Modeling Dynamic Dilemma Zones using Observed Yellow-Onset Trajectories

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By

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ABSTRACT

Yellow phase dilemma zone is dynamically featured both in location and length due to varying driving behaviors. Traditional method of using theoretically assumed contributing factors to estimate the dilemma zone locations fails to reflect the dilemma zone dynamics, and consequently yields inaccurate location data. This paper presents a novel methodology to measure the exact locations of dilemma zones through proposing an observation-based dilemma zone model. A case study was conducted at a high-speed signalized intersection in Ohio. Time-based yellow-onset trajectories obtained with video-capture-based techniques were used to calibrate the dilemma zone model. The calibrated values of dilemma zone contributing factors well reflect the real-world dynamic driving behaviors. As a result, dilemma zone lookup charts were developed based on these factors. These charts provide an easy-to-use tool for engineers to lookup the location and length of a dilemma zone for a specific speed and under a certain yellow duration. The methodology used in this paper is capable of satisfying the needs of states in the U.S. for updating their local dilemma zone tables, and provides a solid basis for determining the advance loops layout for dilemma zone protection.

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INTRODUCTION

Intersection crashes constitute a significant portion of total crashes nationwide. The report "National Agenda for Intersection Safety"[1] quotes that in the year 2000, more than 2.8 million intersection related crashes occurred, which amount to 44 percent of all reported crashes[1]. Among all possible factors contributing to the intersection-signal-related crashes, yellow phase dilemma is one of the major problems that have not been fully solved yet.

A dilemma zone (DZ) is a roadway segment within which a vehicle approaching an intersection during the yellow interval can neither safely clear the intersection, nor stop comfortably at the stop line[2]. It is formed due to the minimum safe stopping distance (X_c) being longer than the maximum yellow clearance distance (X_0), as illustrated by Figure 1.a.

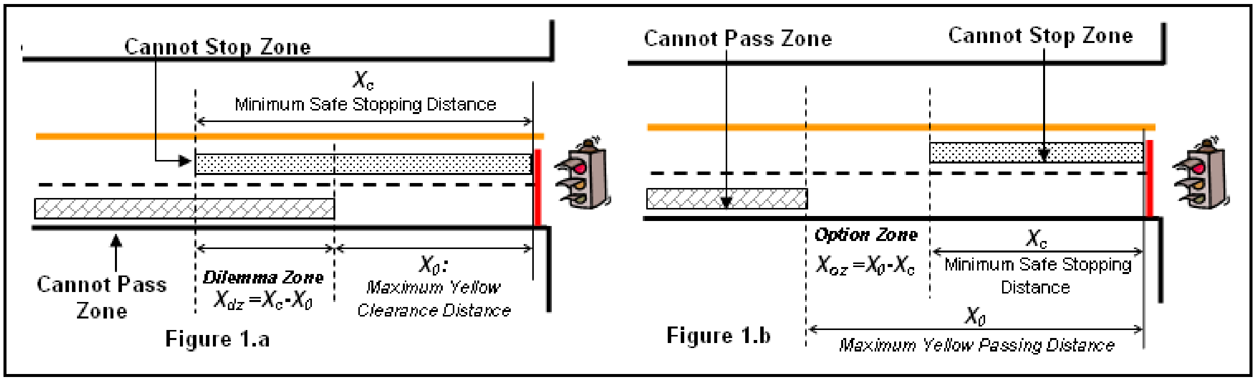

Figure 1. Formation of Dilemma Zone and Option Zone

This definition along with its mathematical model, the GHM model, is further applied in the ITE handbooks[3,4] as a guideline for determining the yellow change and all-red clearance intervals. Based on the "ITE yellow interval formula" and assumed parameter values (i.e. driver's perception-reaction time as 1.0s, and vehicle's deceleration rate as 10 ft/s^2), the calculated yellow time theoretically guarantees that X_0 is longer than X_c. Thus, it would be ensured for an approaching vehicle to either safely stop or clear the intersection during the yellow interval. At this point, the defined yellow dilemma is supposed not to exist. However, in reality this yellow dilemma is hard to be eliminated because: (1) drivers' driving behaviors vary with their different aggressiveness, and the assumed parameter values may not be compatible with all the drivers' driving features. In other words, DZ is dynamically featured in location and length[5,6], and this dynamics is reflected by the varying values of contributing factors, such as perception-reaction time (PRT), acceleration rate for passing, and deceleration rate for stopping; and (2) even though when X_0 is longer than X_c, an option zone (OZ) is formed at this time, as is illustrated by Figure 1.b. Drivers within the option zone at the yellow onset still experience indecisiveness (dilemma) about making pass or stop decisions, which also makes them highly exposed to rear-end or right-angle crashes[7,8].

Therefore, the yellow dilemma is understood as the result of existence of either DZ or OZ, and it cannot be actually eliminated. However, the effect caused by the yellow dilemma can be reduced by applying advance loops detection and green extension strategies, which aim to clear all approaching vehicles out of DZ and OZ before the onset of yellow. In this way, an accurate DZ/OZ table is essential for correctly placing the advance loops. However, the locations of X_c and X_0 in the table are used to be calculated using assumed values of contributing factors[9] based on infrastructure design experiences. Such a calculation is unable to reflect the dynamics of both driving behaviors and the DZ/OZ, and then possibly yields inaccurate DZ/OZ locations. It's hence a challenge to increase accuracy and reliability of the DZ/OZ table in estimating the locations of dynamic DZs and OZs.

Recently, Chang and Liu[6] used *fixed spatial-point* trajectory data to facilitate obtaining the locations of dynamic DZs. They calculated the DZs lengths based on the GHM model by using the average contributing factor values obtained from the trajectory data. It is a big advance in modeling the dynamic dilemma zone with trajectory data. But, calculating the DZs with those average observed factor values is still hard to reflect the DZ dynamics as well as the exact DZ locations.

This study presents a novel methodology to model the dynamic dilemma zones by proposing a new understanding of observation-based dilemma zone model. Data collection is conducted at a high-speed signalized intersection in Ohio to videotape vehicles' reaction to the yellow indications. Video-capture-based software VEVID (Vehicle Video-Capture Data Collector) is used to obtain high-resolution (up to 30 frames per second) *time-based* trajectory data at yellow onsets. *Time-based* trajectories enable obtaining vehicles' speed and distance from stop line at the exact instant when the signal indication changes from green to yellow. Statistical analysis is performed on the yellow-onset trajectories to obtain ground-truth data for calibrating the observation-based dilemma zone model. As a result of the calibration, the obtained contributing factor values vary with vehicles' approach speeds. It well reflects the nature of the dilemma zone dynamics. Finally, dilemma zone lookup charts are developed based on the calibrated dilemma zone models for their practical applications.

NEW UNDERSTANDING AND MODELING OF OBSERVATION-BASED DILEMMA ZONE

As discussed earlier, both OZ and DZ are actually two types of yellow dilemma zones while they have different characteristics. DZ is viewed as a risky zone (RZ) that retains a hazardous chance for a vehicle happening to be located within this zone to run red, because the yellow duration is insufficient for the vehicle to safely pass the stop line while not sufficient distance for the vehicle to stop before the stop line. While not as risky as DZ, the OZ potentially causes the driver's hesitation in the decision-making process whether stop or pass. Therefore, the dilemma zone is defined in this paper as a general concept and it is composed of risky zone and option zone, which are referred to DZ and OZ discussed in previous section of the paper.

In GHM model, the yellow interval is supposed to be used for clearing vehicles through the entire intersection (including the width of the intersection). However, based on field observations, when a driver perceives the yellow indication, he/she does not consider whether he/she could clear the intersection completely during the yellow interval. Actually, his/her concern is whether he/she could pass the stop line before the onset of the red indication. Therefore, in this study, the intersection width and vehicle's length are not considered in calculating the maximum yellow passing distance X_0. It is assumed that the yellow interval is only for clearing vehicles to the stop line rather than through the intersection.

Also, based on the results of previous studies, the values of dilemma contributing factors are not constant but vary at different approach speeds: the deceleration rate for stopping increases as the approach speed increases[10,11]; the acceleration rate for passing decreases as the approach speed increases[2]; and the perception-reaction time (PRT) of drivers decreases as the approach speed increases (faster drivers reacts more quickly)[10].

Based on these understandings, the classic GHM model can be modified into the following equations:

$$X_c(V_0) = V_0\delta_{stop}(V_0) + \frac{V_0^{\,2}}{2\cdot a_{stop}(V_0)} \tag{1}$$

$$X_0(V_0) = V_0\tau + \frac{1}{2}a_{pass}(V_0)\cdot[\tau - \delta_{pass}(V_0)]^2 \tag{2}$$

Where, V_0 = vehicle's approach speed (ft/s);
$X_c(V_0)$ = minimum stopping distance from the stop line at speed V_0 (ft);
$X_0(V_0)$ = maximum yellow passing distance from the stop line at speed V_0 (ft);
$\delta_{stop}(V_0)$ = driver's minimum PRT for safe stopping at speed V_0 (s);
$a_{stop}(V_0)$ = vehicle's maximum deceleration rate for safe stopping at speed V_0 (ft^2/s);
$\delta_{pass}(V_0)$ = driver's minimum PRT for safe passing at speed V_0 (s);
$a_{pass}(V_0)$ = vehicle maximum acceleration rate for passing at speed V_0 (ft^2/s);
τ = duration of the yellow interval (s).

The length of the RZ can be modeled by Equation (3), when $X_c > X_0$, while the length of the OZ can be modeled by Equation (4), when $X_0 > X_c$.

$$L_{RZ}(V_0) = X_c(V_0) - X_0(V_0) = V_0\delta_{stop}(V_0) + \frac{V_0^{\,2}}{2\cdot a_{stop}(V_0)} - \{V_0\tau + \frac{1}{2}a_{pass}(V_0)\cdot[\tau - \delta_{pass}(V_0)]^2\} \tag{3}$$

$$L_{OZ}(V_0) = X_0(V_0) - X_c(V_0) = V_0\tau + \frac{1}{2}a_{pass}(V_0)\cdot[\tau - \delta_{pass}(V_0)]^2 - [V_0\delta_{stop}(V_0) + \frac{V_0^{\,2}}{2\cdot a_{stop}(V_0)}] \tag{4}$$

According to the equations, the locations of X_c and X_0 are highly related to the contributing factors: $\delta_{stop}(V_0)$, a_{stop} $\delta_{stop}(V_0)$, δ_{pass} $\delta_{stop}(V_0)$, and a_{pass} $\delta_{stop}(V_0)$, while these factors are associated with the vehicle approach speed V_0. However, appropriate factor values that reflect the real-world travel behaviors cannot be obtained unless field observations are conducted. A good method is using the filed-observed $X_c(V_0)$s (observed minimum stopping distances at various V_0s) and the field-observed $X_0(V_0)$s (observed maximum passing distances at various V_0s) as ground truth to calibrate the X_c and X_0 models (Equations 1 and 2). In this way, appropriate values of the contributing factors can be simply obtained from the calibrated models. One obstacle for performing the model calibration is that the observed $X_c(V_0)$s *and* $X_0(V_0)$s are hard to be obtained directly from the trajectory data, because the yellow-onset speeds and distances are dynamically distributed due to varying driving behaviors. But, from a statistical point of view, profiles representing the relationship between observed Xc and V_0, and the relationship between the observed X_0 and V_0 can be obtained by performing regression analysis on the trajectory data. The results can provide the ground truth data for performing the model calibration.

To better present the new understanding of the dilemma zone dynamics and model the dilemma zone using an observation-based approach, a heuristic framework illustrating the proposed concepts is developed as shown by Figure 2.

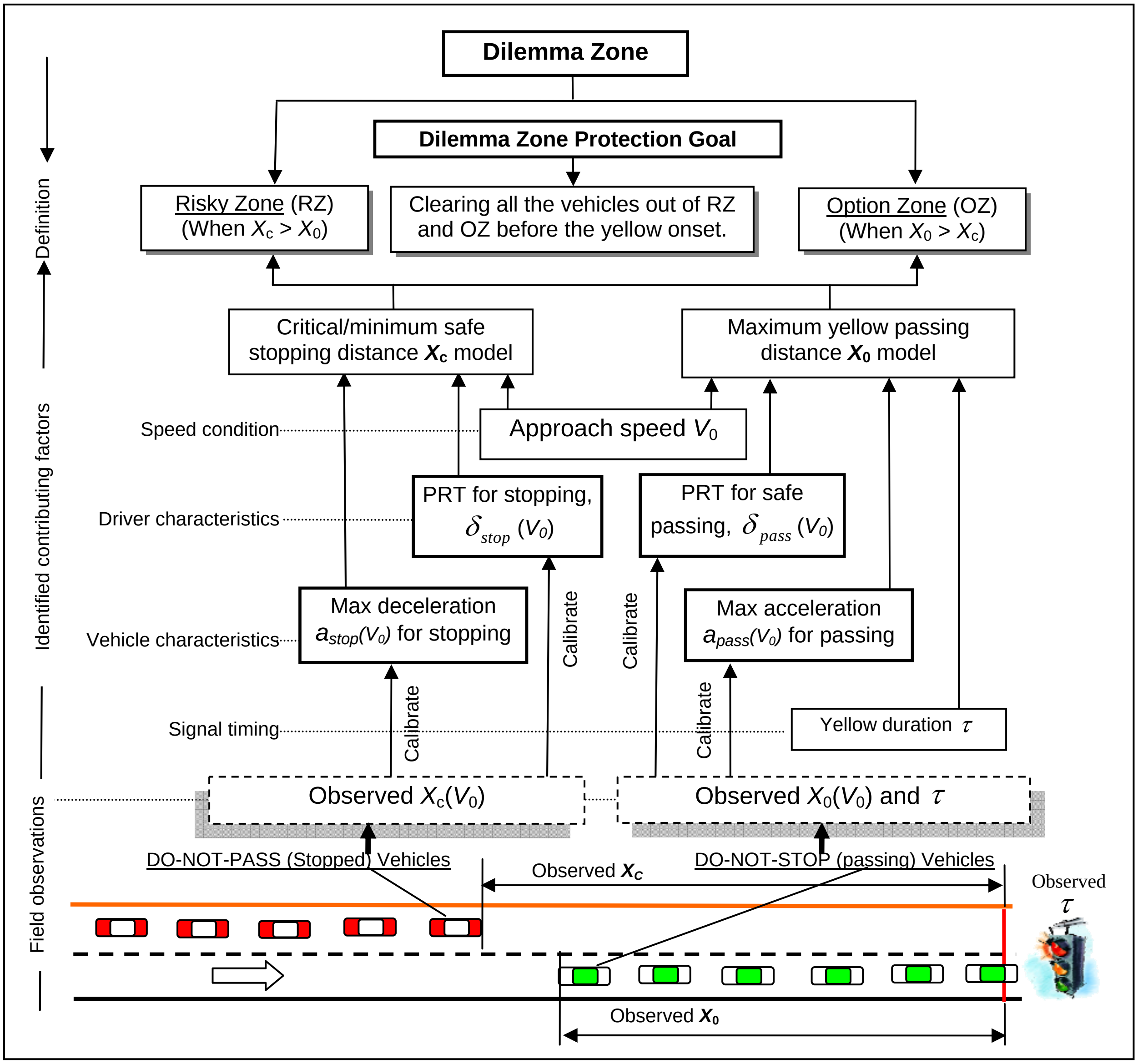

Figure 2. Heuristic Framework of Observation-Based Dilemma Zone Modeling

VIDEO DATA COLLECTION AND TRAJECTORY EXTRACTION

The intersection of OH-4 and Seward Rd. was selected as the case study site where the speed limit is 50 mph on the OH-4 approaches (see Figure 3). The yellow duration of the mainline through phase is 4.5 s. In order to guarantee the full coverage of the dilemma zone, two camcorders were placed at the right of way of the eastbound OH-4 at 300 and 500 ft from stop line, respectively. They were synchronized before videotaping, and 6.5-hour period of traffic operation was videotaped at this location.

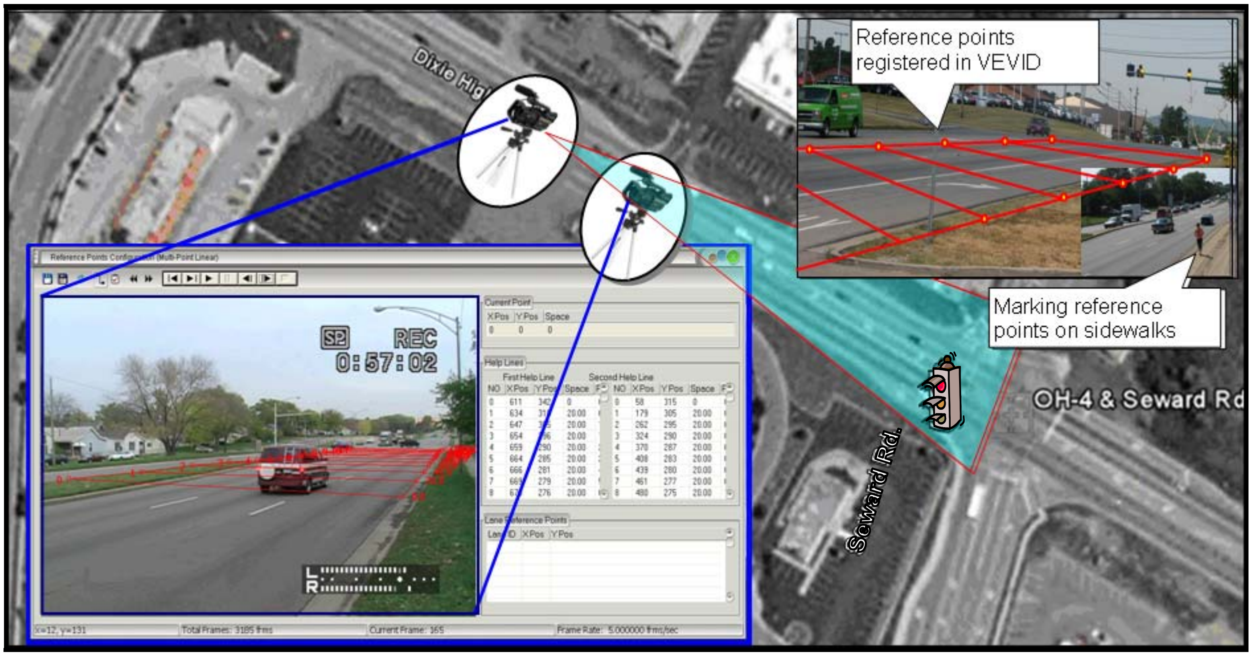

Figure 3. Video Data Collection and Trajectory Data Extraction

In field, reference points were set up from the stop line to the position of the camcorder at a fixed spacing like 20 ft along the curbs of both sides. They are used for VEVID to convert the screen-measured distance into the real world distance[12]. A chalk was used to mark those points on the curbs, and then a surveyor stepped on each mark for a short while (e.g., 5 seconds). All these actions were recorded by the camcorder.

In office, the video was played back in the environment of VEVID. Then, the marked reference points were recognized and registered into the database of VEVID by identifying the surveyor's feet locations when he stepped on the marks in the video, as shown in the top-right corner of Figure 3. In VEVID, the videos can pause at each exact yellow onset, and real world yellow-onset distance from the targeted vehicle to the stop line can be obtained by simply clicking the mouse over the contacting point between the rear tire (or front tire) and the pavement. With the distance, the yellow onset speed can be derived by dividing the distance interval between the frame of yellow onset and the preceding frame by the time interval. (e.g., time interval between two consecutive frames at the frame rate of 30 fps is 1/30 second).

During each yellow interval, only the last-to-pass (excluding those run-reds) and the first-to-stop vehicle in each through lane was targeted for extracting the trajectory data, because only these vehicles directly contribute to the formation of dilemma zone.

Besides the yellow onset distance and speed, the acceleration rate for passing and the deceleration rate for stopping were also derived and recorded for each last-to-pass vehicle and first-to-stop vehicle. And, each driver's PRT for stopping was obtained and recorded through counting the number of frames elapsed from the yellow onset to the instant when the illumination of the brake light is observed. The time used by each last-to-pass vehicle to pass the stop line from the yellow onset was also recorded.

Totally, 522 qualified vehicle samples were obtained. As a result, the observed acceleration rate for passing ranges from -1.16 ft/s^2 to 13.03 ft/s^2; the observed deceleration rate for stopping ranges from -3.25 ft/s^2 to -16.1 ft/s^2; the observed PRT for stopping is within the range from 0.39 s to 2.12 s; and the observed time used to pass the stop line is within the range from 0.1 s to 4.5 s with the 95th percentile value being 4.23 s.

MODEL CALIBRATION WITH TRAJECTORY DATA

This model calibration process is realized by trialing and fitting the modeled X_c and X_0 values (Based on Equations 1 and 2) to the ground-truth X_c and X_0 values, by searching appropriate values of the contributing factors.

During the calibration process, the calibrated values of the contributing factors are guaranteed satisfying the following constrains: the deceleration rate for stopping increases as the approach speed increases; the acceleration rate for passing decreases as the approach speed increases; both PRTs for stopping and passing decrease as the approach speed increases; and all values of the contributing factors are within the observed ranges.

The dilemma zone models are to be calibrated using two different sets of ground-truth data. The first set of ground-truth data is based on the observed maximum yellow passing distance and the observed minimum stopping distance. The model calibration process consists of the following steps.

Step 1: trajectories of the first-to-stop vehicles are plotted on a coordinate system with the yellow-onset speeds on the vertical axis and the yellow-onset distances from stop line on the horizontal axis, as is illustrated by Figure 4.

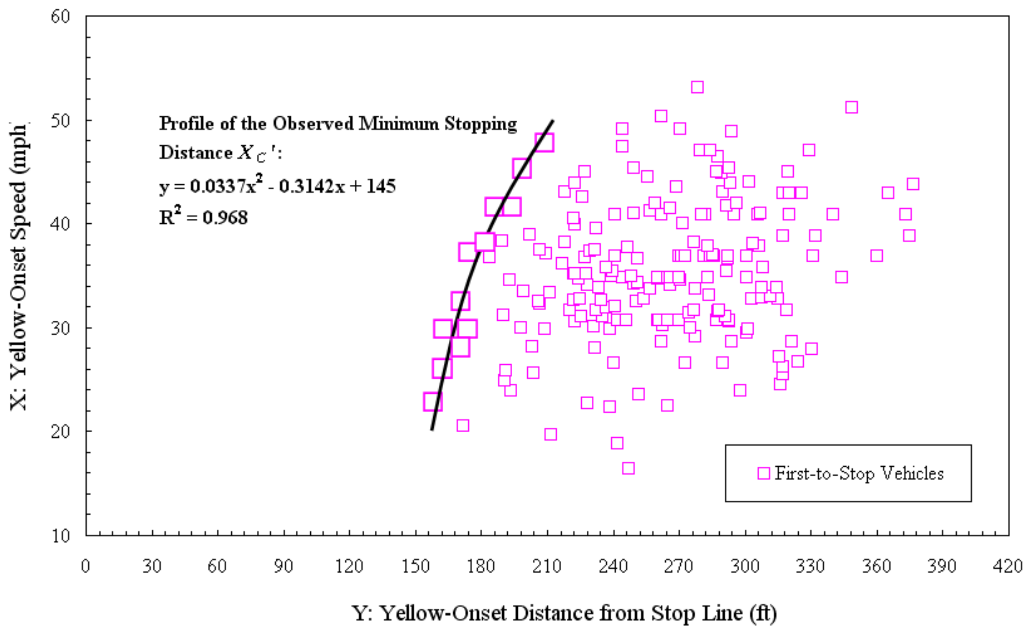

Figure 4. Identifying the Ground-truth Profile of the Observed Min Stopping Distance

The ground-truth profile of the observed minimum stopping distance X_c' is identified by performing regression analysis on those trajectories with minimum stopping distances at various speeds. The relationship between X_c' and V_0 can be mathematically expressed by the following equation.

$$X_c' = 0.0337V_0^2 - 0.3142V_0 + 145 \quad (5)$$

$R^2 = 0.968$

Step 2: Similarly, trajectories of the last-to-pass vehicles are plotted on a coordinate system with the yellow-onset speeds on the vertical axis and the yellow-onset distances from stop line on the horizontal axis, as is illustrated by Figure 5.

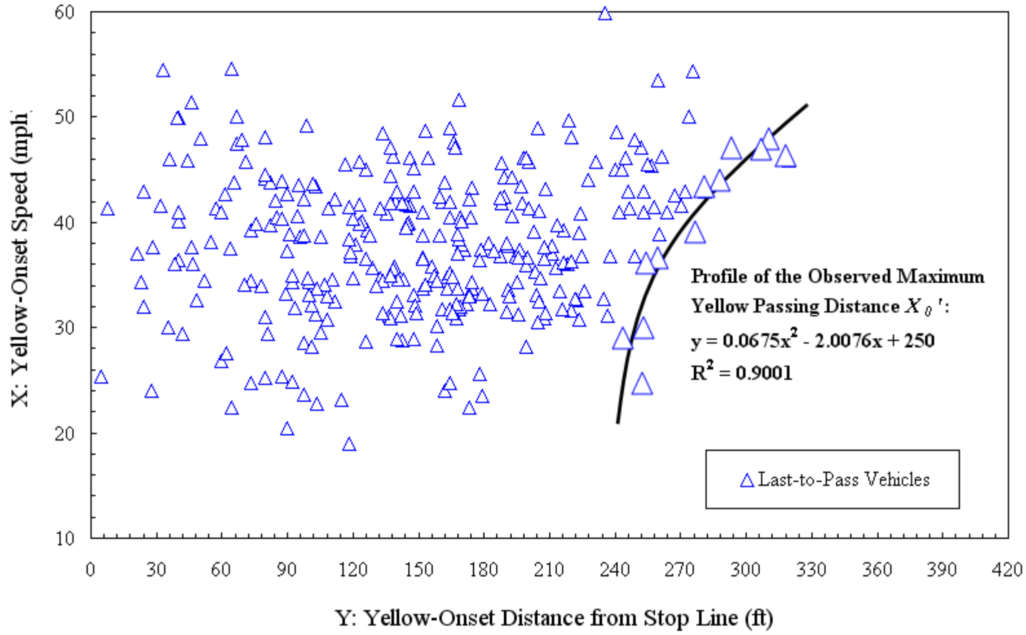

Figure 5. Identifying the Ground-truth Profile of the Max Yellow Passing Distance

The ground-truth profile of the observed maximum yellow passing distance X_0' is identified by performing regression analysis on those samples with maximum passing distances at various speeds. The relationship between X_0' and V_0 can be mathematically expressed by the following equation.

$$X_0' = 0.0675V_0^2 - 2.0076V_0 + 250 \quad (6)$$

$$R^2 = 0.9001$$

Step 3: With the ground-truth profiles of X_0' and X_c', a process of trial-and-fit method is then employed for calibrating the X_0 and X_c models. Appropriate values of the contributing factors are obtained through fitting the theoretically modelled X_c and X_0 values (based upon Equations 1 and 2) to the ground-truth X_0' and X_c' values (based upon Equations 5 and 6) at each given speed. The calibration process is illustrated by Figure 6.

The goodness-of-fit analysis shows that the correlation coefficient R^2 is 0.9998 for profiles of X_c and X_c', while the number is 0.9997 for profiles of X_0 and X_0'. Both R^2 values indicate a good fitting. Through the model calibration, appropriate values of $a_{stop}(V_0)$, $a_{pass}(V_0)$, $\delta_{pass}(V_0)$, and $\delta_{stop}(V_0)$ at various speeds are obtained and shown in Table 1. It has to be noted that during the process of calibrating the X_0 model, the "time used by the last-to-pass vehicle to pass the stop line from the yellow onset (τ')" is set to 4.5 s, which is equal to the full yellow duration. It is because all these vehicles with observed maximum passing distances actually used up the entire yellow duration to pass the stop line (almost passing at the red-onset).

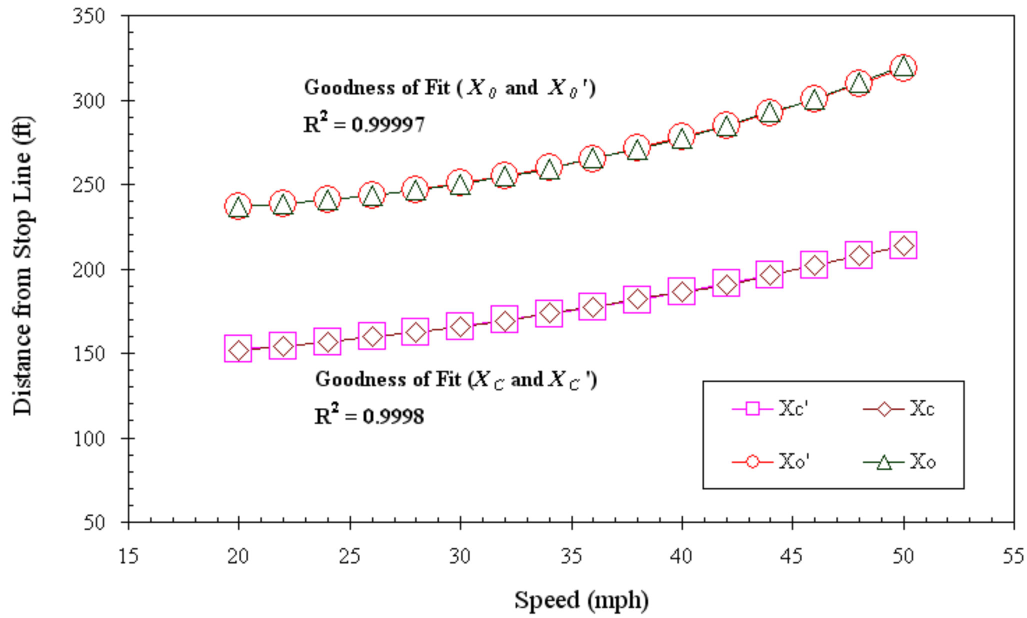

Figure 6. Process of the Model Calibration (Based on Ground-truth Data Set 1).

Table 1. Calibrated Values of Contributing Factors (Based on Ground-truth Data Set 1).

V_0 (mph)	τ' (s)	$\delta_{stop}(V_0)$ (s)	$a_{stop}(V_0)$ (ft/s^2)	$\delta_{pass}(V_0)$ (s)	$a_{pass}(V_0)$ (ft/s^2)	X_c (ft)	X_c' (ft)	X_0 (ft)	X_0' (ft)
20	4.5	0.6	-3.2	0.45	12.78	152	152	237	237
22	4.5	0.595	-3.86	0.425	11.21	154	154	238	239
24	4.5	0.59	-4.55	0.4	9.82	157	157	241	241
26	4.5	0.585	-5.28	0.375	8.48	160	160	244	243
28	4.5	0.58	-6.09	0.35	7.21	162	163	247	247
30	4.5	0.575	-6.89	0.325	5.98	166	166	250	251
32	4.5	0.57	-7.72	0.3	4.92	169	169	255	255
34	4.5	0.565	-8.54	0.275	3.92	174	173	259	260
36	4.5	0.56	-9.45	0.25	3.11	177	177	266	265
38	4.5	0.555	-10.29	0.225	2.21	182	182	271	271
40	4.5	0.55	-11.18	0.2	1.48	186	186	278	278
42	4.5	0.545	-12.07	0.175	0.78	191	191	284	285
44	4.5	0.54	-12.91	0.15	0.23	196	196	293	292
46	4.5	0.535	-13.72	0.1	-0.34	202	202	300	300
48	4.5	0.53	-14.55	0.05	-0.64	208	208	310	309
50	4.5	0.525	-15.35	0	-0.98	214	214	320	318

The contributing factors calibrated by the first set of ground-truth data reflect the extreme conditions of driving behaviors, which usually yield long dilemma zones. From engineering viewpoints, those extremely conservative or aggressive driving behaviors need to be precluded from the ground-truth data by using profiles of x^{th} percentile observed passing distances (x^{th} percentile X_0') and $(1-x)^{th}$ percentile observed stopping distances ($(1-x)^{th}$ percentile X_c') as the ground-truth data. And, the corresponding dilemma zone model is termed as X^{th} Percentile Dilemma Zone.

Therefore, the second set of ground-truth data is based on the 95th percentile X_0' and the 5th percentile X_c', the dilemma zone model calibrated by which will refer to as the 95th percentile dilemma zone. The entire model calibration process consists of the following steps.

Step 1: trajectories of the first-to-stop vehicles and last-to-pass vehicles are plotted on a coordinate system with the yellow-onset speeds on the vertical axis and the yellow-onset distances from stop line on the horizontal axis. All the trajectories are classified into 6 speed groups, which are 20-25 mph, 25-30 mph, 30-35 mph, 35-40 mph, 40-45 mph, and 45-50 mph, respectively.

Step 2: identify the 95th percentile X_0' and the 5th percentile X_c' for each speed group from the cumulative curves of the passing distance and stopping distance, respectively. Boundaries of the highlighted areas in Figure 7 represent the identified 5th percentile X_c' and the 95th percentile X_0' for each speed group. As is illustrated in Figure 7, those circled stopping and passing vehicles are the precluded extremely conservative and aggressive drivers.

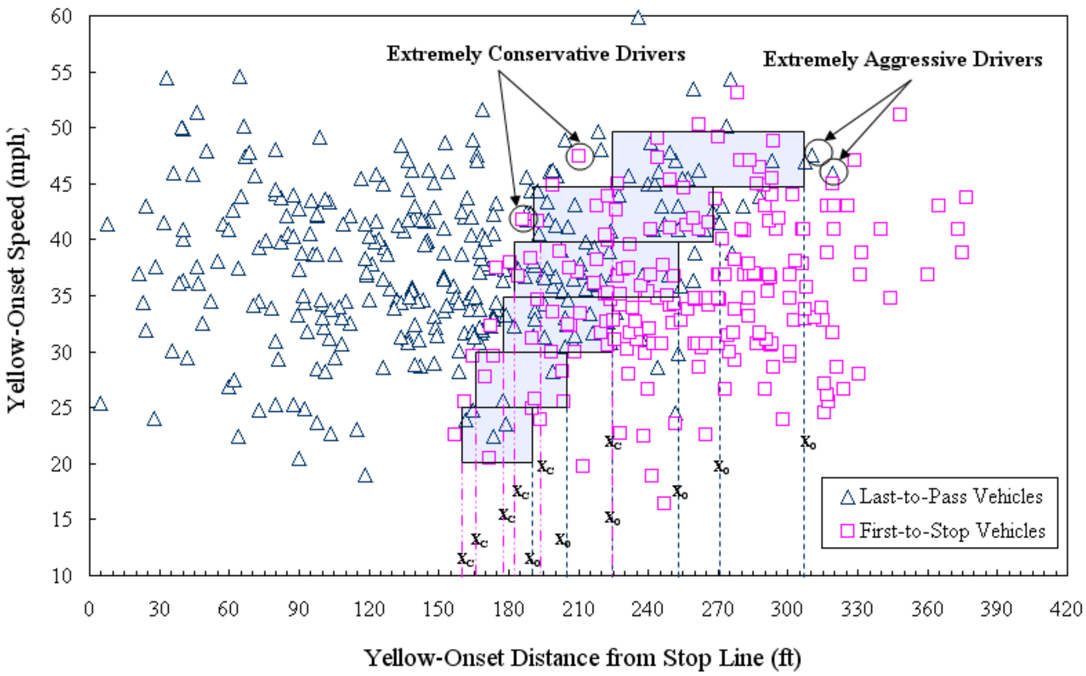

Figure 7. Identified 5th Percentile X_c' and 95th Percentile X_0' for Each Speed Group.

Note that, for determining the 5th percentile X_c' for each speed group, only those stopping distances shorter than the furthest passing distance within the speed group constitute the sample.

Step 3: use the mid-point speed of each speed group (e.g. use 37.5 mph for the speed group 35-40 mph) as the independent variable x, and the corresponding 5th percentile X_c' and 95th percentile X_0' as the dependant variables y, and perform the regression analysis. As is illustrated by Figure 8, profiles of the 5th percentile X_c' and the 95th percentile X_0' are identified. The relationship between 5th percentile X_c' and V_0, and the relationship between 95th percentile X_0' and V_0 can be mathematically expressed by the following equations.

$$X'_{C-5th} = 0.0553V_0^2 - 1.4247V_0 + 162 \quad (7)$$

$R^2 = 0.9593$

$$X'_{0-95th} = 0.0686V_0^2 - 0.1886V_0 + 159.1 \quad (8)$$

$R^2 = 0.9957$

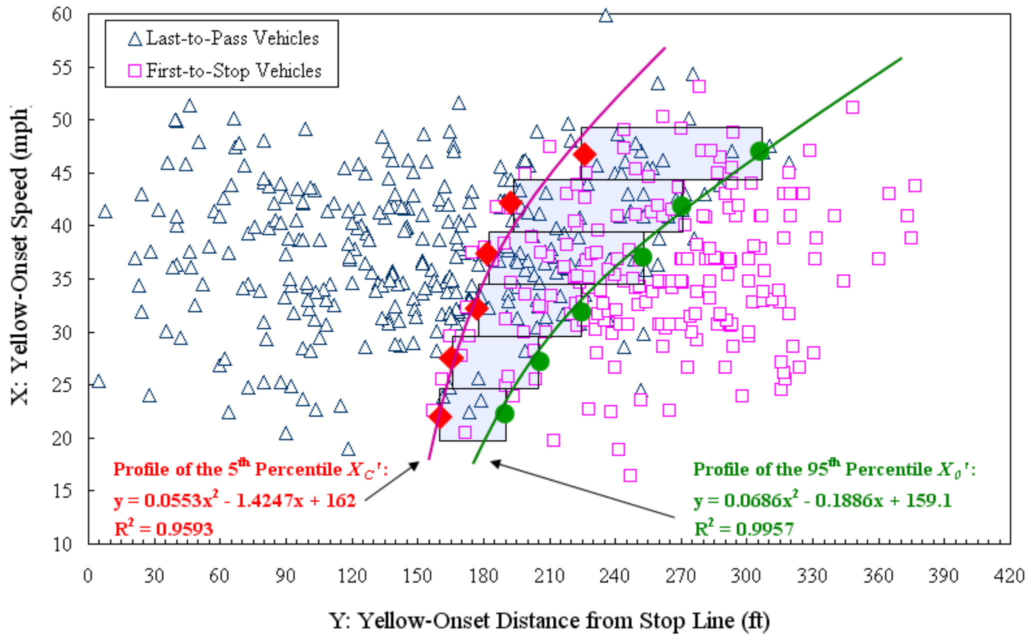

Figure 8. Profiles of the 5th Percentile X_c' and the 95th percentile X_0'

Step 4: with the ground-truth profiles of the 5th percentile X_c' and the 95th percentile X_0', a process of trial-and-fit method is then employed for calibrating the X_0 and X_c models, which is illustrated by Figure 9. The goodness-of-fit analysis shows that the correlation coefficient R^2 is 0.9998 for profiles of X_c' and $X'_{c\text{-}5th}$, while the number is 0.9999 for profiles of X_0' and $X'_{0\text{-}95th}$. Both R^2 values indicate a good fitting. Through the model calibration, appropriate values of $a_{stop}(V_0)$, $a_{pass}(V_0)$, $\delta_{pass}(V_0)$, and $\delta_{stop}(V_0)$ at various speeds are obtained and shown in Table 2. Note that, during the process of calibrating the X_0 model, the "time used by the last-to-pass vehicle to pass the stop line from the yellow onset (τ')" is set to 4.23 s, which is equal to the 95th percentile observed value.

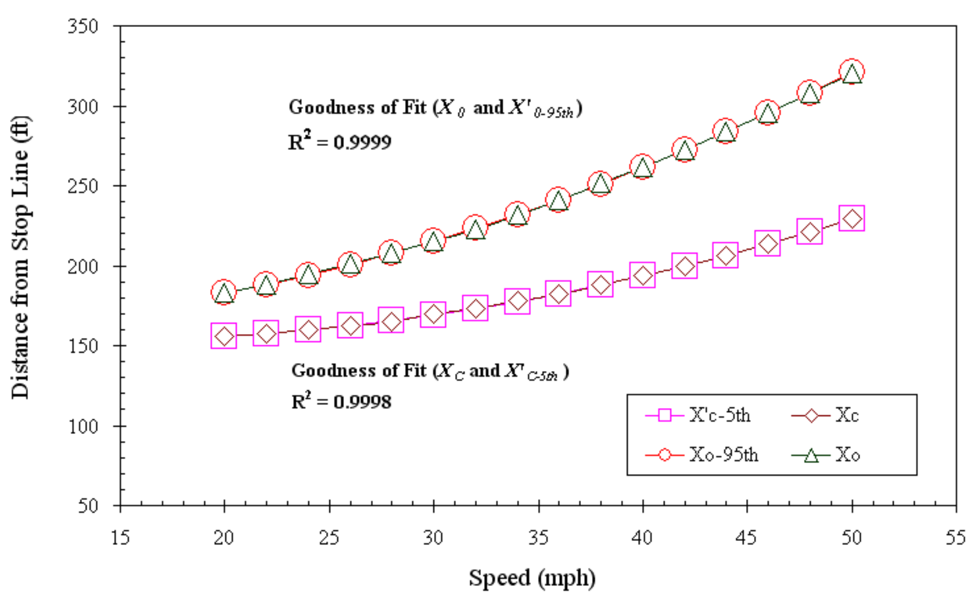

Figure 9. Process of the Model Calibration (Based on Ground-truth Data Set 2)

Table 2. Calibrated Values of Contributing Factors (Based on Ground-truth Data Set 2).

V_0 (mph)	τ' (s)	$\delta_{stop}(V_0)$ (s)	$a_{stop}(V_0)$ (ft/s^2)	$\delta_{pass}(V_0)$ (s)	$a_{pass}(V_0)$ (ft/s^2)	X_c (ft)	X_c' (ft)	X_0 (ft)	X_0' (ft)
20	4.23	0.65	-3.15	0.495	8.45	156	156	183	183
22	4.23	0.645	-3.82	0.47	7.34	157	157	188	188
24	4.23	0.64	-4.51	0.445	6.34	160	160	194	194
26	4.23	0.635	-5.25	0.42	5.46	163	162	201	201
28	4.23	0.63	-6.05	0.395	4.67	165	165	208	208
30	4.23	0.625	-6.82	0.37	3.88	169	169	215	215
32	4.23	0.62	-7.63	0.345	3.23	173	173	223	223
34	4.23	0.615	-8.44	0.32	2.78	178	177	232	232
36	4.23	0.61	-9.27	0.295	2.32	183	182	241	241
38	4.23	0.605	-10.06	0.27	1.98	188	188	251	251
40	4.23	0.6	-10.87	0.245	1.67	194	193	261	261
42	4.23	0.595	-11.65	0.22	1.43	200	200	272	272
44	4.23	0.59	-12.38	0.195	1.31	206	206	284	284
46	4.23	0.585	-13.08	0.12	1.21	213	213	296	296
48	4.23	0.58	-13.76	0.05	1.13	221	221	308	308
50	4.23	0.575	-14.36	0.02	1.09	229	229	320	321

DEVELOPMENT OF DILEMMA ZONE LOOKUP CHART

Based on the calibrated contributing factor values, a dilemma zone lookup chart can be developed. It identifies whether the risky zone or the option zone exists, and what the location and length of the dilemma zone are, for a specific speed and under a certain yellow duration. Figure 10 and Figure 11 illustrate the dilemma zone lookup charts developed based on factor values in Table 1 and Table 2, respectively. The feasibility of placing those X_0 profiles together is based on the research result that change of yellow duration does not affect the driving behavior including PRT and acceleration/deceleration[7,13].

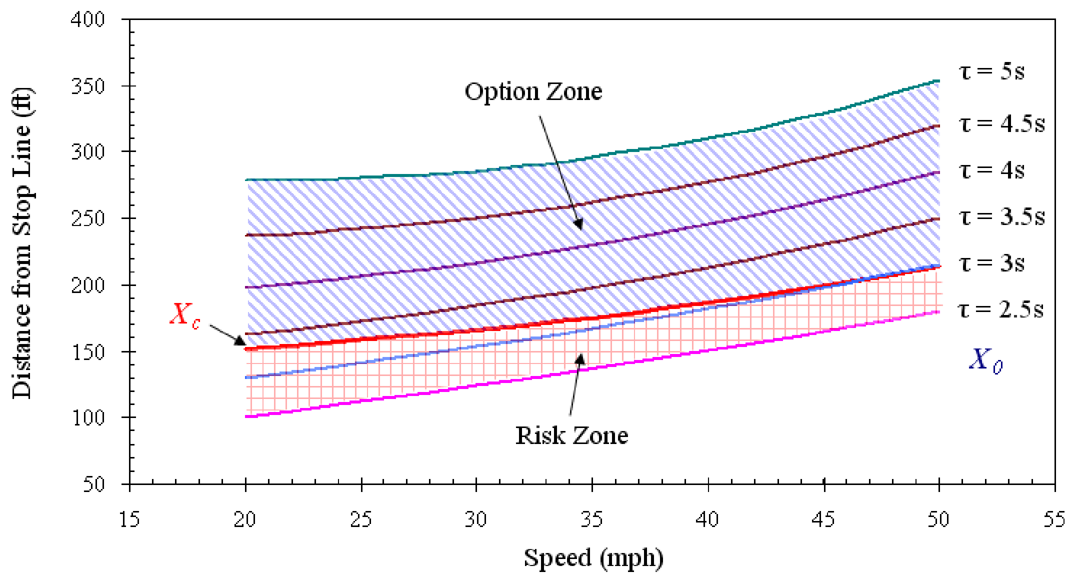

Figure 10. Dilemma Zone Lookup Chart Developed Based on Extreme Driving Behaviors

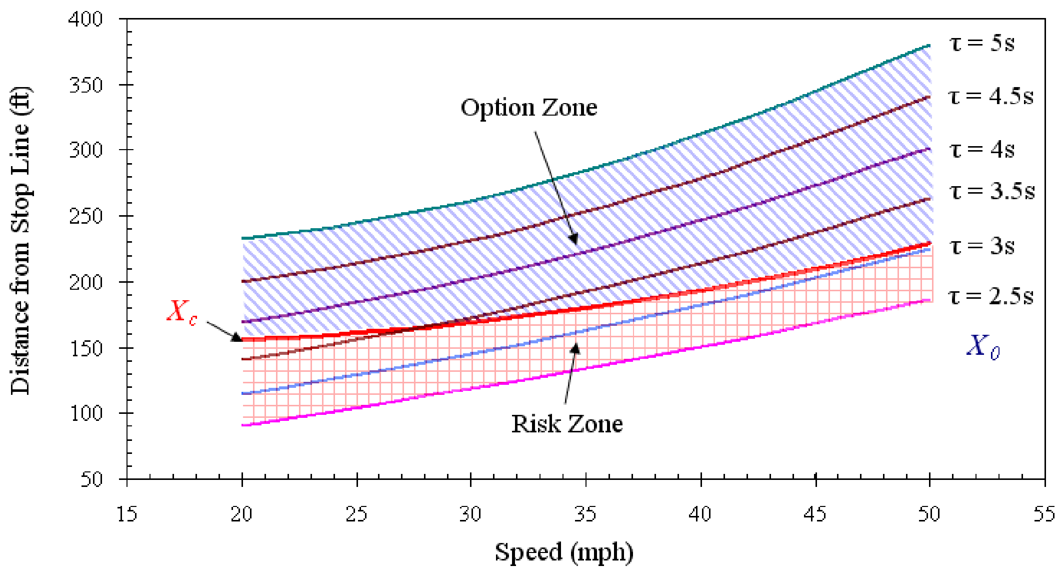

Figure 11. Lookup Chart for 95th Percentile Dilemma Zone

From both charts, it can be identified that the length of option zone becomes longer as the yellow duration increases, while the length of risky zone becomes shorter as the yellow duration increases. It indicates that prolonging the yellow duration can eliminate the risky zone but will yield a longer option zone. And, it can be also found that higher speed vehicles have a longer option zone and shorter risky zone than lower speed vehicles under the same yellow time condition.

CONCLUSION

The results of this study prove that the observation-based dilemma zone model is capable of characterizing dynamics of the dilemma zones. With capability of extracting accurate dilemma zone trajectory data and observed data sets, it became possible to reveal inherences pertaining to the dynamics of the dilemma zone. Moreover, the dilemma zone is then better understood and it concept is getter refined. In addition, performing statistical analysis on the yellow-onset trajectories is one of the best ways to interpret the dynamics of dilemma zone into simple mathematical expressions. And, the calibrated contributing factors, which have varying values at different speeds, well reflect the dynamic driving behaviors. Significantly, the dilemma zone lookup charts developed based on the calibrated dilemma zone models provide an easy-to-use and practical tool for engineers to check the location and length of a dilemma zone for a specific speed and under a certain yellow duration. The methodology used in this study is capable of satisfying the needs of states in the U.S. for updating their local dilemma zone tables.

The dilemma zone lookup charts also provide a solid basis for placing advance loops at high-speed signalized intersections for providing dilemma zone protection. Since option zone has been proved to be hazardous, full protection needs to be provided for option zone in addition to risky zone. The 95th percentile dilemma zone is a useful criterion in the loops layout design, because it precludes those five percent extremely aggressive drivers and five percent extremely-conservative drivers from the protection, which tries to maintain the operational efficiency while enhancing the safety. Issues regarding the balance between the performance of dilemma zone protection and the operational efficiency will be addressed in future research.

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