Characterizing Driver Behavior on Signalized Intersection Approaches at the Onset of a Yellow-Phase Trigger

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Abstract—This paper involves a field test on 60 test participants to characterize driver behavior (perception–reaction time (PRT) and stopping/running decisions) at the onset of a yellow phase. Driver behavior is analyzed for five trigger distances that are measured from the vehicle position at the start of the yellow indication to the stop bar. This paper demonstrates that the 1.0-s 85th-percentile PRT that is recommended in traffic-signal-design procedures is valid and consistent with the field observations. Furthermore, this paper clearly shows that brake PRTs are impacted by the vehicle's time to intersection (TTI) at the onset of a yellow-indication introduction. This paper also demonstrates that either a lognormal or a beta distribution is sufficient to model the stochastic nature of the brake PRT. In terms of stopping decisions, this paper demonstrates that the probability of stopping varies from 100% at a TTI of 5.5 s to 9% at a TTI of 1.6 s. This paper also indicates a decrease in the probability of stopping for male drivers when compared with female drivers. Furthermore, this study suggests that drivers 65 years of age and older are significantly less likely to clear the intersection at short yellow-indication trigger distances when compared with other age groups. The dilemma zone for the less than 40 year old group is found to range from 3.9 to 1.85 s, whereas the dilemma zone for the greater than 70 year old group is found to range from 3.2 to 1.5 s.

Index Terms—Driver behavior, perception–reaction time (PRT), signalized decision zone, signalized dilemma zone.

I. INTRODUCTION

HIGH-SPEED signalized intersections are typically associated with vehicle crashes resulting from dilemma-zone problems. Dilemma zones are defined, in either time or space, as zones where some drivers may decide to proceed through an intersection, whereas others may decide to stop at the onset of a yellow indication. Incorrect driver decisions can lead to rear-end crashes if a driver decides to stop when he should have proceeded and/or to right-angle crashes with side-street traffic when drivers proceed when they should have stopped. Driver decision within a dilemma zone may vary as a function of the driver perception–reaction time (PRT), the driver's acceptable deceleration rate, the driver's age, the driver's gender, and the time to intersection (TTI) at the instant when the yellow indication is introduced.

Several research efforts have attempted to address the dilemma-zone problem using various intelligent-transportation-system (ITS) strategies. These strategies include basic green-extension systems, enhanced green-extension systems, and green-termination systems [1]–[4]. More recently, researchers [5], [6] developed the detection–control system (D–CS), which uses two loop detectors in a speed-trap configuration installed about 300 m upstream of the intersection on the main approach to detect the presence and to measure the speed of individual vehicles. Speed information is then used to predict vehicle arrivals in the dilemma zone, and ultimately at the intersection, assuming that vehicles travel at a constant speed over the 300-m distance. The system assumes a constant dilemma zone, which is defined by TTIs ranging between 5.5 and 2.5 s. The D–CS implements a two-step gap-out strategy to reduce the probability of max-out and thus reduce the probability of trapping vehicles in the dilemma zone. During the first step, the D–CS holds the green indication until the dilemma zone is clear of any vehicles. If the dilemma zone is not cleared after a certain time, the D–CS applies a second-step relaxed criterion that allows the green to end when there is only one car in the dilemma zone (but not a truck). This two-stage operation mimics the operation of the LHOVRA (where each letter—L, H, O, V, R, and A—represents a function of operation) and self optimizing signal control (SOS) systems, developed in Sweden [1], [2].

The current dilemma-zone mitigation systems assume that the driver dilemma zone is fixed (ranges between 5.5 and 2.5 s from the intersection), considering a 1.0-s PRT. However, it is not clear how the driver PRTs and the corresponding dilemma zones vary as a function of driver characteristics. A number of studies have demonstrated that the brake PRTs may be much longer than 1.0 s and that the 85th-percentile PRT is more in the range of 1.5–1.9 s [7]. These studies have also demonstrated that the PRTs on high-speed-intersection approaches (greater than 64 km/h) are lower, with the 85th-percentile PRTs in the

range of 1.1–1.3 s. All studies, however, have measured the PRT as the time difference between the onset of the yellow phase and the activation of the vehicle's brake lights; thus, the PRT estimates include the time lag from the instant the driver presses the brake pedal until the brake lights are displayed.

The objective of this paper is fourfold. First, this paper characterizes brake PRT at high-speed signalized-intersection approaches in an attempt to validate the current design standards. Second, this paper analyzes age, gender, and TTI impacts on the PRTs. Third, this paper shows that either a lognormal or a beta distribution can be used to describe the distribution of the observed PRTs for use within the microscopic traffic simulation software. Fourth, this paper characterizes the impact of driver age and gender on the location of the driver dilemma zone. All of these findings provide key parameters for implementation within the dilemma-zone mitigation strategies.

A. Driver PRTs at Traffic Signals

A review of the fundamental concepts associated with reaction times provides a better understanding of the factors related to PRT and driver behavior within a dilemma zone. When a driver responds to a sensory input, such as the onset of a yellow light at a traffic signal, the total reaction time can be split into a mental processing time (the time required for the driver to perceive the sensory input and to decide on a response) and a movement time (the time used to perform the programmed movement, such as lifting the foot from the accelerator and touching the brake). Because the mental processing time is an internal quantity that cannot be directly and objectively measured without a physical response, it is usually jointly measured with the movement time [8].

In the case of a driver arriving at a signalized intersection when the indication changes from green to yellow, the time interval from the onset of the yellow light to the instant when the brake pedal is pressed is called the PRT [9], [10], the perception response time [11], the brake reaction time [8], [12], the perception-braking response time [13], or the yellow response time [14]. This paper will refer to it as the PRT.

Taoka [7] stresses that the PRTs measured under anticipatory conditions, when drivers are aware that their PRTs are recorded, are shorter than the expected values under normal driving conditions.

In a comprehensive survey which summarized PRT results from most studies published until 2000, Green [8] classified PRT studies into three basic types: simulator studies, controlled-road studies, and naturalistic observation. Controlled-road studies and naturalistic observation are both field approaches but differ in the sense that, in the latter, the driver is unaware of the data-collection effort. Each type of study has limitations to the degree in which results can be generalized to normal driving conditions. PRT measurements from driving simulators are typically shorter than those measured in vehicles because simulators have simplified visuals, smaller fields of view, no depth, no nonvisual cues, and small cognitive loads. Controlled-road studies may also produce shorter PRT measurements because drivers may be more alert than in normal driving conditions. Both simulator and controlled-road studies create practice effects because of the many trials used to gather data for each driver. Alternatively, naturalistic studies have the highest validity but are also limited because it is not possible to test the effects of independent variables, to place drivers in emergency or even in urgent situations, to separately measure perception and movement times, or to control driver demographics to avoid sample bias.

The PRTs at traffic signals also include some lag time because the onset of the yellow does not always require immediate braking reaction unless the driver is close to the intersection. According to a study in which seven intersections were observed and driver PRTs (defined as "the time elapsed from the onset of the yellow until the brake light is observed") were recorded [14], this lag should be small or nonexistent on high-speed signalized-intersection approaches because the high speed requires immediate reactions to avoid excessive deceleration or even collisions with other vehicles. The results suggest that speed effectively influences the median PRT, which converges to 0.9 s at speeds equal to or greater than 72 km/h (45 mi/h). The study also focused on the effect of the distance from the intersection at the onset of a yellow indication because, according to its authors, drivers tend to react faster as vehicles move closer to the intersection; when vehicles are farther away, the PRT might be longer because the urgency to make a decision is not as great.

A study that used a driving simulator to analyze the behavior of 77 drivers approaching signalized intersections at 70 km/h made similar conclusions [15]. The study concluded that the TTI significantly affected the PRT, whereas age did not. The PRT grand mean was 0.96 s, ranging from 0.86 s for drivers closest to the intersection stop line to 1.03 s for drivers farthest from it.

In order to overcome the effect on the PRT of the distance from the intersection at the yellow-indication onset, Wong and Goh [13] used a transitional or dilemma zone that is defined as a zone in which drivers are required to quickly make a decision or are forced to cross. Drivers before the dilemma zone must stop at the intersection (because they cannot legally cross); drivers after the dilemma zone must cross the intersection. The dilemma zone was defined in terms of the TTI which is measured as the actual travel time for those vehicles that crossed the intersection and as the projected travel time for those that stopped. For the three intersections analyzed in Singapore, the dilemma zone was defined as lying between 4.2 and 2.3 s from the intersection stop bar. The PRT was defined as the time elapsed from the yellow-indication onset until the brake lights became visible. The PRT values found for the transitional zone were 0.84 s (median), 0.86 s (mean), 0.64 s (15th percentile), and 1.08 s (85th percentile), following a lognormal distribution; this finding is consistent with the other studies [7]. In another paper [11], the authors reported shorter reaction times at intersections with red-light surveillance cameras: 0.80 s for the median and mean and 1.00 s for the 85th percentile.

B. Driver Behavior at Signalized Intersections

The dilemma-zone problem has been examined in the literature since its initial formulation by Gazis *et al.* [16], who

observed the existence of dilemma zones at approaches to signalized intersections and developed the first dilemma-zone model as a binary-decision problem to either stop or proceed when a yellow indication is triggered. However, an analysis of the literature demonstrates a lack of consensus in defining the dilemma zone. For example, Sheffi and Mahmassani [17] define a dilemma zone "as that zone within which the driver can neither come to a safe stop nor proceed through the intersection before the end of the yellow phase." This definition represents the design definition of a dilemma zone. Senders [18] demonstrated for a specific signalized intersection that a design dilemma zone existed in which a driver traveling at a speed limit had no feasible option and thus would have to break the law. Alternatively, Zegeer [19] defines the dilemma zone from a driver's perspective as the zone in which between 10% and 90% of the drivers stop. Sheffi and Mahmassani [17] summarize the approach in modeling this problem as "developing dilemma zone curves of "percent drivers stopping" versus "distance from stop bar" at the instant when the signal indication changes from green to yellow" and that the driver behavior at high-speed signalized intersections when faced with a yellow indication can be viewed as a binary-choice process, where the relevant decisions are either to stop or proceed through the intersection.

The stopping distance (which is a function of the vehicle's speed, the driver's PRT, and an acceptable deceleration rate) is defined as the distance required for a vehicle to come to a complete stop upstream of the intersection stop bar by considering the braking-, aerodynamic-, rolling-, and grade-resistance forces. Typically, the aerodynamic- and the rolling-resistance forces are ignored, and the stopping distance is computed as

$$d_{\mathrm{s}} = v \cdot t + \frac{v^2}{2g(\eta_{\mathrm{b}}\mu \pm G)} \qquad (1)$$

where d_{s} is the distance required for a vehicle to stop at the stop bar (meters), v is the speed of the approaching vehicle (meters per second), t is the driver PRT (seconds), g is the gravitational acceleration (9.81 m/s^2), η_{b} is the braking efficiency, μ is the coefficient of roadway adhesion, and G is the roadway grade (decimal). Consequently, a driver's stop/run decision is a function of the driver's PRT, and thus, the variability in the PRT and the driver decisions are analyzed in this paper.

Driver behavior on high-speed signalized-intersection approaches in response to a yellow indication has been studied for many years. For example, Shinar and Compton [20] observed the aggressive driving behavior of more than 2000 drivers over a total of 72 h in the immediate proximity of an intersection or an interchange at six different sites with posted speed limits ranging from 70 to 80 km/h (43 to 50 mi/h). Their study concluded that aggressive driving is associated with both situational variables and individual characteristics; men were more aggressive than women, young drivers (less than 45 years old) were more aggressive than older drivers, and the presence of passengers was associated with lower rates of aggressive driving.

The performance of 77 participants (older and younger drivers) while approaching signalized intersections at 70 km/h

(43 mi/h) when traffic signals changed from green to yellow was measured by Caird *et al.* [15] in Calgary, AB, Canada, using a moderate-fidelity driving simulator. They found that older drivers (55 years of age and older) were significantly less likely to stop than those in the younger age groups at the longest TTI, and those older drivers who chose to go through the yellow light were more likely to be in the intersection when the light changed to red. Another study by Hicks *et al.* [21] at nine intersections in Maryland found that driver stopping/passing behavior and vehicle speed performance in response to a yellow-light interval were affected by multiple factors. A driver's gender and age and the use of cellular phones were found to be significant human factors affecting driver behavior and vehicle speed at intersections during yellow intervals. Their study also concluded that the initial position of a vehicle when a yellow-light phase is displayed significantly affects drivers' stopping/passing behavior.

C. Driver Uncertainty Measure

Drivers are typically indecisive within the dilemma zone and thus respond differently during the signal-change interval. A driver approaching a signalized intersection while the traffic signal changes from green to yellow has two alternatives—either to stop at the intersection or to continue to clear the intersection before the signal turns red. A driver in such a situation is experiencing a state of uncertainty and anxiety due to the need to evaluate many parameters before making a final decision. An equation that was proposed in the literature to measure the degree of uncertainty is presented here. The equation attempts to quantify the level of difficulty in choosing between different alternatives in a choice situation. This model was proposed by Yager [22] as

$$A = 1 - \int_0^{\alpha_{\max}} \frac{1}{|A_\alpha|} d\alpha \qquad (2)$$

where A is the degree of uncertainty (anxiety measure), and A_α is the number of alternatives whose choice probability is greater than α.

This measure (which has no physical meaning) attempts to capture the uncertainty that one experiences in selecting an alternative from a number of alternatives. The degree of uncertainty is lowest when the choice is clear; this situation occurs when only one alternative is supported and all other alternatives are not supported, i.e., one element has a probability of one, and all other elements have a probability of zero. Uncertainty increases as more elements get support and are not equal to zero; here, we are faced with the problem of choosing among some equally good solutions. A greater degree of uncertainty occurs in situations when we have no support for any of the alternatives and all the elements have a probability near zero. In this case, we must choose from among a number of bad alternatives.

In the case of a two-choice situation (as in our case "stopping" or "running"), (2), for the measurement of uncertainty, as

introduced by Kikuchi *et al.* [23] and Yager and Kikuchi [24], is reduced to

$$A = 1 - \max(P_s, P_r) + \frac{1}{2}\min(P_s, P_r) \qquad (3)$$

where P_s is the possibility of stopping (fuzzy-set membership), and P_r is the possibility of running.

The uncertainty measure is equal to zero when one of the two possibilities is equal to one and the other is zero, and it is equal to 0.75 when the value of the two possibilities are both equal to 0.50. This means that uncertainty is lowest when the possibility of only one action is fully supported while the other is not, and it is highest when the possibility of the two conflicting actions are equal, indicating that either action is equally possible and that only one has to be chosen.

D. Uniqueness of Study

As presented earlier, research has shown that dilemma-zone protection can help reduce crashes at high-speed signalized intersections. Consequently, this paper attempts to characterize driver behavior within the dilemma zone and to quantify the value of various parameters required within the dilemma-zone protection systems.

This paper is unique because it combines several aspects as follows.

a) All previous studies have either been conducted in a driving simulator or been gathered from the field by randomly recording driver behavior. Alternatively, this paper was a controlled field study, and there were no surrounding vehicles; thus, driver behavior could be isolated without considering its interaction with the surrounding traffic (e.g., lead or following vehicles).

b) Detailed driver information was available, and the driver pool was constructed to achieve the desired sample breakdown.

c) The vehicles were equipped with a differential global positioning system (GPS) and a data acquisition system (DAS), which allowed for the gathering of decisecond vehicle and brake-pedal information, which was not the case in previous field-data-collection efforts.

d) The communication between the vehicle and traffic signal controller ensured that the yellow interval was started when the vehicle was at preselected distances from the intersection; thus, direct comparisons could be made, and statistical tests could be conducted.

II. EXPERIMENTAL DESIGN

The experiment involved having each test participant drive an instrumented vehicle along a 2.6-km private highway at approximately 72 km/h. After a practice run that allowed the participant to get acquainted with the vehicle, the participant approached a signalized intersection a number of times. The behavior of the driver was observed as the signal phases changed, and the data on the participant's responses included the vehicle speed, the signal indication, and the pressing of

Fig. 1. Instrumented vehicle and field-test site.

the accelerator and brake pedals. The experiment could then be classified as a controlled-road study according to Green's classification scheme [8]. It should be noted that the objective of this paper was to analyze driver behavior in response to a red-light-running warning system and was not intended to characterize driver behavior at the onset of a yellow indication. The drivers were unaware of the paper's objectives during the test runs. This section describes the instrumented vehicle, the test track, the test participants, and how the data were collected.

A. Instrumented Vehicle and Signal Controller Box

A real-time DAS was installed in a 2004 Chevrolet Impala, concealed from the driver's view, in the car trunk, as shown in Fig. 1. This DAS was developed and built by the Center for Technology Development at the Virginia Tech Transportation Institute (VTTI) to collect data for experiments such as this one. A notebook computer connected to the DAS controlled the sequence of test runs.

Signal-phase data were also recorded in the data stream using a communication link between the DAS and the signal controller box installed at the intersection, as shown in Fig. 1. This signal controller box, which was also developed at the VTTI, was used to trigger the yellow phase when the front of the vehicle reached predetermined distances from the intersections. Phase changes were controlled from the instrumented car using a differential GPS—to determine the distance from the intersection—and a wireless communication link to trigger the phase changes.

The DAS was capable of collecting data at 0.1-s intervals. Among the almost 80 data streams recorded in real time, this paper used the following data: signal phase (green, yellow, or red), time remaining in the yellow phase, distance from the intersection to trigger the yellow phase, current vehicle travel speed, current distance to the intersection stop bar, current travel time to the intersection, percent of brake application, and percent of throttle application. The last two data streams were sampled and recorded at 100 Hz.

TABLE I
AGE AND GENDER STRUCTURE FOR PARTICIPANT SAMPLE

Age	Younger drivers		Older drivers	
	≤ 40	40 to 64	65 to 69	≥ 70
Women	9	7	5	9
Men	7	9	8	6
Total	16	16	13	15

B. Intersection and Intersection Approaches

The test bed used for data collection was a signalized intersection at the Virginia Department of Transportation's Smart Road facility, located at the VTTI, which is a state-of-the-art facility built for full-scale research and evaluation of pavement and ITS systems, technologies, and products. The Smart Road is a 3.5-km private highway that is limited to test vehicles. The section of the Smart Road used for the data collection includes a four-way signalized intersection, a high-speed banked turnaround, and a low-speed turnaround. The horizontal alignment is fairly straight, and the vertical profile of this segment is a 3% slope. Thus, half of the trials run by each participant were on a 3% upgrade, whereas the other half of them were on a 3% downgrade. The uphill approach to the intersection was nearly 1.6 km long, starting from the low-speed turnaround; the downhill approach was 0.5 km long starting from the high-speed turnaround. To the test participants, the appearances of the traffic signal and of the intersection were no different from the normal signalized intersections on roads with a similar layout in Southwest Virginia.

C. Test Participants

The test participants for this paper were recruited using posters, word of mouth, local newspaper ads, and the VTTI volunteer database. The participants were paid $20/h. Interested drivers were screened to verify that they were licensed drivers and to determine if they had any health problems that could exclude them from participating in the study. Sixty drivers were recruited (30 in each gender); 32 drivers were younger than 65 years of age (50% men and 50% women), whereas 28 drivers were 65 years old or older, who were also equally divided by gender. Table I shows the age and gender structure of the participant sample. The age structure was designed to allow the possible effects of slower response times among older drivers to be more evident. The younger group had ages ranging between 20 and 64 years, with a mean age of 40 years; the older group had a mean age of 71 years, and their ages ranged from 65 to 82 years.

D. Procedure

Participants were individually tested under good conditions (daylight, good weather, dry pavement, etc.). Upon arrival at the VTTI, the participants were submitted to visual-acuity and color-vision tests. All participants selected had a minimum of 20/40 vision, passed the color-vision test, and were screened by

a medical questionnaire for drug/alcohol use and any medical conditions that might impair driving. The participants were then escorted to the test vehicle and asked to familiarize themselves with the car, adjusting seat, mirrors, seat belts, etc., and to drive to the Smart Road that was about 0.5 km away. Two experimenters rode in the car with the participant. During the drive to the Smart Road, one of the experimenters instructed the participant and answered questions, whereas the other, in the back seat, used the onboard computer to control the trial conditions and the DAS. During the initial practice run, the participants were asked to brake the car to a full stop from 40, 55, and 70 km/h to become familiar with the handling of the car under hard braking.

In the experiment, the participants were instructed to drive the car at 72 km/h (45 mi/h), except in the turnarounds or when stopping at the intersection. The participants were instructed to normally behave when faced with a yellow light, making the decision whether to stop or to go as they usually would. Not counting the initial practice run, the participants drove along the entire test course (2.1-km downhill, low-speed turnaround, 2.1-km uphill, and high-speed turnaround) 12 times, passing through the traffic lights 24 times (12 times uphill and 12 times downhill), composing 24 trials. At the beginning of each trial run, the signal displayed a green light. As the car approached the intersection, the onboard computer decided whether to trigger the yellow and, if so, at what distance from the stop bar.

The yellow duration was 4 s and was initiated when the front of the car was at the following distances from the stop bar: 32 m (105 ft), 55 m (180 ft), 66 m (215 ft), 88 m (290 ft), or 111 m (365 ft). This corresponds to the TTIs of 1.6, 2.7, 3.3, 4.4, or 5.6 s, respectively, assuming a speed of 72 km/h (20 m/s).

Each participant faced phase changes from green to yellow four times for each TTI. These 24 trial conditions (20 yellow lights and four green lights) ran in a predetermined randomized sequence, with a different order for each participant. This implies that the number of times a participant encountered a yellow light at a given TTI on a given grade (up or down) varied between one and three times.

III. PRT MEASUREMENTS

A. Field-Test Data

PRT was defined as the time elapsed between the onset of the yellow indication and the instant the driver started to press the brake pedal; only the cases where the driver's foot was on the accelerator pedal at the yellow interval onset were considered. For each participant, the average of the observed PRTs for each TTI was calculated for both grades, which provided a sample of 351 average observed PRTs ranging between 0.3 and 1.7 s, with a mean equal to 0.742 s, a median of 0.700 s, and a standard deviation of 0.189 s. The observed distribution can be represented by either a lognormal or a beta distribution, as shown in Fig. 2. Fig. 2 shows a fitted beta distribution that passes the χ^2 test. Because the observed distribution of the PRTs was skewed, the median was used, instead of the mean, to avoid any bias that could be introduced by a few very long PRTs.
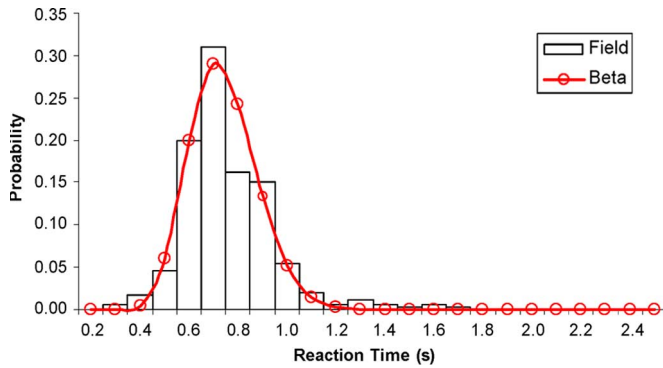
Fig. 2. Distribution of observed average PRTs for all TTIs ($n = 351$).

TABLE II
MEDIANS OF OBSERVED PRTS (IN MILLISECONDS)

TTI (s)	Women				Men			
	< 65 years		65 or older		< 65 years		65 or older	
	N	PRT	N	PRT	N	PRT	N	PRT
1.6	–	–	4	650	1	600	2	567
2.7	15	700	16	700	14	667	18	600
3.3	17	633	20	700	24	700	21	600
4.4	25	700	22	717	27	725	23	650
5.6	27	750	25	900	27	850	23	850

TABLE III
MEDIANS OF OBSERVED PRTS, WOMEN (IN MILLISECONDS)

TTI (s)	Uphill				Downhill			
	< 65 years		65 or older		< 65 years		65 or older	
	N	PRT	N	PRT	N	PRT	N	PRT
1.6	–	–	3	650	–	–	1	650
2.7	10	700	11	700	5	700	5	600
3.3	9	750	11	700	8	600	9	700
4.4	16	700	14	742	9	700	8	700
5.6	15	833	13	900	12	725	12	833

TABLE IV
MEDIANS OF OBSERVED PRTS, MEN (IN MILLISECONDS)

TTI (s)	Uphill				Downhill			
	< 65 years		65 or older		< 65 years		65 or older	
	N	PRT	N	PRT	N	PRT	N	PRT
1.6	1	600	1	600	–	–	1	533
2.7	7	667	9	600	7	600	9	600
3.3	15	700	12	625	9	600	9	600
4.4	14	775	12	700	13	700	11	600
5.6	15	900	11	867	12	700	12	750

Table II shows the median PRTs for the sample of 351 average PRTs, disaggregated by gender, age group, and TTI, as well as the number of observations in each case. Alternatively, Tables III and IV summarize the median PRTs disaggregated by grade, age group, and TTI for each gender.

B. Analysis of the Field-Test Data

Table II shows that very few drivers attempted to stop at short TTI values. A series of χ^2 tests was carried out to further investigate this behavior. These tests compared the number of drivers who stopped and the number of drivers who proceeded at the onset of a yellow phase change for a TTI of 1.6 s.

The results indicated that while there were no differences in driving behavior between the uphill and downhill trips, men were less likely to stop for the yellow at this short distance when compared with women ($p < 0.01$, $\chi^2(1) = 7.460$), and younger drivers were less likely to stop than older drivers ($p < 0.01$, $\chi^2(1) = 12.668$). The test results also indicated that older women were more likely to stop than younger women ($p < 0.01$, $\chi^2(1) = 8.316$) and that there were no significant differences in behavior between younger and older men.

From the results of these χ^2 tests, two conclusions can be made. The first is that most drivers will not try to stop at the traffic signal if the TTI is 1.6 s at the onset of a yellow phase. This is expected because the deceleration rate that is required to stop a car traveling at 72 km/h (20 m/s) at such a short distance (32 m) is significant, and the driver would not be able to legally stop the car (before the stop line). The second conclusion is that older women are more likely to stop at a green-to-yellow signal change when the TTI is 1.6 s. This could be attributed to a false idea that safe driving requires always stopping at traffic signals at the onset of the yellow phase. This behavior, however, is obviously unsafe because it is not always possible to stop the car before the intersection when the TTI is so short.

Table II also shows that nearly all drivers stopped when the TTI at the onset of the yellow was 5.6 s and that the median PRT for this case was generally longer than those observed for shorter TTIs. Using the data presented in Tables III and IV, ANOVA tests were used to investigate the effects of the TTI, gender, age group, and grade on the brake PRT. Initially, a set of one-way ANOVA tests was carried out to investigate the effect on PRT of each of the following variables: age group (younger or older drivers), TTI (2.7, 3.3, 4.4, and 1.6 s), gender, and roadway grade (uphill or downhill). The medians for TTIs of 1.6 s were not included in the analysis because the results of the χ^2 tests demonstrated that the majority of the drivers do not try to stop at such TTIs.

The one-way ANOVA results show that the TTI had a significant effect on the median PRT ($F(3, 28) = 13.706$, $p < 0.001$). A *post hoc* test, using the Scheffé method, revealed that the median PRTs were significantly longer for a TTI of 5.6 s when compared with the other three TTIs ($p < 0.01$). However, the median PRTs for the other three TTIs were not significantly different from one another. For this reason, all further analyses were conducted excluding the median PRTs for TTIs of 1.6 and 5.6 s.

There was a significant difference in the PRT for the upgrade ($M = 696$ ms) and downgrade ($M = 629$ ms) conditions ($F(1, 22) = 12.288$, $p < 0.01$). Even if this difference is small enough to be disregarded from an engineering design point of view, it indicates that drivers are more alert when driving downhill because of the additional deceleration required to stop the vehicle.

No significant differences were found between the men and women's PRTs or between younger and older drivers. However, the data suggest that older women tended to have longer PRTs when compared with younger women and men of both age groups ($F(1, 20) = 2.914$, $p = 0.10$). Again, the difference in the PRT was so small that it may be unimportant in terms of changing design procedures.
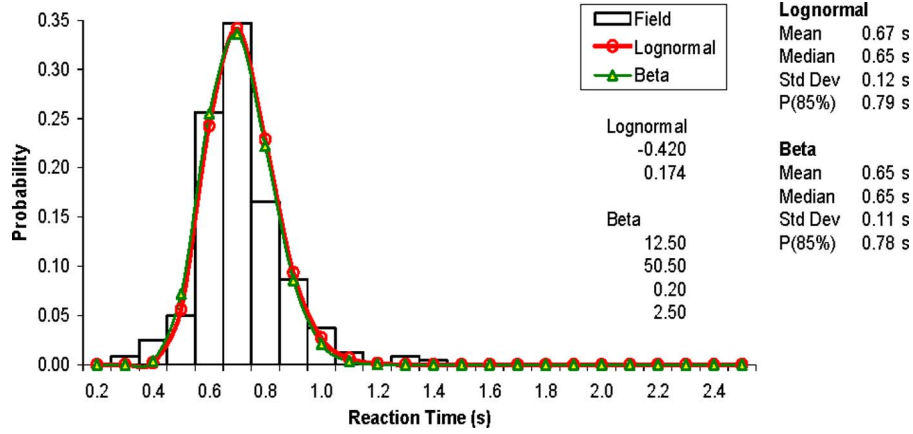
Fig. 3. Observed average PRTs and proposed models for observations within driver dilemma zone ($n = 242$).
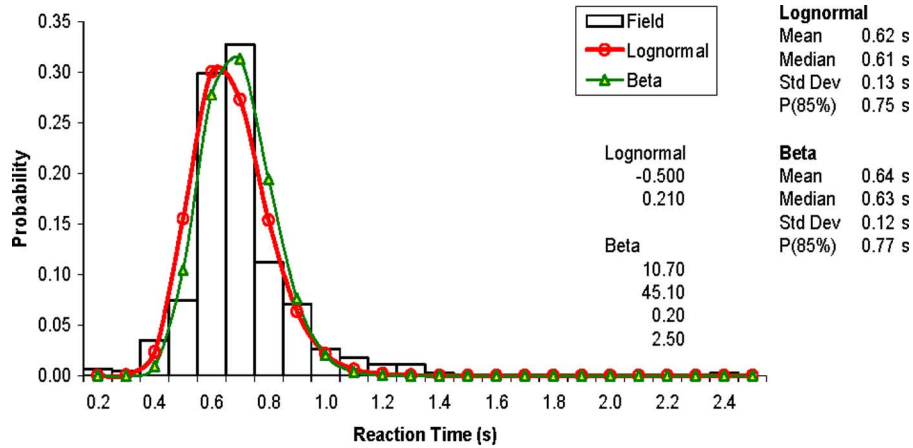

Fig. 4. Raw field data and proposed PRT models (all observations; $n = 455$).

Fig. 2 shows the observed PRT distribution after removing observations for TTIs of 1.6 and 5.6 s to ensure that only the data within the driver dilemma zone (probability of stopping ranging between 10% and 90%) are analyzed ($n = 242$). Superimposed on the field data are the lognormal and beta distributions that are fit to the data as will be described in detail in the next section. The 50th (median) and 85th percentiles for these distributions are 0.67 and 0.79 s, respectively.

IV. DRIVER PRT DISTRIBUTION

The typical approach in modeling driver PRTs is to consider a lognormal distribution [7]. Consequently, a lognormal distribution was initially fit to the data. Subsequently, a beta distribution was considered given that it offers a bounded model between the two finite limits a and b [25]. The model is formulated as

$$f_x(x) = \begin{cases} \dfrac{1}{B(q,r)} \dfrac{(b-x)^{r-1}(x-a)^{q-1}}{(b-a)^{q+r-1}}, & \text{for } a \leq x \leq b \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where q and r are the parameters of the distribution, and $B(q, r)$ is the beta function, which is computed as

$$B(q,r) = \int_0^1 x^{q-1}(1-x)^{r-1} dx. \quad (5)$$

Fig. 3 not only shows that both models provide similar fits to the data but also supplies the various optimal model parameters. These parameters include the natural logarithm of the mean and the PRT dispersion parameter (ζ) in the case of the lognormal distribution. Alternatively, in the case of the beta distribution, the q, r, a, and b parameters are presented. Statistical tests revealed no statistical evidence to reject the null hypothesis that the data either follow a lognormal or a beta distribution ($p = 0.508$, $\chi^2(6) = 5.29$ and $p = 0.517$, $\chi^2(6) = 5.21$), respectively.

In addition to using the average data, the lognormal and beta models were fit to the raw field data ($N = 808$ observations). Unfortunately, there was no evidence that the field data were consistent with the two theoretical models ($p < 0.001$, $\chi^2(7) = 67.74$ and $p < 0.001$, $\chi^2(7) = 336.58$ for the lognormal and beta models, respectively). The 85th-percentile PRT was 0.87 s (0.2 s less than the PRT reported in literature).

Fig. 4 shows the field-observed PRTs for the entire experiment, excluding the data for TTIs of 1.6 s and 5.6 s ($N = 455$ observations), in addition to the two models that were fit to the data: the lognormal and the beta model. Again, as was the case for the entire data set, there was no evidence that the field data were consistent with the two theoretical models ($p < 0.001$, $\chi^2(6) = 32.47$ and $p < 0.001$, $\chi^2(6) = 21.46$ for the lognormal and beta models, respectively). Based on these
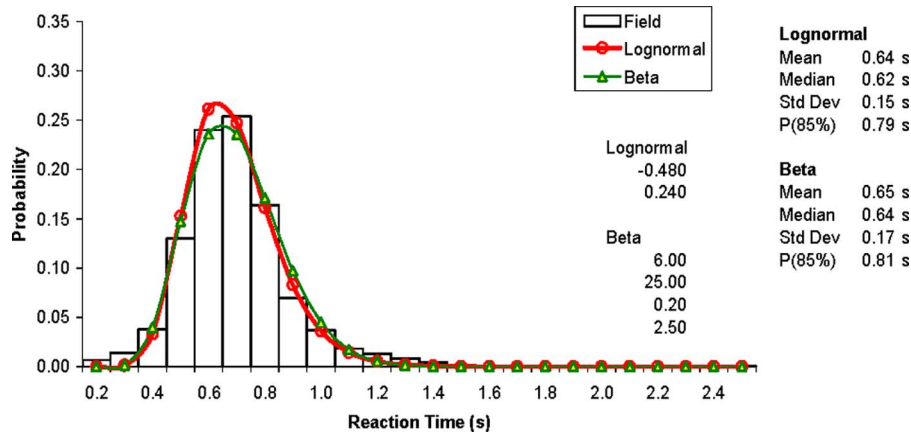
Fig. 5. Smoothed field data and proposed PRT models (all observations; $n = 455$).

two distributions, the 85th-percentile PRTs were 0.75 and 0.77 s for the lognormal and beta distributions, respectively. Consequently, the field data were smoothed using an Epanechnikov kernel of bandwidth 2 [26], as shown in Fig. 5. Again, the lognormal and beta models were fit to the field data, and the results demonstrated a lack of statistical evidence to reject the hypothesis that the field data followed either a lognormal or beta distribution ($p = 0.876$, $\chi^2(8) = 3.78$ and $p = 0.687$, $\chi^2(8) = 5.64$ for the lognormal and beta models, respectively). The 85th-percentile PRTs found after these changes were slightly higher: 0.79 s (lognormal distribution) and 0.81 s (beta distribution).

Other studies [7] have shown that the 85th-percentile brake PRTs for unalerted drivers typically range from 1.1 to 1.3 s on high-speed signalized-intersection approaches (greater than 64 km/h). These studies typically measure the PRTs from the onset of the yellow interval to the instant when the brake lights are actuated. Alternatively, this paper did not include the delay between the instant when the brake pedal is pressed and the instant when the brake lights are activated, which could explain the lower PRTs. Furthermore, the fact that the drivers were aware that they were being observed could also explain the lower PRTs observed in this paper. In fact, Green [8] reports that when drivers are fully aware of the time and location of the brake signal, the PRTs in the range of 0.70–0.75 s have been observed. Another aspect that could explain the lower PRTs is the practice effect, given that the participants encountered more yellow runs (20 out of 24 runs) during the experiment.

To quantify the impact of the practice effect, the 85th-percentile PRTs were estimated using only the data collected on the first trials for each driver. The PRTs were 1.1 s using the data from the first trial, 1.0 s for the first two trials, and 0.9 s if the data from the first three trials are used to estimate the 85th-percentile PRTs. These results clearly show that the repetitive nature of the field test affected the estimation of the 85th-percentile PRT and that the estimates obtained using the fitted distributions should be carefully used as they represent conditions that might not be fully representative of normal driving.

V. DILEMMA-ZONE ANALYSIS

After characterizing the typical driver PRTs, this paper analyzes the driver stopping/running behavior as a function of
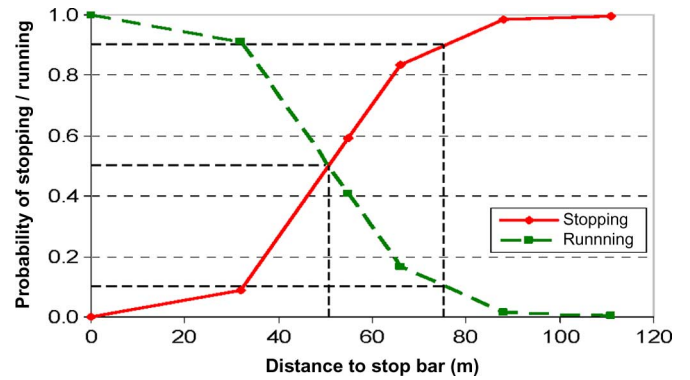

Fig. 6. Probability of stopping/running.

the distance to the stop bar, as shown in Fig. 6. Overall, the probabilities of stopping for the 32-, 55-, 66-, 88-, and 111-m (105-, 180-, 215-, 290-, and 365-ft) trigger distances were 0.09, 0.59, 0.83, 0.99, and 1.00, respectively. The 0.9/0.1 probability of stopping/running laid between 66 and 88 m (3.3 and 4.4 s) from the stop bar, whereas the 50% stopping/running decision point occurred when the yellow indication was triggered when the vehicle was at a distance of 51 m (2.55 s) from the stop bar.

As was mentioned earlier, the driver gender and age were recorded, and test subjects were grouped into two age groups: younger drivers (age < 65 years) and older drivers (age ≥ 65 years). Driver stopping/running behavior was compared between the two age and gender groups using a χ^2 goodness-of-fit test by comparing the probability of stopping distributions.

The percentage of the older drivers (65 years of age and older) who elected to stop at the short yellow-phase trigger distances was larger than the younger drivers. The older drivers were significantly less likely to run through the intersection at the 32-, 55-, and 66-m (105-, 180-, and 215-ft) trigger distances than the younger drivers. Specifically, at the 32-m (105-ft) trigger distance, the probability of stopping for the older drivers (65 years of age and older) was 0.17 compared with 0.02 for the younger drivers. Also, as shown in Fig. 7, the probabilities of stopping for those who were 65 years of age and older were 0.69 at the 55-m (180-ft) trigger distance and 0.88 at the 66-m (215-ft) trigger distance compared with 0.50 (at 55-m trigger distance) and 0.79 (at 66-m trigger distance)
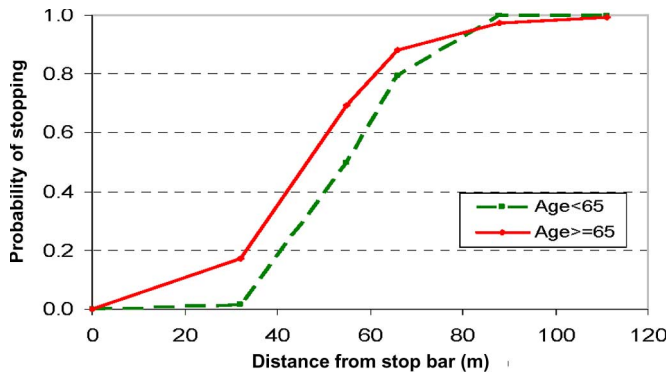
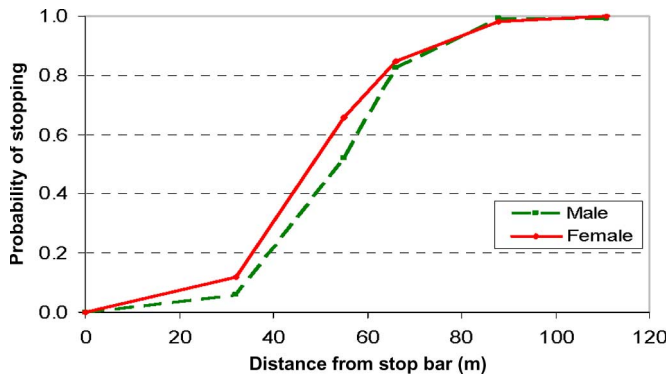Fig. 7. Probability of stopping (function of age group).

Fig. 8. Probability of stopping (function of gender).

Fig. 9. Driver uncertainty levels.

Fig. 10. Dilemma-zone boundaries by age groups.

for the younger drivers. At the longer trigger distance (88 m), 97% of the older drivers (65 years of age and older) stopped, whereas all of the younger drivers stopped. The χ^2 test analysis demonstrated that the effect of age was highly significant at the 32-m $(\chi^2(1) = 17.66, p < 0.001)$ and the 55-m $(\chi^2(1) = 9.16, p = 0.002)$ yellow-phase trigger distances, whereas it was marginal at the longer trigger distances of 66 m $(\chi^2(1) = 3.31, p = 0.069)$ and 88 m $(\chi^2(1) = 3.52, p = 0.061)$, and no significant differences $(\chi^2(1) = 1.13, p = 0.29)$ were obtained between the older and younger drivers at the 111-m (365-ft) trigger distance.

The female drivers appeared to be more likely to stop when compared with the male drivers. Fig. 8 shows that the probability of stopping curve for the female drivers was shifted to the left when compared with the male drivers in the range between 32 and 66 m (105 and 215 ft). This shift correlates to an increase in the probability of stopping for the female drivers relative to the male drivers at the short yellow-phase trigger distances. The χ^2 analysis revealed that significant differences $(\chi^2(1) = 4.6, p = 0.03)$ exist between the male and female drivers only for the 55-m (180-ft) yellow-phase trigger distance with 52% versus 66% of the population stopping. There were no statistically significant differences for the other four trigger distances.

In addition, the data were utilized to derive the probability of stopping and to compute the degree of uncertainty associated with the different driver groups. The drivers were classified into the following four age groups: 20–39, 40–64, 65–69, and 70 years of age and older. With the probability of stopping/running
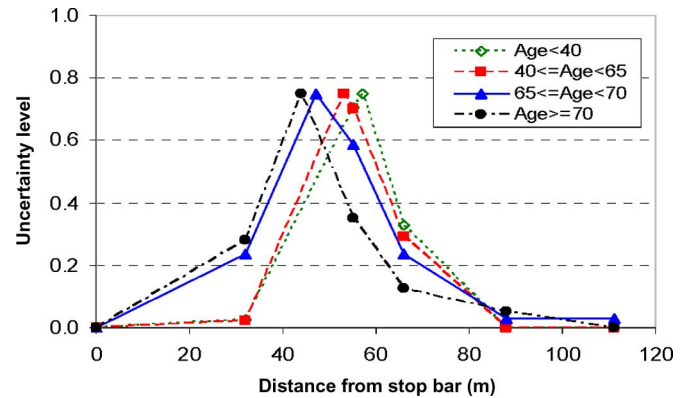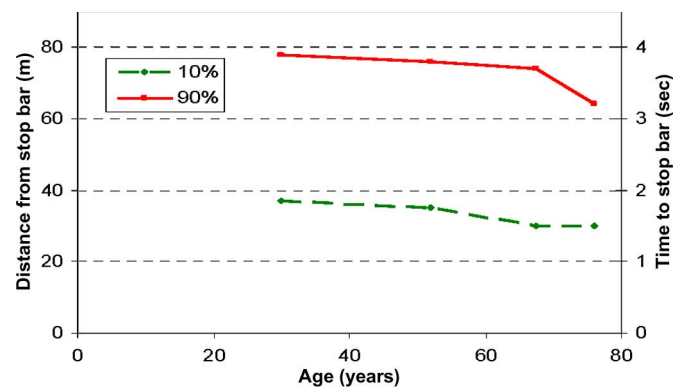
obtained, the degree of uncertainty for each age group was computed using (3) and is shown in Fig. 9. The figure shows that the highest degree of uncertainty occurred when the probabilities of stopping and running were equal. The location of the uncertainty zone and maximum uncertainty point for the oldest group (70 years of age and older) was offset to the left, demonstrating that the older drivers tend to make their decisions when they are closer to the intersection as a result of their longer PRTs. The results demonstrate that older drivers are more likely to stop in response to a yellow-phase transition and only attempt to run when they are in close proximity to the intersection. A χ^2 test for the four age groups demonstrated that the effect of age was highly significant at the 32-m $(\chi^2(3) = 18, p < 0.001)$ and 55-m $(\chi^2(3) = 12.6, p = 0.006)$ yellow-phase trigger distances, whereas there were no significant differences at the longer trigger distances.

Fig. 10 shows the dilemma-zone boundaries within the range of 10%–90% probability of stopping for the different age groups. The figure clearly shows that the dilemma-zone boundaries decrease as the driver population age increases. For example, the dilemma zone ranges from 64 m (3.2 s) to 30 m (1.5 s) for the 70-year-old and older drivers, compared with from 78 m (3.9 s) to 37 m (1.85 s) for the 20–39 age group. It is apparent that the driver stopping/running behavior in response to the yellow-phase trigger distance is age-related, with the younger drivers being approximately 20% more likely to attempt to run the yellow light when compared with the older drivers. Furthermore, it appears that the 70 and older age group

experiences a significant reduction in the size of the dilemma zone (1.5 versus 2.0 s). In addition, the dilemma-zone boundaries are significantly closer to the intersection with a change in the slope in the dilemma-zone boundary function. Although the older age group had similar PRTs in comparison with the other age groups, they appeared to delay their decisions, which results in a dilemma zone that is smaller and closer to the signalized intersection.

VI. CONCLUSION AND RECOMMENDATIONS

This paper demonstrates that the 1.0-s 85th-percentile PRT that is recommended in the traffic-signal-design procedures is valid and consistent with the field observations. These findings are consistent with the results of previous studies. Furthermore, this paper clearly shows that brake PRTs are impacted by the vehicle's TTI at the onset of a phase transition to yellow. Consequently, we recommend that only TTIs of 2.2–4.4 s be considered in the characterization of brake PRT behavior. This paper has also shown that gender and age do not affect the PRTs. Even if the statistical analysis has shown that drivers have shorter PRTs when going downhill, this difference is so small that, from an engineering point of view, it can be disregarded. This paper also indicates that either a lognormal or a beta distribution is sufficient to model the brake PRT behavior.

The driver stopping/running behavior at high-speed signalized intersections is sensitive to the distance from the intersection at the onset of a phase transition, the age, and the gender of the driver. Specifically, the drivers are less likely to stop at the onset of a yellow phase transition at shorter distances. The male drivers are less likely to stop when compared with the female drivers in the 32–66-m (105–215-ft) distance range (TTI of 1.6–3.3 s). Drivers in the 65 years of age and older group are more likely to stop at the onset of a yellow-phase trigger (74% compared with 66% for drivers who are less than 65 years old). Younger drivers are approximately 20% more likely to attempt to run the yellow light when compared with the older drivers. Specifically, the dilemma zone for the less than 40 years of age group ranges from 1.85 to 3.9 s, whereas the dilemma zone for the greater than 70 year old group ranges from 1.5 to 3.2 s. These age-related differences in driver behavior are significant and should be considered in the design of yellow times and dilemma-zone mitigation strategies at signalized intersections. Furthermore, this paper demonstrates that the point of highest uncertainty moves closer to the intersection as the driver age increases, implying that the older drivers make their decisions later and closer to the intersection.

Because the drivers all drove the same test vehicle, we believe that the results can be generalized for a number of reasons. First, we hypothesize that driver behavior is the most critical factor in driver stop/go decisions if we only consider light-duty vehicles. Second, the driver PRTs and stop/go decisions are consistent with the results of earlier field studies and, thus, demonstrate the validity of the study results.

It should be noted that a caveat of this paper is that drivers experienced more yellow indications than green indications and, thus, could be more willing and prepared to stop than would be typical in a natural environment. The trends in driver response to a yellow indication, however, are consistent with the results of previous field studies reported in the literature. It should also be noted that the drivers were not distracted by the surrounding conditions and did not have other vehicles in close proximity to them when they made their stop/go decisions. Consequently, additional field studies are needed to characterize driver behavior at the onset of a phase transition, considering the impact of a leading vehicle, the proximity of a following vehicle, the surrounding environment, and the impact of the approaching speed on driver behavior. Finally, it is recommended that these stop/go decision models be implemented within the microscopic traffic simulation software to better capture the behavior of the drivers at the onset of yellow-phase transitions and to evaluate alternative yellow-timing strategies.

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