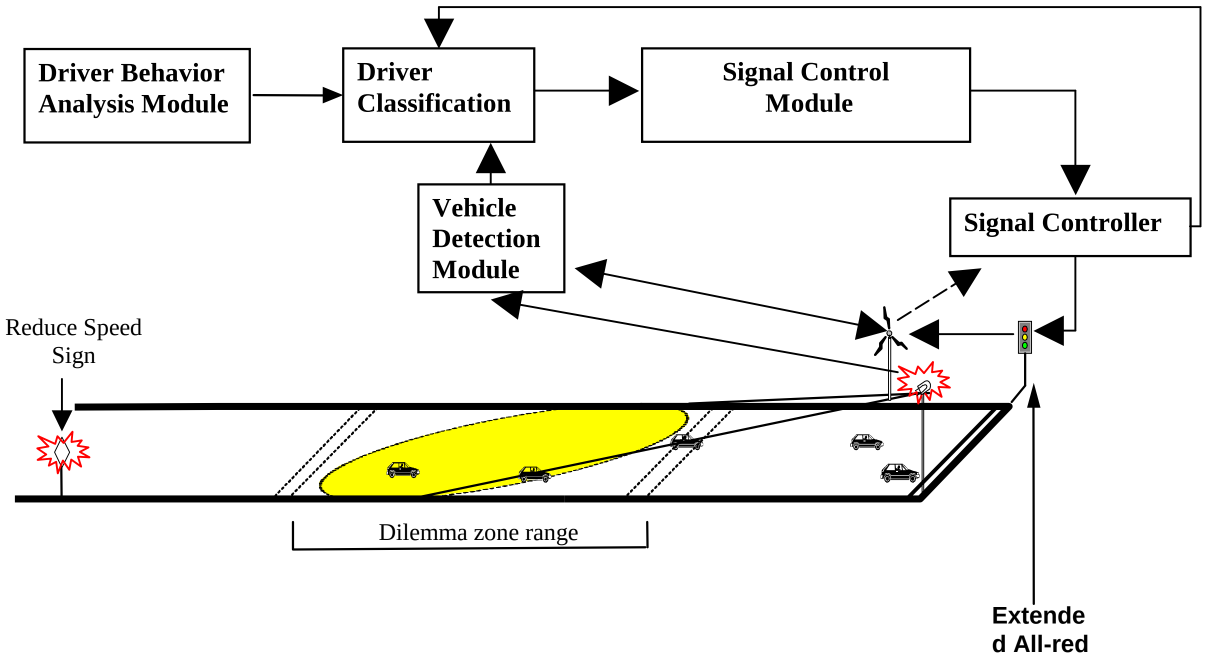
The above analysis of dilemma zones shown in Figure 5-7 can reflect the following findings:

- *For all six observed intersections, the length and the location of their dilemma zones vary with the speed of the approaching vehicles, driver reaction times, and vehicle acceleration/deceleration rates of different driving populations;*
- *There exists significant differences between the theoretically estimated and the actual distributed dilemma zones;*
- *Extension of the yellow phase alone may not eliminate all the dilemma zones.*

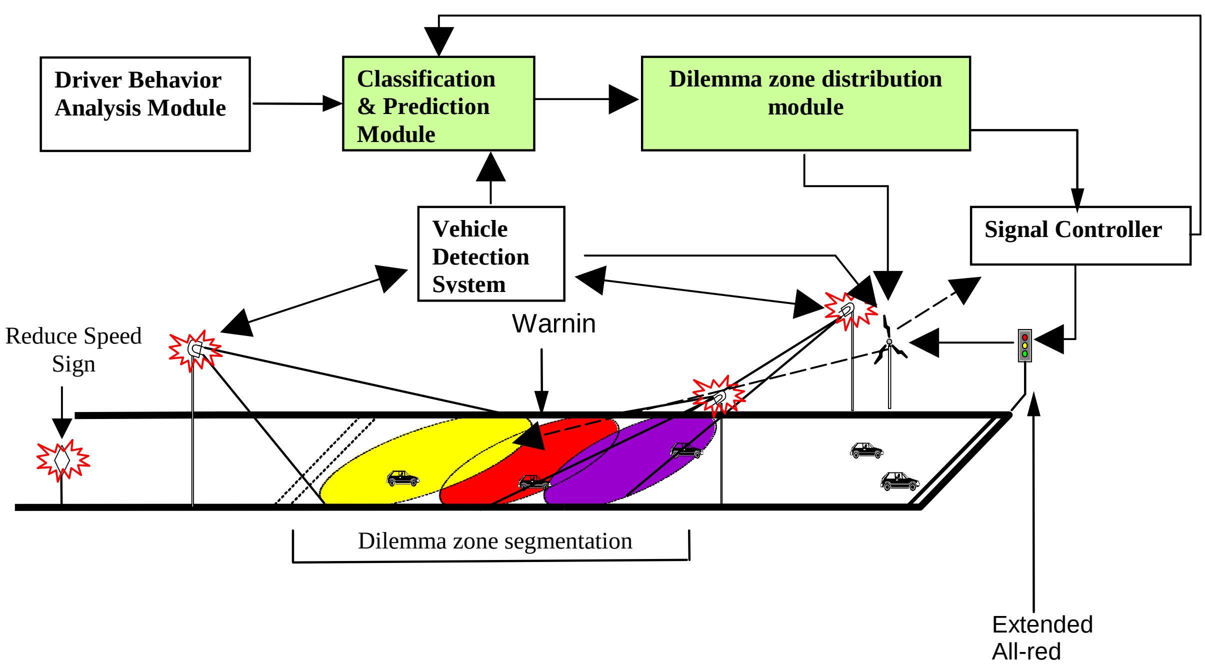
5. POTENTIAL APPLICATIONS OF THE RESEARCH RESULTS

As evidenced in the above empirical results, simply extending the yellow phase will not eliminate all the dilemma zones due to their dynamic nature. To contend with the safety issues caused by the distribution of those dilemma zones, one can apply the research results in the following two types of safety improvement designs:

The Type-I design consists of the driver behavior analysis module, vehicle detection module, and the signal control module. It is proposed to ensure that those drivers trapped into the dilemma zone can receive an extended yellow or all-red phase to clear the intersection safely (see Figure 8a). The vehicle detection module provides the system with the target vehicle's speed and position information. The driver behavior analysis module can then determine whether this vehicle could be trapped into a dilemma zone. The signal control module will be activated to extend the red-clearance time and may issue a ticket to the driver for red light violation if he/she decides to run through the intersection.



(a) Type – I design



(b) Type – II design

FIGURE 8 Safety improvement designs to eliminate the dilemma zones

Compared with Type-I, the Type-II design adds the classification and prediction module as well as the dilemma zone distribution module for different driver groups (see Figure 8b). Once a target vehicle is approaching the intersection, the classification and prediction module will identify the location of the dilemma zone for the target driver. With such a function, the system can precisely classify drivers and identify the difference in their potential to encounter dilemma zones.

6. CONCLUSIONS

The paper has presented the results of our empirical study on the distribution of dilemma zones for different groups of drivers at signalized intersections. Using a specially designed video-based system, this study has conducted extensive field observations of 1,123 drivers' responses to a yellow phase at six intersections of high accident frequency, including all critical data such as the speed evolution during the yellow phase, the acceleration/deceleration rates, and the approximate reaction time to an encountered yellow phase. The empirical results have clearly indicated the existence of multiple dilemma zones at all six intersections, and the location and range of those dilemma zones vary with the behavior of the driving population. Aggressive driver group is more likely to encounter a wide range of dilemma zone. Our numerical analyses have further evidenced the substantial differences between the theoretical dilemma zone based on the existing practice and the actual distribution of such zones. In brief, this study has concluded that:

- *The video-based measuring system developed in the study is cost-effective for measuring speed evolution at a signalized intersection, which is necessary in computing the speed, acceleration/deceleration rates, and the response time of different driving populations;*
- *The length and the location of the dilemma zone vary with the speed of the approaching vehicles, driver reaction times, vehicle acceleration/deceleration rates, and the yellow phase duration;*
- *Significant discrepancies exist between the theoretically computed distribution and the actual distribution of dilemma zones at signalized intersections;*
- *Extension of the yellow phase alone may not eliminate all dilemma zones at intersections having a high speed approaching flows.*

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