Evaluation of Driver Behavior in Type II Dilemma Zones at High-Speed Signalized Intersections

David S. Hurwitz, A.M.ASCE[1]; Michael A. Knodler Jr., A.M.ASCE[2]; and Bruce Nyquist, P.E., A.M.ASCE[3]

Abstract: Unlike traditional Type I dilemma zones, where inappropriate signal timings or detector placements restrict the ability of motorists to safely proceed through the intersection or safely stop in advance, Type II dilemma zones are attributed to driver difficulties in decision making. Type II issues become more prevalent at high-speed intersections, which have greater variability in operating speeds and greater potential for serious crashes. Although several features related to Type II dilemma zones are known, inconsistency remains in the application of the boundary definitions. This research characterizes driver behavior and comprehension related to Type II dilemma zones for the purpose of defining these boundary conditions. Empirical observations of 10 high-speed signalized intersection approaches were conducted, and the analyses of the observed driver behavior resulted in an expanded understanding of how and where drivers make their decision to stop or proceed when approaching a signal. Specifically, distributions of vehicle location and driver behavior were examined using multiple boundary definitions, and in several instances the distributions of driver behaviors varied depending on the dilemma-zone definition employed.
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Introduction

Given the lack of design standards for the calculation of change or clearance intervals, several different approaches have been adopted across the United States. In response to the lack of design standards, the Institute of Transportation Engineers (ITE) developed a recommended calculation for these two intervals that accounts for grade of the approach roadway, perception-reaction time of driver, deceleration rate of vehicle, velocity of approaching vehicle, length of car, and the width of the intersection (Roess et al. 2004; ITE 1999).

In addition to the ITE recommended calculations, even more alternatives have also been adopted to handle change and clearance intervals. For intersections with relatively level approaches, some authorities calculate the yellow clearance interval as the operating speed of the approaching vehicles divided by 10, with a red clearance interval of 1 or 2 s. Additionally, some jurisdictions will apply consistent (i.e., fixed) change and clearance timings to roads of similar functional classification or closely grouped intersections (ITE 2004).

The lack of a generally accepted standard lexicon for dilemma zones and the absence of national standards for the timing of the change and clearance intervals have resulted in a variety of strategies being implemented across the county. This lack of uniformity, when coupled with the variation among the vehicle and user composition interacting on today's roadways, requires an updated examination of the dilemma-zone issue.

This research seeks to develop an updated database of naturalistic driver behavior when interacting with the solid yellow indication at high-speed signalized intersections. Once assembled, the database will allow for a reexamination of previous definitions of the indecision zone. Of particular interest will be any differences in vehicle distributions or driver behaviors between different definitions.

Research Objectives

The Type II dilemma-zone conflict has proven difficult to fully diagnose and mitigate. Numerous factors contribute to this difficulty, including the varying operational characteristics of individual vehicles, composition of vehicles in the traffic stream, driver attributes, and intersection design components. Additionally, there are issues with the consistency of legal definitions for interacting with the yellow indication across states as well as yellow-interval timing practices. This research directly quantifies the compounding results of this existing level of variation as related to the description of drivers' decisions to stop the vehicle in advance of the stop bar or to proceed through the intersection on the basis of their initial position and speed. The primary focus was to identify an improved method of capturing this data and determining the fit and effect of some of the more commonly applied dilemma-zone definitions. It is the writers' contention that for the same intersection, certain dilemma-zone definitions actually describe different vehicle distributions. If the range of resulting behaviors can be more adequately understood, improved traffic signal design will likely result. Specifically, this research provides a quantified data set and analysis, which is the necessary initial step associated with understanding this specific research question that is so fundamental to basic signal timing practices.

[1]Assistant Professor, Oregon State Univ., 220 Owen Hall, Corvallis, OR 97331 (corresponding author). E-mail: david.hurwitz@oregonstate.edu

[2]Assistant Professor, Univ. of Massachusetts, 216 Marston Hall, Amherst, MA 01003. E-mail: mknodler@ecs.umass.edu

[3]Traffic and Safety Engineer, Vermont Agency of Transportation, One National Life Drive, Montpelier, VT 05633. E-mail: bruce.nyquist@state.vt.us

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Background

To establish the research motivation and background, it is critical to present a consistent lexicon within this document to accurately describe the nature of the dilemma-zone conflict. This is consistent with previous work (Gates et al. 2007; Urbanik and Koonce 2007). Some of the key elements affecting dilemma-zone descriptions include the variation in legal requirements, terminology of the intervals, and assorted boundary definitions as described in the following sections.

Varying Legal Requirements

As emphasized by Awadallah (2009), there is a lack of uniformity in the legal requirement for the driver's interaction with the circular yellow indication. Parsons (2003) found that the law is implemented as either permissive (about half of all states) or some form of restrictive. These designations can be described as follows:

1. *Permissive yellow law:* allows drivers to enter the intersection (typically considered as crossing the stop bar with the front vehicle axle) at any point while the yellow indication is displayed, therefore allowing the vehicle permission to be in the intersection during the red indication as described in the Uniform Vehicle Code (NCUTLO 1992), or
2. *Restrictive yellow law:* either does not allow the driver to enter or be in the intersection on red or requires the driver to stop on yellow unless it is not safe to do so.

Change and Clearance Intervals

The long history of literature regarding signal design reveals that the terms "change" and "clearance" have been used in a wide variety of ways (ITE 2004; Gates et al. 2007). For a thorough review of this history, readers are referred to the work of Eccles and McGee, "A History of the Yellow and All-Red Intervals for Traffic Signals" (Eccles and McGee 2001). For the purpose of clarity, this document adopts a consistent usage of both terms. In this paper, the change interval describes the yellow indication that is displayed at the termination of the green indication and in advance of the red or all-red indication. The clearance interval refers to the all-red interval (Roess et al. 2004).

The change interval serves to alert oncoming vehicles that the right-of-way currently allocated to their approach is about to be reassigned (ITE 1999). It allows for an approaching vehicle presented with the termination of the green indication, while within safe stopping distance from the stop line, to maintain its speed and legally enter the intersection on the yellow (Roess et al. 2004). Crossing the stop line with the front wheels of the vehicle is the accepted definition of entering the intersection (Roess et al. 2004). The typical duration for the change interval at a high-speed intersection is approximately 5 s (ITE 1999). Eck and Sabra conducted a survey of 110 state and local agencies to better understand perceptions about safety countermeasures at high-speed signalized intersections. They determined that, "yellow time adjustment had the lowest median installation cost and annual maintenance cost" (Eck and Sabra 1985).

The clearance interval displays the red indication to all approaches to allow any vehicle that entered the intersection during the change interval to safely clear the intersection before conflicting movements are released (Roess et al. 2004). The typical duration of the clearance interval at a high-speed intersection is approximately 2 s (ITE 1999). This process is intended to mitigate potentially serious right-angle crashes. However, the inclusion of a clearance interval has the potential to increase red light running (RLR) at signalized intersections.

Because there is no legally required design standard for the calculation of change or clearance intervals, several approaches have been adopted by different agencies across the country. In response to the lack of design standards, ITE has developed a recommended calculation. The work of the ITE Technical Committee 4A-16 in 1985 and July 1989 resulted in the initial proposal for basing the timing of the change and clearance interval on a kinematic equation (ITE Technical Committee 4A-16 1985, 1989). The current version of the ITE equation accounts for grade of approach roadway, perception-reaction time of driver, deceleration rate of vehicle, velocity of approaching vehicle, length of car, and the width of the intersection. The ITE equation for the change interval (ITE 1999, 2004) is as follows:

$$y = t + \frac{V}{2a + 64.4g}$$

where y = length of change interval (seconds); t = driver reaction time (typically 1 s); V = 85th percentile speed, posted speed limit, or design speed as appropriate (ft/s); a = deceleration rate of vehicles (ITE uses 10 ft/s^2 whereas AASHTO uses 11.2 ft/s^2); g = grade of approach (positive for upgrade, negative for downgrade, express as decimal); 64.4 = twice the acceleration of gravity (ft/s/s).

The ITE equation for the clearance interval (ITE 1999, 2004) is calculated as

$$r = \frac{W + L}{V}$$

where r = length of clearance interval (seconds); W = width of intersection (feet); L = length of vehicle (typically 20 ft); V = 15th percentile speed (ft/s).

Several alternative practices to the ITE recommended calculations have been adopted to handle change and clearance intervals. For intersections with relatively level approaches, some authorities calculate the yellow clearance interval as the operating speed of the approach vehicles divided by 10, with a red clearance interval of 1 or 2 s. Additionally, some jurisdictions will apply the same change and clearance timings to roads of similar functional classification or closely grouped intersections (ITE 1999, 2004).

Dilemma Zones

The development of successful design solutions to transportation problems, or any other complex system, can be greatly hindered by poor problem identification. Such has been the case in the diagnosing of dilemma-zone issues at signalized intersections. It is critical that a common lexicon be established if this traffic safety issue is to be adequately addressed. This document, building on previously established terminology (Gates et al. 2007; Urbanik and Koonce 2007), will refer to two general classes of dilemma-zone conflicts (Type I and Type II).

The Type I dilemma zone was first referenced in the literature by Gazis et al. (1960). The Type I dilemma zone describes the situation of a motorist who, when presented a yellow indication while approaching a signalized intersection will, because of the physical parameters of the situation, be unable to safely pass through the intersection or stop prior to the stop bar. It was not until 1974 that the Type II dilemma zone was formally identified in a technical committee report produced by the southern section of ITE (Parsonson 1974). The Type II dilemma zone describes the area in which the driver experiences difficulty making the correct stop/go behavior. The driver may incorrectly decide to proceed when the correct action is to stop and vice versa (Schultz and Talbot

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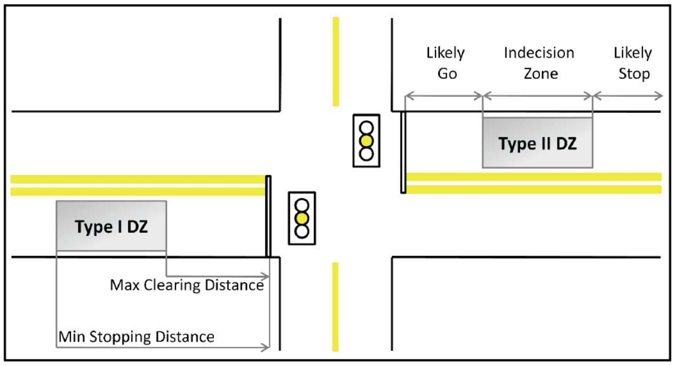

Fig. 1. Type I and Type II dilemma-zone diagram

2009; Pant and Huang 1992; Gibby et al. 1992). The Type I and Type II dilemma zones are depicted in Fig. 1.

Several further attempts have been made to quantify the location of the Type II dilemma zone. Zegeer and Deen (1978) defined the boundaries of the Type II dilemma zone in terms of driver decision making, suggesting that the beginning of the zone occurs at the position where 90% of drivers stopped and the end of the zone as occurring where only 10% of the drivers stopped. This definition was supported by the works of May (1968) and Herman et al. (1963). Subsequently, Chang et al. (1985) attempted to define the boundaries in terms of travel time to the stop bar. Their research found that 85% of drivers stopped if they were 3 s or more back from the stop bar whereas almost all drivers continued through the intersection if they were 2 s or less from the stop bar. Supporting examples of defining the Type II dilemma zone in relation to the stop bar can be seen in the works of Webster and Elison (1965) and Bonneson et al. (1994). Bonneson et al. (2002) synthesized results from several of the previously mentioned studies. This synthesis resulted in the popular adoption of the notion that the Type II dilemma zone exists in the area between 5.5 s and 2.5 s from the stop bar (Bonneson et al. 2002).

Regardless of the definition, the two resulting crash situations associated with dilemma zones are abrupt stops leading to rear-end crashes and failure to stop leading to right-angle crashes. On average, right-angle crashes tend to result in more serious injuries; therefore more emphasis is typically placed on their prevention. As the approach speeds of the intersecting roadways increase, so too does the severity of the collisions, which is one reason why an added emphasis is placed on dilemma-zone issues at high-speed signalized intersections. The location and size of dilemma zones are directly related to the speed, size, and weight of the vehicle approaching the intersection.

Methodology

The aim of the current research initiative was to compile field data associated with drivers' interactions with change and clearance intervals in an effort to revisit the existing definitions of the Type II dilemma zones. To that end, the inclusion of both speed and video data collection allowed for a more complete understanding of the dilemma-zone influence because individual vehicle speed and position both affect the potential for conflicts during clearance intervals.

As with many experiments that incorporate field observation, the identification of adequate experimental sites was of crucial importance. The Vermont Agency of Transportation (VTrans) provided specific recommendations for selection of the test sites on the basis of existing operational and safety attributes of the roadways. Specifically, the selected roadways were all high speed with some variation in existing geometries but overall similar in nature. Both major approaches of the following intersections, located in the municipalities of Clarendon and Rutland, were observed in the experiment:

- Route 62 at Paine Turnpike (eastbound and westbound approaches);
- Route 62 at Airport Road (eastbound and westbound approaches);
- Route 62 at Berlin Road (eastbound and westbound approaches);
- Route 7 at North Shrewsbury Road (northbound and southbound approaches); and
- Route 7 at Route 103 (northbound and southbound approaches).

The approach at Route 7 and Route 103 southbound was removed from the analysis because of a lack of significant sample size. An initial intersection inventory was completed to help adequately describe some of the relevant geometric characteristics of each individual intersection approach. Consistent with the methods of Pant and Huang, approach alignment, number of lanes, and posted speed limits were among the aspects considered in site selection (Pant and Huang 1992). Additionally, from the work of Gibby et al. (1992), median types and width were excluded, but the sum of the change and clearance interval was considered. Table 1 describes relevant characteristics of the selected intersections, including aspects such as the cycle length and clearing widths.

Table 1. Geometric Characteristic of Test Site Intersection Approaches

	Route 7 at				Route 62 at					
	North Shrewsbury		Route 103		Airport		Berlin		Paine Turnpike	
Intersection approach	Southbound	Northbound	Southbound	Northbound	Eastbound	Westbound	Eastbound	Westbound	Eastbound	Westbound
Horizontal curvature	Y	N	N	N	N	Y	N	Y	N	N
Grade %	−0.5	+0.6	−0.5	+1.7	−4.0	+5.6	+0.4	−0.2	−0.9	+1.0
Presence of guard rails	Y	N	N	N	Y	Y	Y	N	N	N
Clear zones	Y	Y	Y	Y	Y	N	N	N	N	N
Yellow time	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	4.0	4.0
All-red time	3	3	3	3	3	3	3	3	2	2
Speed limit	55	55	55	55	50	50	45	45	50	50
Clearing widths	38	38	58	58	66	66	50	50	42	42
Average daily traffic	7,458	7,440	6,662	3,840	7,396	8,773	6,958	5,400	7,120	8,434

Note: All intersections were isolated and uncoordinated.

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Admittedly, this sample provides some limitations. Ideally, it would be preferable to have an even larger number of experimental sites with a greater level of diversity to help provide broader answers to the issues being explored. However the writers believe that the analysis process described in this paper will allow for the analysis of many additional intersections as well as providing good representation of high-speed facilities that result in the greatest safety concerns. Additionally, the durations for the yellow change intervals predicted by the ITE equations do not correlate with the observed yellow change intervals at the study intersections. An overwhelming majority of intersections are timed for one set of conditions and in fact have another set of conditions. Although it may be possibleto predict certain types of behavior on the basis of the difference from the theoretical best yellow, it is essential to know the impact with this existing yellow.

An extensive data collection effort was conducted to capture video and speed data for a statistically significant sample of vehicles encountering dilemma-zone conflicts on each of the 10 approaches examined. Speed data were collected on each intersection approach at the stop bar and at the advanced detector; however, for analysis purposes, speed data in the vicinity of the advanced detector was exclusively considered. Because of the short-term nature of the measurements (windows of approximately 48 to 72 h), pneumatic tubes were used to capture vehicle speeds. The data were collected on a per vehicle basis to provide insight into individual driver behavior.

Observations of intersection operations and driver behavior were also conducted through the collection of video data. Cameras were unobtrusively mounted (15 to 20 ft off the ground) on fixed structures along the roadside with an approach setback of 500 to 600 ft from the stop bar. The cameras were oriented to face toward the signal heads on each major intersection approach. This system allowed for the clear identification of vehicle position and signal phase from a single location. Fig. 2 depicts the installation of one such camera installation.

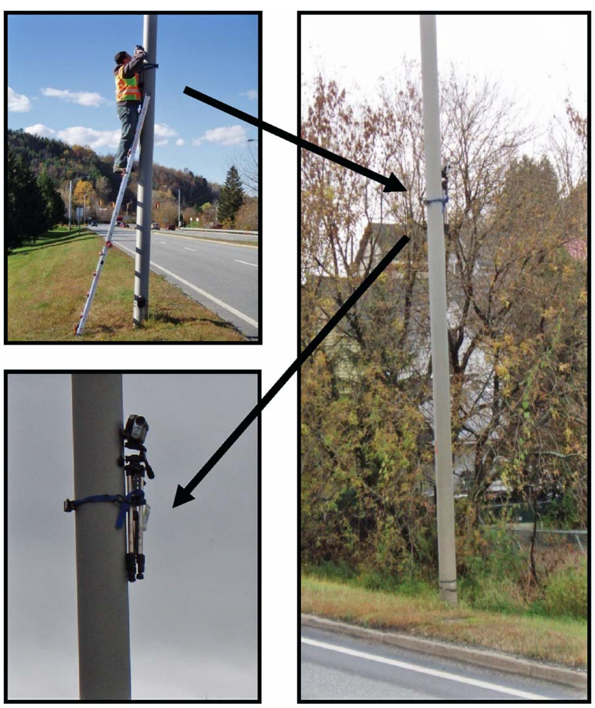

Fig. 2. Example of typical video camera installation (photos courtesy of David S. Hurwitz)

To effectively use the 8 mm video tapes used in the field as a means for accurately identifying the position of a vehicle at the onset of the solid yellow indication, the tapes were digitized and measurement points (gridlines at 50-ft intervals) were transposed onto the digital files. The grid lines were drawn in Photoshop and superimposed on the video files. Vehicle position was determined (i.e., which 50-ft interval) from the position of the vehicle's front axle. This procedure allowed for the capture the time stamp of the yellow indication onset (hours, minutes, seconds), the lane the vehicle was in, the vehicle position in the queue (e.g., leading or trailing), the vehicle position at the onset of the yellow light (to the nearest 50 ft), and the driver decision (stop, proceed on yellow, run red). Vehicle class was recorded for passenger car, truck, and bus; however, the small sample of trucks and buses did not allow for additional analysis of this variable.

Using the digitized files with measurement zones, the data reduction was carried out by a team of researchers. The research team was briefed about the specific attributes to be identified from the video files; as a part of the training component, researchers reviewed the same video file to ensure consistent results across researchers. In addition, random files were watched by multiple researchers in an effort to ensure consistency and validation of the research findings.

Results and Analysis

Speed Data Results

Per vehicle speed data were collected on each of the 10 mainline intersection approaches. Data were collected for three 24-h periods (midnight to midnight) at each location. In an aggregated fashion, the speed observations were further reduced to provide descriptive statistics of the traffic streams, such as the mean speed and 85th and 95th percentile speeds, and variance and standard deviation were also calculated. The 85th percentile speeds ranged from 56 to 60 mi/h along Route 7 and 39 to 51 mi/h along Route 62.

The incorporation of individual vehicle speeds would make for expanded capabilities in the analysis; however, it is the writers' contention that there is still much to be learned by studying the effects of the aggregated fleet of vehicles. Indeed, most intersection design attributes are derived from the aggregate and associated percentiles and distributions.

The impact of approach speed on the position of the Type II dilemma zone was also considered as an important component to the evaluation of the dilemma-zone conflicts at each intersection approach. Table 2 presents an analysis whereby several different critical speeds were used to calculate the position of the Type II dilemma zone for each intersection approach, on the basis of the time to stop bar definition of 2.5 to 5.5 s. More specifically, this table demonstrates the variation in the predicted dilemma zone at each location on the basis of the specific speed value used in its determination.

To select an appropriate input speed for the definition of the Type II dilemma-zone boundary, the sensitivity analysis displayed in Table 2 was considered with the evidence provided in Fig. 3. In Fig. 3, four different critical speeds (mean, posted, 85th percentile, and 95th percentile) were used to calculate four slightly different Type II dilemma zones. An examination of driver behavior in relation to the four regions resulted in the selection of the 85th percentile speed as the relevant approach speed for the calculation of the dilemma-zone position.

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Table 2. Variation Predicted Dilemma-Zone Boundaries on the Basis of the Speed Values Used in Calculation (Feet from Stop Bar)

	Route 7 at				Route 62 at					
	North Shrewsbury		Rte 103		Airport		Berlin		Paine Turnpike	
Type II dilemma zone calculated with	Southbound	Northbound	Southbound	Northbound	Eastbound	Westbound	Eastbound	Westbound	Eastbound	Westbound
Mean	183 to 403	147 to 323	169 to 371	183 to 403	136 to 298	143 to 315	147 to 323	128 to 282	154 to 339	147 to 323
85th percentile	216 to 476	205 to 452	209 to 460	220 to 484	169 to 371	169 to 371	176 to 387	165 to 363	187 to 411	216 to 476
95th percentile	235 to 516	227 to 500	224 to 492	238 to 524	183 to 403	183 to 403	191 to 403	183 to 403	205 to 452	198 to 436
Speed limit	202 to 444	202 to 444	202 to 444	202 to 444	183 to 403	183 to 403	165 to 363	165 to 363	183 to 403	183 to 403

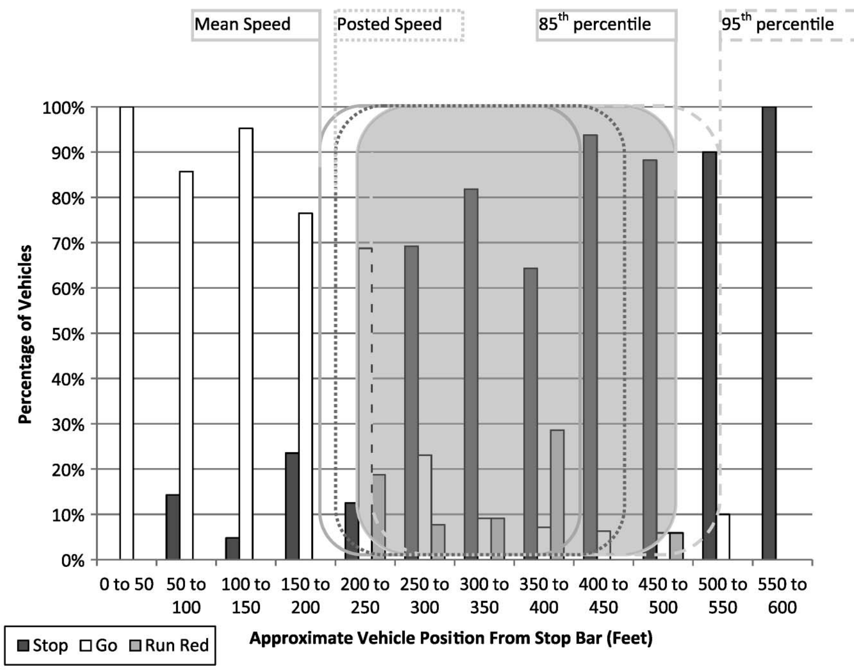

Fig. 3. Influence of selected approach speed on Type II dilemma zone, 2.5 to 5.5-s time to stop bar boundaries

Once a determination was made on the appropriate approach speed for the calculation of the Type II dilemma-zone position, the driver behaviors were considered in more detail.

Individual Intersection Approach Observations

Approximately 510 h of video-taped observation were collected across all 10 high-speed intersection approaches. Of this 510-h sample, approximately 75 h of video was reduced, representing approximately 15% of the overall sample with an approximate range of 5 to 15 h per intersection approach. Reduced observations yielded a sample size of approximately 1,900 vehicles that experienced an incursion with the change interval while approaching one of the signalized intersections from either direction on the main line.

The graphs displayed in Figs. 4–7 are a representative sample of the data collected as a part of this research initiative to provide a visual model for presenting the relative position and driver decision at the onset of the solid yellow indication for each individual intersection approach. These figures were also used to describe the nature of any existing dilemma-zone issues for the observed approaches. The vertical axis measures the percent of vehicles performing one of three possible actions (stop on yellow, go on yellow, go on red), whereas the horizontal axis describes the distance from the stop bar of each individual vehicle at the onset of the solid yellow indication in 50-ft intervals. In addition to the driver behavior and vehicle position information, the Type II dilemma-zone region (2.5 to 5.5 s time to stop bar definition) is identified in gray for each individual graph. For this set of analyses, the Type II boundaries were established using the 85th-percentile speed.

In Fig. 4, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication, the more likely it will be to enter the intersection. It does appear that there may be a larger than expected tendency for RLR from the 500 to 550-ft (5.8 to 6.4-s) region back from the stop bar. On the basis of the 85th-percentile speed of 59 mi/h, the predicted dilemma-zone region exists between 216 and 476 ft (2.5 to 5.5 s). This region seems to correlate with the presence of increased percentages of RLR. Although it seems that there is some RLR in the 100 to 200-ft (1.2 to 2.3-s) region, this trend is not captured within the dilemma zone. The current change interval is programmed to last 4.0 s; however, the ITE equation predicts yellow time duration of approximately 5.4 s.

In Fig. 5, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication, the more likely it will be to enter the intersection. On the basis of the 85th-percentile

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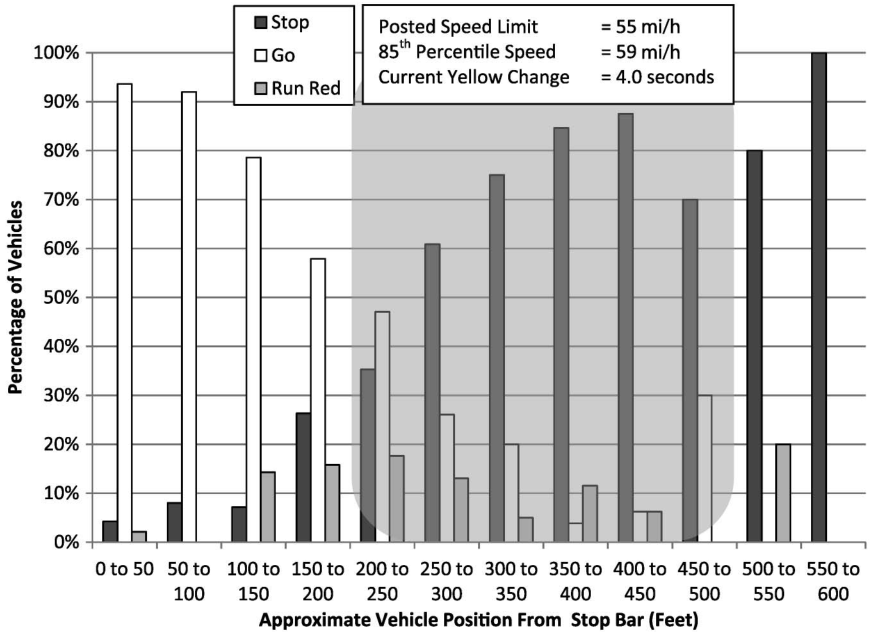

Fig. 4. Relative position and driver action of vehicles at onset of yellow indication, North Shrewsbury at Route 7 (southbound approach)

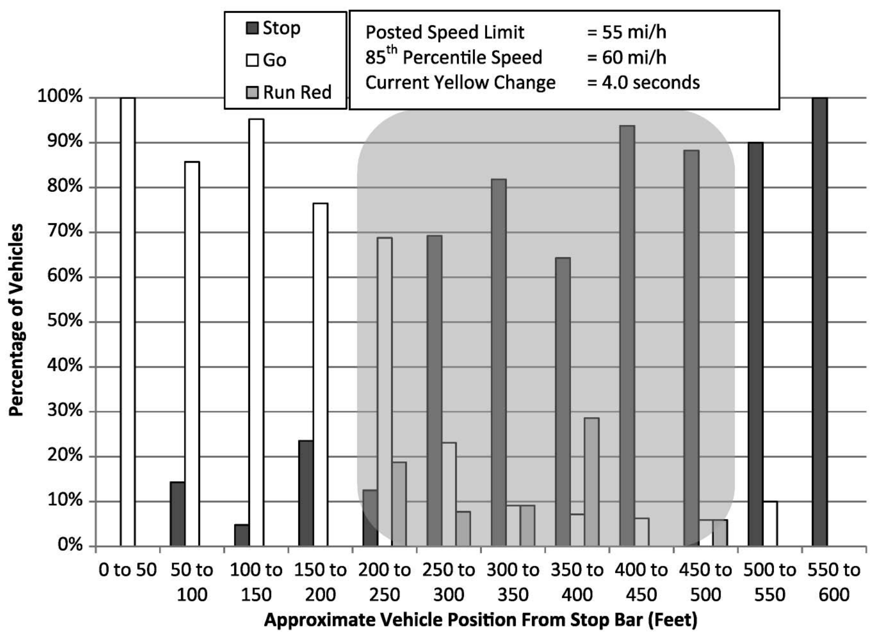

Fig. 5. Relative position and driver action of vehicles at onset of yellow indication, Route 103 at Route 7 (northbound approach)

speed of 60 mi/h, the predicted dilemma-zone region exists between 220 and 484 ft (2.5 to 5.5 s). This region seems to correlate relatively nicely with the presence of increased percentages of RLR. The current change interval is programmed to last 4.0 s; however, the ITE equation predicts yellow time duration of approximately 5.0 s.

In Fig. 6, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. On the basis of the 85th-percentile speed of 57 mi/h, the predicted dilemma-zone region exists between 209 and 460 ft (2.5 to 5.5 s). This region seems to correlate with the presence of increased percentages of RLR, although it seems that there is some RLR in the 150 to 200-ft (1.8 to 2.4-s) region that is not captured. It also seems that the last hundred feet or so may be incorrectly identified as being within the dilemma zone because of the very high tendency of drivers to stop. The current change interval is programmed to last 4.0 s; however, the ITE equation predicts yellow time duration of approximately 5.25 s.

In Fig. 7, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication, the more likely it will be to enter the intersection. On the basis of the 85th-percentile speed of 49 mi/h, the predicted dilemma-zone region exists between 180 and 395 ft (2.5 to 5.5 s). Furthermore, according to the data, this region exhibits an increased percentage of

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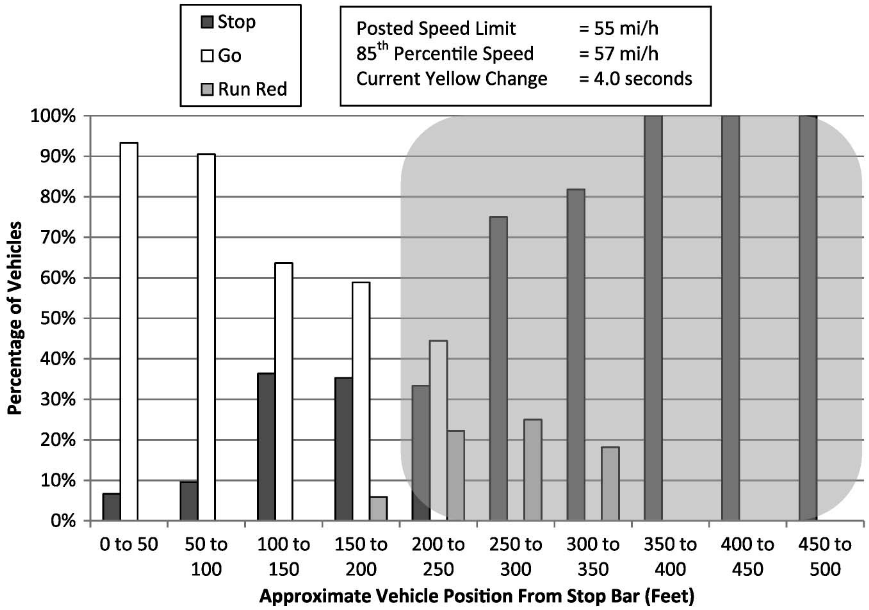

Fig. 6. Relative position and driver action of vehicles at onset of yellow indication, Route 103 at Route 7 (southbound approach)

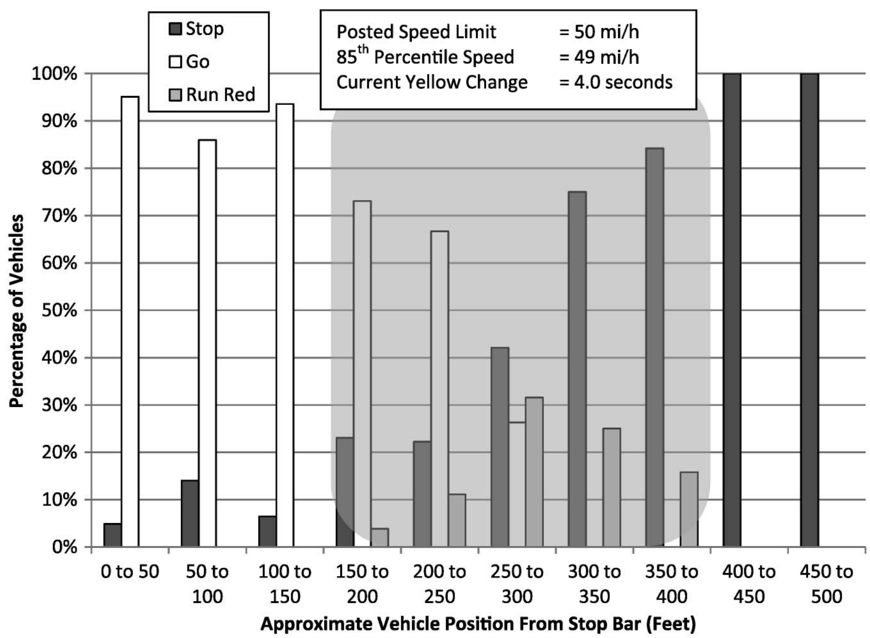

Fig. 7. Relative position and driver action of vehicles at onset of yellow indication, Paine Turnpike at Route 62 (westbound approach)

RLR. The current change interval is programmed to last 4.0 s; however, the ITE equation predicts yellow time duration of approximately 4.48 s.

Aggregated Intersection Approach Observations

After the examination of driver behavior at the individual intersection approaches was considered using the 2.5 to 5.5-s definition on the basis of an 85th-percentile speed, a question of interest persisted. Might there be any new insight garnered by the reconsideration of the boundary definition (time to stop bar versus driver decision to stop) for the Type II dilemma zone for the updated database. Numerous chi-square tests were conducted to better understand the distribution of vehicles and driver behaviors described by the data for each dilemma-zone definition. Table 3 displays the data used to compare aggregated vehicle distributions under different indecision zone definitions. The data presented for each intersection approach are the same sample data analyzed using each definition of indecision zone. As shown in Table 3, the frequency of vehicles in each dilemma-zone area varies considerably across definitions.

Chi-square tests were employed specifically to address the following question: when the boundaries of the indecision zone are defined by the time to stop bar or decision to stop, for the resulting vehicle distributions downstream of the dilemma zone, in the dilemma zone, or upstream of the dilemma zone, can any statistically significant differences be determined?

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Table 3. Comparison of Observed Frequencies for Aggregated Vehicle Distributions under Different Indecision Zone Definitions

	Indecision zone definition						
	2.5 to 5.5 s			10 to 90%			
Intersection approach	Downstream	In dilemma zone	Upstream	Downstream	In dilemma zone	Upstream	Chi-square P-value
Route 7 at Route 103 (southbound)	64	31	14	15	73	21	< 0.001
Route 62 at Airport (westbound)	48	19	19	25	37	24	0.001
Route 62 at Berlin (westbound)	87	73	0	40	120	0	—
Route 62 at Airport (eastbound)	88	43	0	54	77	0	—
Route 7 at North Shrewsbury (southbound)	137	154	32	83	208	32	< 0.001
Route 62 at Paine Turnpike (westbound)	216	127	0	102	194	47	< 0.001
Route 62 at Paine Turnpike (eastbound)	163	56	0	0	210	9	< 0.001
Route 7 at Route 103 (northbound)	76	98	19	38	146	9	< 0.001
Route 62 at Berlin (eastbound)	151	109	50	75	138	97	< 0.001
Total	1,030	710	134	432	1,203	239	< 0.001

Table 3 specifically displays the number of observed vehicles in each of three gross areas (downstream of, within, or upstream of dilemma zone) on the approach to the signalized intersection when exposed to the circular yellow indication on the basis of both definitions of indecision zones considered. Specifically, the resulting aggregated vehicle distributions are shown when the indecision zone boundaries are determined with a time to stop bar definition or decision to stop definition. This approach allowed for the quantification of the differences between vehicle distributions resulting from alternative dilemma-zone definitions. In other words, how did the two dilemma-zone definitions describe the same sample of data? As shown, they described the data quite differently.

When the intersection approaches were considered in the aggregate under a single definition, either time to stop bar or decision to stop, could a consistent trend be identified for each definition? The chi-square test of this question resulted in P-values for the time to stop bar and the decision to stop boundaries of $P < 0.001$ and $P < 0.001$, respectively. Therefore, under each definition, the aggregate intersection approaches showed a statistically significant trend at the 99% confidence interval.

It was also of interest to examine possible differences in vehicle distributions when the total number of vehicles observed on all approaches was summed for each of the three regions (upstream, in, and downstream of the dilemma zone) as described by each boundary definition. This comparison (Table 3, last row) resulted in a statistically significant difference in the distribution of vehicles ($P < 0.001$). The time to stop bar definition describes far more vehicles exposed to the solid yellow indication downstream of the dilemma zone, whereas the decision to stop definition resulted in far more vehicles predicted to be captured within the dilemma zone and upstream from the dilemma zone.

Additionally, there was interest in determining how the distribution of vehicles downstream, in, and upstream of the dilemma zone across both definitions compared at a single intersection approach. This question resulted in the P-values displayed in the right-most column for rows 1–9 of Table 3. These tests show statistically significant results that mirrored exactly the trends of the total vehicle distribution at eight of the 10 approaches that could be analyzed in this way.

Beyond vehicle distributions, the driver behavior (stop, go, run red) that was evident within the dilemma zone was of interest. Table 4 displays the driver behavior captured within the indecision zone as defined by both the time to stop bar and decision to stop definitions.

When a single definition, time to stop bar or decision to stop, is applied to the driver behavior (stop, go, run red) within the indecision zone at each intersection approach, one question is whether there any differences between vehicle distributions on individual approaches. Both the time to stop bar and the decision to stop boundaries resulted in statistically significant differences ($P > 0.001$).

Another issue of interest was whether there was a difference in the distribution of the total number of vehicles stopping, going, or

Table 4. Comparison of Driver Behavior from within the Indecision Zone When Considering Different Dilemma-Zone Boundary Definitions

	Indecision zone definition							
	2.5 to 5.5 s				10 to 90%			
Intersection approach	Stop	Go	Run red	Chi-square P-value	Stop	Go	Run red	Chi-square P-value
Route 7 at Route 103 (southbound)	22	4	5		27	40	6	
Route 62 at Airport (westbound)	15	1	3		13	19	5	
Route 62 at Berlin (westbound)	57	8	8		65	46	9	
Route 62 at Airport (eastbound)	8	20	15		9	53	15	
Route 7 at North Shrewsbury (southbound)	99	34	21		103	81	24	
Route 62 at Paine Tpke (westbound)	93	17	17		62	114	18	
Route 62 at Paine Tpke (eastbound)	46	7	3		73	134	3	
Route 7 at Route 103 (northbound)	67	20	11		81	54	11	
Route 62 at Berlin (eastbound)	101	2	6	< 0.001	81	37	20	< 0.001
Total	508	113	89		514	578	111	< 0.001

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running red at all of the approaches within the indecision zone as defined by both the time to stop bar and decision to stop definition. When distributions were compared between the two definitions of the indecision zone, a statistical significance was determined ($P < 0.001$). The decision to stop definition results in far more vehicles proceeding through the intersection on the yellow than that of the time to stop bar definition.

Lastly, a chi-square test conducted on the distribution of RLR vehicles captured within the dilemma zone for all approaches under each definition yielded no statistical significance ($P = 0.98$).

Summary of Findings

The following section describes the research findings associated with the naturalistic study of driver behavior. These findings are primarily associated with the distribution of vehicles upstream of, in, and downstream of the dilemma zone as well as the distribution of stop, go, and run red driver behavior within the dilemma zone.

Vehicle Distribution Upstream of, In, and Downstream of the Dilemma Zone

- When the empirical data is aggregated across the 10 observation locations, the time to stop bar dilemma-zone boundary describes a distribution of vehicles that is statistically different from that described by the decision to stop boundary. Time to stop bar describes a shift in the vehicle distribution downstream of the dilemma zone, whereas the decision to stop describes a shift of vehicles within and upstream of the dilemma zone.
- When the empirical data are examined on an individual intersection approach basis, the vehicle distributions are statistically different under each boundary definition and the shifts mirror those of the aggregated results.

Driver Behavior within the Dilemma Zone

- Individual intersection approaches showed statistically different distributions of driver behavior within both boundary definitions.
- The decision to stop definition results in far more vehicles proceeding through the intersection on the yellow than that of the time to stop bar definition.
- There is no statistical difference between RLR tendencies of drivers exposed to the circular yellow within the dilemma zone as defined by either the time to stop bar or decision to stop definition.

Conclusions

For the signalized intersections specifically observed for the purpose of this study, using the plotted driver behaviors in Figs. 4–7, there is some evidence to suggest that lengthening the yellow change interval duration may provide an added time frame for safer driver decision-making behavior. Plots of this type can prove useful in determining both the presence and location of possible dilemma zones along intersection approaches, information that proves valuable in the development of strategies that will be used to eliminate and/or shorten the dilemma-zone range.

More broadly, this work has expanded the understanding of how the distribution of driver behaviors and vehicle are shifted by using a time to stop bar and a decision to stop definition of the dilemma-zone boundary. It is the writers' contention that when less than complete speed information is available for every approach vehicle, the use of a driver decision to stop definition is more descriptive than the time to stop bar dilemma-zone definition. This understanding will contribute to the ability of transportation professionals to identify Type II dilemma zones at high risk locations.

Looking forward, the experimental approach demonstrated in this research effort could be replicated on a per-vehicle basis comparison. It is the researchers' sense that the findings will be similar. Additionally, this work has raised a question regarding the appropriateness of treating the Type I and Type II dilemma-zone definitions as independent occurrences. Future study is needed to determine what, if any, interactive effects exist between these two scenarios.

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