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Development of a Framework for Evaluating Yellow Timing at Signalized Intersections

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16. Abstract:

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This study developed a novice approach for computing the clearance interval duration that explicitly accounts for the reliability of the design (probability that drivers are not caught in a dilemma zone). Lookup tables based on the limited data available from this study are provided to illustrate how the framework could be used in the design of yellow timings. The approach was developed using data gathered along Virginia's Smart Road test facility for dry and clear weather conditions for two approach speeds: 72.4 km/h (45 mph) and 88.5 km/h (55 mph). Each dataset includes a complete tracking of the vehicle every deci-second within 150 m (500 ft) before and after the intersection. A total of 3,454 stop-run records were gathered. These include 1,727 records (687 running records and 1,040 stopping records) for an approach speed of 45 mph and 1,727 records (625 running records and 1,102 stopping records) for an approach speed of 55 mph. Using these data, models that characterize driver perception-reaction times and deceleration levels were developed.

The application of the proposed approach demonstrates that the current design procedures are consistent with a reliability level of 98%.

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FINAL REPORT

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ABSTRACT

Studies show that the proper design of clearance intervals has significant implications for intersection safety. For example, in 2001, approximately 218,000 red-light-running crashes occurred at signalized intersections in the United States. These crashes resulted in nearly 181,000 injuries and 880 fatalities and an economic loss of $14 billion. Driver behavior while the driver is approaching high-speed signalized intersections at the onset of a yellow indication varies as a function of many parameters. Some of these parameters are related to the driver's attributes, e.g., age, gender, perception-reaction time, and acceptable deceleration levels. Other parameters that relate to the intersection geometry include the approach speed, distance, and time to the intersection at the onset of the yellow indication.

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INTRODUCTION

The onset of a yellow-indication is typically associated with the risk of vehicle crashes resulting from dilemma-zone and red-light-running problems. Such risk of vehicle crashes is greater on high-speed signalized intersection approaches. In general, the driver is considered to be trapped in a dilemma zone, if at the onset of yellow, the driver’s perceived distance to the intersection is neither greater than or equal to the distance required for safe stopping nor less than or equal to the distance required to run—and in some jurisdictions clear the intersection—before the yellow indication ends. Alternatively, the driver option zone is defined as the zone (distance and time) from the point at which 90% of the drivers elect to stop to the point at which only 10% of the drivers elect to stop. Dilemma and option zones are always defined either in time or space. If the driver decides to stop when he or she should have proceeded, rear-end crashes could occur. Alternatively, if the driver proceeds when he or she should have stopped, he or she would run the red light and a right-angle crash with side-street traffic could occur. In 2001, approximately 218,000 red-light-running crashes occurred at signalized intersections in the United States. These crashes resulted in nearly 181,000 injuries and 880 fatalities and an economic loss of 14 billion dollars (Huang et al., 2006). Driver behavior while drivers are approaching high-speed signalized intersections at the onset of a yellow indication varies as a function of many parameters. Some of these parameters are related to the driver’s attributes, e.g., age, gender, and perception-reaction time (PRT). Other parameters are related to the intersection, e.g., approaching speed, distance, and time to the intersection at the onset of the yellow indication, and the safe acceptable acceleration and deceleration rates the driver is willing to exert to either run or stop.

The current traffic signal timing guidelines assume that the driver option zone is fixed (ranging between 5.5 to 2.5 s from the intersection), considering a 1.0 s PRT (85th percentile perception time) and a deceleration rate of 3.0 m/s^2 (10.0 ft/sec^2) (Institute of Transportation Engineers [ITE]; 1999; Institute of Transportation Engineers (ITE), 2001; Federal Highway Administration (FHWA), 2008). However, it is not clear how driver PRT and accepted deceleration rates vary as a function of drivers' characteristics (age, gender, etc.), intersection characteristics (approaching speed, speed limit, time-to-intersection, etc.), and roadway surface conditions. Consequently, there is a need to better understand how these factors impact the design of yellow timing.

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 (Peterson et al., 1986; Kronborg, 1993; Kronborg et al., 1997; Pant and Cheng, 2001). More recently, researchers (Bonneson et al., 2002; Zimmerman and Bonneson, 2006) 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 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 vehicles travel at a constant speed over the 300-meter distance. The system assumes a constant dilemma zone, defined by a time-to-intersection (TTI) 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 user-specified 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 (Kronborg, 1993; Kronborg et al., 1997).

The research effort presented in this report first characterizes driver behavior within the option/dilemma zone using data gathered in a controlled field environment and then develops a new procedure for estimating traffic signal yellow timings that explicitly accounts for the risk that drivers will be in a dilemma zone (i.e., unable to make a correct decision). Lookup tables based on the limited data collected in this study are developed to provide practitioners with illustrative guidelines for the design of yellow timing durations. Unlike the current state-of-practice procedures, these lookup tables allow the practitioner to explicitly identify the risk associated with the yellow timing setting.

PURPOSE AND SCOPE

The purpose of this study was to analyze driver behavior at the onset of the yellow interval at signalized intersections, including stop-run decisions, PRT, deceleration levels, dilemma zone, and red-light running. This characterization was then used to develop a new procedure for estimating yellow timings. The scope of the study was limited to light-duty vehicles and dry and clear weather conditions at a high-speed signalized intersection.

The objectives of this study were as follows:

1. Determine the percentage of drivers who run the yellow light as a function of their TTI, their speed, surrounding traffic, gender, and age.
2. Study the impact of the yellow interval duration on red-light-running behavior.
3. Determine the percentage of violators and how drivers behave while violating.
4. Determine the influence of other vehicles on drivers’ responses to a yellow signal, and the influence of lead vehicle yellow-light running on the percentage of violators and violating behavior.
5. Address the issue of whether the option zone is determined solely by TTI, or varies with vehicle speed, presence of a following vehicle, gender, and age of driver.
6. Construct illustrative lookup tables for the computation of yellow interval duration for different posted speed limits, based on the data collected in this study.

METHODS

Five tasks were conducted to fulfill the study objectives:

1. Literature Review
2. Experimental Design Development
3. On-Road Testing
4. Data Analysis
5. Yellow Interval Design Procedure.

The design of the experiment for the study is presented in this section. Included is a description of the test facility, test vehicles, and test subjects.

Roadway Layout

The Virginia Smart Road at the Virginia Tech Transportation Institute (VTTI) was the site of the field test. The Smart Road is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of Intelligent Transportation System (ITS) concepts, technologies, and products. The Smart Road is a 3.5 km (2.2 miles) two-lane road with one four-way signalized intersection (Figure 1) and a high-speed banked turnaround at one end and a medium-speed flat turnaround at the other end. Access to the Smart Road is controlled by electronic gateways, making the test facility a safe location to conduct field tests.

Figure 1. Signalized intersection at testing site.

The study section that was considered for the tests included only the section between the high-speed turnaround and marker 108 (where a third turnaround is located). The horizontal layout of the test section is fairly straight with some minor horizontal curvature which does not impact vehicle speeds. The vertical layout of the test section has a substantial grade of 3%. The details of how the vertical profile was generated are described by Rakha et al. (Rakha et al., 2001). Because participants turned around at the end of each run, half the trials were on a 3-percent upgrade and the other half were on a 3-percent downgrade.

IRB Procedures

In order to start recruiting participants to run the designed experiment, approvals were required from the Institutional Review Board (IRB) office at Virginia Tech. The process of obtaining these approvals required the following steps:

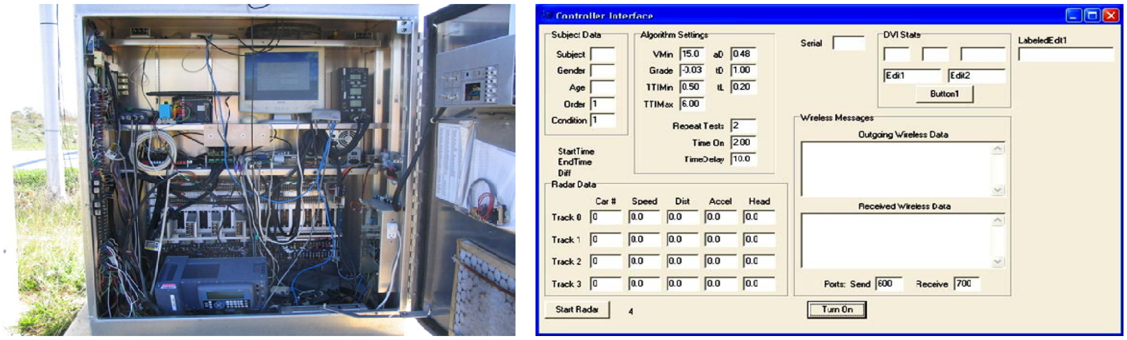
1. Obtain conditional approval for initial project activities.
2. Receive the IRB Initial Review template approval (VTTI IRB Coordinator).
3. Submit the IRB Initial Review application.
4. Supply necessary forms and applications, including:
   - Sample Flyer and Newspaper Advertisement
   - Driver Screening Questionnaire
   - Informed Consent Form
   - On-site Health Screening Questionnaire.
5. Make revisions requested by the IRB.

After going through these procedures, IRB approval for one year was obtained in April 2008 and was renewed again in April 2009. In addition, the IRB required that the entire research team attend a human subject training course and receive a completion certificate.

Intersection and Test Vehicles Equipment

The designed experiment required communication between the intersection control cabinet and the subject car through a programmed wireless communication interface (Figure 2). In addition, three vehicles were used in the study; one was driven by test participants (accompanied by the in-vehicle experimenter) and the other two vehicles were driven by two research assistants.

A 2000 Chevrolet Impala (Figure 3) was driven by the test participants as the subject car. The vehicle was instrumented with additional equipment that included a Differential GPS (DGPS), a real-time Data Acquisition System (DAS), and a computer to run the different experimental scenarios. The data recording equipment had a communications link to the intersection signal control box that synchronized the vehicle data stream with changes in the traffic signal controller. The DAS contained within the vehicle was custom built by the Center for Technology Development at VTTI. The DAS was located inside the trunk in a custom durable mounting case for accurate measurement and out of the view of the test subject (Figure 3). One of the other two vehicles leads or follows the subject car as a confederate car (1997 Ford Taurus; Figure 4), whereas the other car services as the side-street traffic. All three vehicles were equipped with a communications system between vehicles, operated by the research assistants.



Subject
Gender
Age
Order 1
Condition 1

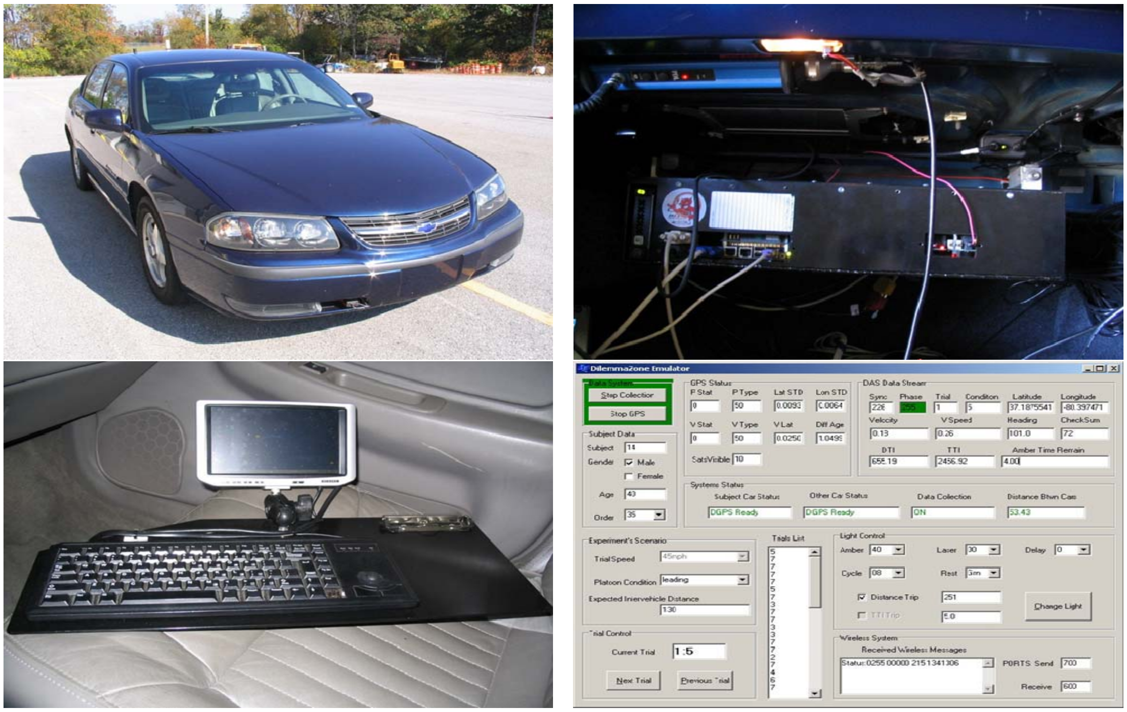
VMin 15.0
aD 0.48
Grade -3.03
tD 1.00
TTIMin 0.50
tL 0.20
TTIMax 6.00
Repeat Tests 2
Time On 2.00
TimeDelay 10.0

	Car #	Speed	Dist	Accel	Head
Track 0	0	0.0	0.0	0.0	0.0
Track 1	0	0.0	0.0	0.0	0.0
Track 2	0	0.0	0.0	0.0	0.0
Track 3	0	0.0	0.0	0.0	0.0

4

Ports: Send 600 Receive 700

Figure 2. Wireless communication interface in the intersection signal cabinet.



GPS Status
P Stat: 0
P Type: 50
Lat STD: 0.0093
Lon STD: 0.0064
V Stat: 0
V Type: 50
V Lat: 0.0250
Diff Age: 1.0499
SatsVisible: 10

Subject Data
Subject: 14
Gender: ☑ Male ☐ Female
Age: 40
Order: 35

DAS Data Stream
Sync: 228
Phase: 255
Trial: 1
Conditon: 5
Latitude: 37.1875541
Longitude: -80.397471
Velocity: 0.13
VSpeed: 0.26
Heading: 101.0
CheckSum: 72
DTI: 655.19
TTI: 2456.92
Amber Time Remain: 4.00

Systems Status
Subject Car Status: DGPS Ready
Other Car Status: DGPS Ready
Data Collection: ON
Distance Btwn Cars: 53.43

Experiment's Scenario
Trial Speed: 45mph
Platoon Condition: leading
Expected Intervehicle Distance: 130

Trials List: 5 7 7 7 7 5 7 3 7 7 3 3 7 7 2 7 4 6 7

Light Control
Amber: 40
Laser: 30
Delay: 0
Cycle: 08
Rest: 3m
☑ Distance Trip: 251
☐ TTI Trip: 5.0

Trial Control
Current Trial: 1:5

Wireless System
Received Wireless Messages: Status:0255 00000 2151341306
PORTS Send: 700
Receive: 600

Figure 3. DAS and communication interface in the subject car.


```
SDL Version 2.0          DilemmaZone   Researcher
Dilemmazone_Display

Trial_Number: 1                        Experiment_Number: 5 / 45mph
Expected_Intervehicle_Distance: 130.000000 feet
Light_Change_Distance: 251.000000 feet
Distance_Between_Cars: 122.116989 feet
Distance_To_Intersection: -754.778076 feet
Time_To_Intersection: -7537.115234 seconds

TOO CLOSE                                                      TOO FAR

    TIME_TO_YELLOW                    DISTANCE BETWEEN CARS
29.35                                 122.11

'<-' or '->' Switch Among Displays
```

Figure 4. Communication interface in the confederate car.

Participants

Participants were licensed drivers recruited from the VTTI participant database, word-of-mouth, posters, and through ads in the local Blacksburg, Virginia, newspaper. Participants were screened through a verbal telephone questionnaire to determine if they were licensed drivers and if they had any health concerns that would exclude them from participating in the study. Six pilot participants were recruited to run pilot sessions for the purpose of training the research team, testing vehicle equipment, validating collected data, and adjusting the most appropriate yellow trigger distances. After finishing the pilot sessions and having the yellow distances chosen, 24 drivers were recruited in three equal age groups (under 40 years old, 40 to 59 years old, and 60 years of age or older); equal numbers of males and females were assigned to each group.

Procedures

There were two main steps to the makeup of this study. The first step involved determining eligibility and obtaining an informed consent from the participant. The second step involved the Smart Road test-track driving portion of the study, which required six sessions, once per day, where each participant was assigned to six different test conditions. The different test conditions were based on two instructed vehicle speeds of 72.4 km/h (45 mph) and 88.5 km/h (55 mph) and three platoon conditions (leading, following, and no other vehicle). The various conditions were run in predetermined randomized orders, with a different order for each participant. Each participant was assigned to the entire six test conditions (sessions), one test condition per day, taking approximately 1.5 hours per session to complete.

Participants drove loops on the Smart Road, crossing a four-way signalized intersection where the data were collected. Exclusive of practice trials, the participant drove the entire test course 24 times for a total of 48 trials, where a trial consists of one approach to the intersection. Each participant was tested individually. Among the 48 trials, there were 24 trials in which each yellow trigger time to stop-line occurred four times. On the remaining 24 trials the signal indication remained green. This scheme would result in yellow/red signals being presented on 50% of the 48 trials; conversely, 50% of intersection approaches would consist solely of a green indication. To examine whether willingness to stop varies with speed, the onset of yellow was based on the time-to-stop line (between 2.0 s and 4.6 s) at the instructed speed rather than on distance from the stop line. Radar was used to determine vehicle distance from the intersection. Outputs from the radar triggered the phase change events.

Upon arrival at VTTI, each participant was asked to review and sign an informed consent form. In addition, each participant was asked to complete a medical questionnaire to verify that he or she was not under the influence of any drugs or alcohol and did not have medical conditions that would impair his or her ability to drive. Subsequently, the participant was escorted to the test vehicle. After becoming familiar with the test vehicle (e.g., adjusting mirrors or seat, fastening seat belt), the participant drove to the Smart Road with the in-vehicle experimenter (who was present at all times during the study to provide instructions, supervise the operation of the computer system, and answer questions as necessary). Before the first trial, the participant drove two loops (four intersection passes or four trials) to become familiar with the vehicle and the Smart Road. During the drive to the first turn-around, the participant was asked to accelerate and brake several times to ensure that he or she was familiar with the vehicle's handling characteristics under hard braking. On each of the four practice trials, the participant was asked to cruise the road at the instructed speed of 72.4 km/h (45 mph) or 88.5 km/h (55 mph). If a participant drove more than 8 km/h (5 mph) above or below the instructed speed he or she was asked to drive at the instructed speed. The participant was told that maintenance vehicles will occasionally be entering and leaving the road via a standard signalized intersection. These maintenance vehicles were the confederate vehicles driven by trained experimenters who were involved in the study. The participant was asked to follow all normal traffic rules and to obey all traffic laws. After each trial run the participant was reminded of the instructed speed at the turnaround approached after that trial if they exceeded or failed to reach the instructed speed.

Three vehicles were used; one was driven by the test participants (accompanied by the in-vehicle experimenter) and the other two vehicles were driven by two researchers. The first confederate vehicle was either leading or following the test vehicle to investigate the effect of the presence of a lead or following vehicle on the participant's driving behavior. The second confederate vehicle (this vehicle was felt to be a necessary addition to the scenario to simulate real-world conditions) crossed the intersection from the conflicting approach when the traffic light was green. All three vehicles were equipped with a communications system, operated by the research assistants and the Smart Road control tower.

During each session the participant was assigned to one of the platoon conditions (leading, following, or no other vehicle). In the leading platoon condition, the participant's vehicle was followed by the first confederate vehicle. The confederate vehicle maintained a 2-second headway which is equivalent to a 40-meter (130 ft) spacing at a speed of 72.4 km/h (45 mph) and a 50-meter (163 ft) spacing at the 88.5 km/h (55 mph) instructed speed. In the following platoon condition, the participant driver followed the first confederate vehicle. The participant was asked to follow the confederate vehicle at a 2-second headway which is equivalent to 8 car lengths at the 72.4 km/h (45 mph) instructed speed and 10 car lengths at the 88.5 km/h (55 mph) instructed speed. In the *no other vehicle present* condition, there was no leading or following confederate vehicle traveling in the same direction as the participant or approaching the participant in the opposing lane. Only the second confederate vehicle was crossing the intersection from the conflicting approach when the traffic signal was red for the test vehicle.

During the test runs the participants drove a distance of 1.6 km (1 mile) going downhill to approach the intersection followed by a 0.5-kilometer (0.3 mile) leg to a high-speed turnaround, and another 0.5-kilometer (0.3 mile) approach going back to the intersection. The yellow interval used for the 72.4 km/h (45 mph) instructed speed is 4 s, whereas for the 88.5 km/h (55 mph) the instructed speed is 4.5 s. Those yellow intervals were triggered for a total of 24 times (four repetitions at six distances). The yellow indications were triggered when the front of the test vehicle was 40.2, 54.3, 62.5, 70.4, 76.5, and 82.6 m (132, 178, 205, 231, 251, and 271 ft, respectively) from the intersection for the 72.4 km/h (45 mph) instructed speed, and 56.7, 76.2, 86, 93.6, 101, and 113 m (186, 250, 282, 307, 331, and 371 ft, respectively) for the 88.5 km/h (55 mph) instructed speed to ensure that the entire dilemma zone was within the range. An additional 24 green trials were randomly introduced into the 24 yellow trials to introduce an element of surprise into the experiment. The run sequence was generated randomly and thus was different from one trial to another. As was mentioned earlier, the phase change events were controlled by the test vehicle through the use of a wireless communication system between the vehicle and the custom-built signal controller.

RESULTS AND DISCUSSION

Literature Review

This section provides a brief review of the relevant literature that relates to dilemma zone and red-light-running modeling and the parameters affecting the driver behavior while approaching a high-speed intersection at the onset of a yellow indication. In addition, the section sheds light on a previous experiment conducted by the investigators that serves as a basis for the current study.

Dilemma Zone and Red Light Running

Traffic signals are introduced at highway intersections in order to accommodate and guarantee the safe movement of the traffic streams which conflict at the intersection. In order to provide a smooth transition between the movements of different approaches, a yellow interval is provided at the end of the green time of each phase. According to the Manual on Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration (FHWA), 2003), “the yellow signal indication warns the vehicles that their green movement is being terminated and a red signal indication will be exhibited immediately” (p. 4D-2). Accordingly, upon the onset of a yellow indication, a driver has two choices: either to come to a safe complete stop before the stop line, or to continue at their current speed or accelerate to the speed limit to clear the intersection before the onset of the red indication. Although these choices may seem straightforward, there are many problems associated with the decision of the drivers at the onset of the yellow indication, including those related to the option/dilemma zone and the possibility of red light running.

First, it is important to describe the different situations that the driver encounters while approaching the intersection at the onset of a yellow indication; namely the dilemma and option zones. An earlier study by the current authors (El-Shawarby et al., 2007b) summarized the differences between dilemma and option zones, stating that the driver’s approach speed and distance from a signalized intersection at the onset of a yellow-phase indication affect his or her stop/go decision. Drivers can either come to a safe stop if they are far enough from the intersection or clear the intersection if they are close enough to the intersection. The inability to perform either option successfully is attributed to a shortcoming in the design of the signal timings and is termed the design dilemma zone in some literature (e.g., Sheffi and Mahmassani, 1981). This dilemma zone is created when the minimum stopping distance (d_s) is greater than the maximum running (clearing) distance (d_r) which is the distance within which the vehicle can clear the intersection before the end of the yellow interval. 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 line by considering the braking, aerodynamic, rolling, and grade resistance forces as in Equation (1).

$$d_s = v \cdot t + \frac{\gamma_b W}{2 g k_a} \ln\left[1 + \frac{k_a v^2}{\eta_b \mu W + f_{rl} W \pm WG}\right] \qquad (1)$$

where d_s is the distance required for a vehicle to stop at the stop line (m),
v is the speed of the approaching vehicle (m/s),
t is the driver PRT (s),
γ_b is the mass factor accounting for moments of inertia during braking (recommended 1.04),
W is the vehicle weight (N),

g is the gravitational acceleration (9.81 m/s^2),
k_a is the aerodynamic coefficient ($k_a = \rho/2C_D A_f$),
ρ is the air density kg/m^3,
C_D is the drag coefficient,
A_f is the vehicle’s frontal area (m^2),
η_b is the braking efficiency,
μ is the coefficient of roadway adhesion,
f_{rl} is the rolling coefficient ($frl \approx 0.01(1+v/44.73)$), and
G is the roadway grade (decimal).

Typically the aerodynamic and the rolling resistance forces are ignored and the stopping distance is computed as

$$d_s = v \times t + \frac{v^2}{2g\left(h_b m \pm G\right)} = v \times t + \frac{v^2}{2a \pm 2gG} \tag{2}$$

where a is the deceleration rate (m/s^2).

Equation (2) is typically used in the literature to compute a vehicle’s stopping distance and this equation is identical to the ITE formula that is used in yellow interval calculation (Tarnoff, 2004), as shown in Equation (3).

$$y = t + \frac{v}{2\left(a \pm gG\right)} \tag{3}$$

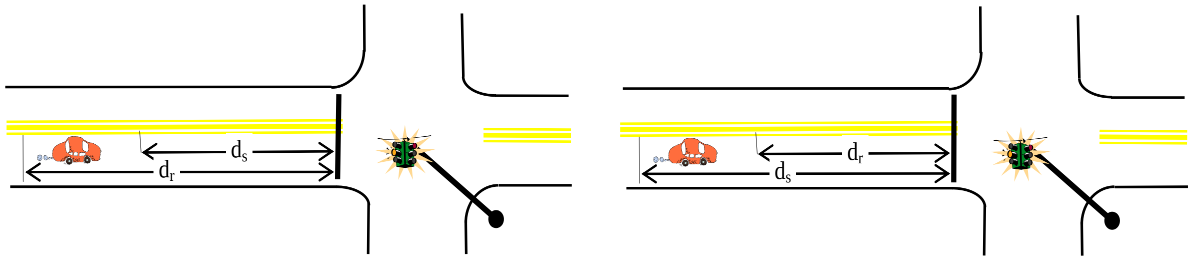
where y is the duration of the yellow interval (s).

On the other hand, a vehicle that is closer than d_s from the stop line when the yellow is displayed will not have sufficient distance to decelerate to a stop before reaching the stop line. In this case, the driver has to clear the intersection at the speed limit before the yellow interval ends. Considering the approach speed, the running distance required for a vehicle to enter the intersection prior to the end of the yellow interval is computed in Equation (4).

$$d_r = v \cdot y \tag{4}$$

where d_r is distance required for a vehicle traveling at v to reach the stop line (m).

A vehicle should be able to safely come to a stop or proceed through the intersection before the end of the yellow interval. An option zone is defined as the zone within which the driver can safely come to a stop during the signal yellow interval and also can clear the intersection during the same interval. Figure 5 illustrates the definition of option and dilemma zones that a driver faces when approaching a high-speed signalized intersection. When a vehicle approaches an intersection during a yellow warning interval, if $d_s < d_r$ and if the vehicle is farther than d_s or closer than d_r such that $d_s < d < d_r$, then an option zone exists where a driver can choose between stopping and clearing the intersection. If $d_s > d_r$ and the vehicle is placed between them such that $d_r < d < d_s$, then a design dilemma zone exists where a vehicle can neither stop nor clear the intersection.



(a) Option Zone $d_s < d_r$

(b) Dilemma Zone $d_s > d_r$

Figure 5. Option and dilemma zones at signalized intersections

Many studies were conducted in order to capture the parameters affecting the driver behavior within the dilemma zone and the red-light-running behavior. In 1999, two databases were employed in order to identify the characteristics of red-light-running crashes (Retting et al.., 1999). The analysis indicated that red-light runners were more likely to be young males and more likely to be fatally injured in red light crashes. In addition, fatally injured red-light runners were much more likely to have high blood alcohol concentrations and to have been driving with suspended or invalid driver’s licenses. Regarding time of day, younger males make up a greater percentage of red-light runners in nighttime crashes than in daytime crashes. Another study, a forward stepwise logistic regression model was calibrated, based on data collected at six intersections located in three cities in Virginia, in order to test explanatory variables of yellow-light versus red-light runners (Porter and England, 2000). The model showed that city, time, safety belt use, and ethnicity were the most significant variables; i.e., unbuckled drivers and non-Caucasian drivers were more likely to run red lights. An interesting illustration was presented in another paper (Lum and Wong, 2003) that summarizes the situations the driver encounters at the onset of a yellow indication as represented by the approach speed and the distance from the stop line for different yellow times. They considered four zones; running, stopping, option, and dilemma zones. As part of this research effort a similar relationship was developed by varying the deceleration level from $0.31g$ ($3\ m/s^2$) to $0.51g$ ($5\ m/s^2$). The driver encounters a dilemma zone if he or she travels faster than the design speed, as illustrated in Figure 6. The driver may avoid the dilemma zone by decelerating at a more aggressive level. Another paper calibrated a statistical model that can be used to project the red-light-running frequency for any given intersection, based on 6-hour traffic flow data on approaches of five different intersections (Bonneson and Son, 2003). The analysis revealed that significant relationships exist between red-light-running frequency and yellow interval duration, use of signal head back plates, speed, clearance path length, and platoon ratio. The paper suggested that the model can be used to evaluate the effectiveness of different countermeasures addressing the red-light-running problem, before introducing these measures to an intersection. These measures include increasing the cycle length, increasing the yellow duration, adding advance detection, adding back plates, changing the speed limit, and adjusting platoon arrival time and concentration.

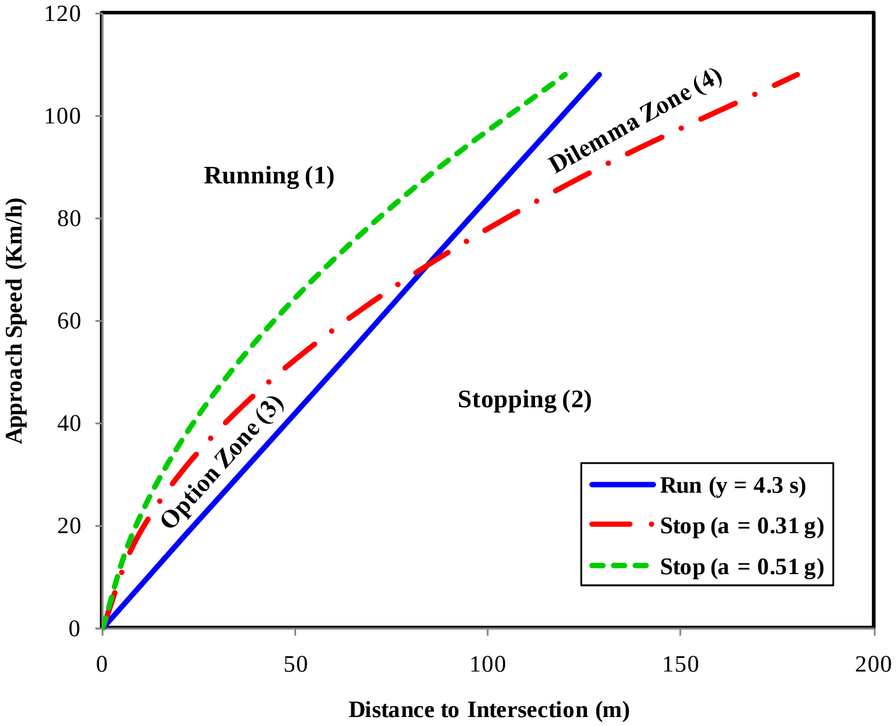


Figure 6. Drivers' situations at the onset of yellow for different deceleration levels.

In another recent study, two methods for reducing red-light running were evaluated at two intersections in Philadelphia, PA (Retting et al., 2008). The first method involved extending the yellow duration by 1 s, demonstrating a reduction in the red-light violation rates between 21 to 63% at all sites. The second method involved the installation of red-light-running cameras, reducing the violation rates by 87% to 100%. The paper confirmed that adequate yellow-duration timing is important for reducing red-light running. However, red-light running remains a problem that can be reduced further through the use of camera enforcement. One last study (Yang and Najm, 2007) presented an interesting comprehensive review of the different factors affecting red light violations across the literature. The study divided the factors to three major groups; driver-related, intersection-related, and traffic-and-environment-related factors. For the driver-related group, age showed that younger drivers were more likely to run red lights compared to older ones, whereas gender showed that red light runners were more likely to be male. For the intersection-related group, signal timing showed that shorter yellow times increased the red light running frequency, whereas higher approach speeds decreased the probability of stopping. Finally, for the traffic-and-environment-related group, higher approaching volumes showed higher red light running rates, while inclement weather had an insignificant effect on red light running (Yang and Najm, 2007).

Perception-Reaction Time

The driver PRT is of significant importance in highway design. For example, it is used to estimate the stopping sight distance in the computation of horizontal and vertical profiles in highway design (Dimitropoulos and Kanellaidis, 1998) and also used in the calculation of the yellow interval duration in traffic signal design (Thompson, 1994). At the onset of a yellow-indication transition on high-speed signalized intersections, a driver decides to either stop safely or to proceed through the intersection before the end of the yellow interval. Accordingly, the proper design of traffic signals requires the computation of a yellow interval that entails an estimate of the driver's PRT. The state-of-practice in different dilemma zone alleviation strategies typically recommends a 1.0 s PRT, which is assumed to equal or exceed the 85th percentile brake PRT (Milazzo et al., 2002). However, a number of studies have demonstrated that brake PRTs are much longer than 1.0 s and that the 85th percentile PRT is more in the range of 1.5 to 1.9 s (Taoka, 1989). These studies have also demonstrated that the PRT on high-speed intersection approaches (greater than 64 km/h or 40 mph) are lower, with 85th percentile PRTs in the range of 1.1 to 1.3 s.

A review of the fundamental concepts associated with reaction times will give a better understanding of the factors related to PRT. A comprehensive survey by Green (Green, 2000) summarized PRT results from most studies published until 2000. The study concludes that when a driver responds to the onset of a yellow light at a traffic signal, the total reaction time can be split into a mental processing (perception) time—which is the time required for the driver to decide on a response, and a movement (reaction) time—which is the time used to lift the foot from the accelerator and touch the brake pedal. Because the mental processing time is an internal quantity that cannot be measured directly and objectively without a physical response, it is usually measured jointly with movement time. Green classified PRT studies into three basic types: simulator studies, controlled road studies, and naturalistic observation. Each type of study has limitations to the degree in which results can be generalized to normal driving conditions. Both simulator and controlled-road studies create practice effects because of the many trials used to gather data for each driver and may produce shorter PRT measurements because drivers may be more alert than in normal driving conditions. Controlled road studies and naturalistic observation are both field approaches but they differ in the sense that, in the latter, the driver is unaware of the data collection effort. Naturalistic studies have the highest validity, but are also limited because it is not possible to test effects of independent variables, place drivers in emergency or even urgent situations, measure perception and movement times separately, or control driver demographics to avoid sample bias. Furthermore, Green demonstrated that older female drivers respond more slowly than younger male drivers.

A study (Caird et al., 2005) which used a driving simulator to analyze the behavior of 77 drivers approaching signalized intersections at speeds of 70 km/h concluded that the PRT did not differ by age and was affected by TTI. 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 another study (Setti et al., 2006), the authors used data gathered from a controlled field test on 60 test participants to characterize driver brake PRTs at the onset of a yellow indication at a high-speed signalized intersection approach. Participants were instructed to drive the car at 72.4 km/h (45 mph) on a closed test course with no other vehicles. The study concluded that the 1.0-second 85th percentile PRT that is recommended in traffic signal design procedures is valid and consistent with field observations and demonstrated that either a lognormal or beta distribution is sufficient for modeling brake PRT. Another study by Gates et al. (Gates et al., 2007) recorded vehicle behavior at six signalized intersections in the Madison, WI area comprising 463 first-to-stop and 538 last-to-go records. The study found that the addition of potential predictor variables related to the activity of other vehicles nearby had statistically significant correlation with stop–

go activity. The analysis of the brake-response time for first-to-stop vehicles showed that the 15th, 50th, and 85th percentile brake-response times were 0.7, 1.0, and 1.6 s, respectively.

Driver Deceleration Behavior

Driver deceleration levels are critical in the design of yellow-interval timings. The state-of-practice is to assume a constant deceleration level of 3 m/s^2 or 10 ft/sec^2. In addition, driver deceleration levels play a critical role in most traffic simulation software and vehicle fuel consumption and emission models. Furthermore, deceleration levels are critical in the design of deceleration lane lengths.

A study (Williams, 1977) conducted at an intersection in Connecticut concluded that the average maximum deceleration level of stopping vehicles traveling at 16.1 to 40.2 km/h (10 to 25 mph) was 2.95 m/s^2 (9.7 ft/sec^2). Another study (Parsonson and Santiago, 1980) reported that 3 m/s^2 (10 ft/sec^2) was a reasonable value for the deceleration level based on a study of 54 intersection approaches in four counties in the southeastern United States (Council et al., 2005). Two other studies (Wortman and Matthias, 1983; Wortman et al., 1985) conducted at different intersections in metropolitan areas in Phoenix and Tucson (AZ) concluded that the mean deceleration level ranged from 2.1 m/s^2 (7.0 ft/sec^2) to 4.2 m/s^2 (13.9 ft/sec^2) with a mean value of 3.5 m/s^2 (11.6 ft/sec^2) at posted speed limits ranging from 48.3 to 80.5 km/h (30–50 mph). The second study found that mean deceleration levels ranged from 2.5 m/s^2 (8.3 ft/sec^2) to 4 m/s^2 (13.2 ft/sec^2) for approach speeds ranging from 57.6 to 76.4 km/h (35.8 to 47.5 mph). Wang et al. (Wang et al., 2005) studied the deceleration behavior of passenger cars approaching stop-controlled intersections on urban streets using an in-vehicle Global Positioning System (GPS). They found that the recommended maximum deceleration level of 3.4 m/s^2 (11.2 ft/sec^2) was applicable to most drivers, with 92.5% of the measured deceleration trips having maximum deceleration levels less than 3.4 m/s^2 (11.2 ft/sec^2) and 87.6% of the deceleration maneuvers having maximum deceleration levels less than 3 m/s^2 (10 ft/sec^2). Haas et al. (Haas et al., 2004) reported in their study that deceleration and acceleration rates observed at rural stop-sign-controlled intersections in southern Michigan varied significantly. The initial speed accounted for about 18% of the variation in deceleration levels while each of the other factors (driver demographics and time-of-day) accounted for only 5% of the variation.

Another study (Hicks et al., 2005) analyzed nine intersections in Maryland. The study found that driver stopping/running behavior and vehicle speed performance in response to a yellow-light interval were affected by the driver's gender and age and found that vehicles with higher entering or initial speeds were more likely to experience a sharp stop, applying deceleration levels greater than 3.4 m/s^2 (11.2 ft/sec^2). Another study (Caird et al., 2005) analyzed the performance of 77 participants (older and younger drivers) approaching at a speed of 70 km/h (42 mph) at the onset of a yellow interval using a moderate-fidelity driving simulator. The study found that older driver deceleration levels (3.7 m/s^2) were significantly lower than younger driver deceleration levels (4.2 m/s^2). A recent study (Gates et al., 2007) analyzed vehicle behavior 5.5 to 2.5 s upstream of six signalized intersections in the Madison, WI area at the start of a yellow interval. A total of 463 first-to-stop and 538 last-to-go records were analyzed. First-to-stop vehicles approaching at speeds $>$ 40 mph applied greater deceleration levels than those approaching at speeds $\leq$ 40 mph. The analysis of the deceleration levels for first-to-stop vehicles showed that the 15th, 50th, and 85th percentile deceleration levels were 2.19, 3.02, and 3.93 m/s^2 (7.2, 9.9, and 12.9 ft/sec^2), respectively. A deceleration level of 3.05 m/s^2 (10 ft/sec^2) was the 69th percentile and the 26th percentile for vehicle approach speeds of >40 mph and ≤40 mph, respectively.

Previous Study

In a previous study conducted by the current investigators, a field data collection effort funded by FHWA, the Mid-Atlantic Universities Transportation Center (MAUTC), and VDOT collected data on 60 subjects approaching a signalized intersection at Virginia's Smart Road facility. In the experiment, participants were instructed to drive the car at 72.4 km/h (45 mph) except in the turnarounds or when stopping at the intersection. Participants were instructed to behave normally when faced with a yellow light, making the decision whether to stop or to go as they usually would do. Not counting the initial practice run, participants drove along the entire test course (2.1 km downhill, low-speed turnaround, 2.1 km uphill, high-speed turnaround) 12 times, passing through the traffic lights 24 times (12 times uphill, 12 times downhill), resulting in 24 trials. At the beginning of each trial run, the signal displayed a green light. As the car approached the intersection, the on-board computer decided whether or not to trigger the yellow and, if so, at what distance from the stop line.

The yellow duration was fixed at 4 s and was initiated when the front of the car was at the following distances from the stop line: 32 m (105 ft), 55 m (180 ft), 66 m (215 ft), 88 m (290 ft), or 111 m (365 ft). This corresponds to TTIs of 1.6 s, 2.7 s, 3.3 s, 4.4 s, and 5.6 s, respectively, assuming a speed of 72.4 km/h (45 mph). Each participant faced phase changes from green to yellow four times for each TTI. These 24 trial conditions (20 yellow lights and 4 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.

The study showed that brake PRTs are impacted by the vehicle's TTI at the onset of a yellow indication. The paper also demonstrated that either a lognormal or a beta distribution is sufficient to model the stochastic nature of the brake PRT. In terms of stopping decisions, the study demonstrated that the probability of stopping varies from 100% at a TTI of 5.5 s to 9% at a TTI of 1.6 s. The study also indicated a decrease in the probability of stopping for male drivers when compared to female drivers. Furthermore, the study suggested 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-years-old group is found to range from 3.9 to 1.85 s, whereas the dilemma zone for the greater than 70-years-old group is found to range from 3.2 to 1.5 s (Rakha et al., 2007).

In the previous study no vehicles other than that driven by the participants were present on the Smart Road. Had the drivers in the previous studies been following other vehicles that ran the yellow, they too might have proceeded. Furthermore, had there been vehicles following the subject drivers in the preceding studies, the drivers might have decided differently because of a perceived risk of a rear-end collision. Furthermore, the previous study only considered a single speed of 45 mph.

On-Road Testing

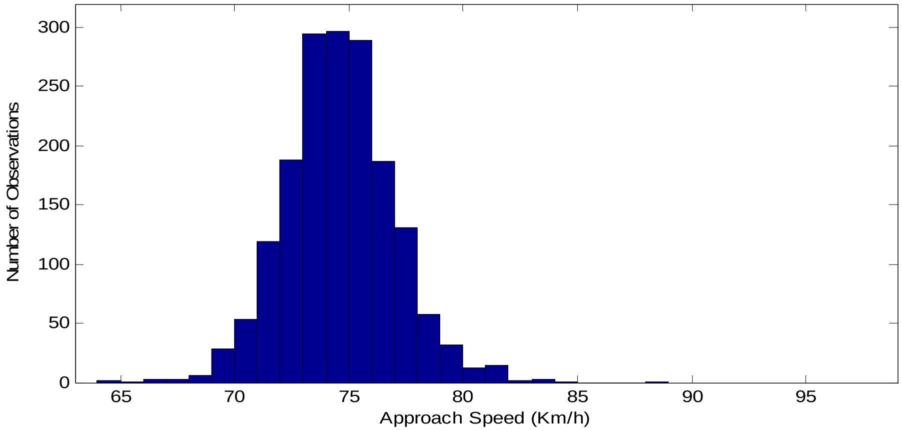
As described earlier, the data were gathered for two instructed approach speeds; 72.4 km/h (45 mph) and 88.5 km/h (55 mph). Each dataset included a complete tracking every decisecond of the subject vehicle within about 150 m (500 ft) before and after the intersection. These tracking data included, in addition to the binary (0 or 1) stop-run decision, the driver's age and gender, platoon scenario (leading, following, or no other), approach grade (uphill or downhill), remaining yellow time (RYT) traveling speed, distance-to-intersection (DTI), PRT, and deceleration rate if the vehicle stopped, and acceleration rate and maximum speed if the vehicle ran through the yellow light. The 72.4 km/h dataset included 1,727 records (687 running records and 1,040 stopping records), whereas the 88.5 km/h dataset included 1,727 records (625 running records and 1,102 stopping records). This yields a total of 3,454 stop-run records.

Although the drivers were instructed to drive at either 72.4 km/h (45 mph) or 88.5 km/h (55 mph), the instantaneous approach speeds at the yellow interval onset varied considerably. In the case of the 72.4 km/h (45 mph) instructed speed, speeds varied from 64.5 to 88.6 km/h (40.1 to 55.1 mph), with a mean of 74.6 km/h (46.4 mph), a median of 74.6 km/h (46.4 mph), and a standard deviation of 2.4 km/h (1.5 mph). Alternatively, in the case of the 88.5 km/h (55 mph) instructed speed, the test vehicle speed varied from 73.5 to 99.8 km/h (45.7 to 62 mph), with a mean speed of 89.5 km/h (55.6 mph), a median of 89.5 km/h (55.6 mph), and a standard deviation of 2.8 km/h (1.7 mph). Consequently, the average approach speed tended to be slightly higher than the instructed speed in both cases. The histograms of the two approach speeds, as illustrated in Figure 7, appear very close to a normal distribution, which is consistent with naturalistic field data that are reported in the literature.

Modeling of Driver Stop-Run Decision

Distribution of Driver Stop-Run Decision

Current practice in most states is to use a driver PRT of 1 s and a deceleration rate that ranges between 3 m/s^2 (10 ft/sec^2) and 4.5 m/s^2 (15 ft/sec^2) as standard assumptions when calculating the yellow signal interval time (Milazzo et al., 2002). In the current study, the two instructed approach speeds to the intersection were 72.4 km/h (45 mph) or 20.1 m/s (66 ft/sec) with a 4-second yellow interval and 88.5 km/h (55 mph) or 24.6 m/s (80.7 ft/sec) with a 4.5-second yellow interval. Considering the standard assumptions (deceleration rate of 3 m/s^2) and by using Equation (2), the minimum stopping distance for the 72.4 km/h (45 mph) approach speed is computed as 81.6 m (267.7 ft) while traveling along the 3% uphill direction ($G = 0.03$) and 94.9 m (311.4 ft) while traveling downhill ($G = -0.03$). The maximum running distance for a 72.4 km/h (45 mph) approach speed and a 4-second yellow interval can be computed using Equation (4) as 80.5 m (264.1 ft). For the 88.5 km/h (55 mph) approach speed, the minimum stopping distance is 116.4 m (381.9 ft) while traveling on the 3% uphill direction ($G = 0.03$) and 136.3 m (447.2 ft) while traveling downhill ($G = -0.03$), and the maximum running distance for a 4.5-second yellow interval is computed as 110.7 m (363.2 ft).


(a) 72 Km/h Instructed Speed

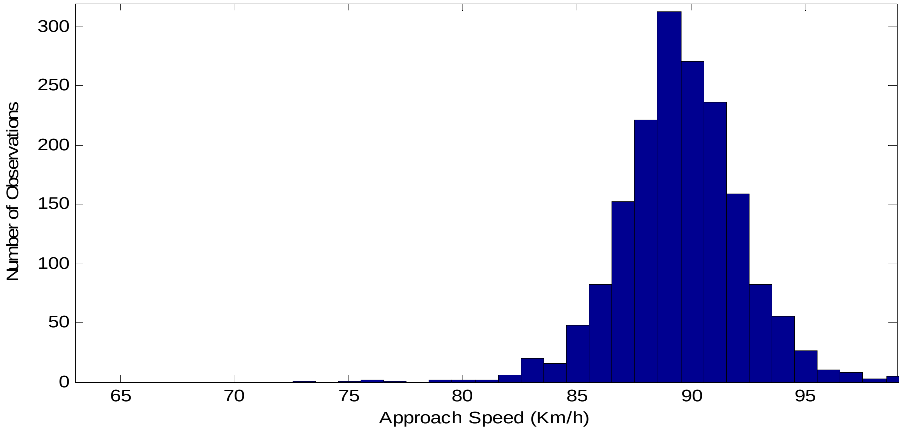

(b) 88 Km/h Instructed Speed

Figure 7. Histogram of approach speed at the onset of yellow.

Consequently, if one considers a deceleration rate of 3 m/s^2 a dilemma zone exists between 81.6 m (267.7 ft) and 80.5 m (264.1 ft) upstream of the intersection for the uphill approach and exists between 94.9 m (311.4 ft) and 80.5 m (264.1 ft) for the downhill approach for the 72.4 km/h (45 mph) approach speed. This represents a negligible dilemma zone of 1.1 m (3.6 ft) going uphill and 14.4 m (47.2 ft) going downhill with a dilemma zone time of 0.7 s into the red. However no dilemma zone exists if one considers the upper limit deceleration rate of 4.5 m/s^2. For the 88.5 km/h (55 mph) approach speed, a dilemma zone of 5.7 m (18.7 ft) exists in the distance between 116.4 m (381.9 ft) and 110.7 m (363.2 ft) from the intersection going uphill and a dilemma zone of 25.6 m (84 ft) in the distance between 136.3 m (447.2 ft) and 110.7 m (363.2 ft) going downhill with a dilemma zone time of 1.0 s into the red. Again, no dilemma zone exists for the upper deceleration rate of 4.5 m/s^2.

The stopping/running probabilities versus the TTI at the onset of the yellow signal indication for the two instructed speeds are presented in Figure 8. The 0.9/0.1 probability of stopping/running was between 3.6 and 3.8 s from the stop line at the onset of yellow for the 72.4 km/h (45 mph) instructed speed, while the 50% stopping/running decision point occurred when the yellow indication was triggered while the vehicle was 3.1 s from the stop line. For the 88.5 km/h (55 mph) instructed speed, the 0.9/0.1 probability of stopping/running was between 4.1 and

4.3 s from the stop line at the onset of the yellow indication and the 50% stopping/running decision point occurred when the yellow indication was triggered when the vehicle was 3.2 s from the stop line.

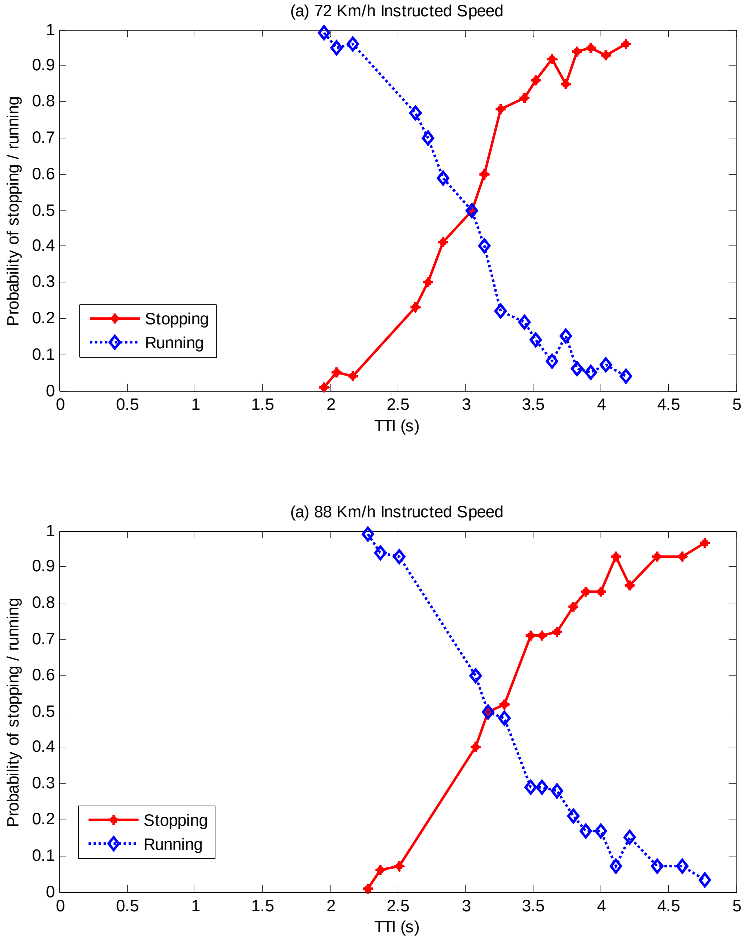
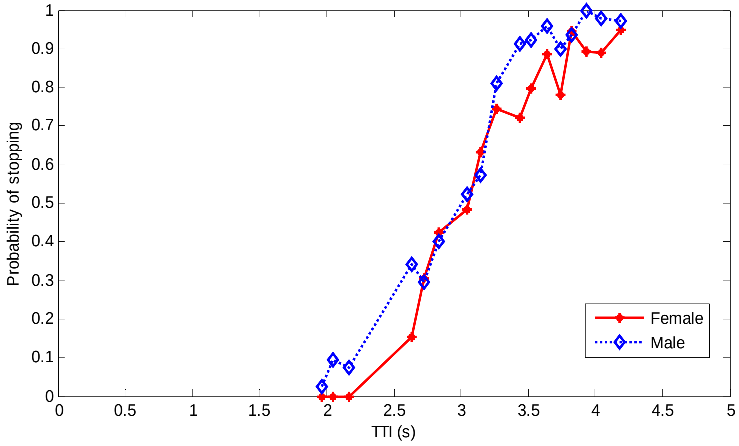


Figure 8. Probability distributions of stopping/running.

The data were then sorted based on the driver's TTI, at the onset of the yellow indication, into equal-sized bins (equal number of observations) and the average TTI and the probability of stopping for each bin was computed for illustration purposes only given the large number of observations. The probabilities of stopping at each TTI for both the 72.4 km/h (45 mph) and 88.5 km/h (55 mph) instructed speeds were used to illustrate various trends and effects. A general linear model procedure (GLM) was conducted using the SAS software to investigate the effects of the TTI, grade, age, gender, and platoon for the two instructed speed levels (72.4 km/h and 88.5 km/h) on the stopping/running probability. Male drivers appeared to be more likely to stop when compared to female drivers for the two instructed speed levels as shown in Figure 9. The figure demonstrates that the probability of stopping for male drivers is shifted to the left when compared to female drivers; this shift correlates to an increase in the probability of stopping for male drivers relative to female drivers. The F-statistic generated from the GLM revealed that these differences are statistically significant (P = 0.0005) for the 72.4 km/h instructed speed while there were no statistically significant differences at the 0.05 level (P = 0.06) for the 88.5 km/h instructed speed.

(a) 72 Km/h Instructed Speed



(a) 88 Km/h Instructed Speed

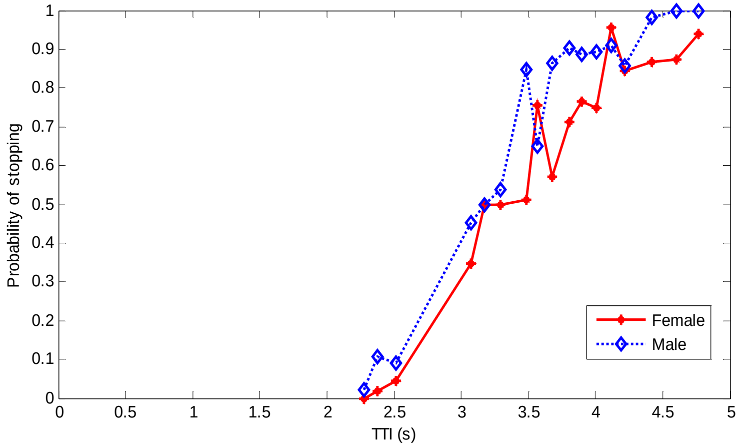
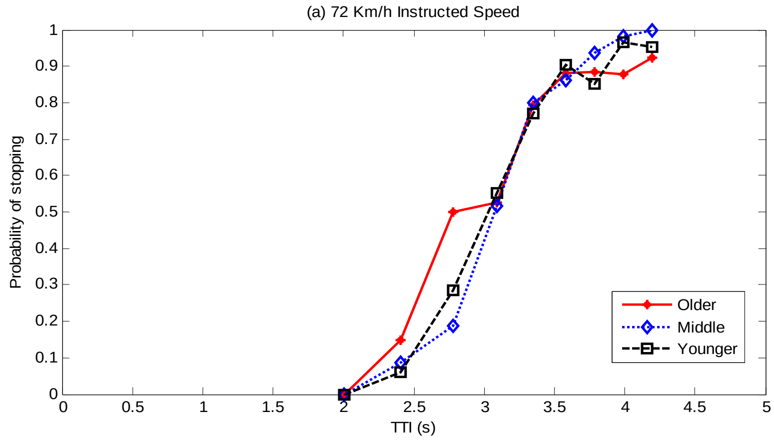


Figure 9. Probability of stopping as a function of gender.

A comparison of driver stopping/running probabilities at the onset of the yellow indication for the three different age groups (under 40-years-old, 40 to 59-years-old, and 60 years of age or older) was performed in order to characterize the effect of age on driver behavior. Figure 10 demonstrates that the percentage of older drivers (60 years of age and older) who elected to stop at the short yellow trigger times was larger than the younger drivers for both the 72.4 km/h (45 mph) and 88.5 km/h (55 mph) instructed speeds. Older drivers were significantly more likely to stop for average TTIs, at the onset of the yellow indication, ranging between 2 to 3.1 s when compared to younger drivers for the 72.4 km/h (45 mph) instructed speed and ranging from 2.3 to 3.7 s for the 88.5 km/h (55 mph) instructed speed. The F-statistic generated from the GLM for the three age groups demonstrated that significant differences, with P-values less than 0.0001, exist between the driver age groups for the 72.4 km/h (45 mph) instructed speed (F = 26.8) and also for the 88.5 km/h (55 mph) instructed speed (F = 36.5).



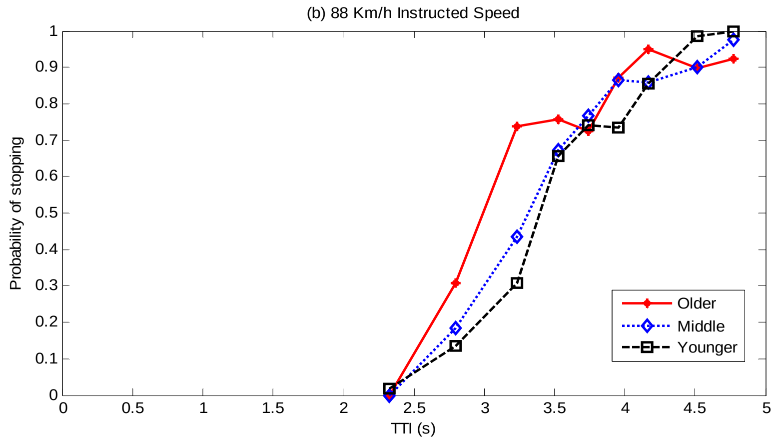


Figure 10. Probability of stopping as a function of different age groups.

Statistical Modeling of Driver Stop-Run Decision

A total of 3,328 valid data records were available for analysis, of which 1,658 valid records (687 running records and 971 stopping records) were for those who were instructed to drive at 72.4 km/h (45 mph) and 1,670 valid records (625 running records and 1,045 stopping records) were for a speed of 88.5 km/h. Using these data, a GLM of the logistic type was fit to the data considering a binomial distribution. After testing many forms of the model, including absolute and normalized variables, the final form is shown in Equation (5).

$$\ln\left(\frac{P_s}{P_r}\right) = \ln\left(\frac{P_s}{1-P_s}\right) = \beta_0 + \beta_1 g + \beta_2 \frac{a}{\bar{a}} + \beta_3 \frac{TTI}{y} + \beta_4 \frac{v}{v_f} \qquad (5)$$

where P_r is the probability of running,
P_s is the probability of stopping,

β_i's are model constants,

g is the gender,
a and $\bar{a}$ are the age and mean age (years),
TTI is the time-to-intersection (s),
y is the yellow time (s), and
v and v_f are the approaching speed and the speed limit (km/h).

The model calibrated coefficients and their corresponding P-values are summarized in Table 1, showing a good statistical fit. In addition, the model was used to replicate the dataset producing an 82.03% success rate (i.e., a total of 2,730 correctly estimated decisions of the 3,328 total decisions).

Table 1. Statistical stop-run model calibration results.

Coefficients	Coefficient Values	P-value
β_0	-6.1773	0.0003
β_1	0.5745	0.0000
β_2	0.8677	0.0000
β_3	12.4665	0.0000
β_4	-4.2307	0.0088

Sensitivity Analysis

Furthermore, the statistical model was used to conduct a sensitivity analysis of the impact of different independent variables on driver stopping decisions. Figure 11 shows the sole impact of changing four different variables (gender, age, yellow time corresponding to speed limit, ratio of speed to speed limit) separately while keeping other variables unchanged.

It can be inferred from Figure 11 that female drivers and younger drivers are more willing to run the intersection for the same TTI value. In addition, those drivers facing longer yellow times are encouraged to run and those traveling at speeds higher than the speed limit are also more willing to run.

Analysis of Yellow/Red Light Running Behavior

After analyzing the driver stop-run decision, the analysis investigates both the running and the stopping behaviors. The analysis investigates the different actions associated with each behavior; running yellow and red lights for the running behavior and PRT and deceleration level for the stopping behavior. As mentioned earlier, the 72.4 km/h dataset includes 687 valid running records, whereas the 88.5 km/h data set includes 625 valid running records. This yields a total of 1,312 running records.

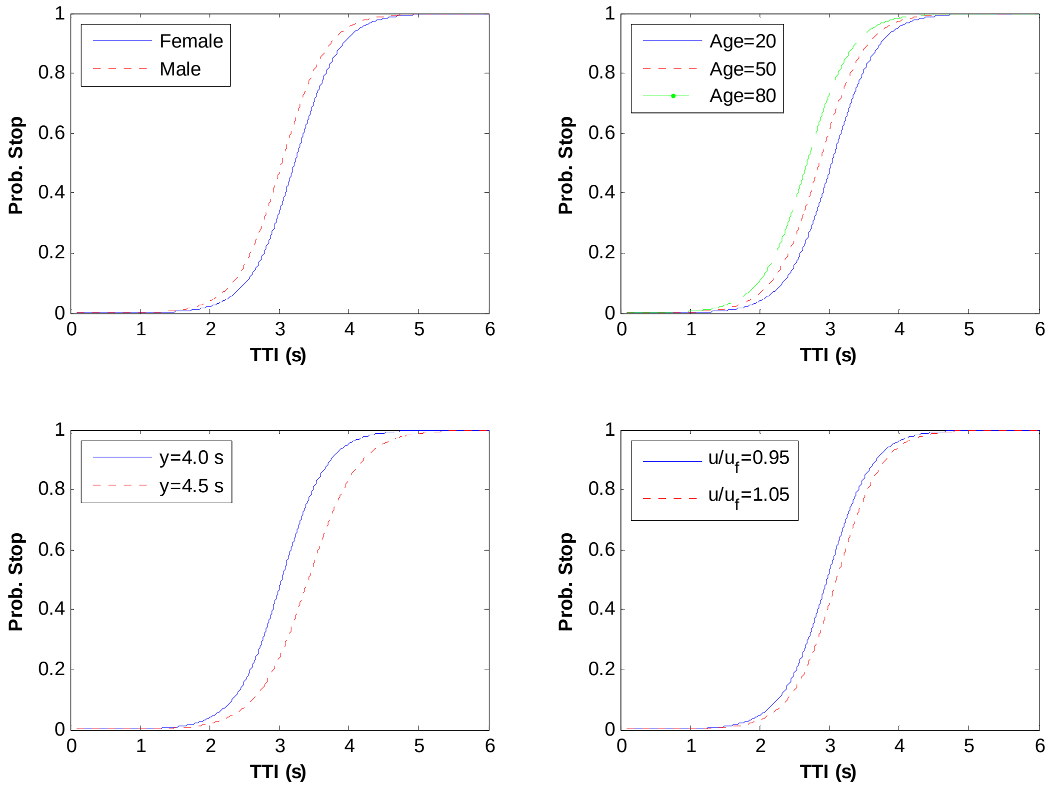
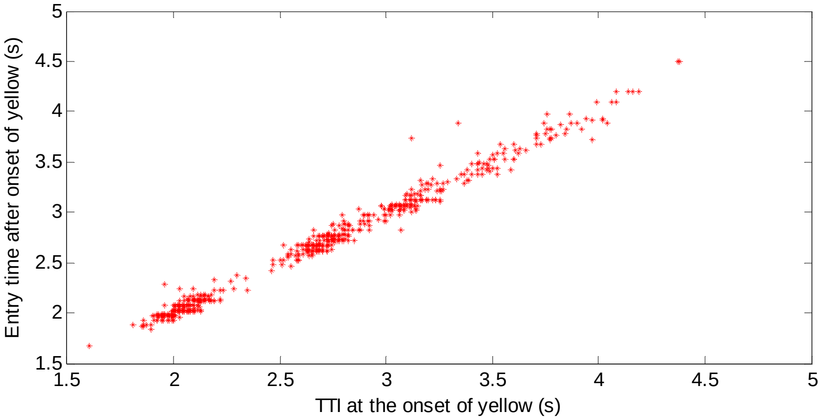


Figure 11. Sensitivity analysis of the statistical model independent variables.

Figure 12 presents the scatter diagrams between the vehicles' TTIs at the onset of the yellow indication and the time elapsed after the onset of the yellow indication at the instant the vehicle enters the intersection (i.e., when the vehicle hits the intersection stop line). It can be seen from the figure that for both instructed speeds, the scatter plots follow a line with a slope of 1 and zero intercept (i.e., a 45° line). This trend implies that the running drivers maintain their approach speed after the onset of the yellow and do not accelerate in order to ensure that they cross the intersection safely before the onset of red. In other words, the approaching speed at the onset of yellow can be reasonably considered representative for the driver's speed at the intersection entry instant. This is valid for both drivers running during yellow, who hit the intersection stop line before the end of yellow time (4 s for 72.4 km/h instructed speed and 4.5 s for 88.5 km/h instructed speed), and those running during red, who hit the intersection stop line after the end of yellow time. Accordingly, it appears that the red-light runners did not violate the red light intentionally; instead they appeared to misjudge their stop-run decision. It is worth noting here that in a real situation, drivers would intentionally violate the traffic signal mostly at light traffic volumes (e.g., late night traffic), where they can secure that there will be no movement conflicting them when they run the red light. On the other hand, in the present study, side street traffic was always present as a conflicting movement, which minimizes the number of those intentional violators.

(a) 72 Km/h Instructed Speed



(a) 88 Km/h Instructed Speed

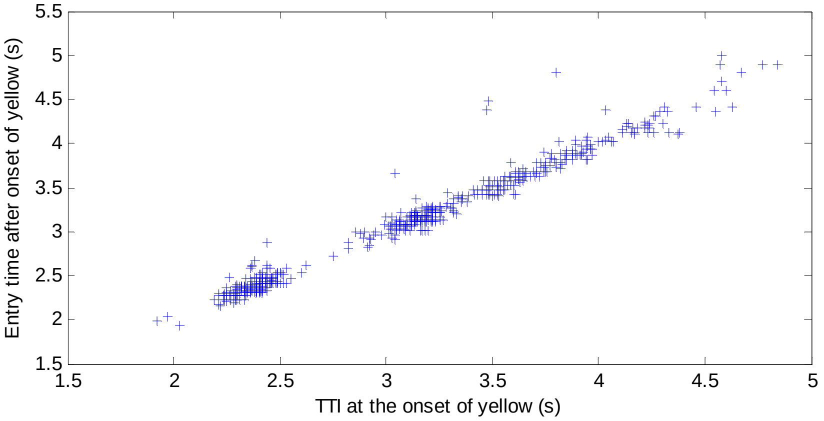


Figure 12. Relation between yellow entry time and TTI at yellow onset.

In terms of the number of running drivers as a function of the entry time after the yellow onset, Figure 13 shows histograms of yellow/red-light runners as a function of the time elapsed after the onset of the yellow indication until reaching the stop line. According to the figure, it can be seen that, for both instructed speeds, the number of running drivers is inversely proportional with the entry times after the onset of yellow indication; i.e., the longer the elapsed time after the yellow onset at the intersection entry, the fewer number of drivers decide to run. Furthermore, it is obvious from Figure 13 that, for both instructed speeds, the last bin in the histograms (with entry time more than 4 s for the 72.4 km/h instructed speed and more than 4.5 s for the 88.5 km/h instructed speed) represents the red-light runners, those who entered the intersection after the onset of the red indication.

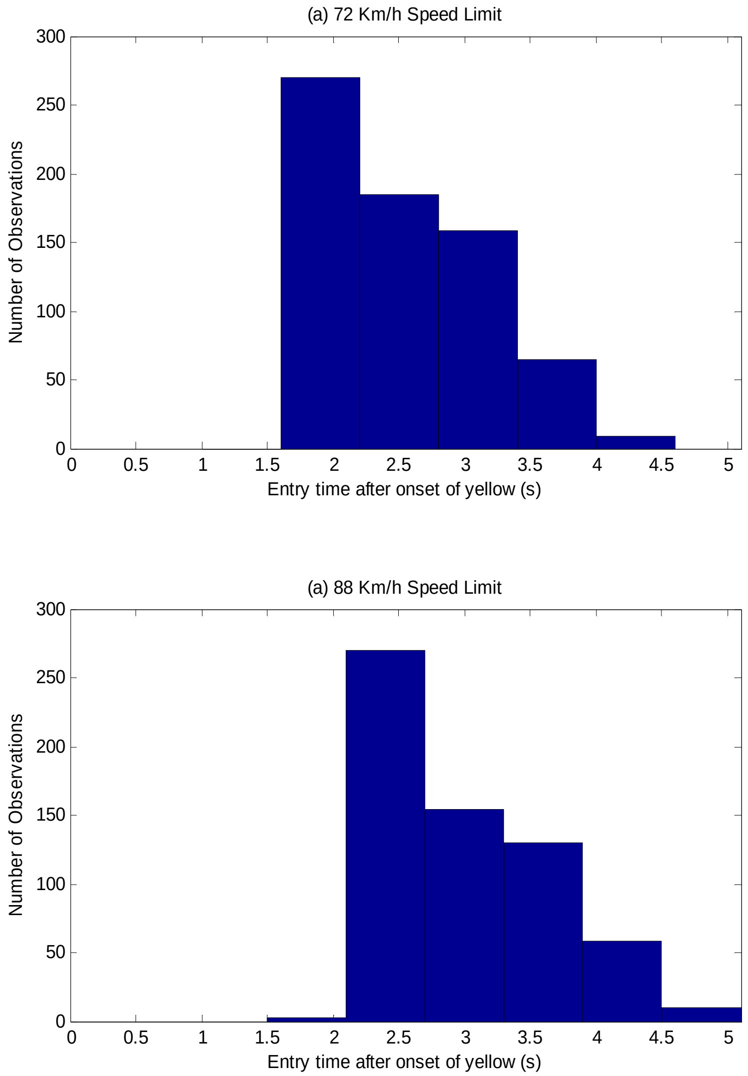


Figure 13. Histograms of yellow/red-light runners' entry times after yellow onset.

Another interesting illustration for the yellow/red-light running behavior is shown in Figure 14, which presents the relation between the vehicle's TTI at the onset of yellow and its position at the end of the yellow indication with reference to the stop line. The interesting point in this figure is that it combines both the potential red-light runners versus the actual red-light runners. Throughout the figure, the potential red-light runners can be recognized for both instructed speeds by those points laying at TTI more than the yellow time (4 s for the 72.4 km/h instructed speed and 4.5 s for the 88.5 km/h instructed speed), whereas the actual red-light runners can be easily distinguished as those points upstream of the intersection stop line (i.e., positive DTI). Accordingly, it can be seen that a small number of the potential red light runners, who faced the onset of yellow at a TTI more than the yellow time, were able to pass the intersection stop line legally before the end of the yellow time by accelerating to a speed higher than their approaching speed. Those drivers can be said to be intentionally deciding to run and are able to avoid the dilemma zone by increasing their speed.

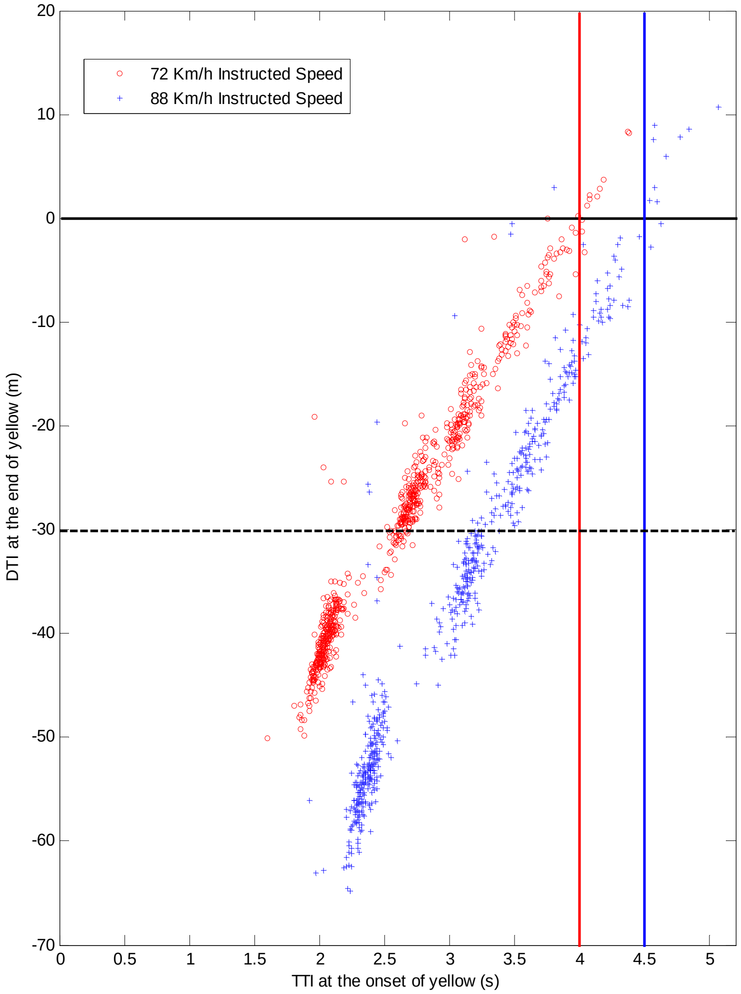


Figure 14. Relation between DTI at end of yellow and TTI at yellow onset.

Furthermore, although the number of actual red-light runners, who were behind the stop line at the onset of red indication, is not large (Table 2), a substantial number of the other drivers, who crossed the stop line during the yellow time, were not able to completely clear the intersection width, which equals 30 meters (Table 2). In order for the driver to be able to clear the 30-meter intersection width, approximately 1.5 s for the 72.4 km/h instructed speed or 1.2 s for the 88.5 km/h instructed speed is needed. Accordingly, if the adopted all-red interval is the minimum conventional 1 s, then there is a potential risk that the yellow-light runners would not be able to completely clear the intersection at the instant the side-street traffic gains the right-of-way (Table 2). This conclusion assumes that there is no start-up lost time for the side-street traffic in order to consider the worst case scenario, while considering a side-street start-up lost time or applying slightly longer all-red times could then minimize this risk.

Table 2. Number of yellow/red-light runners with potential crash risk.

		Instructed Speed		
		72 km/h	**88 km/h**	**All**
No. of Yellow/Red Light Runners	**Behind Stop Line at Onset of Red**	9 (1.3%)	10 (1.6%)	19 (1.4%)
	Inside Intersection at Onset of Red	368 (53.6%)	194 (31.0%)	562 (42.8%)
	Inside Intersection at End of 1-s All-Red	51 (7.4%)	22 (3.5%)	73 (5.6%)
Sample Size		**687 (100%)**	**625 (100%)**	**1312 (100%)**

An incorrect running decision may result in a red-light violation, which may increase the exposure to right-angle crashes. Figure 15 illustrates the running probabilities versus the TTIs at the onset of the yellow signal indication for the two instructed speeds. The figure shows that as the distance from the intersection increases, the probability of a running decision decreases, demonstrating that drivers far away from the intersection are less likely to run. The figure also indicates a similar running decision trend for the two instructed speeds and demonstrates that the probability of running for the 88.5 km/h (55 mph) instructed speed was higher than the 72.4 km/h (45 mph) instructed speed over the entire TTI range at the onset of the yellow indication. This shift correlates to a higher probability of running for those drivers traveling at higher speeds at the onset of the yellow interval. The results generated using the regression procedure (REG) of the SAS software showed that the approach speed had a significant effect, with P-values less than 0.001 for the running decision.

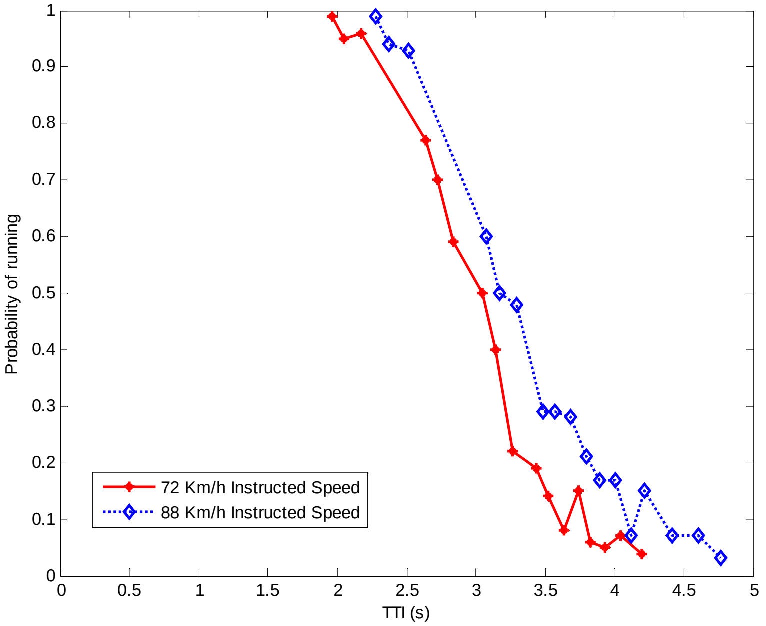
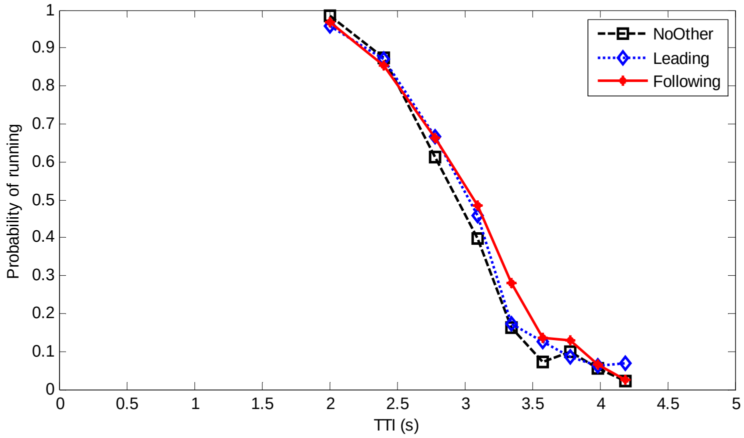


Figure 15. Effect of instructed speed on probability of running.

The other situational variable that significantly affects the driver's running decision is whether the vehicle is a leader or follower at the onset of yellow signal indication. The data were used to analyze the stop/run decision associated with the three different platooning scenarios (following, leading, or alone) in order to characterize the effect of surrounding traffic on the running decision. The observed running decision under the same TTI at the onset of the yellow in both cases of driving in a platoon (either leading another vehicle or following another vehicle that proceeded through the intersection without slowing or stopping) were slightly higher compared to the alone scenario as shown in Figure 16. Consequently, the drivers who are leading the traffic flow are more likely to make a running decision and go through the intersection in order to avoid a rear-end collision. In addition, the presence of another leading vehicle that ran through the intersection also increases the probability of the running of the subject vehicle. The F-statistic generated from the GLM using the SAS software revealed that no significant differences (P = 0.19) exist between the three different platoons for the 72.4 km/h instructed speed and that significant differences, with P-values equal to 0.014, exist between the different platoons for the 88.5 km/h instructed speed.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

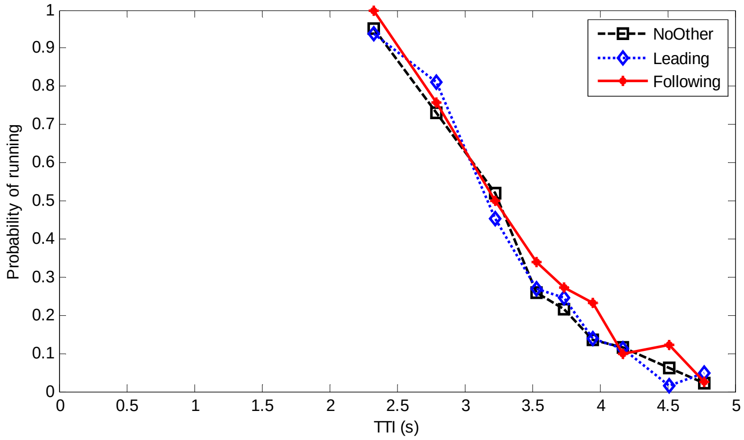


Figure 16. Effect of surrounding traffic on probability of running.

Characterization of Driver Perception-Reaction Time

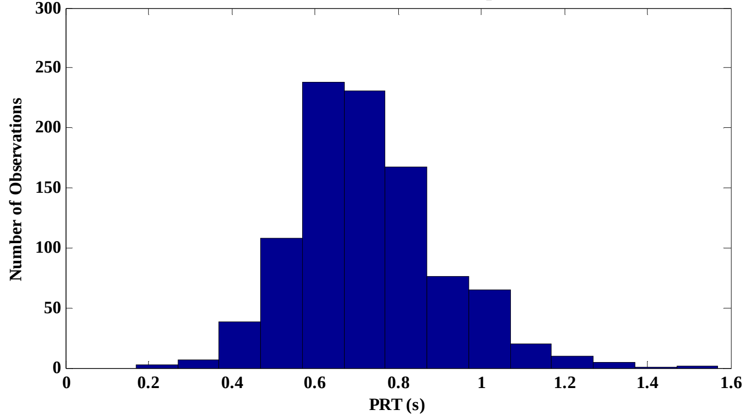
As described earlier, video and vehicle performance data were assembled digitally from the test vehicle DAS. Video frame, driver's information (subject number, age, and gender), platoon, trial number, and condition were reported in the data file. The data that were gathered included, but were not limited to, the current state and duration of the traffic signal interval, heading of the vehicle clockwise from north (deg), vehicle speed (mph), acceleration (g), distance to intersection stop line (ft), TTI computed as distance/speed (s), time-to-yellow (s), percentage of throttle application (percent), brake application (on/off), and distance between confederate and subject vehicle (ft). Data files were stored on a secure server within the VTTI facilities. These data files were available to a few selected secure workstations for reduction and analysis in spreadsheets and MATLAB software.

Distribution of Perception-Reaction Time

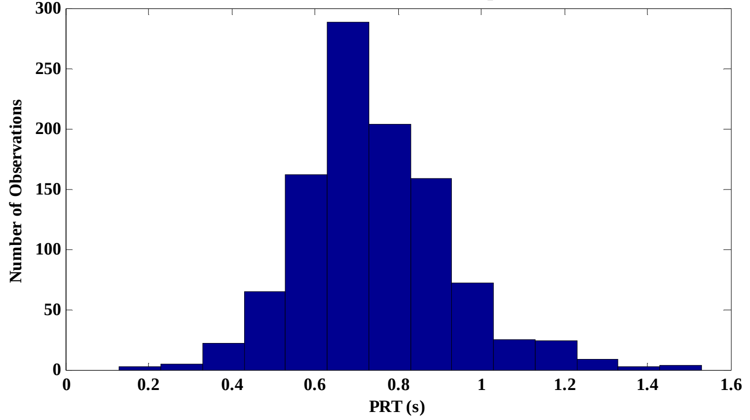
A total of 2,016 valid data records were available for analysis, of which 971 valid data records were for those who were instructed to drive at 72.4 km/h (45 mph) and 1045 valid observations were for a speed of 88.5 km/h (55 mph). The TTI for the 72.4 km/h instructed speed ranged from a minimum of 1.93 s to a maximum of 4.69 s with a mean equal to 3.59 s, a median of 3.66 s, and a standard deviation of 0.45 s. The remaining 1,045 data records for an instructed speed of 88.5 km/h (55 mph) included TTIs ranging between 2.31 s to 5.33 s with a mean equal to 3.98 s, a median of 3.99 s, and a standard deviation of 0.53 s. In other words, drivers decelerated at farther distances when they traveled at higher speeds.

A study of driver PRTs at the onset of the yellow indication was performed considering all stopping events. As was noted earlier, it was possible to determine the approach speed of the vehicle, the TTI, and the brake application of the stopping vehicles from the data files. Using this information, PRT characteristics and profiles were examined. 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. The PRT ranged from a minimum of 0.22 s to a maximum of 1.52 s with a mean of 0.73 s, a median of 0.72 s, and a standard deviation of 0.18 s for the participants who were instructed to drive at 72.4 km/h (45 mph). Alternatively, the PRT ranged between 0.18 s and 1.53 s with a mean of 0.74 s, a median of 0.72 s, and a standard deviation of 0.18 s for those who were instructed to drive at 88.5 km/h (55 mph). The histogram for the observed PRTs of the 2016 stopping events for the two approach speeds is shown in Figure 17. These figures demonstrate that the driver PRTs were very similar for both instructed speeds.

The observed 15th, 50th, and 85th percentile PRTs were 0.57, 0.72, and 0.92 s, respectively, in the case of the 72.4 km/h instructed speed; and were 0.58, 0.72, and 0.92 s, respectively, in the case of the 88.5 km/h instructed speed. The 85th percentile is consistent with earlier studies which showed that the 85th percentile PRT on high-speed intersection approaches (greater than 64 km/h or 40 mph) is in the range of 1.1 to 1.3 s. The lower value of PRTs in the current study may be attributed to the fact that the PRT was defined from the instant the signal indication changed to yellow until the driver touched the brake pedal, and not when the brake light was activated as in most studies; thus the PRT did not include the time lag from the instant the driver presses the brake pedal until the brake lights activate. Consequently, the results



(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

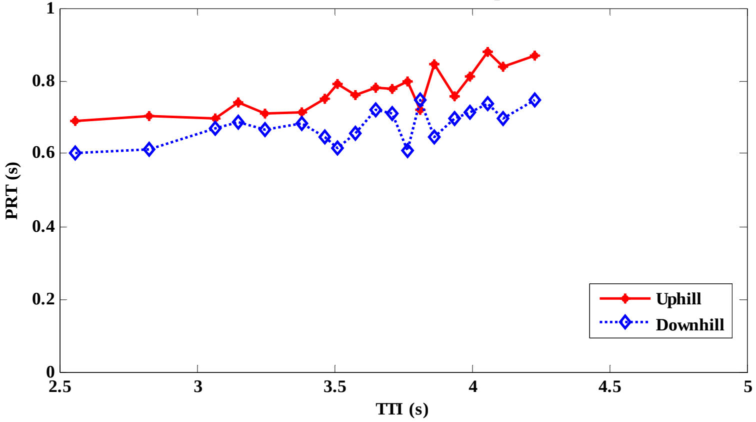
Figure 17. Histogram of perception–reaction times.

appear to be consistent with other naturalistic field study findings. The data were sorted based on the driver's TTI, at the yellow-indication onset, into equal-sized bins (equal number of observations) and the average TTI and PRT for each bin was computed (for illustration purposes only) given the large number of observations.

Effects of Other Variables on Perception-Reaction Time

A GLM was conducted using the SAS software to investigate the effects of the TTI, grade (uphill and downhill), age group (under 40-years-old, between 40 and 59-years-old, and 60 years of age or older), gender (male and female), and platoon (leading, following, and no other vehicle), for the two instructed speed levels (72.4 km/h and 88.5 km/h) on PRT. The results showed that the TTI had a significant effect ($P < 0.0001$) on the PRT for both the 72.4 km/h (45 mph) instructed speed and the 88.5 km/h (55 mph) instructed speed. The mean PRT estimates at each TTI for the two instructed speed levels and approaches (uphill and downhill) were used to illustrate various trends and effects, as demonstrated in Figure 18. The results showed that the PRT on either approach (i.e., on upgrade or downgrade) exhibit similar trends, with slightly higher PRTs in the case of the uphill approach. This difference, which is significant, demonstrates that drivers traveling uphill might be pushing harder on the accelerator and thus take longer to release their push and move their feet to press the brake pedal, while drivers traveling downhill might not be pressing the accelerator in order to maintain some desired speed and are more alert because they realize that the deceleration level needed to stop the vehicle is greater. For TTIs in the range of 1.93 to 4.69 s, for the 72.4 km/h (45 mph) instructed speed, the PRT ranged from 0.22 to 1.67 s for the uphill approach, and from 0.23 to 1.27 s for the downhill approach. Similarly, for the 88.5 km/h instructed speed, the PRT ranged from 0.22 to 1.53 s and from 0.18 to 1.43 s for the uphill and downhill approaches, respectively. These results occurred for TTIs ranging from 2.31 to 5.33 s, as shown in Table 3. Significant differences in PRTs were observed for the uphill (M = 0.78 s) and downhill (M = 0.68 s) conditions (F (1,972) = 65.4, P < 0.0001) for the 72.4 km/h (45 mph) instructed speed, and also for the uphill (M = 0.77 s) and downhill (M = 0.71 s) conditions (F (1,1045) = 30.1, P < 0.0001) for the 88.5 km/h (55 mph) instructed speed.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

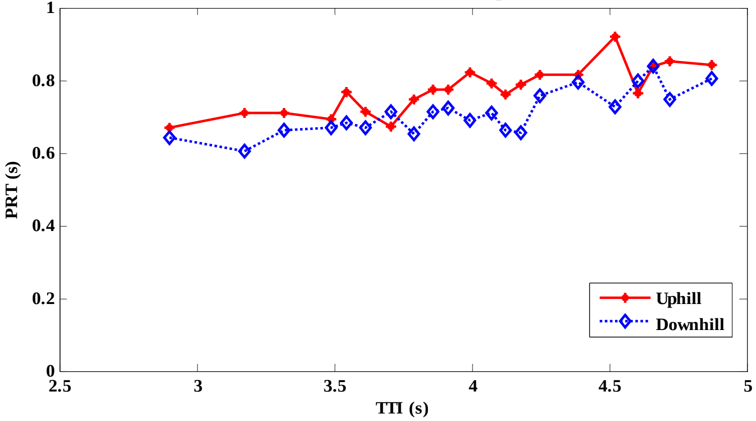
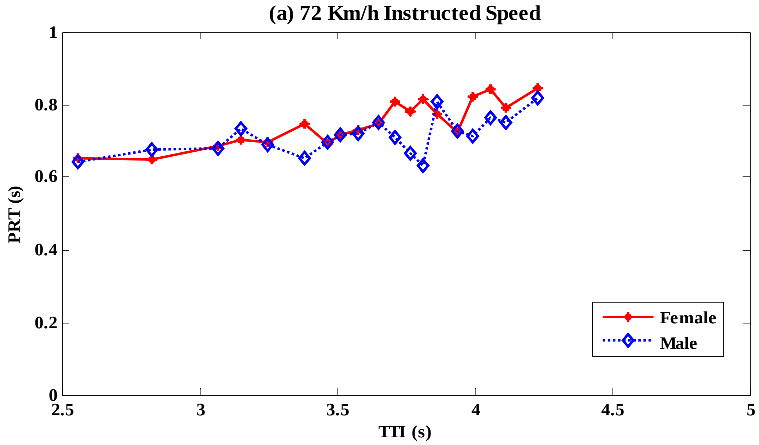


Figure 18. Effect of roadway grade on perception–reaction times.

Female drivers appeared to have slightly longer PRTs when compared to male drivers for both the 72.4 km/h (45 mph) and 88.5 km/h (55 mph) instructed speeds, as shown in Figure 19. For the 72.4 km/h (45 mph) instructed speed, the mean PRT was found to be 0.75 s for the female drivers and 0.71 s for the male drivers (as shown in Table 3); for the 88.5 km/h (55 mph) instructed speed, the mean PRT was found to be 0.76 s and 0.73 s for the female and male drivers, respectively. Although the difference in PRT between male and female drivers seems small, the F-statistic generated from the GLM demonstrated that these differences are statistically significant for both approach speeds (F [1,972] = 22.3, P < 0.0001 for the 72.4 km/h instructed speed and F [1,1045] = 10.9, P = 0.001 for the 88.5 km/h instructed speed).



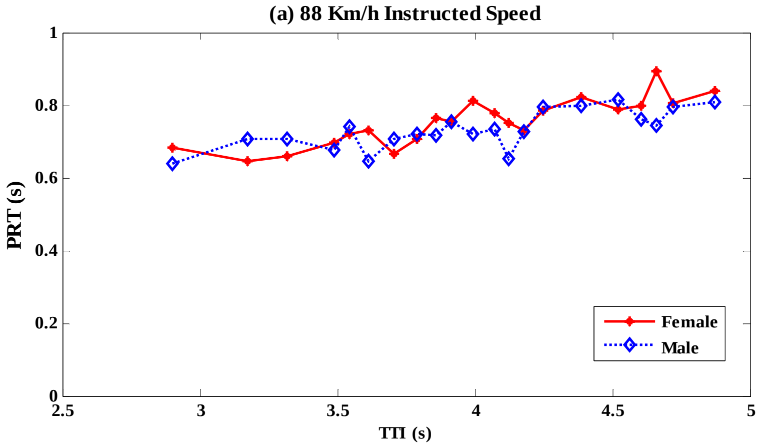


Figure 19. Effect of gender on perception-reaction times.

The data were used to analyze differences in driver PRTs associated with driver age. The PRT for drivers 60 years of age and older (M = 0.79 s for the 72.4 km/h instructed speed and 0.81 s for the 88.5 km/h instructed speed) were found to be significantly higher than those for the 40 to 59 age group (M = 0.71 s for the 72.4 km/h and 0.72 s for the 88.5 km/h) and those for the under 40-years-old age group (M = 0.70 s for the 72.4 km/h and 0.69 s for the 88.5 km/h), as shown in Table 3 and Figure 20. The F-statistic generated from the GLM for the three age groups demonstrated that significant differences, with P-values less than 0.0001, exist between the driver age groups for the 72.4 km/h (45 mph) instructed speed (F [2,972] = 33.9) and also for the 88.5 km/h (55 mph) instructed speed (F [2,1045] = 66.6).

Table 3. Descriptive statistical results of PRT for grade, age, gender, and platoon.

Variable		N	PRT (s)						
			Min	Max	Mean	15%	50%	85%	StD
Grade	**Uphill**	532	0.22	1.67	0.78	0.62	0.74	0.96	0.18
	Downhill	440	0.23	1.27	0.68	0.53	0.67	0.83	0.16
Gender	**Female**	462	0.23	1.42	0.75	0.58	0.73	0.93	0.18
	Male	510	0.22	1.67	0.71	0.57	0.68	0.88	0.17
Age	**Older**	317	0.42	1.42	0.79	0.63	0.78	0.93	0.15
	Middle	345	0.37	1.31	0.71	0.57	0.67	0.88	0.17
	Younger	310	0.22	1.67	0.70	0.53	0.67	0.88	0.20
Platoon	**Following**	309	0.22	1.47	0.74	0.58	0.72	0.92	0.18
	Leading	325	0.23	1.42	0.73	0.57	0.71	0.92	0.18
	Single	338	0.37	1.67	0.73	0.57	0.72	0.91	0.17
Overall		972	0.22	1.52	0.73	0.57	0.72	0.92	0.18

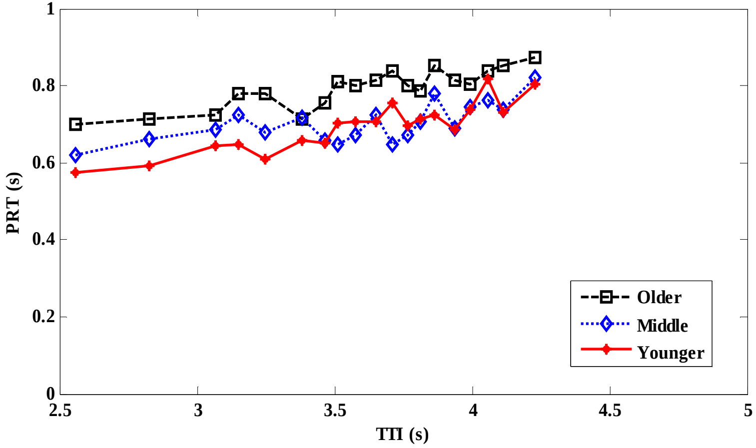
(a) 72 km/h instructed speeds

Variable		N	PRT (s)						
			Min	Max	Mean	15%	50%	85%	StD
Grade	**Uphill**	544	0.22	1.53	0.77	0.62	0.73	0.93	0.18
	Downhill	501	0.18	1.43	0.71	0.53	0.68	0.87	0.18
Gender	**Female**	489	0.22	1.53	0.76	0.61	0.73	0.92	0.18
	Male	556	0.18	1.48	0.73	0.57	0.68	0.92	0.18
Age	**Older**	360	0.51	1.48	0.81	0.66	0.78	0.97	0.16
	Middle	366	0.22	1.53	0.72	0.57	0.68	0.88	0.18
	Younger	319	0.18	1.32	0.69	0.57	0.68	0.85	0.17
Platoon	**Following**	336	0.22	1.48	0.78	0.62	0.77	0.93	0.18
	Leading	351	0.18	1.27	0.71	0.57	0.68	0.88	0.17
	Single	358	0.32	1.53	0.74	0.58	0.72	0.90	0.18
Overall		1045	0.18	1.53	0.74	0.58	0.72	0.92	0.18

(b) 88 km/h instructed speeds

A comparison of driver PRTs for the three different platooning scenarios (following, leading, or alone) was performed in order to characterize the effect of surrounding traffic on driver behavior. This behavior is important in designing traffic signal timing plans within the IntelliDrive^{SM} initiative. The results showed that the PRT was not impacted by the platooning scenario in the case of the 72.4 km/h instructed speed (M = 0.74, 0.73, and 0.73 s for the leading, following, and alone scenarios, respectively), as shown in Table 3 and Figure 21 (F (2,972) = 1.4, P = 0.26). Alternatively, in the case of the 88.5 km/h (55 mph) instructed speed, the mean PRTs for the following, leading, or single vehicle scenarios were 0.78, 0.71, and 0.74 s, respectively. Figure 21 shows that in the following platoon scenario, where the test vehicle was following another vehicle that proceeded through the intersection without slowing or stopping, the mean PRT was higher compared to the other two scenarios. A potential explanation for the higher PRT values could be that because the lead vehicle ran through the intersection, the subject driver was also inclined to proceed. This initial inclination to run increased the deliberation time for the drivers that eventually elected to stop. In the case of the leading platoon condition, a shorter mean PRT was observed (compared to the other two scenarios) as the driver may have been forced to decide faster in order to provide the following vehicle with sufficient braking time to avoid a rear-end collision. The F-statistic generated from the GLM demonstrated that significant differences, with P-values less than 0.0001 (F [2,1045] = 16.9), exist between the different scenarios.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

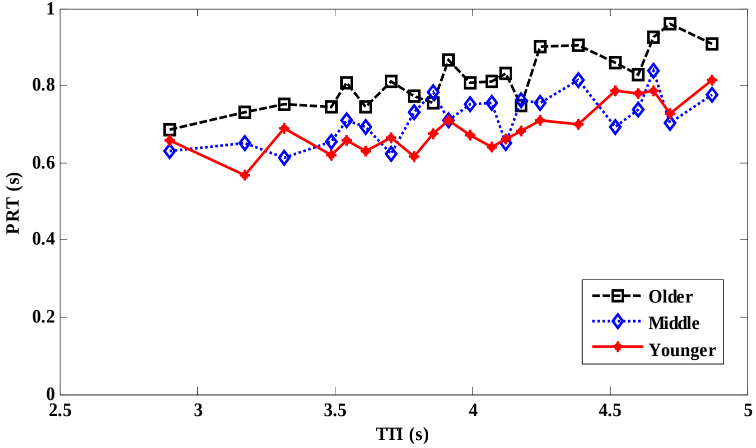
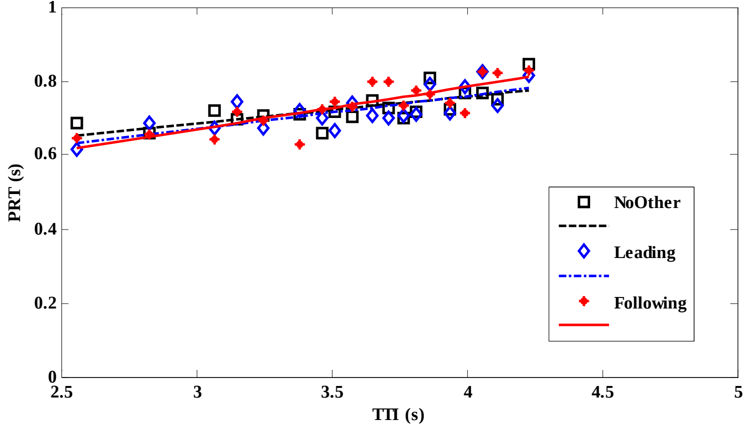


Figure 20. Effect of age on perception-reaction times.

The mean PRTs for the 4-second (72.4 km/h instructed speed) and 4.5-second (88.5 km/h instructed speed) yellow intervals were plotted against the TTI at the yellow interval change time, as shown in Figure 22. The results show that the PRT tends to increase as the TTI increases. For the range of TTIs from 4.69 to 1.93 s for the 72.4 km/h (45 mph) instructed speed, the PRT decreased from 1.53 to 0.22 s with a mean of 0.73s, while for the range of TTIs from 5.33 to 2.31 s for the 88.5 km/h (55 mph) instructed speed, the PRT decreased from 1.53 to 0.18 s with a mean of 0.74s. The figure demonstrates that the mean PRT curve for the 72.4 km/h (45 mph) instructed speed was higher than the 88.5 km/h (55 mph) instructed speed over the entire TTI range. This shift correlates to a lower PRT for those drivers traveling at higher speeds on the onset of the yellow interval. The results, however, indicate a similar PRT trend at different speeds. The results generated using the regression procedure (REG) of the SAS software showed that the approach speed had a significant effect, with P-values equal to 0.0006, on the average PRT.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

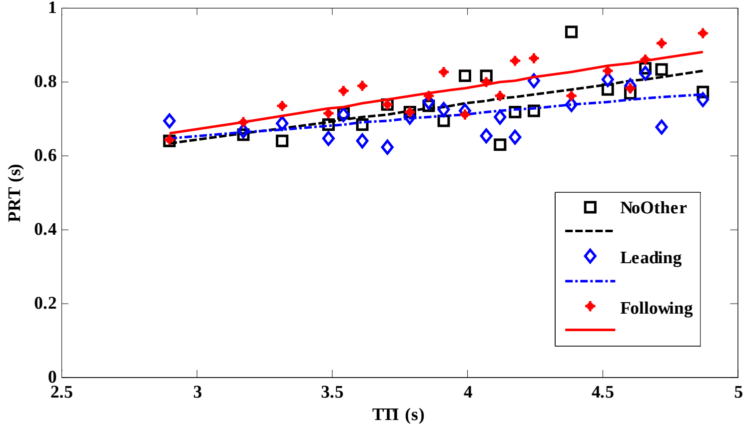


Figure 21. Effect of surrounding traffic on perception-reaction times.

Statistical Modeling of Perception-Reaction Time

As previously mentioned, a total of 2,016 stopping data records were available for the analysis. Using these observations, a stepwise linear regression model was fit to the data. After experimenting with different model forms, including absolute and normalized variables, the selected form is shown in Equation (6).

$$PRT = \beta_0 + \beta_1 g + \beta_2 a + \beta_3 G + \beta_4 \frac{TTI}{y} + \beta_5 \frac{v}{v_f} \tag{6}$$

where PRT is the perception-reaction time (s),

β_i's are model constants,

g is the gender (0 female and 1 male),
a is the age (years),
G is the roadway grade (percent/100),
TTI is the time-to-intersection (s),
y is the yellow time (s), and
v and v_f are the approaching speed and the speed limit (km/h).

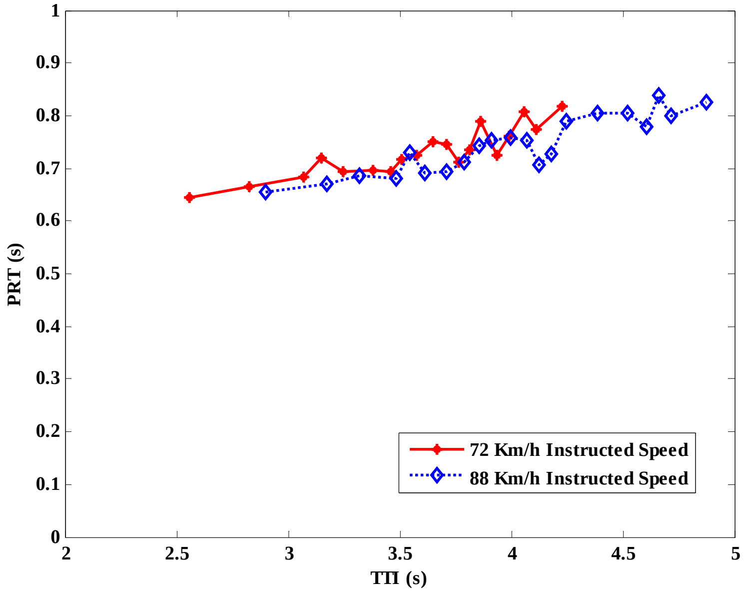


Figure 22. Effect of vehicle speed on PRTs.

The model calibrated coefficients and their corresponding P-values are summarized in Table 4, showing a good statistical fit. Although the model has a low adjusted-R^2 of 18%, there is a good relation between the PRT and each of the explanatory variables. Figure 23 shows histograms of the model residuals and the calibrated PRT values.

Table 4. Statistical PRT model calibration results.

Coefficients	Coefficient Values	P-value
β_0	0.7775	
β_1	-0.0415	0.0000
β_2	0.0025	0.0000
β_3	1.1966	0.0000
β_4	0.3980	0.0000
β_5	-0.4897	0.0000

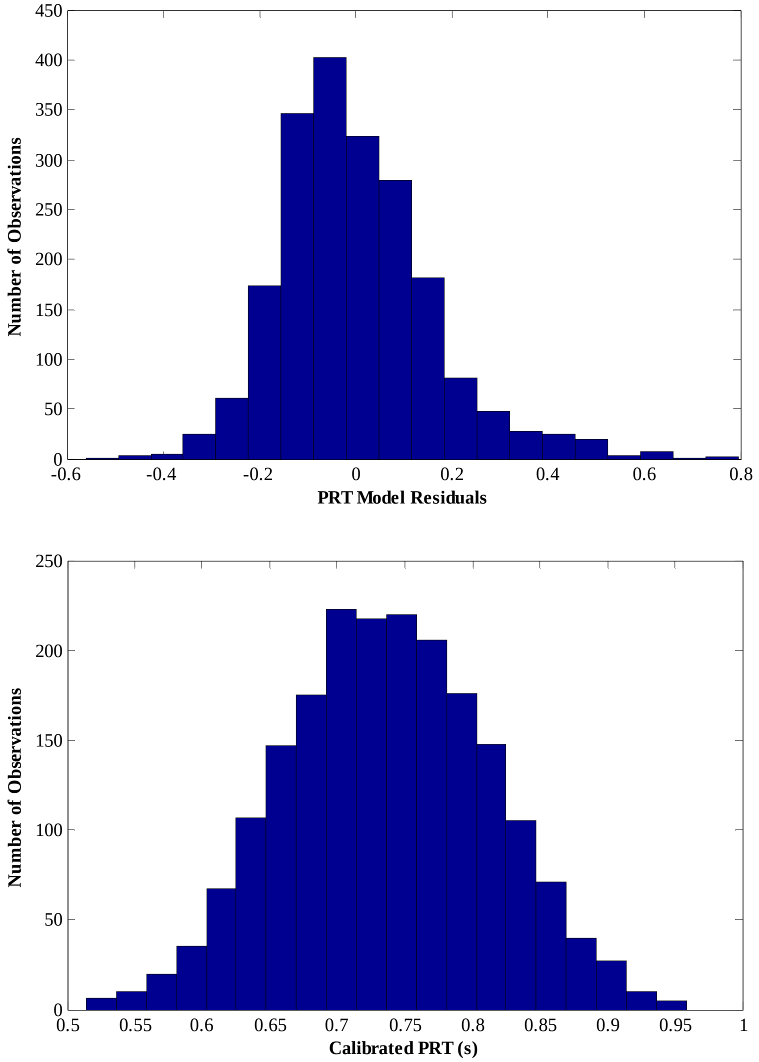


Figure 23. Histograms of model residuals and the calibrated PRT.

Characterization of Driver Deceleration Level

Distribution of Deceleration Level

The deceleration levels at the onset of a yellow indication were found to vary considerably. Consequently, further analysis of the driver deceleration behavior and characteristics was considered. Similar to the analysis of the PRT, a total of 2016 valid deceleration events were available for analysis, of which 971 valid data records were for the 72.4 km/h (45 mph) instructed speed and 1045 valid observations were for a speed of 88.5 km/h (55 mph). As has been noted, it was possible to determine the approach speed to the intersection, the deceleration distance, and the deceleration time of the stopping vehicles from the field data. With this information, the effect of the approach speed and surrounding vehicles on the deceleration level characteristics and profiles was examined. Average deceleration levels were calculated in m/s^2 from the time the driver started to press the brake pedal after the onset of the yellow indication until the final speed of the deceleration event (this was less than 3.6 km/h [2.2 mph], which is the speed of a pedestrian).

The second-by-second speed profile data collected by the in-vehicle GPS unit in this study provide more accurate measurements of driver deceleration behavior such as the approach speed to the intersection, TTI, and the brake application of the stopping vehicles. The average deceleration levels for the deceleration event when the yellow indication was triggered at the signalized intersection can be estimated using Equation (7).

$$d_{avg} = \frac{v - v_o}{t \times 3.6} \qquad (7)$$

where d_{avg} is the average deceleration level (m/s^2),

v is the vehicle speed at the instant the driver started to press the brake pedal after the onset of the yellow indication (km/h),

v_o is the final vehicle speed for the deceleration event (less than 3.6 km/h), and

t is the braking time (s).

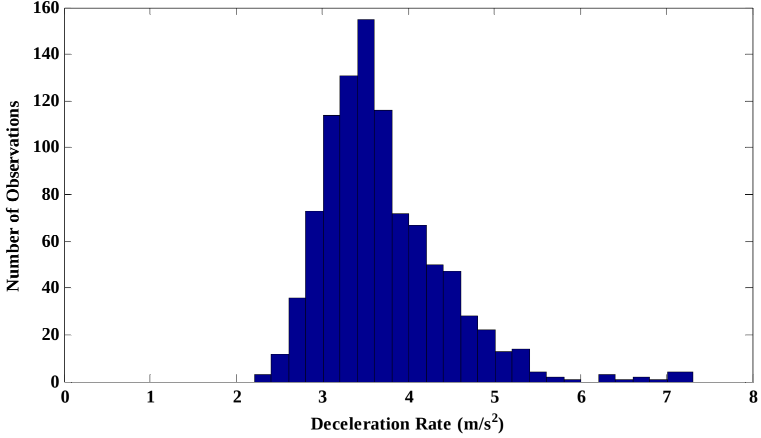
The deceleration level ranged from a minimum of 2.31 m/s^2 (7.6 ft/sec^2) to a maximum of 7.31 m/s^2 (24 ft/sec^2) with a mean of 3.7 m/s^2 (12.1 ft/sec^2), a median of 3.55 m/s^2 (11.6 ft/sec^2), and a standard deviation of 0.71 m/s^2 (2.3 ft/sec^2) for the participants who were instructed to drive at 72.4 km/h (45 mph). Alternatively, the deceleration level ranged between 2.3 m/s^2 (7.5 ft/sec^2) and 7.28 m/sec^2 (23.9 ft/sec^2) with a mean equal to 3.91 m/s^2 (12.8 ft/sec^2), a median of 3.82 m/s^2 (12.5 ft/sec^2), and a standard deviation of 0.74 m/s^2 (2.4 ft/sec^2) for those who were instructed to drive at 88.5 km/h (55 mph). The histogram for the observed deceleration levels of the 2016 stopping events for the two approach speeds are shown in Figure 24. These figures demonstrate that the driver deceleration levels were very similar for both instructed speeds.

Effects of Other Variables on Driver Deceleration Behavior

A six-way analysis of variance (ANOVA) was conducted using the SAS software to investigate the effects of the TTI, grade (uphill and downhill), age group (under 40-years-old, between 40 and 59-years-old, and 60 years of age or older), gender (male and female), platoon (leading, following, and no other vehicle), and approach speed (72.4 km/h and 88.5 km/h) on the average deceleration level. The ANOVA results using the GLM procedure of the SAS software, where a set of generated F-statistics was used, showed that the TTI had a significant effect on the average deceleration level (F (39, 2016) = 28.6, P < 0.0001).

The data were then sorted based on the driver’s TTI, at the yellow-indication onset, into equal-sized bins (equal number of observations) and the average TTI and deceleration level for each bin was computed for illustration purposes only given the large number of observations. The mean deceleration level estimates at each TTI for the two instructed speed levels and approaches (uphill and downhill) were used to illustrate various trends and effects, as demonstrated in Figure 25. The results show that the deceleration level on either approach (i.e.,

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

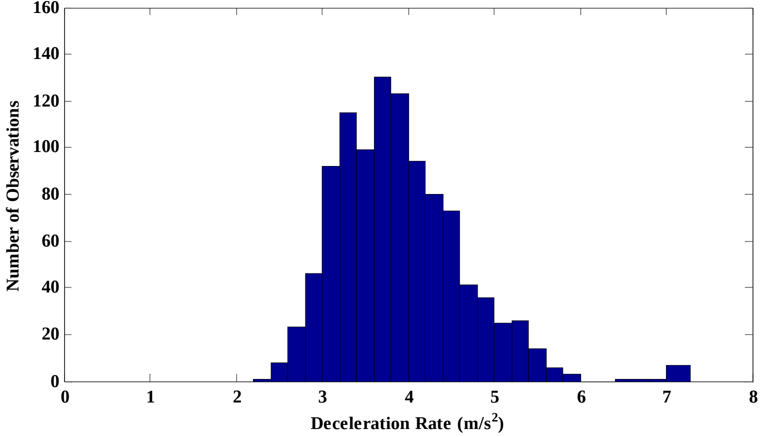
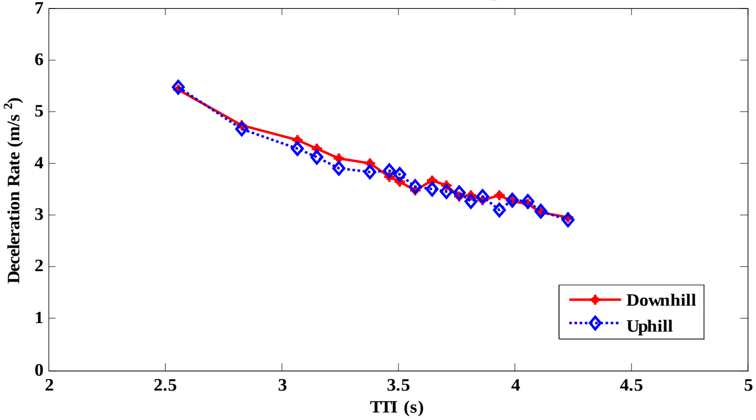


Figure 24. Histogram of deceleration levels.

on upgrade or downgrade) exhibit similar trends, with slightly higher deceleration levels in the case of the downhill approach. This difference, which is significant, demonstrates that the deceleration needed to stop the car when driving downhill is greater than when traveling uphill, as would be expected. For TTIs in the range of 1.93 to 4.69 s, for the 72.4 km/h (45 mph) instructed speed, the deceleration level ranged from 2.31 m/s^2 (7.6 ft/sec^2) to 7.31 m/s^2 (24 ft/sec^2) for the uphill approach, and from 2.31 m/s^2 (7.6 ft/sec^2) to 7.25 m/s^2 (23.8 ft/sec^2) for the downhill approach. Similarly, for the 88.5 km/h (55 mph) instructed speed, the deceleration level ranged from 2.43 m/s^2 (8 ft/sec^2) to 7.28 m/s^2 (23.9 ft/sec^2) and 2.3 m/s^2 (7.5 ft/sec^2) to 7.28 m/s^2 (23.9 ft/sec^2) for the uphill and downhill approaches, respectively. These results occurred for a mean TTI from 2.31 to 5.33 s, as shown in Table 5. Significant differences in mean deceleration levels were observed for the uphill (M = 3.65 m/s^2) and downhill (M = 3.75 m/s^2) conditions (F [1,972] = 5.4, P = 0.02) for the 72.4 km/h (45 mph) instructed speed, and also for the uphill (M = 3.87 m/s^2) and downhill (M = 3.94 m/s^2) conditions (F [1,1045] = 16.9, P < 0.0001) for the 88.5 km/h (55 mph) instructed speed.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

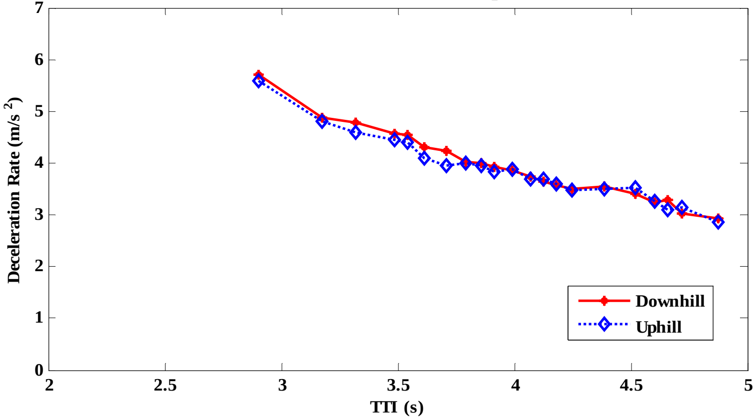
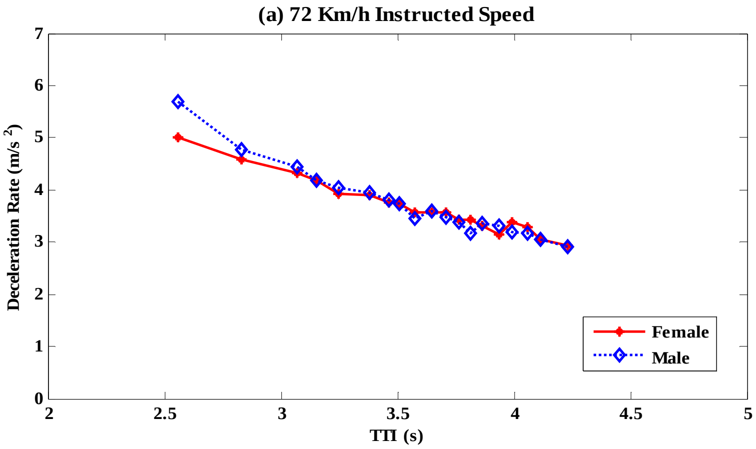


Figure 25. Effect of roadway grade on deceleration levels.

Male drivers appeared to show slightly higher levels of deceleration when compared to female drivers for both the 72.4 km/h (45 mph) and 88.5 km/h (55 mph) instructed speeds, as shown in Figure 26. For the 72.4 km/h (45 mph) instructed speed, the mean deceleration level was found to be 3.65 m/s^2 (12 ft/sec^2) for the female drivers and 3.74 m/s^2 (12.3 ft/sec^2) for the male drivers as shown in Table 5; for the 88.5 km/h (55 mph) instructed speed, the mean deceleration level was found to be 3.84 m/s^2 (12.6 ft/sec^2) and 3.96 m/s^2 (13 ft/sec^2) for the female and male drivers, respectively. The figure demonstrates that the mean deceleration level curve for male drivers was shifted to the right when compared to female drivers in the range between the 2.6 to 3.5 s yellow-indication trigger times for the 72.4 km/h (45 mph) instructed speed, and from 2.9 to 3.9 s for the 88.5 km/h (55 mph) instructed speed. This shift correlates to an increase in the deceleration level for male drivers relative to female drivers at short trigger times. The F-statistic generated from the ANOVA test revealed that no significant differences (F [1,972] = 0.34, P = 0.56 for the 72.4 km/h instructed speed and F [1,1045] = 1.75, P = 0.19 for the 88.5 km/h instructed speed) exist between male and female drivers for both approach speeds.


(a) 72 Km/h Instructed Speed

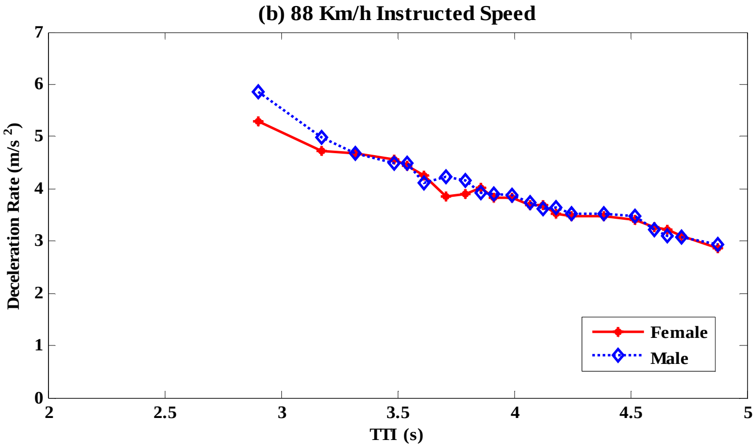

(b) 88 Km/h Instructed Speed

Figure 26. Effect of gender on deceleration levels.

In addition, the data were used to analyze the deceleration levels associated with different driver age groups (under 40 years of age, between 40 and 59 years of age, and 60 years of age or older). The analysis of the deceleration levels showed that the 15th percentile deceleration levels chosen by those under 40-years-old (3.04 m/s^2 for the 72.4 km/h and 3.15 m/s^2 for the 88.5 km/h) and 60 years of age or older (3.15 m/s^2 for the 72.4 km/h and 3.33 m/s^2 for the 88.5 km/h) were significantly higher ($p < 0.05$) than those of the age group between 40 and 59 years of age (2.98 m/s^2 for the 72.4 km/h and 3.07 m/s^2 for the 88.5 km/h) as shown in Table 5 and Figure 27.

The F-statistic generated from the ANOVA test revealed that significant differences (F [2,972] = 4.24, P = 0.015 for the 72.4 km/h instructed speed and F [2,1045] = 44.5, P < 0.0001 for the 88.5 km/h instructed speed) exist between driver age groups for both approach speeds. As was found in a previous study (El-Shawarby et al., 2007a) conducted by the present

Table 5. Descriptive statistical results of deceleration level for grade, age, gender and platoon.

Variable		N	Min	Max	Mean	15%	50%	85%	StD
Grade	**Uphill**	532	2.31	7.31	3.65	3.00	3.54	4.37	0.71
	Downhill	440	2.31	7.25	3.75	3.12	3.58	4.48	0.71
Gender	**Female**	462	2.42	5.52	3.65	3.05	3.55	4.34	0.61
	Male	510	2.31	7.31	3.74	3.06	3.56	4.45	0.79
Age	**Older**	317	2.51	6.31	3.77	3.15	3.61	4.51	0.68
	Middle	345	2.31	7.31	3.69	2.98	3.50	4.46	0.83
	Younger	310	2.42	5.40	3.63	3.04	3.56	4.24	0.58
Platoon	**Following**	309	2.42	7.31	3.74	3.11	3.60	4.46	0.70
	Leading	325	2.31	7.25	3.71	3.10	3.55	4.38	0.71
	Single	338	2.42	7.20	3.65	2.98	3.50	4.40	0.72

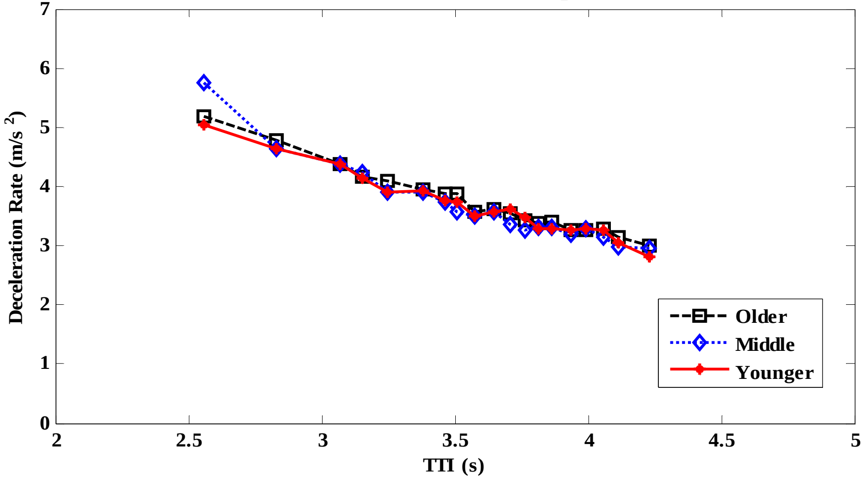
(a) 72 km/h instructed speeds

Variable		N	Min	Max	Mean	15%	50%	85%	StD
Grade	**Uphill**	544	2.43	7.28	3.87	3.19	3.82	4.55	0.72
	Downhill	501	2.30	7.28	3.94	3.17	3.80	4.73	0.76
Gender	**Female**	489	2.30	6.47	3.84	3.15	3.75	4.58	0.69
	Male	556	2.43	7.28	3.96	3.20	3.88	4.64	0.78
Age	**Older**	360	2.30	5.89	4.08	3.33	3.98	4.86	0.69
	Middle	366	2.43	7.28	3.88	3.07	3.76	4.59	0.85
	Younger	319	2.51	5.81	3.75	3.15	3.70	4.39	0.61
Platoon	**Following**	336	2.51	7.28	3.96	3.19	3.88	4.78	0.72
	Leading	351	2.52	7.28	3.89	3.16	3.80	4.59	0.75
	Single	358	2.30	7.18	3.87	3.18	3.78	4.57	0.75

(b) 88 km/h instructed speeds

investigators, older drivers (60 years of age or older) applied greater deceleration levels when compared to drivers in the 40 to 59 age group. It is hypothesized that the higher deceleration levels for the older driver population (60 years of age or older) could be because they are typically more cautious and thus apply higher deceleration levels in order to ensure that they stop prior to the stop line.

A comparison of driver deceleration levels for the three different platoon scenarios (following, leading, or alone) was performed in order to characterize the effect of surrounding traffic on driver behavior. This behavior is important in designing traffic signal timing plans within the IntelliDrive^{SM} initiative in order to improve the safety of signalized intersections. The observed 15th, 50th, and 85th percentile deceleration levels in the following platoon scenario, where the test vehicle was following another vehicle that proceeded through the intersection without slowing or stopping, were higher compared to the other two scenarios as shown in Table 5 and Figure 28. The observed 15th, 50th, and 85th percentile deceleration levels in the following platoon scenario were 3.11 m/s^2 (10.2 ft/sec^2), 3.6 m/s^2 (11.8 ft/sec^2), and 4.46 m/s^2 (14.6 ft/sec^2), respectively, in the case of the 72.4 km/h (45 mph) instructed speed compared to 3.1 m/s^2 (10.2 ft/sec^2), 3.55 m/s^2 (11.6 ft/sec^2), and 4.38 m/s^2 (14.4 ft/sec^2) in the leading platoon scenario and 2.98 m/s^2 (9.8 ft/sec^2), 3.5 m/s^2 (11.5 ft/sec^2), and 4.4 m/s^2 (14.4 ft/sec^2) in the single vehicle scenario. Also, in the 88.5 km/h (55 mph) instructed speed case, the observed deceleration levels for the 15th (3.19 m/s^2 [10.5 ft/sec^2]), 50th (3.88 m/s^2 [12.7 ft/sec^2]), and 85th (4.78 m/s^2 [15.7 ft/sec^2]) percentile in the following platoon scenario were higher compared to the leading platoon (3.16 m/s^2 [10.4 ft/sec^2], 3.8 m/s^2 [12.5 ft/sec^2], and 4.59 m/s^2 [15.1 ft/sec^2]) and the single vehicle (3.18 m/s^2 [10.4 ft/sec^2], 3.78 m/s^2 [12.4 ft/sec^2], and 4.57 m/s^2 [15.0 ft/sec^2]) scenarios.


(a) 72 Km/h Instructed Speed

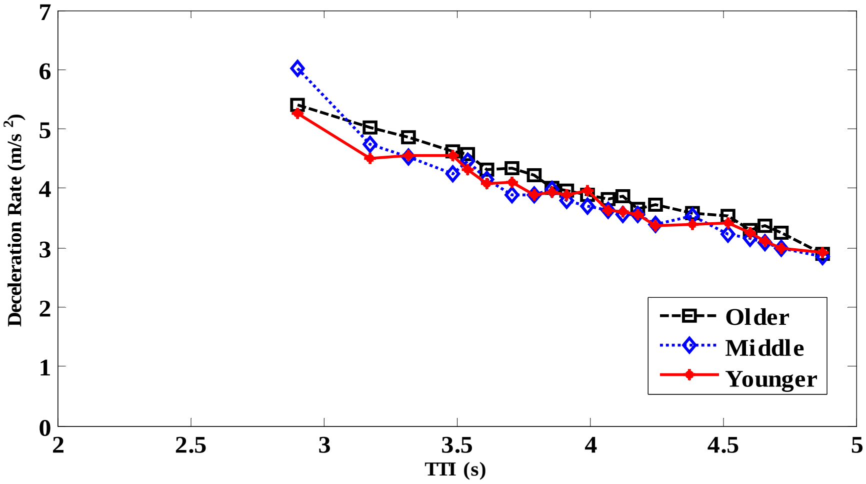
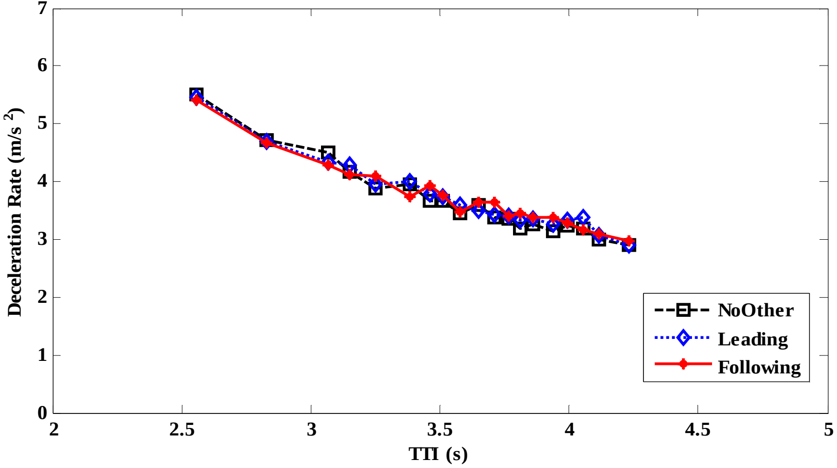

(b) 88 Km/h Instructed Speed

Figure 27. Effect of age on deceleration levels.

A potential explanation for the higher deceleration level values could be that because the lead vehicle ran through the intersection the subject driver was also inclined to proceed. This initial inclination to run resulted in the driver reacting later and thus forced the drivers to apply higher deceleration levels in order to ensure that they stop prior to the stop line. The F-statistic generated from the ANOVA test for the three scenarios demonstrated that significant differences, with P-values equal to 0.007, exist between the different scenarios for the 72.4 km/h (45 mph) instructed speed (F [2,972] = 5.1) and also for the 88.5 km/h (55 mph) instructed speed with P-values equal to 0.0001 (F [2,1045] = 9.3).

Another hypothesis that is common is the assumption that drivers who lead another vehicle (leading case) exert lesser deceleration levels in order to ensure that the vehicle behind them has sufficient time to stop without colliding with them. The results of the experiment clearly indicate that this hypothesis is not true and that there is no difference between a single vehicle on the roadway and a leading vehicle in terms of vehicle deceleration behavior at the onset of a yellow indication.

(a) 72 Km/h Instructed Speed



(b) 88 Km/h Instructed Speed

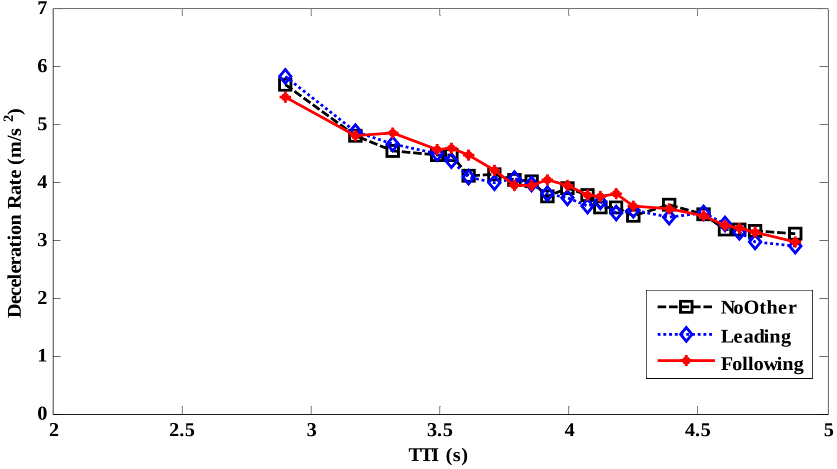


Figure 28. Effect of surrounding traffic on deceleration levels.

The mean deceleration levels for the 4-second (72.4 km/h instructed speed) and 4.5-second (88.5 km/h instructed speed) yellow intervals were plotted against the TTI at the yellow interval change time, as shown in Figure 29. The figure demonstrates that the mean deceleration level curve for the 88.5 km/h (55 mph) instructed speed was higher than the 72.4 km/h (45 mph) instructed speed over the entire TTI range. This shift correlates to a higher deceleration level for those drivers traveling at higher speeds at the onset of the yellow interval. The results, however, indicate a similar deceleration level trend at different speeds. The ANOVA results using the regression procedure (REG) of the SAS software showed that the approach speed had a significant effect, with P-values less than 0.0001, on the average deceleration level.

The results show that the deceleration level tends to increase as the TTI decreases. For the range of mean TTIs from 4.23 to 2.56 s for the 72.4 km/h (45 mph) instructed speed, the deceleration level increased from 2.31 to 7.31 m/s^2 (7.6–24 ft/sec^2) with a mean of 3.7 m/s^2 (12.1 ft/sec^2), while for the range of mean TTIs from 4.87 to 2.9 s for the 88.5 km/h (55 mph) instructed speed, the deceleration level increased from 2.3 to 7.28 m/s^2 (7.5–23.9 ft/sec^2) with a mean of 3.91 m/s^2 (12.8 ft/sec^2). The observed 15th, 50th, and 85th percentile deceleration levels were 3.05 m/s^2 (10 ft/sec^2), 3.55 m/s^2 (11.6 ft/sec^2), and 4.39 m/s^2 (14.4 ft/sec^2), respectively, in the case of the 72.4 km/h (45 mph) instructed speed compared to 3.17 m/s^2 (10.4 ft/sec^2), 3.82 m/s^2 (12.5 ft/sec^2), and 4.61 m/s^2 (15.1 ft/sec^2) for the 88.5 km/h (55 mph) instructed speed case.

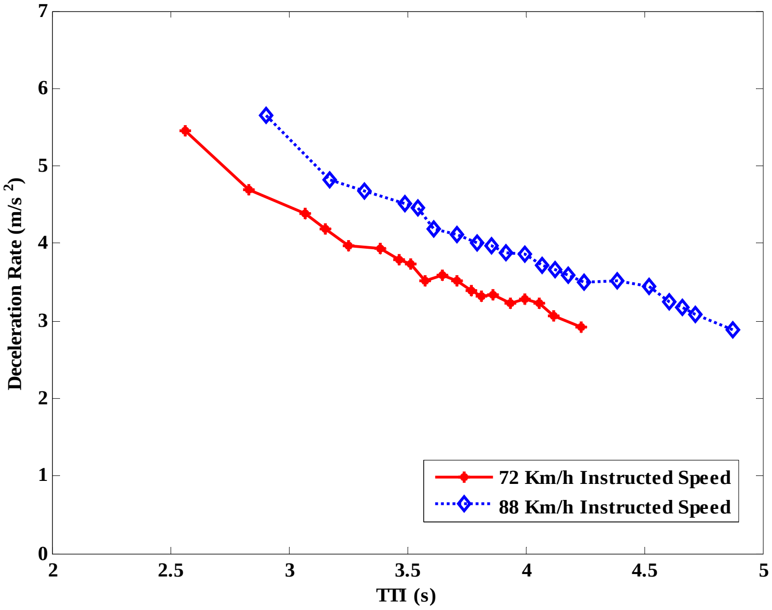


Figure 29. Effect of vehicle speed on deceleration levels.

Statistical Modeling of Driver Deceleration Behavior

As previously mentioned, a total of 2,016 stopping data records were available for the analysis. Using the data, a stepwise linear regression model was tested. After trying many model forms, including absolute and normalized variables, the final form that was selected is shown in Equation (8).

$$Dec = \beta_0 + \beta_1 g + \beta_2 a + \beta_3 G + \beta_4 \frac{TTI}{y} + \beta_5 \frac{v}{v_f} \tag{8}$$

where Dec is the deceleration level (m/s^2),

β_i's are model constants,

g is the driver gender (0 female and 1 male),
a is the driver age (years),
G is the roadway grade (percent/100),
TTI is the time-to-intersection (s),
y is the yellow time (s), and
v and v_f are the approaching speed and the speed limit (km/h).

The model calibrated coefficients and their corresponding P-values are summarized in Table 6, showing a good statistical fit. Contrary to the PRT model, the deceleration model has a good adjusted-R^2 of 75.4%. Figure 30 shows histograms of the model residuals and the calibrated deceleration levels' values.

Table 6. Statistical deceleration level model calibration results.

Coefficients	Coefficient Values	P-value
β_0	7.2379	
β_1	0.0371	0.0236
β_2	0.0028	0.0000
β_3	-1.1091	0.0000
β_4	-5.4233	0.0000
β_5	1.2234	0.0000

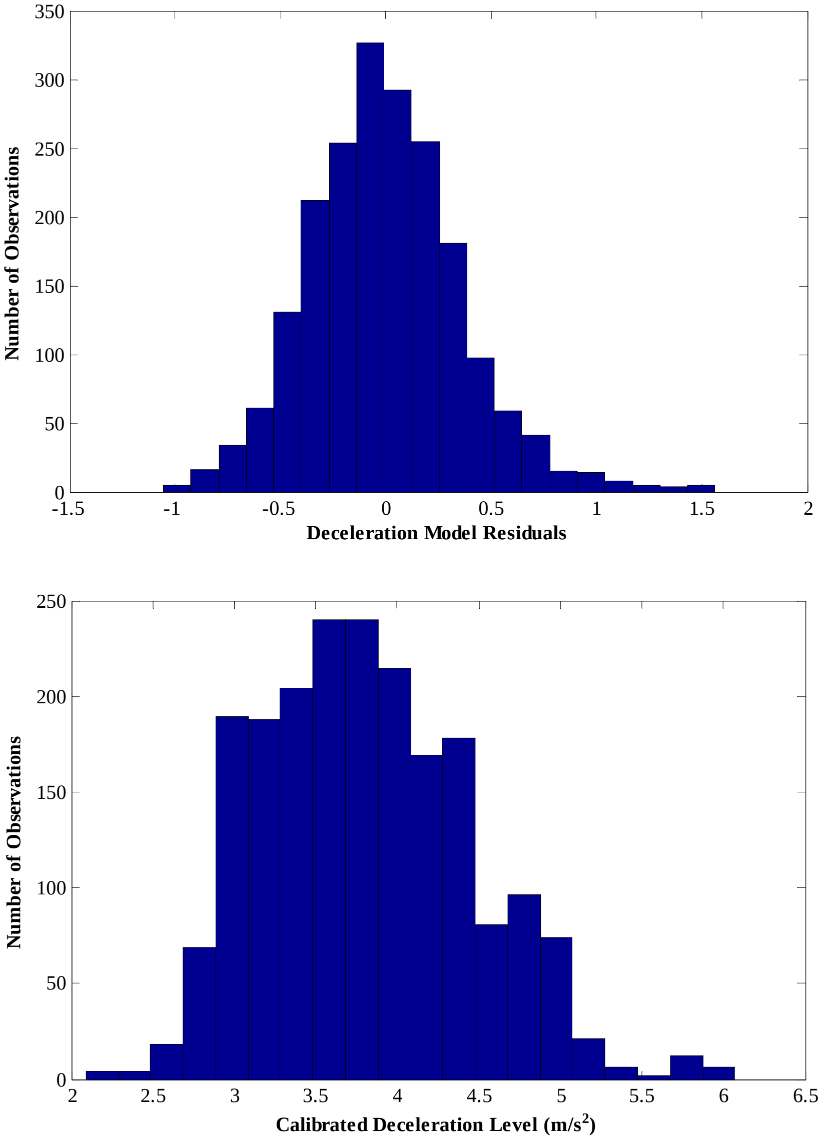


Figure 30. Histograms of model residuals and the calibrated deceleration level.

Proposed Procedure for Yellow Interval Design

After analyzing the driver running and stopping behavior, including driver stop-run decisions, red-light running, PRTs, and deceleration levels, the analysis logically extends to cover the yellow-time design. As mentioned earlier, the current guidelines for computing the traffic signal clearance interval consider a fixed 1.0 s PRT and 3.0 m/s^2 (10.0 ft/sec^2) deceleration level. The use of constant deterministic values for the PRT and the deceleration level is simplistic. Furthermore, the current approach fails to account for variations between different drivers approaching the same intersection at the onset of yellow. These variations include variations in each driver's PRT and deceleration level. It is worth noting that it is not possible to vary signal timing parameters based on individual driver characteristics with today's technology. Although not immediately implementable, this section of the report is intended to illustrate how variations in driver characteristics impact the required clearance interval and the potential for more sophisticated timing algorithms in the future. Such variations are confirmed based on the above analyses made on both PRT and deceleration level. Due to these variations, the standard yellow interval (based on a 1.0 s PRT and a 3.0 m/s^2 deceleration level) may be insufficient for some drivers when their PRT is longer than 1.0 s and/or their deceleration rate is less than 3.0 m/s^2. On the other hand, the standard yellow interval may be more than sufficient for drivers with PRTs shorter than 1.0 s and/or deceleration rates greater than 3.0 m/s^2. Accordingly, it is more appropriate to consider: first, the differences in average PRT and deceleration levels compared to the standard values, and second, the differences in individual PRT and deceleration levels between different drivers at a specific intersection. In this section, the yellow clearance interval calculation formula, presented earlier and represented here for convenience in Equation (9), is used to carry out a Monte Carlo simulation exercise to model the required yellow time based on the actual mean values and the statistical models calibrated earlier for the PRT and the deceleration level.

$$y = t + \frac{v}{2\left(d \pm 9.81G\right)} \tag{9}$$

where y is the duration of the yellow interval (s),
t is the driver PRT (s),
v is the speed of the approaching vehicle (m/s),
d is the deceleration rate (m/s^2), and
G is the roadway grade (percent/100; uphill +ve and downhill −ve).

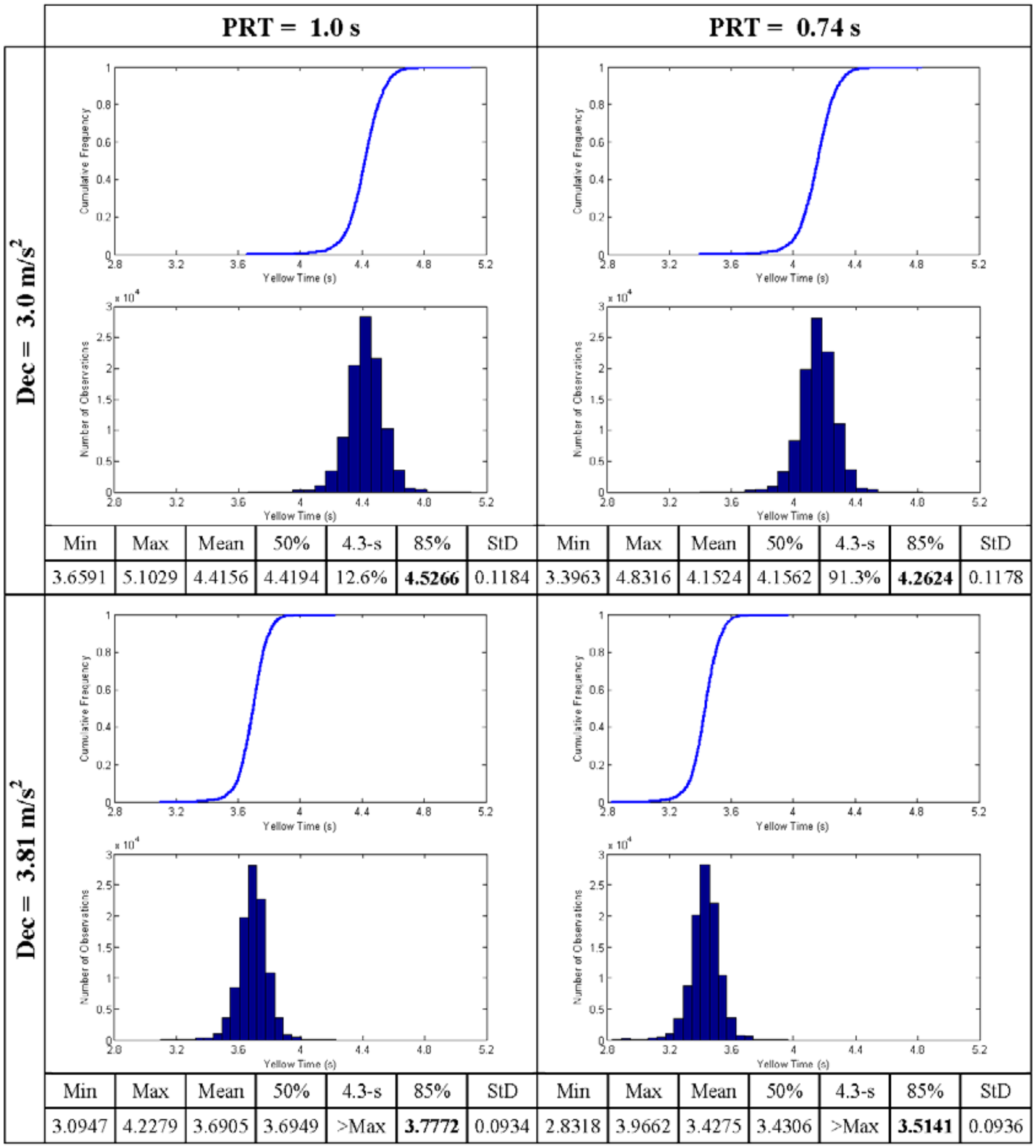
The purpose of the Monte Carlo simulation of the yellow time computation is twofold: first, to compare the yellow timings derived using the field-observed mean PRT and/or deceleration level versus the current guideline values; second, to investigate how the probabilistic distributions of the PRT and the deceleration level affect the yellow-time computation, given that both PRT and deceleration levels are functions of age and gender. That implies investigating the impact of these driver attributes on the yellow time and how the composition of the driver population at an intersection affects the required yellow time. Finally, a set of lookup tables are developed for different posted speed limits and different cumulative percentiles (reliability measures). These tables are derived from the limited dataset collected in this study and are provided for illustrative purposes only.

In order to model the required yellow time, a Monte Carlo simulation considering a sample of 100,000 drivers is simulated by randomly generating the independent variables affecting the PRT and the deceleration level with the corresponding yellow time. These variables listed above include the driver's gender and age, roadway grade, TTI, and approach speed. In order to generate a TTI distribution, a uniform random number generator is used to produce TTI values from a range that is slightly larger than the dilemma zone boundaries corresponding to the posted speed limit. On the other hand, the approach speed is generated using the empirical distribution of the speed observations. However, in order to generalize the approach speed distribution to be able to generate a speed distribution for any posted speed limit, the actual speed distribution for the 88.5 km/h (55 mph) instructed speed is shifted left by the difference between its mean and the mean of the 72.4 km/h (45 mph) instructed speed, and then both distributions are combined resulting in one generalized empirical distribution for the 72.4 km/h (45 mph) speed limit. Accordingly, in order to generate a speed distribution for any speed limit other than 72.4 km/h (45 mph), the generalized empirical distribution is shifted by the difference between the 72.4 km/h (45 mph) and the desired speed limit.

Impacts of PRT and Deceleration Level on Yellow Time Computation

In order to examine the impacts of PRT and deceleration level, first a posted speed limit of 45 mph (72.4 km/h) and a level roadway (G = 0%) are considered. Four sample realizations of the yellow times are generated. The first sample is constructed using the current guideline deterministic values for PRT (1 s) and deceleration level (3 m/s^2). Subsequently, two samples are generated by replacing the deterministic PRT value by the actual PRT mean value that was observed in the study (0.74 s) while using guideline's deceleration level and vice versa with the field-observed mean deceleration level (3.81 m/s^2). One last sample is made using the actual mean values for both PRT and deceleration levels. The histograms and the cumulative distributions of the four realizations and their corresponding statistics are presented in Figure 31. Traditionally, the recommended yellow time for the 72.4 km/h (45 mph) speed limit is 4.3 s. In order to compare the simulated yellow times distribution to the deterministic guideline yellow time, the percentile corresponding to the 4.3-second yellow time is determined and compared to 85%.

It can be seen from Figure 31 that using the proposed 1-second PRT and 3 m/s^2 deceleration level requires an 85th-percentile yellow time of approximately 4.53 s, which is longer than the 4.3-second recommended yellow time. The recommended yellow time corresponds to only a 12.6 percentile, which means that most of the drivers will encounter a yellow time that is shorter than what they really needed; i.e., they will be trapped in a dilemma zone. In order for these drivers to be able to avoid being in a dilemma zone, they either need to react faster (have short PRTs) and/or brake harder (have higher deceleration levels). It is interesting that this conclusion is consistent with the actual data, where the mean PRT is 0.74 s and the mean deceleration level is 3.81 m/s^2. It can be seen from the figure that when the PRT is equal to 0.74s while maintaining the 3 m/s^2 deceleration, the recommended yellow time of 4.3 s is found to be sufficient for 91.3% of the drivers. On the other hand, increasing the deceleration level to 3.81 m/s^2, with a 1-second PRT, makes the maximum required yellow time (~4.23 s) even less than the recommended yellow time. Almost the same findings are observed when adopting both adjustments: a short PRT and a higher deceleration level.



Dec	PRT	Min	Max	Mean	50%	4.3-s	85%	StD
3.0 m/s²	1.0 s	3.6591	5.1029	4.4156	4.4194	12.6%	**4.5266**	0.1184
3.0 m/s²	0.74 s	3.3963	4.8316	4.1524	4.1562	91.3%	**4.2624**	0.1178
3.81 m/s²	1.0 s	3.0947	4.2279	3.6905	3.6949	>Max	**3.7772**	0.0934
3.81 m/s²	0.74 s	2.8318	3.9662	3.4275	3.4306	>Max	**3.5141**	0.0936

Figure 31. Yellow time distributions for different PRT and deceleration levels.

Yellow Time Based on Gender and Age

It can be concluded from the above results that determining the required yellow time as a probabilistic distribution would be better than having a single deterministic value. This is because generating a distribution of yellow time realizations provides a measure of the level of dilemma zone risk associated with each yellow time value. In addition, the yellow time realizations can be generated for different gender and age groups. This can be done by cross-classifying the population of drivers by gender and age, and determining the yellow time distribution for each gender and age group. Such group distributions would enable obtaining the overall yellow time distribution for a certain intersection by adding up the distributions of gender and age groups by the percentage of each group at that intersection. For convenience, Equations

(10) and (11) list the PRT and the deceleration level calibrated earlier with their calibrated coefficients.

$$PRT = 0.78 - 0.04g + 0.003a + 1.20G + 0.40\frac{TTI}{y} - 0.49\frac{v}{v_f} + e_{PRT} \qquad (10)$$

$$Dec = 7.24 + 0.04g + 0.003a - 1.11G - 5.42\frac{TTI}{y} + 1.22\frac{v}{v_f} + e_{Dec} \qquad (11)$$

where *PRT* is the perception-reaction time (s),
Dec is the deceleration level (m/s^2),
g is the gender (0 female and 1 male),
a is the age (years),
G is the roadway grade (percent/100),
TTI is the time-to-intersection (s),
y is the yellow time (s), and
v and v_f are the approaching speed and the speed limit (km/h).

In order to illustrate this procedure, the population of stopped drivers in the available data, which include 2,016 records, is stratified by gender (female and male) and age (young < 40 years, 40 ≤ mid-age < 60, old ≥ 60 years). For each of the six cross-classes, a realization of the yellow-time distribution is generated. Figure 32 shows the cumulative distribution function (CDF) and the corresponding statistics for each of the six groups.

The figure demonstrates that, in general, female drivers need longer yellow times compared to male drivers. In addition, the age slightly affects the required yellow time, where older drivers need slightly longer yellow times when compared to younger drivers. The extreme comparison here could arise from comparing an intersection with a majority of old female drivers to another intersection with majority of young male drivers.

After generating the realizations for all groups, the overall distribution for all drivers can be obtained by weighting each realization by its ratio in the population. In other words, if n is the total number of drivers and n_i is the number of drivers in each gender and age group, the overall cumulative distribution function can be obtained by weighting each value within each group by the ratio (n_i/n), and then combining and sorting all realizations in the six groups based on their yellow times, and finally adding the weights up to 1. Applying the procedure to the data, the number of observations and percentage of drivers in each gender/age group are summarized in Table 7, whereas the overall distribution of yellow time and its corresponding statistics is shown in Figure 33.

It can be seen from Figure 33 that in order to ensure that at least 85% of all the drivers in the dataset do not encounter a dilemma zone, the yellow time should be approximately 3.8 s. Nevertheless, applying the recommended 4.3-second yellow time would decrease the percentage of drivers trapped in a dilemma zone to 3.2%. The concept of having the required yellow time as a function of the underlying variables can serve perfectly within the IntelliDrive^{SM} initiative, where each individual driver can receive advice on the specific time he or she needs in order to react before the signal turns to red. This novel advance provides each driver with his or her exact yellow-time duration.

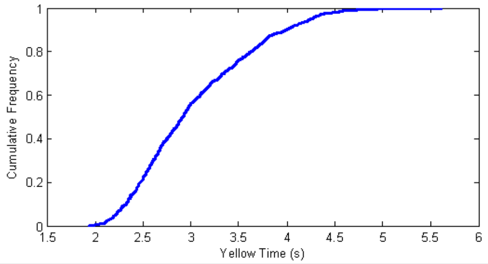
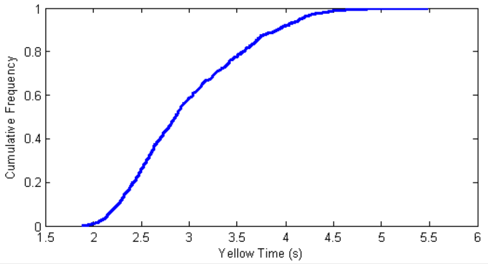
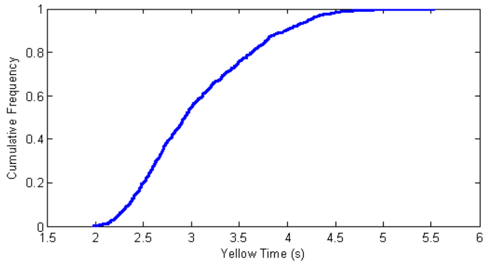
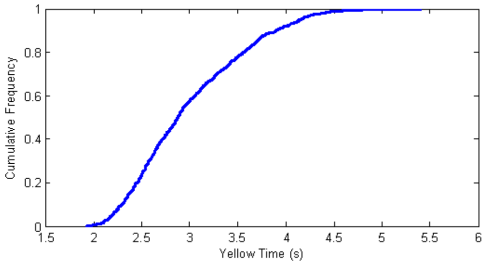
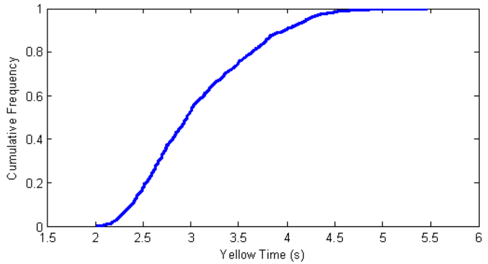
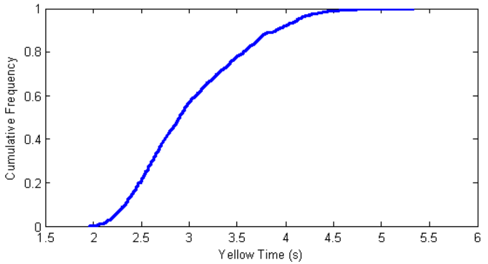
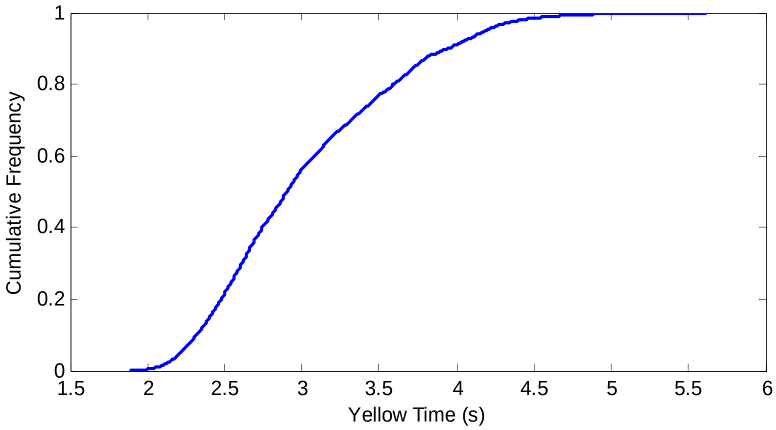
<table>
<tr><th></th><th colspan="7">Female Drivers</th><th colspan="7">Male Drivers</th></tr>
<tr><td rowspan="3">Young Drivers</td><td colspan="7">
</td><td colspan="7">
</td></tr>
<tr><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td></tr>
<tr><td>1.9474</td><td>5.6177</td><td>3.0456</td><td>2.9157</td><td>96.0%</td><td>3.7721</td><td>0.6427</td><td>1.8964</td><td>5.4873</td><td>2.9823</td><td>2.8558</td><td>97.3%</td><td>3.6984</td><td>0.6323</td></tr>
<tr><td rowspan="3">Mid-age Drivers</td><td colspan="7">
</td><td colspan="7">
</td></tr>
<tr><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td></tr>
<tr><td>1.9826</td><td>5.5361</td><td>3.0626</td><td>2.9369</td><td>96.3%</td><td>3.7733</td><td>0.6274</td><td>1.9318</td><td>5.4103</td><td>3.0000</td><td>2.8772</td><td>97.4%</td><td>3.7002</td><td>0.6174</td></tr>
<tr><td rowspan="3">Old Drivers</td><td colspan="7">
</td><td colspan="7">
</td></tr>
<tr><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td><td>Min</td><td>Max</td><td>Mean</td><td>50%</td><td>4.3-s</td><td>85%</td><td>StD</td></tr>
<tr><td>2.0181</td><td>5.4612</td><td>3.0806</td><td>2.9592</td><td>96.4%</td><td>3.7758</td><td>0.6127</td><td>1.9675</td><td>5.3397</td><td>3.0185</td><td>2.8988</td><td>97.46%</td><td>3.7049</td><td>0.6032</td></tr>
</table>

Figure 32. Yellow-time distributions for different gender and age groups.

Table 7. Drivers' distribution among gender and age groups.

		Gender		
		Female	**Male**	**All**
Age	**Young (< 40)**	330 (16.4%)	298 (14.8%)	**628 (31.2%)**
	Mid-age (40 – 60)	337 (16.7%)	374 (18.6%)	**711 (35.3%)**
	Old (≥ 60)	284 (14.1%)	393 (19.5%)	**677 (33.6%)**
	All	**951 (47.2%)**	**1065 (52.8%)**	**2016 (100%)**



Min	Max	Mean	50%	4.3-s	85%	StD
1.8964	5.6177	3.0314	2.9047	96.80%	**3.7391**	0.6236

Figure 33. Overall yellow-time distribution for weighted gender and age groups.

Lookup Tables for Yellow Clearance Intervals

In this section a lookup table is developed that computes the yellow time duration based on different posted speed limits, different roadway grades, and a reliability factor (percentage of drivers that are not trapped in the dilemma zone [percentile]). Three posted speed limits are presented here: 35 mph (56.3 km/h), 45 mph (72.4 km/h), and 55 mph (88.5 km/h). Also, nine roadway grades are presented ranging from –4% downhill to 4% uphill. Table 8 summarizes the different yellow times corresponding to each speed limit, grade, and reliability level. This table serves as an easy tool to look up the required yellow time for a specific intersection at the desired reliability level depending on the importance of the intersection and the traffic volumes on its approaches. The reader is reminded that these tables are derived from data collected from a limited number of test subjects in an experimental environment involving only light-duty vehicles and clear, dry weather.

Furthermore, this table could be extended to cover other variables affecting the yellow time, e.g., gender and age. A set of six lookup tables for each age and gender group are presented in the appendix. If the available information permitted, the required yellow time for each age and gender group could be looked up from these tables and then the overall yellow time can be calculated as the weighted average across the various groups.

FINDINGS AND CONCLUSIONS

The research presented in this report developed a novice stochastic approach for estimating the yellow interval duration. The approach explicitly accounts for design reliability using a Monte Carlo simulation approach that accounts for the stochastic nature of driver PRT and deceleration behavior. The model was developed using data gathered on 24 participants that drove along the Virginia Smart Road through a four-way signalized intersection. Each participant was tested six times at two instructed speeds, 72.4 km/h and 88.5 km/h (45 and 55 mph, respectively) and three platooning conditions (alone, leading, and following). Exclusive of

Table 8. Yellow clearance interval lookup table for all drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.6	3.1	3.6	2.5	3.0	3.6	2.5	3.0	3.5	**50%**
60%	2.8	3.3	3.8	2.8	3.3	3.8	2.7	3.2	3.7	**60%**
70%	3.1	3.6	4.1	3.0	3.5	4.0	3.0	3.5	3.9	**70%**
80%	3.4	3.9	4.4	3.3	3.8	4.3	3.3	3.7	4.2	**80%**
85%	3.6	4.1	4.6	3.5	4.0	4.5	3.4	3.9	4.4	**85%**
90%	3.8	4.3	4.8	3.7	4.2	4.7	3.7	4.1	4.6	**90%**
95%	4.2	4.6	5.1	4.1	4.5	5.0	4.0	4.4	4.9	**95%**
96%	4.3	4.7	5.2	4.2	4.6	5.1	4.1	4.5	5.0	**96%**
97%	4.4	4.9	5.3	4.3	4.7	5.2	4.2	4.6	5.1	**97%**
98%	4.6	5.0	5.5	4.4	4.9	5.3	4.3	4.7	5.2	**98%**
99%	4.8	5.3	5.7	4.7	5.1	5.6	4.6	5.0	5.4	**99%**
99.9%	5.8	6.0	6.5	5.5	5.8	6.3	5.3	5.8	6.1	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.5	2.5	2.9	3.4	2.4	2.9	3.4	**50%**
60%	2.7	3.2	3.7	2.7	3.1	3.6	2.6	3.1	3.6	**60%**
70%	2.9	3.4	3.9	2.9	3.4	3.8	2.8	3.3	3.8	**70%**
80%	3.2	3.7	4.2	3.2	3.6	4.1	3.1	3.6	4.0	**80%**
85%	3.4	3.8	4.3	3.3	3.8	4.2	3.3	3.7	4.2	**85%**
90%	3.6	4.0	4.5	3.5	4.0	4.4	3.4	3.9	4.4	**90%**
95%	3.9	4.3	4.8	3.8	4.2	4.7	3.7	4.1	4.6	**95%**
96%	4.0	4.4	4.9	3.9	4.3	4.8	3.8	4.2	4.7	**96%**
97%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.3	4.8	**97%**
98%	4.2	4.6	5.1	4.1	4.5	5.0	4.0	4.4	4.9	**98%**
99%	4.4	4.8	5.3	4.3	4.7	5.2	4.2	4.6	5.1	**99%**
99.9%	5.1	5.5	5.9	4.9	5.3	5.8	4.8	5.1	5.7	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.9	3.3	2.4	2.9	3.3	2.4	2.8	3.3	**50%**
60%	2.6	3.1	3.5	2.6	3.0	3.5	2.6	3.0	3.4	**60%**
70%	2.8	3.3	3.7	2.8	3.2	3.7	2.8	3.2	3.6	**70%**
80%	3.1	3.5	4.0	3.0	3.5	3.9	3.0	3.4	3.9	**80%**
85%	3.2	3.7	4.1	3.2	3.6	4.0	3.1	3.5	4.0	**85%**
90%	3.4	3.8	4.3	3.3	3.8	4.2	3.3	3.7	4.1	**90%**
95%	3.6	4.1	4.5	3.6	4.0	4.4	3.5	3.9	4.4	**95%**
96%	3.7	4.1	4.6	3.6	4.1	4.5	3.6	4.0	4.4	**96%**
97%	3.8	4.2	4.7	3.7	4.1	4.6	3.6	4.1	4.5	**97%**
98%	3.9	4.3	4.8	3.8	4.2	4.7	3.8	4.2	4.6	**98%**
99%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.3	4.8	**99%**
99.9%	4.6	5.0	5.5	4.5	4.9	5.3	4.4	4.8	5.2	**99.9%**

practice trials, for each test the participant drove the entire test course 24 times for a total of 48 trials, where a trial consisted of a single approach to the intersection. Among the 48 trials, there were 24 trials in which each yellow trigger time to stop-line occurred four times. On the remaining 24 trials the signal indication remained green. This scheme resulted in yellow/red signals being presented on 50% of the 48 trials; conversely, 50% of intersection approaches consisted solely of a green indication. To examine whether willingness to stop varied with speed, the onset of yellow was based on the TTI (between 2.0 s and 4.6 s) at the instructed speed rather than on the distance from the stop line. Radar was used to determine vehicle distance from the intersection. Outputs from the radar triggered the phase-change events. A DAS in the vehicle collected the signal timing and vehicle data at a frequency of 10 Hz. Based on the study approach, the following conclusions are drawn:

- PRT values obtained in the study are consistent with earlier studies, producing 85th-percentile PRT values that are consistent with previously reported results. The driver behavior observed in the controlled field experiment appears to be consistent with naturalistic and non-obtrusive field-observed driver behavior.

- Driver PRT is higher for female and older drivers (60+ age group) compared to younger male drivers. The PRT is larger for vehicles traveling along an upgrade section given that the driver is typically accelerating when the yellow indication is initiated.

- Driver PRTs are typically higher if they are following a vehicle that runs a yellow light. Furthermore, driver PRTs decrease when they are followed by another vehicle. Finally, driver PRTs increase as the TTI at the onset of the yellow interval increases.

- Driver deceleration levels obtained in the study are significantly higher than the 3 m/s^2 deceleration level used in the state-of-the-practice traffic signal design guidelines. Specifically, the mean deceleration level is more in the range of 3.6 to 4.1 m/s^2.

- The study results demonstrate that driver deceleration levels are higher at shorter TTIs at the onset of yellow. Drivers are willing to exert deceleration levels in excess of 7 m/s^2 at very short TTIs (less than 2.5 s). Furthermore, younger (less than 40 years old) and older (60+ years old) drivers employ greater deceleration levels compared to middle-aged drivers (40 to 59 years old).

- Driver following another vehicle that proceeds legally through the intersection without stopping exerts higher deceleration levels compared to drivers driving alone or leading another vehicle. Drivers leading a platoon of vehicles are not affected by the vehicles behind them with regard to their deceleration behavior.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division should consider the stochastic nature of yellow-time design's underlying elements*. Those include driver PRT and deceleration behavior and how they are affected by the intersection characteristics, e.g., speed limit and roadway grade.

2. *VDOT's Traffic Engineering Division should consider the design reliability in determining traffic signal yellow times.* This can be accomplished by using the framework developed in this study (illustrated in Table 8 and Tables A-1 through A-6).

3. *The Virginia Center for Transportation Innovation & Research (VCTIR) Safety, Operations, and Traffic Engineering Team should consider funding further field testing to develop yellow-timing lookup tables for heavy duty trucks, for wet roadway conditions, and/or inclement weather conditions.* This is essential to improve the validity of the lookup tables that are provided in this report since they are valid only for light-duty vehicles on dry roadway surfaces and in clear weather conditions.

4. *VCTIR's Safety, Operations, and Traffic Engineering Team should consider the findings of this study as their involvement in the IntelliDrive^{SM} initiative continues.* Applications designed to improve traffic signal operations will benefit from the insight on driver behavior gained through this research.

COSTS AND BENEFITS ASSESSMENT

As was mentioned earlier, in 2001, approximately 218,000 red-light-running crashes occurred at signalized intersections in the United States. These crashes resulted in nearly 181,000 injuries and 880 fatalities and an economic loss of 14 billion dollars. The proposed approach for computing the duration of the yellow interval that explicitly accounts for the reliability of the design (i.e., the probability that drivers do not encounter a dilemma zone) has the potential to enhance the safety of signalized intersections and reduce red-light-running crashes.

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APPENDIX

YELLOW TIMES FOR SPECIFIC AGE AND GENDER GROUPS

Tables A1 through A6 illustrate yellow times for specific age and gender groups.

Table A-1. Yellow clearance interval lookup table for young female drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.6	3.1	3.6	2.6	3.1	3.6	2.5	3.0	3.5	**50%**
60%	2.8	3.3	3.9	2.8	3.3	3.8	2.7	3.2	3.7	**60%**
70%	3.1	3.6	4.1	3.0	3.5	4.0	3.0	3.5	4.0	**70%**
80%	3.4	3.9	4.4	3.4	3.8	4.3	3.3	3.8	4.3	**80%**
85%	3.6	4.1	4.6	3.6	4.0	4.5	3.5	4.0	4.4	**85%**
90%	3.9	4.4	4.9	3.8	4.3	4.8	3.7	4.2	4.7	**90%**
95%	4.2	4.7	5.2	4.1	4.6	5.1	4.0	4.5	5.0	**95%**
96%	4.4	4.8	5.3	4.2	4.7	5.2	4.1	4.6	5.0	**96%**
97%	4.5	4.9	5.4	4.4	4.8	5.3	4.2	4.7	5.2	**97%**
98%	4.7	5.1	5.6	4.5	4.9	5.4	4.4	4.8	5.3	**98%**
99%	4.9	5.4	5.8	4.8	5.2	5.7	4.6	5.0	5.5	**99%**
99.9%	5.9	6.2	6.7	5.7	6.0	6.4	5.4	5.7	6.2	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.5	2.5	3.0	3.4	2.5	2.9	3.4	**50%**
60%	2.7	3.2	3.7	2.7	3.2	3.6	2.6	3.1	3.6	**60%**
70%	2.9	3.4	3.9	2.9	3.4	3.9	2.9	3.3	3.8	**70%**
80%	3.2	3.7	4.2	3.2	3.6	4.1	3.1	3.6	4.1	**80%**
85%	3.4	3.9	4.4	3.3	3.8	4.3	3.3	3.7	4.2	**85%**
90%	3.6	4.1	4.6	3.5	4.0	4.5	3.5	3.9	4.4	**90%**
95%	3.9	4.4	4.8	3.8	4.3	4.7	3.7	4.2	4.7	**95%**
96%	4.0	4.5	4.9	3.9	4.4	4.8	3.8	4.3	4.7	**96%**
97%	4.1	4.6	5.0	4.0	4.5	4.9	3.9	4.4	4.8	**97%**
98%	4.3	4.7	5.2	4.2	4.6	5.1	4.1	4.5	4.9	**98%**
99%	4.5	4.9	5.4	4.4	4.8	5.2	4.3	4.7	5.1	**99%**
99.9%	5.2	5.6	6.0	5.0	5.5	5.9	4.9	5.3	5.7	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.9	3.4	2.4	2.9	3.3	2.4	2.8	3.3	**50%**
60%	2.6	3.1	3.5	2.6	3.0	3.5	2.6	3.0	3.5	**60%**
70%	2.8	3.3	3.8	2.8	3.2	3.7	2.8	3.2	3.7	**70%**
80%	3.1	3.5	4.0	3.0	3.5	3.9	3.0	3.4	3.9	**80%**
85%	3.2	3.7	4.1	3.2	3.6	4.1	3.1	3.6	4.0	**85%**
90%	3.4	3.9	4.3	3.4	3.8	4.3	3.3	3.7	4.2	**90%**
95%	3.7	4.1	4.6	3.6	4.0	4.5	3.5	4.0	4.4	**95%**
96%	3.7	4.2	4.6	3.7	4.1	4.6	3.6	4.0	4.5	**96%**
97%	3.8	4.3	4.7	3.8	4.2	4.6	3.7	4.1	4.6	**97%**
98%	4.0	4.4	4.8	3.9	4.3	4.8	3.8	4.2	4.7	**98%**
99%	4.1	4.6	5.0	4.0	4.5	4.9	4.0	4.4	4.8	**99%**
99.9%	4.7	5.2	5.6	4.6	5.0	5.5	4.4	4.9	5.4	**99.9%**

Table A-2. Yellow clearance interval lookup table for young male drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.6	2.5	3.0	3.5	2.5	3.0	3.5	**50%**
60%	2.7	3.3	3.8	2.7	3.2	3.7	2.7	3.2	3.7	**60%**
70%	3.0	3.5	4.0	3.0	3.5	4.0	2.9	3.4	3.9	**70%**
80%	3.3	3.8	4.4	3.3	3.8	4.3	3.2	3.7	4.2	**80%**
85%	3.5	4.0	4.5	3.5	4.0	4.5	3.4	3.9	4.4	**85%**
90%	3.8	4.3	4.8	3.7	4.2	4.7	3.6	4.1	4.6	**90%**
95%	4.2	4.6	5.1	4.1	4.5	5.0	3.9	4.4	4.9	**95%**
96%	4.3	4.7	5.2	4.1	4.6	5.1	4.0	4.5	5.0	**96%**
97%	4.4	4.8	5.3	4.3	4.7	5.2	4.1	4.6	5.1	**97%**
98%	4.6	5.0	5.5	4.4	4.9	5.3	4.3	4.7	5.2	**98%**
99%	4.8	5.3	5.7	4.7	5.1	5.6	4.5	5.0	5.4	**99%**
99.9%	5.7	6.1	6.5	5.5	5.9	6.2	5.3	5.7	6.1	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.9	3.4	2.4	2.9	3.4	2.4	2.9	3.3	**50%**
60%	2.6	3.1	3.6	2.6	3.1	3.6	2.6	3.1	3.5	**60%**
70%	2.9	3.4	3.8	2.8	3.3	3.8	2.8	3.3	3.7	**70%**
80%	3.2	3.6	4.1	3.1	3.6	4.0	3.1	3.5	4.0	**80%**
85%	3.3	3.8	4.3	3.3	3.7	4.2	3.2	3.7	4.1	**85%**
90%	3.5	4.0	4.5	3.5	3.9	4.4	3.4	3.9	4.3	**90%**
95%	3.8	4.3	4.8	3.7	4.2	4.7	3.7	4.1	4.6	**95%**
96%	3.9	4.4	4.8	3.8	4.3	4.7	3.8	4.2	4.6	**96%**
97%	4.0	4.5	4.9	3.9	4.4	4.8	3.8	4.3	4.7	**97%**
98%	4.2	4.6	5.1	4.1	4.5	4.9	4.0	4.4	4.9	**98%**
99%	4.4	4.8	5.3	4.3	4.7	5.1	4.2	4.6	5.1	**99%**
99.9%	5.1	5.4	5.9	4.9	5.3	5.8	4.8	5.2	5.6	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.8	3.3	2.3	2.8	3.3	2.3	2.8	3.2	**50%**
60%	2.6	3.0	3.5	2.5	3.0	3.4	2.5	3.0	3.4	**60%**
70%	2.8	3.2	3.7	2.7	3.2	3.6	2.7	3.1	3.6	**70%**
80%	3.0	3.5	3.9	3.0	3.4	3.9	2.9	3.4	3.8	**80%**
85%	3.2	3.6	4.1	3.1	3.6	4.0	3.1	3.5	3.9	**85%**
90%	3.4	3.8	4.2	3.3	3.7	4.2	3.2	3.7	4.1	**90%**
95%	3.6	4.0	4.5	3.5	4.0	4.4	3.5	3.9	4.3	**95%**
96%	3.7	4.1	4.6	3.6	4.0	4.5	3.5	3.9	4.4	**96%**
97%	3.8	4.2	4.6	3.7	4.1	4.6	3.6	4.0	4.5	**97%**
98%	3.9	4.3	4.8	3.8	4.2	4.7	3.7	4.1	4.6	**98%**
99%	4.1	4.5	4.9	4.0	4.4	4.8	3.9	4.3	4.7	**99%**
99.9%	4.7	5.0	5.5	4.5	4.9	5.3	4.4	4.8	5.2	**99.9%**

Table A-3. Yellow clearance interval lookup table for mid-age female drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.6	3.1	3.6	2.6	3.1	3.6	2.5	3.0	3.5	**50%**
60%	2.8	3.3	3.9	2.8	3.3	3.8	2.7	3.2	3.7	**60%**
70%	3.1	3.6	4.1	3.0	3.5	4.1	3.0	3.5	4.0	**70%**
80%	3.4	3.9	4.4	3.4	3.8	4.3	3.3	3.8	4.3	**80%**
85%	3.6	4.1	4.6	3.6	4.0	4.5	3.5	3.9	4.4	**85%**
90%	3.9	4.3	4.8	3.8	4.2	4.7	3.7	4.2	4.6	**90%**
95%	4.2	4.7	5.2	4.1	4.6	5.0	4.0	4.5	4.9	**95%**
96%	4.3	4.8	5.3	4.2	4.7	5.1	4.1	4.5	5.0	**96%**
97%	4.5	4.9	5.4	4.3	4.8	5.2	4.2	4.6	5.1	**97%**
98%	4.6	5.0	5.5	4.5	4.9	5.4	4.4	4.8	5.2	**98%**
99%	4.9	5.3	5.8	4.7	5.2	5.6	4.6	5.0	5.5	**99%**
99.9%	5.8	6.1	6.5	5.6	5.9	6.4	5.3	5.7	6.2	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.5	2.5	3.0	3.4	2.5	2.9	3.4	**50%**
60%	2.7	3.2	3.7	2.7	3.2	3.6	2.7	3.1	3.6	**60%**
70%	3.0	3.4	3.9	2.9	3.4	3.9	2.9	3.3	3.8	**70%**
80%	3.2	3.7	4.2	3.2	3.6	4.1	3.1	3.6	4.1	**80%**
85%	3.4	3.9	4.4	3.4	3.8	4.3	3.3	3.7	4.2	**85%**
90%	3.6	4.1	4.5	3.6	4.0	4.5	3.5	3.9	4.4	**90%**
95%	3.9	4.4	4.8	3.8	4.3	4.7	3.8	4.2	4.6	**95%**
96%	4.0	4.4	4.9	3.9	4.3	4.8	3.8	4.3	4.7	**96%**
97%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.3	4.8	**97%**
98%	4.2	4.7	5.2	4.1	4.6	5.0	4.0	4.5	4.9	**98%**
99%	4.4	4.9	5.4	4.3	4.8	5.2	4.2	4.7	5.1	**99%**
99.9%	5.1	5.5	6.0	5.0	5.4	5.8	4.8	5.2	5.7	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	2.9	3.4	2.4	2.9	3.3	2.4	2.9	3.3	**50%**
60%	2.6	3.1	3.6	2.6	3.1	3.5	2.6	3.0	3.5	**60%**
70%	2.8	3.3	3.8	2.8	3.3	3.7	2.8	3.2	3.7	**70%**
80%	3.1	3.5	4.0	3.0	3.5	3.9	3.0	3.4	3.9	**80%**
85%	3.2	3.7	4.1	3.2	3.6	4.1	3.1	3.6	4.0	**85%**
90%	3.4	3.9	4.3	3.4	3.8	4.2	3.3	3.7	4.2	**90%**
95%	3.7	4.1	4.5	3.6	4.0	4.5	3.5	4.0	4.4	**95%**
96%	3.7	4.2	4.6	3.7	4.1	4.5	3.6	4.0	4.5	**96%**
97%	3.8	4.3	4.7	3.8	4.2	4.6	3.7	4.1	4.5	**97%**
98%	4.0	4.4	4.8	3.9	4.3	4.7	3.8	4.2	4.6	**98%**
99%	4.1	4.5	5.0	4.0	4.5	4.9	3.9	4.4	4.8	**99%**
99.9%	4.7	5.0	5.5	4.5	5.0	5.4	4.4	4.8	5.3	**99.9%**

Table A-4. Yellow clearance interval lookup table for mid-age male drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.6	2.5	3.0	3.5	2.5	3.0	3.5	**50%**
60%	2.8	3.3	3.8	2.7	3.2	3.7	2.7	3.2	3.7	**60%**
70%	3.0	3.5	4.0	3.0	3.5	4.0	2.9	3.4	3.9	**70%**
80%	3.3	3.8	4.3	3.3	3.8	4.3	3.2	3.7	4.2	**80%**
85%	3.5	4.0	4.5	3.5	3.9	4.4	3.4	3.9	4.3	**85%**
90%	3.8	4.2	4.7	3.7	4.2	4.7	3.6	4.1	4.6	**90%**
95%	4.1	4.6	5.1	4.0	4.5	4.9	3.9	4.4	4.8	**95%**
96%	4.2	4.7	5.2	4.1	4.6	5.0	4.0	4.4	4.9	**96%**
97%	4.3	4.8	5.3	4.2	4.7	5.1	4.1	4.6	5.0	**97%**
98%	4.5	4.9	5.4	4.4	4.8	5.3	4.3	4.7	5.2	**98%**
99%	4.8	5.2	5.7	4.6	5.0	5.5	4.5	4.9	5.4	**99%**
99.9%	5.6	6.0	6.4	5.4	5.8	6.2	5.2	5.6	6.0	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	2.9	3.4	2.4	2.9	3.4	2.4	2.9	3.3	**50%**
60%	2.7	3.1	3.6	2.6	3.1	3.6	2.6	3.1	3.5	**60%**
70%	2.9	3.4	3.8	2.8	3.3	3.8	2.8	3.3	3.7	**70%**
80%	3.2	3.6	4.1	3.1	3.6	4.0	3.1	3.5	4.0	**80%**
85%	3.3	3.8	4.3	3.3	3.7	4.2	3.2	3.7	4.1	**85%**
90%	3.5	4.0	4.5	3.5	3.9	4.4	3.4	3.8	4.3	**90%**
95%	3.8	4.3	4.7	3.7	4.2	4.7	3.7	4.1	4.5	**95%**
96%	3.9	4.4	4.8	3.8	4.3	4.7	3.7	4.2	4.6	**96%**
97%	4.0	4.5	4.9	3.9	4.3	4.8	3.8	4.3	4.7	**97%**
98%	4.1	4.6	5.0	4.0	4.5	4.9	3.9	4.4	4.8	**98%**
99%	4.4	4.8	5.3	4.2	4.7	5.1	4.1	4.6	5.0	**99%**
99.9%	5.0	5.4	5.9	4.9	5.3	5.7	4.7	5.1	5.5	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.9	3.3	2.4	2.8	3.3	2.4	2.8	3.2	**50%**
60%	2.6	3.0	3.5	2.6	3.0	3.4	2.5	3.0	3.4	**60%**
70%	2.8	3.2	3.7	2.7	3.2	3.6	2.7	3.2	3.6	**70%**
80%	3.0	3.5	3.9	3.0	3.4	3.9	2.9	3.4	3.8	**80%**
85%	3.2	3.6	4.1	3.1	3.6	4.0	3.1	3.5	3.9	**85%**
90%	3.3	3.8	4.2	3.3	3.7	4.2	3.2	3.7	4.1	**90%**
95%	3.6	4.0	4.5	3.5	4.0	4.4	3.5	3.9	4.3	**95%**
96%	3.7	4.1	4.5	3.6	4.0	4.5	3.5	4.0	4.4	**96%**
97%	3.8	4.2	4.6	3.7	4.1	4.5	3.6	4.0	4.5	**97%**
98%	3.9	4.3	4.7	3.8	4.2	4.6	3.7	4.1	4.6	**98%**
99%	4.0	4.4	4.9	4.0	4.4	4.8	3.9	4.3	4.7	**99%**
99.9%	4.6	5.0	5.4	4.4	4.9	5.3	4.3	4.7	5.2	**99.9%**

Table A-5. Yellow clearance interval lookup table for old female drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.6	3.1	3.6	2.6	3.1	3.6	2.6	3.1	3.6	**50%**
60%	2.8	3.4	3.9	2.8	3.3	3.8	2.8	3.3	3.8	**60%**
70%	3.1	3.6	4.1	3.0	3.5	4.0	3.0	3.5	4.0	**70%**
80%	3.4	3.9	4.4	3.4	3.8	4.3	3.3	3.8	4.3	**80%**
85%	3.6	4.1	4.6	3.5	4.0	4.5	3.5	3.9	4.4	**85%**
90%	3.9	4.3	4.8	3.8	4.2	4.7	3.7	4.1	4.6	**90%**
95%	4.2	4.6	5.1	4.1	4.5	5.0	4.0	4.4	4.9	**95%**
96%	4.3	4.7	5.2	4.2	4.6	5.1	4.1	4.5	5.0	**96%**
97%	4.4	4.8	5.3	4.3	4.7	5.2	4.2	4.6	5.1	**97%**
98%	4.6	5.0	5.5	4.4	4.9	5.3	4.3	4.8	5.2	**98%**
99%	4.8	5.3	5.7	4.7	5.1	5.6	4.5	5.0	5.4	**99%**
99.9%	5.7	6.0	6.4	5.4	5.8	6.2	5.3	5.7	6.1	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.5	2.5	3.0	3.5	2.5	3.0	3.4	**50%**
60%	2.7	3.2	3.7	2.7	3.2	3.7	2.7	3.1	3.6	**60%**
70%	3.0	3.5	3.9	2.9	3.4	3.9	2.9	3.4	3.8	**70%**
80%	3.2	3.7	4.2	3.2	3.7	4.1	3.2	3.6	4.1	**80%**
85%	3.4	3.9	4.3	3.4	3.8	4.3	3.3	3.7	4.2	**85%**
90%	3.6	4.1	4.5	3.5	4.0	4.5	3.5	3.9	4.4	**90%**
95%	3.9	4.3	4.8	3.8	4.3	4.7	3.7	4.2	4.6	**95%**
96%	4.0	4.4	4.9	3.9	4.3	4.8	3.8	4.2	4.7	**96%**
97%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.3	4.8	**97%**
98%	4.2	4.6	5.1	4.1	4.5	5.0	4.0	4.4	4.9	**98%**
99%	4.4	4.8	5.3	4.3	4.7	5.2	4.2	4.6	5.1	**99%**
99.9%	5.1	5.4	5.9	4.9	5.3	5.8	4.8	5.1	5.6	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	2.9	3.4	2.5	2.9	3.4	2.5	2.9	3.3	**50%**
60%	2.7	3.1	3.6	2.6	3.1	3.5	2.6	3.1	3.5	**60%**
70%	2.9	3.3	3.8	2.8	3.3	3.7	2.8	3.2	3.7	**70%**
80%	3.1	3.6	4.0	3.1	3.5	4.0	3.0	3.5	3.9	**80%**
85%	3.3	3.7	4.1	3.2	3.6	4.1	3.2	3.6	4.0	**85%**
90%	3.4	3.9	4.3	3.4	3.8	4.2	3.3	3.7	4.2	**90%**
95%	3.7	4.1	4.5	3.6	4.0	4.5	3.5	4.0	4.4	**95%**
96%	3.7	4.2	4.6	3.7	4.1	4.5	3.6	4.0	4.5	**96%**
97%	3.8	4.3	4.7	3.8	4.2	4.6	3.7	4.1	4.5	**97%**
98%	3.9	4.4	4.8	3.9	4.3	4.7	3.8	4.2	4.6	**98%**
99%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.4	4.8	**99%**
99.9%	4.6	5.0	5.5	4.5	4.9	5.4	4.4	4.8	5.3	**99.9%**

Table A-6. Yellow clearance interval lookup table for old male drivers.

G	**-4%**			**-3%**			**-2%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.6	3.1	3.6	2.5	3.0	3.5	2.5	3.0	3.5	**50%**
60%	2.8	3.3	3.8	2.7	3.2	3.7	2.7	3.2	3.7	**60%**
70%	3.0	3.5	4.0	3.0	3.5	4.0	2.9	3.4	3.9	**70%**
80%	3.3	3.8	4.3	3.3	3.8	4.3	3.2	3.7	4.2	**80%**
85%	3.5	4.0	4.5	3.5	3.9	4.4	3.4	3.9	4.3	**85%**
90%	3.8	4.2	4.7	3.7	4.1	4.6	3.6	4.1	4.5	**90%**
95%	4.1	4.5	5.0	4.0	4.4	4.9	3.9	4.3	4.8	**95%**
96%	4.2	4.6	5.1	4.1	4.5	5.0	4.0	4.4	4.9	**96%**
97%	4.3	4.7	5.2	4.2	4.6	5.1	4.1	4.5	5.0	**97%**
98%	4.5	4.9	5.4	4.3	4.8	5.2	4.2	4.7	5.1	**98%**
99%	4.7	5.1	5.6	4.6	5.0	5.5	4.4	4.9	5.3	**99%**
99.9%	5.5	5.8	6.3	5.3	5.7	6.2	5.1	5.5	6.0	**99.9%**

G	**-1%**			**0%**			**1%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.5	3.0	3.4	2.5	2.9	3.4	2.4	2.9	3.4	**50%**
60%	2.7	3.2	3.6	2.7	3.1	3.6	2.6	3.1	3.5	**60%**
70%	2.9	3.4	3.9	2.9	3.3	3.8	2.8	3.3	3.7	**70%**
80%	3.2	3.6	4.1	3.1	3.6	4.1	3.1	3.5	4.0	**80%**
85%	3.3	3.8	4.3	3.3	3.7	4.2	3.2	3.7	4.1	**85%**
90%	3.5	4.0	4.5	3.5	3.9	4.4	3.4	3.9	4.3	**90%**
95%	3.8	4.3	4.7	3.7	4.2	4.6	3.7	4.1	4.5	**95%**
96%	3.9	4.3	4.8	3.8	4.2	4.7	3.7	4.2	4.6	**96%**
97%	4.0	4.4	4.9	3.9	4.3	4.8	3.8	4.3	4.7	**97%**
98%	4.1	4.6	5.0	4.0	4.5	4.9	3.9	4.4	4.8	**98%**
99%	4.3	4.8	5.2	4.2	4.6	5.1	4.1	4.6	5.0	**99%**
99.9%	5.0	5.3	5.8	4.8	5.2	5.6	4.6	5.1	5.5	**99.9%**

G	**2%**			**3%**			**4%**			***G***
vf (mi/h)	**35**	**45**	**55**	**35**	**45**	**55**	**35**	**45**	**55**	***vf (mi/h)***
50%	2.4	2.9	3.3	2.4	2.9	3.3	2.4	2.8	3.3	**50%**
60%	2.6	3.1	3.5	2.6	3.0	3.5	2.6	3.0	3.4	**60%**
70%	2.8	3.3	3.7	2.8	3.2	3.7	2.7	3.2	3.6	**70%**
80%	3.0	3.5	3.9	3.0	3.4	3.9	3.0	3.4	3.8	**80%**
85%	3.2	3.6	4.1	3.1	3.6	4.0	3.1	3.5	3.9	**85%**
90%	3.4	3.8	4.2	3.3	3.7	4.2	3.3	3.7	4.1	**90%**
95%	3.6	4.0	4.5	3.5	3.9	4.4	3.5	3.9	4.3	**95%**
96%	3.7	4.1	4.5	3.6	4.0	4.5	3.5	3.9	4.4	**96%**
97%	3.7	4.2	4.6	3.7	4.1	4.5	3.6	4.0	4.4	**97%**
98%	3.8	4.3	4.7	3.8	4.2	4.6	3.7	4.1	4.5	**98%**
99%	4.0	4.4	4.9	3.9	4.4	4.8	3.9	4.3	4.7	**99%**
99.9%	4.5	4.9	5.4	4.4	4.8	5.3	4.3	4.7	5.1	**99.9%**