MODELING DRIVER BEHAVIOR AT THE ON-SET OF A YELLOW PHASE TRANSITION

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16. Abstract

This report presents five research efforts that are being published in various journals. The first research effort conducts two experiments to provide partial validation for the concept of a system to warn the potential victims of red-light violators. As conceived, the warning system would entail sensors to detect approaching vehicles that are unlikely or incapable of stopping at red traffic signals. The system would then use flashing signs and lights to warn drivers on the intersection approaches that are in the green phase. Several human factors issues are identified that would need to be addressed before such a system could be deployed. The present experiments addressed one of these issues—would a sufficient number of drivers respond to such a warning in a way that would avoid collision with a red-light violator? The results suggest that the majority of drivers will brake sharply in response to a conspicuous warning, at least for the case where no other vehicles are preceding or following the potential victim. Comparisons between field test and driving simulator response measures are discussed, as are the implications for further research.

The second effort characterizes driver behavior at the onset of a yellow-phase transition on high-speed signalized intersection approaches using field data gathered from 60 test subjects (approximately balanced in gender and age). The driver stopping/running decisions are analyzed for five trigger distances, measured from the vehicle position to the stop bar when the yellow phase starts, as drivers approach the intersection at a speed of 72 km/h (45 mi/h). The study demonstrates that the probability of stopping varies from 9 percent at a time to intersection of 1.6 s to approximately 100 percent at a time to intersection of 5.5 s. The study also demonstrates an increase in the probability of running for male drivers when compared to female drivers. This difference increases as the trigger distance decreases. Furthermore, the study demonstrates that drivers 65 years of age and older are significantly less likely to clear the intersection at short yellow-phase trigger distances when compared to other age groups. The dilemma zone for the less than 40 year age group is found to range from 1.85 to 3.9 s while the dilemma zone for the greater than 70 year age group is found to range from 1.5 to 3.2 s. Dilemma zone boundaries (distances where 10 to 90 percent of the vehicles stop) are derived and uncertainty zones for different age groups are also developed.

The third effort used the field data to characterize driver brake perception-reaction times at the onset of an amber phase actuation at a high-speed signalized intersection approach. The study demonstrates that the 1.0 s, 85th percentile perception-reaction time that is recommended in traffic signal design procedures is valid and consistent with field observations. Furthermore, the study demonstrates that brake perception-reaction times are impacted by the vehicle’s time-to-intersection at the onset of a phase transition. Consequently, the study recommends that time-to-intersection in the range of 2.2 to 4.4 s be considered in the characterization of brake perception-reaction time behavior. Finally, the study demonstrates that either a lognormal or beta distribution is sufficient for modeling brake perception-reaction time.
The fourth effort characterizes driver stopping behavior at the onset of a yellow-phase on high-speed signalized intersection approaches using controlled field data gathered from 60 test subjects using an in-vehicle Differential Global Positioning System (DGPS). A total of 745 data records were available for analysis for all drivers who stopped at the onset of the yellow-phase, ranging from a minimum time to the stop bar (TTS) of 1.34 s to a maximum of 6.19 s. Statistical analyses were used to investigate the effects of the time to stop bar, grade (uphill and downhill), age (under 40-years-old, 40 to 59-years-old, and 60 years of age or older), and gender on seven dependent measures of driver performance including perception time, reaction time, perception-reaction time, braking time, stopping time, and stopping accuracy. The study demonstrates that driver perception time is not impacted by TTS while reaction time is dependent on TTS, roadway grade, and driver age. Younger drivers have longer reaction times in comparison to the older group but they are able to stop over a shorter period of time as they typically apply more aggressive braking rates. A lower perception-reaction time was found for drivers who have their foot lifted off the accelerator at the onset of the yellow-phase. Male drivers show slightly higher braking times when compared to female drivers with no significant differences between male and female drivers. Furthermore, the results demonstrate that drivers who try to stop at short TTSs are more likely to stop downstream of the stop line and that older drivers are significantly more accurate when they stopped compared to other age groups.

The fifth effort used the field data to develop models that characterize driver brake perception-reaction times, brake times, and stop-go decisions at the onset of a yellow indication at a high-speed signalized intersection approach. The study demonstrates that driver perception-reaction times (PRTs) are only influenced by the driver’s time-to-intersection (TTI) at the onset of the yellow indication. The driver PRT is found to increase linearly with TTI and is not impacted by the vehicle speed (in the range of 54 to 88 km/h), driver gender, or driver age. In the case of stop-go behavior, the older driver (≥ 65 years of age) dilemma zone is wider, ranging from a TTI of 4.81 to 1.66 s versus 4.90 to 2.87 s for the younger age group. Female drivers are more likely to stop when compared to male drivers and tend to have a dilemma zone that is closer to the intersection. Finally, the study demonstrates that dilemma zone control systems should consider a dilemma zone from 5.0 to 1.5 s instead of the current state of practice of 5.5 to 2.5 s in order to capture all potential driver age and gender groups.

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Field and Driving Simulator Validations of System for Warning Potential Victims of Red-Light Violators

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INTRODUCTION

The studies reported here were intended to contribute to the development of an infrastructure-based countermeasure to straight crossing-path (SCP) crashes at signalized intersections. These crashes result when a vehicle violates a red light and collides with a vehicle that has the right-of-way. Zimmerman and Bonneson (report that the median time into the red phase of the violations that result in collisions is about 9 s. They suggest that the majority of these collisions occur after the queue has cleared on the approach that has the green. In this situation, both the signal violator and victim are likely to be traveling close to free-flow speed. Thus, the consequences of such collisions can be serious. In the United States, about 1,000 fatalities and 100,000 injuries result each year from crashes that involve red-light violations (Ferlis described an infrastructure-based intelligent transportation system countermeasure for SCP crashes at signalized intersections. In his analysis, Ferlis estimated that, where deployed, an infrastructure based warning to both the violator and victim might reduce SCP collisions by as much as 88 percent. This estimate was based on the assumption that 80 percent of violators would respond to a timely warning, and that 40 percent of potential victims could be warned and that all would respond appropriately. Of course, not all drivers might respond to a timely warning. Nevertheless, if a system could detect 80 percent of all dangerous violations, and then warn both the violator and a potential victim, a substantial proportion of collisions might be avoided. For instance, if only 40 percent of violators and 90 percent of victims responded appropriately, then 94 percent of collisions would be prevented. The present research examined how the potential victims of these crashes might react to a countermeasure such as that described by Ferlis.

The Victim Warning Concept

The countermeasure examined in this report would use sensors to detect the speed of vehicles approaching a red traffic signal, a processor and algorithm to compute the likelihood that these vehicles will stop, and infrastructure-based lights and/or changeable message signs to warn both the potential violator and victim. The first of two studies reported here examined three alternative victim-warning configurations and a control condition. The most effective warning in the first study, which was conducted in a driving simulator, employed flashing red beacons on either side of a conventional signal head, white strobe lights mounted on an illuminated stop-sign symbol, red in-roadway light emitting diode (LED) markers, and intelligent rumble-strips to
alert the potential victim. The second of two studies reported here tested the combination of flashing red beacons, a changeable message sign, and strobes in a closed-road field experiment. Intelligent rumble strips do not yet exist and thus could not be field tested. In-roadway LED markers are available, but it was not feasible to install them for the field study. Nonetheless, the configuration tested in the field was only 6 percent less effective in the simulation than the most effective configuration, and that 6 percent difference was not statistically significant. Thus, the field-tested warning was a viable candidate for evaluation.

For an infrastructure-based red-light violation system to be effective, several conditions must be fulfilled. Among these, a warning that clearly communicates the required response must be deployed and a substantial proportion of drivers must be willing to make that response. The probability of response was the only condition for success evaluated in this study. Other conditions include the development of a highly sensitive violator detection system that has a very low false alarm rate, and demonstration that the system would not induce more crashes than it prevents. The studies reported here did not address the latter very important conditions, but rather assumed that they are achievable. If a substantial proportion of drivers will not respond to such a warning, the assumptions are moot.

Validation Approach

Red-light violators can only be detected reliably when they are relatively close to an intersection. It has been suggested that a violator who approaches an intersection at 35 mi/h (56 km/h) could be detected at about 141 ft (43 m) from an intersection (3). Warnings to potential victims would come no earlier than the detection of potential violators, with the implication that the potential victim might be relatively committed to entering the intersection by the time a warning could be given. Thus, it is likely that a relatively compelling warning would be required. To ensure a rapid response, the meaning of the warning would need to be immediately comprehended. The simulator study tested potential warnings. The field study examined whether the responses obtained in the simulation could reasonably be expected outside of the simulation laboratory.

METHODS

Driving Simulator Study

The simplest driver infrastructure interface that was simulated was a shortened amber phase. In the first of the four conditions that were tested, the signal changed from green to amber, and then after 0.5 s, it changed to red. Such a driver interface would require no new infrastructure, but would be distinguishable from a normal phase change only by the duration of the amber. This would have the advantage of low installation cost, but might not be compelling enough to induce most drivers to respond, given that if the amber were of normal duration, drivers could expect to clear the intersection before the onset of the red.

The second condition was to immediately change the signal from green to red (no amber), and to supplement the red signal lenses with additional signs and lights on the signal mast arm. This simulated alternative is depicted in Figure 1. Red lenses on either side of the normal red lens alternated at 1 hertz (Hz). A variable message sign was scaled to 4 ft on a side. When active, it displayed a red hexagonal stop symbol and strobe lights in the lower corners alternated at 2 Hz.
A third condition included the mast arm treatment of the second condition, but added intelligent rumble strips and simulated red LEDs in the roadway. The intelligent rumble strip concept consists of rumble strips, placed laterally across the roadway, which are deployed only when a warning is warranted, and are undetectable otherwise. The intelligent rumble strips were simulated by activating a 0.75 in (1.9 cm) vertical heave of the driving simulator motion base at 4 Hz for a duration of 1 s. The LEDs were placed every 20 ft (6 m) along both left and right lane markings and every 24 in (60 cm) across the intersection stop bar. All warnings were triggered when the potential victim was 180 ft (55 m) from the intersection.

The fourth condition was included as a control. It comprised a 4-second amber phase that was triggered when participants were 180 ft (55 m) from the intersection. This condition was included to verify the assumption that 180 ft (55 m) was beyond the dilemma zone (the point at which drivers would not stop in response to amber onset) at the instructed travel speed of 45 mi/h (72 km/h).

The Federal Highway Administration (FHWA) Highway Driving Simulator that was used for this experiment had an interactive 3 degree-of-freedom motion-based system and an 88 degree horizontal field of view. Each simulation session took approximately 27 minutes.

Participants were told that the experiment was an evaluation of signal phase timing. They were not told that an emergency warning would be presented, or that the research concerned red-light running. The instructions were to drive straight on the current road and obey all traffic laws. The posted speed was 45 mi/h (72 km/hr). Participants were asked to maintain that speed when not responding to the traffic signals. Participants were reminded via a loud speaker to “watch your speed” when they exceeded 50 mi/h (73 km/hr) or when they were below 40 mi/h (59 km/hr). The simulated road was an 0.8 mi (1.3 km) segment of a straight and level two-lane rural road. At intersections, the road widened to include a dedicated left turn lane. The same intersection appeared at the end of each segment. Figure 2 shows the intersection as it appeared when the warning that included in-roadway lights were active. The first 32 intersection signals that participants drove through were timed such that a green signal would be expected at the 33rd intersection. The intended expectation was violated by the activation of one of the four experimental conditions. Before arrival at the 33rd intersection, participants encountered only three red signals that required that they stop or slow, and none of those three phase changes occurred when the participants were within 300 ft (91 m) of the stop bar.
The dependent measures were throttle release latency, brake response time, and whether the warning delayed arrival at the intersection by at least 1 s.

Participants
Because FHWA considers older drivers to be an important vulnerable population, that group was oversampled. Thus, two age groups were represented: an older group, range 66 to 87 years of age, mean = 74, and a group to represent the rest of the driver population, range 18 to 65 years of age, mean = 46. This later group is hereafter referred to as the young/middle group. The samples of four experimental conditions were approximately balanced for both age group and gender. Useable data were obtained from 202 of 214 participants. Twelve participants failed to complete the experiment because of simulator sickness symptoms.

Field Experiment
The field experiment, which was conducted on the Virginia Tech Smart Road, implemented the same mast arm warning that was used in the simulator. This implementation is shown in Figure 3. As configured, the Smart Road was a two-lane road with one signalized intersection. Participants drove a 1 mi (1.6 km) approach to the intersection followed by a 0.3 mi (0.5 km) leg to a high-speed turnaround and another 0.3 mi (0.5 km) approach. The Smart Road has a three percent grade. Because participants turned around at the end of each run, half the trials were on a three percent upgrade and half were on a three percent downgrade. The vehicle used was a 2004 Chevrolet Impala. Instrumentation on the vehicle included a differential global positioning system receiver, a longitudinal accelerometer, and sensors for accelerator position and brake pressure. The data recording equipment in the vehicle had a communications link to the traffic
signal control box. That link synchronized the vehicle data stream with changes in the traffic signal controller. Accelerator and brake position were recorded at 100 Hz. All other sensor and vehicle data were recorded at 10 Hz.

As in the simulation study, participants were told that the experiment was an evaluation of signal phase timing. They were not told that an emergency warning would be presented, or that the research concerned red light running. They were instructed to maintain 45 mi/h (66 km/h) except when turning around or responding to the traffic signal. They traveled through the intersection 24 times, 12 times in each direction, before the violator collision warning was issued on the 25th approach.

There were two important procedural differences between the simulation and the field study. First, in the field study there were frequent amber-phase onsets when the vehicle was close to the intersection. There were four trials each with a 4-second amber-phase triggered at approach distances of 105 ft (32 m), 180 ft (55 m), 215 ft (66 m), 290 ft (88 m), and 365 ft (111 m). On four approaches, the signal remained green. The order of phase-change distances was randomized for each participant, except that the emergency warning was always triggered on the 25th trial. There were two trials at each trigger distance on the upgrade and two on the downgrade.

The second important difference was that the emergency warning was triggered at two distances: half of the participants received the warning at 105 ft (32 m), and half at 180 ft (55 m) from the stop bar. The warning always occurred on the upgrade.

The inclusion of many approaches with phase changes close to the intersection was to clarify the location of the dilemma zone. The addition of the shorter emergency warning distance was to determine if responses to the warning would vary with distance from the intersection.

Participants
Participants were licensed drivers recruited from the Virginia Tech Transportation Institute participant database, word-of-mouth, and through ads in a local Blacksburg, Virginia newspaper.
The drivers were randomly assigned to warning distance groups with the constraint that there be roughly equal numbers of young/middle and older males and females in each group. The young/middle group consisted of 32 persons with a mean age of 40 years and a range of 20 to 64 years. The older group had a mean age of 71 years, with a range of 65 to 82 years.

RESULTS

Proportion of Drivers Slowing or Stopping for the Emergency Warning in the Simulator

In the simulation experiment, drivers were classified as responding as desired to the warnings if they were delayed in reaching the stop bar by a least 1 s relative to the time they would have arrived if they had continued at their current speed. This criterion was to allow for drivers who do not stop in response to the warning, but do slow sufficiently to allow a hypothetical violator to clear the collision zone. Only two drivers who met the 1-second criterion were traveling more than 10 mi/h (16 km/h) when they reached the stop bar, and none were traveling more than 15 mi/h (24 km/h). The proportion of drivers in each condition who met the 1-second delay criterion is shown in Table 1.

TABLE 1  Simulation Results Based on Whether Participant Was Delayed by 1 S or More Based on Speed at the Beginning of the Event.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Delayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Control (4 s Amber)</td>
<td>31%</td>
</tr>
<tr>
<td>2. ½ s Amber</td>
<td>49%</td>
</tr>
<tr>
<td>3. Flashing Lamps and Sign</td>
<td>61%</td>
</tr>
<tr>
<td>4. Added Rumble Strips and In-Road Lights</td>
<td>67%</td>
</tr>
</tbody>
</table>

Proportion of Drivers Stopping for the Amber Signal in the Field Experiment

The 180 ft (55 m) trigger distance was chosen because previous research (5) had suggested that distance to be beyond the dilemma zone. The finding that nearly a third of participants stopped for the 4-second amber-phase raised concern about the validity of the simulation. This concern was alleviated by the field experiment result that showed 55 percent of participants stopped for the 4-second amber-phase that was triggered at 180 ft (55 m). Participants in the field study were more likely to stop for the 4-second amber-phase than participants in the simulator, \( \chi^2 (1) = 21.4, p < 0.01 \). This finding suggests that 180 ft (55 m) is not beyond the dilemma zone when travel speed is 45 mi/h (72 km/h). The proportion of field study approaches in which field study participants stopped for the 4-second amber signal is shown in Table 2 as a function of the amber trigger distance. Recall that in the simulation, the 4-second amber occurred only once, at the last intersection. In the field, the 4-second amber-phase was not given on the final trial, but occurred four times at each trigger distance. Thus, the 4-second amber-phase was a true control condition for the emergency warnings in the simulator, but may not be comparable to the warning conditions in the field experiment.
TABLE 2  Field Experiment Driver Responses to 4-Second Amber Signal as a Function of Trigger Distance.

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Proportion of Trials in which Driver Stopped</th>
</tr>
</thead>
<tbody>
<tr>
<td>105</td>
<td>0.03</td>
</tr>
<tr>
<td>180</td>
<td>0.55</td>
</tr>
<tr>
<td>215</td>
<td>0.81</td>
</tr>
<tr>
<td>290</td>
<td>0.95</td>
</tr>
<tr>
<td>365</td>
<td>1.00</td>
</tr>
</tbody>
</table>

1 ft = 0.305 m

Proportion of Drivers Stopping for the Emergency Warning in the Field Experiment

In the field experiment, when the violator warning was triggered at 180 ft (55 m), 27 of the 30 participants (90 percent) stopped. By comparison, in the simulator study, 64 percent of drivers in the two conditions that included an immediate red warning at 180 ft stopped, or were delayed by 1 s or more. In the field, when the warning was triggered at 105 ft, one participant (3 percent) stopped. From either warning trigger distance, none of those who stopped went more than 17 ft (5.2 m) beyond the stop bar. Based on velocity when the warning was triggered, none of the field test drivers who did not stop in the warning conditions was delayed in reaching the stop bar by 1 s or more.

Throttle Release Response Time

Throttle release response time, which is sometimes referred to as perception time (6), was calculated from the first decrease in throttle position that followed the onset of the phase change and continued to zero throttle. Figure 4 shows throttle response time to onset of the 4-second amber-phase from both studies. As only 3 out of 60 drivers stopped for a 4-second amber-phase when its onset came when the vehicle was 105 ft (32 m) from the stop bar, the 4-second amber-phase condition is omitted from the figure. The field-study data are means of the means of drivers that stopped at least once at the given distance. The number of drivers who contributed to each data point ranged from 17 to 30. In the simulator study, 27 of 50 drivers showed measurable throttle responses to the 4-second amber-phase; the only amber signal that they encountered at 180 ft. The error bars in the figure represent two standard errors of the mean. Thus, assuming equal variance, means that fall outside the error bars of another mean are significantly different \( p < 0.05 \) from that mean. In the field, throttle response times on either approach (i.e., on upgrade or downgrade) were about the same, except for the longer approach distances, where drivers may have delayed throttle release on the upgrade. Simulator mean throttle release response time was nearly twice as long as that from the field.
1 ft = 0.305 m

FIGURE 4  Mean throttle response time to onset of 4 s amber as a function of distance to the stop bar.

Figure 5 shows the throttle response times to the violator collision warning. Throttle response times were not available for all participants because some did not slow for the warning, and others did not have the throttle depressed when the signal changed. In the field, 16 participants provided throttle response times to the warning that was triggered at 180 ft, and their mean response time was not distinguishable from those given to the amber signal. Measurable throttle response times to the 105 ft (32-m) warning were obtained from 18 participants. These response times were not significantly different from the throttle response times to the 180 ft (55 m) warning configuration in the driving simulation but were significantly faster than the response times to the 180 ft (55m) warning that were observed in the field.
FIGURE 5 Mean throttle response times to the red-light violation warning in the field and simulator studies.

**Brake Application Response Time**

Brake response time was calculated as the time between the onset of the phase change and the beginning of a brake application. Brake response time includes throttle release response time, and is frequently referred to as perception-reaction time (6).

Brake response times to the 4-second amber-phase are shown in Figure 6. A brake response time was recorded whether or not the driver eventually stopped. Thus, the times shown in Figure 6 include responses from drivers who initially braked and then accelerated. As grade had no effect on response time, except at the longest phase-change-onset distance, the data shown in the figure include stops from both approaches. Only 22 participants contributed to the 105 ft (32 m) trigger distance mean, and 26, 59, 60 and 60 drivers contributed, respectively, at the 180-, 215-, 290-, and 365-ft (55-, 66-, 88-, and 111-m) trigger distances. In the simulator, where the 4-second amber-phase served as a control condition, 26 of 48 participants braked for the amber, and are thus represented in Figure 6.
FIGURE 6 Mean brake response times to the onset of the 4 s amber shown as a function of study and phase change trigger distance.

Figure 7 shows the mean brake response times to the onset of the collision warning in the two studies. The simulator data include response times from the two mast arm conditions, as these did not differ significantly from each other ($t(73) = 1.7, p > 0.10$). For the 180 ft (55 m) onset, brake response time from the field experiment was significantly less than in the simulator, $t(96) = 10.5, p < 0.001$. The responses to 105 ft (32 m) onset in the field were significantly longer than the 180 ft field condition, $t(32) = 3.9, p < 0.05$, and significantly less than the 180 ft simulator warning $t(40) = 3.3, p < 0.05$. (6)
FIGURE 7  Mean brake response times for all drivers who applied the brake and stopped following onset of the signal violation red-light warning.

Maximum Deceleration

the simulator study, participants who were delayed in reaching the stop bar by at least one second had a mean maximum deceleration of -0.77 g. In the field, the average maximum deceleration for the 27 participants who stopped for the warning that was triggered at 180 ft was -0.67 g. In neither study did deceleration force vary as a function of age category or gender. Although the difference in mean maximum deceleration between the simulator and the field is statistically reliable ($p < 0.05$), it is small, and probably resulted because participants in the simulator appeared to have difficulty judging distance from the stop bar, and thus often stopped well short of the stop bar. In the field, drivers uniformly stopped within a few feet of the stop bar.

DISCUSSION

The purpose of the simulation and field studies was to evaluate the feasibility of warning the potential victims of red-light runners that they need to slow or stop to avoid a collision. In the simulation, participants drove the only vehicle on the simulated roadway, and experienced a series of 29 green lights and 3 red lights that changed long before a decision to decelerate was needed. These scenarios were intended to induce drivers to expect a green signal when the collision warning was issued. Given that their accelerator release and brake application response times were comparable to the surprise response times reported by Olson and Sivik (7) it appears that the participants were surprised by the warning, which had not been explained beforehand.
The main question in the simulator study was whether drivers would respond as desired to an unfamiliar warning, and for a majority the answer was “yes”.

The results of the simulator study suggested that the majority of drivers might respond appropriately to an unexpected and unfamiliar warning, if that warning was sufficiently conspicuous and distinct from a normal phase change. Although the simulator results were encouraging for further exploration of the warn-the-victim concept, many questions remained. Because the decelerations observed in the simulation were quite severe, one of those questions was whether drivers of actual vehicles would be willing to decelerate as severely to such a warning. To address this question, one of the simulation conditions was replicated in a field experiment. The results of that field experiment largely validated the simulation and the warning-the-victim concept. Participants in the field study braked nearly as hard as those in the simulation had braked. The small 0.1 g difference between the studies was largely attributable to the field study participants’ superior ability to modulate their approach to the stop bar, presumably because of the better distance cues in the real world environment.

One concern for use of infrastructure to warn potential victims of red-light violators is that drivers, who are close enough to the intersection to pass through before the violator arrives, might be slowed by the warning and then become a victim because of the warning. This concern has led to the suggestion that the warning be designed to be visible only to the drivers who need to be warned (3). However, in the field study, only one driver who received the warning at 105 ft slowed more than would be expected without a warning, and she stopped short of the stop bar. Of the remaining 29 drivers, 85 percent were delayed by less than 150 ms, and none was delayed more than 312 ms, relative to their velocity at warning onset.

A greater proportion of drivers stopped for the warning in the field experiment than did in the simulator experiment; 64 percent stopped in the simulator in the conditions that included an immediate red phase, and 90 percent stopped in the field. The available evidence does not indicate which of these percentages is closer to what might be expected in an operational environment. However, there are some clues in the data. The reaction time means from the field experiment are close to those Olson and Sivak reported for anticipated stimuli (7), whereas the response times in the simulator were close to those investigators reported to a surprise object on the roadway. This suggests that the events that led up to the emergency warning led participants in the field study to anticipate a stopping response, albeit to an amber signal, not a violator warning. Before the violator warning, participants had driven through the intersection 24 times, and had been presented with an amber phase change 20 times, 4 times at each of five trigger distances. Thus, although it is unlikely that field-study participants anticipated the violator warning, they may well have anticipated an amber phase change, and many had stopped for amber onsets at the 180- and 215-ft (55- and 66-m) trigger distances. This anticipation does not invalidate the field experiment findings, but it does suggest that with pre-warning procedures more similar to those used in the simulator, the field experiment findings may have been more similar to the simulator findings. That is, in this case the simulator throttle and brake response times are probably closer to the surprise response times that would obtain with a deployed system, given that actual warnings events would be rare. If this surmise is correct, then perhaps the proportion of drivers who respond to a surprise warning will also be closer to the simulator result of 64 percent, than to the field result of 90 percent.

CONCLUSIONS AND RECOMMENDATIONS

Together, the results of the two studies suggest that a majority of drivers may respond appropriately, by stopping or slowing, for an intersection collision warning that they have not
experienced before. However, many questions remain. In both studies, no other vehicles were on the roadway. It is not clear whether similar responses would have obtained if there had been following vehicles. It is also not clear whether following drivers in a platoon would respond in time to avoid a rear-end collision with leading vehicles that brake for the warning. Although any rear-end collision that might result would be likely to be less severe than a side-impact collision with a red-light violator, further development of the warn-the-victim concept includes a need to examine and quantify the potential for rear-end collisions that may result from signal violation warnings.

Another factor that might influence drivers’ response to the warning is whether lead vehicles in a platoon that proceed through an intersection, perhaps because they are too close to stop, may influence following drivers, who should stop, to also proceed. Additional research is needed to evaluate the effect of leading driver responses on following drivers.

The present research assumed that a reliable violator detection system is feasible and that such a system would have a false alarm rate that approaches zero. It did not address how drivers would react after observing false warnings from such a system. It also did not address secondary effects such a system might have on potential red-light violators if they know intersecting traffic would be warned, nor did it address how such a secondary effect might be mitigated. However, the present results do suggest these unaddressed issues are worthy of exploration.

REFERENCES

Age and Gender Impact on Driver Behavior at the Onset of a Yellow Phase on High-Speed Signalized Intersection Approaches

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ABSTRACT

The paper characterizes driver behavior at the onset of a yellow-phase transition on high-speed signalized intersection approaches using field data gathered from 60 test subjects (approximately balanced in gender and age). The driver stopping/running decisions are analyzed for five trigger distances, measured from the vehicle position to the stop bar when the yellow phase starts, as drivers approach the intersection at a speed of 72 km/h (45 mi/h). The study demonstrates that the probability of stopping varies from 9 percent at a time to intersection of 1.6 s to approximately 100 percent at a time to intersection of 5.5 s. The study also demonstrates an increase in the probability of running for male drivers when compared to female drivers. This difference increases as the trigger distance decreases. Furthermore, the study demonstrates that drivers 65 years of age and older are significantly less likely to clear the intersection at short yellow-phase trigger distances when compared to other age groups. The dilemma zone for the less than 40 year age group is found to range from 1.85 to 3.9 s while the dilemma zone for the greater than 70 year age group is found to range from 1.5 to 3.2 s. Dilemma zone boundaries (distances where 10 to 90 percent of the vehicles stop) are derived and uncertainty zones for different age groups are also developed.

INTRODUCTION

The yellow signal interval is designed to warn approaching drivers of an impending loss of right-of-way for the traffic crossing a signalized intersection in the previous green signal phase. When a yellow phase is triggered, the driver decides whether to stop safely or to proceed through the intersection before the end of the yellow interval. Incorrect driver decisions may result in either a rear-end collision, if the driver fails to come to a safe stop, or a straight crossing-path crash, if the driver does not have enough time to safely cross the intersection before the conflicting flow is released.

The dilemma zone problem has been examined in the literature since its initial formulation by Gazis et al. (1), that observed the existence of dilemma zones at approaches to signalized intersections and developed the first dilemma zone model, as a binary decision problem to either stop or proceed when a yellow indication is triggered. However, an analysis of the literature demonstrates a lack of consensus in defining the dilemma zone. For example, Sheffi and Mahmassani (2) define a dilemma zone “as that zone within which the driver can neither come to a safe stop nor proceed through the intersection before the end of the yellow phase”. This definition represents the design definition of a dilemma zone. Senders (3) demonstrated for a specific signalized intersection that a design dilemma zone existed in which a driver traveling at the speed limit had no feasible option and would have to break the law. Alternatively, Zegeer (4) defines the dilemma zone from a driver’s perspective as the zone in which between 10 to 90 percent of the drivers stop. Sheffi and Mahmassani (2) summarize the approach to modeling this problem as “developing dilemma zone curves of ‘percent drivers stopping’ versus ‘distance from stop bar’ at the instant when the signal indication changes from green to yellow” and that the driver behavior at high speed signalized intersections when faced with a yellow indication can be viewed as a binary choice process, where the relevant decisions are either to stop or proceed through the intersection. Research has shown that dilemma zone protection can help reduce crashes at high speed signalized intersections. For example, Parsonson (5) developed detector-controller solutions for the dilemma zone problem at high speed signalized approaches by establishing option zone boundaries within the range of 10 to 90 percent probability of stopping for various speeds.
Driver behavior on high-speed signalized intersection approaches in response to yellow phasing has been studied for many years. For example, Shinar and Compton (6) observed the aggressive driving behavior of more than 2000 drivers over a total of 72 hours in the immediate proximity of an intersection or an interchange at six different sites with posted speed limits ranging from 70 to 80 km/h (43 to 50 mi/h). The study concluded that aggressive driving is associated with both situational variables and individual characteristics, men were more aggressive than women, young drivers (less than 45-years-old) were more aggressive than older drivers, and the presence of passengers was associated with lower rates of aggressive driving. The performance of 77 participants (older and younger drivers) while approaching signalized intersections at 70 km/h (43 mi/h) when traffic signals changed from green to yellow was measured by Caird et al. (7) in Calgary, Canada using a moderate-fidelity driving simulator. They found that older drivers (55 years of age and older) were significantly less likely to stop than those in the younger age groups at the longest time to stop-line and those older drivers who chose to go through the yellow light were more likely to be in the intersection when the light changed to red. Another study by Hicks et al. (8) at nine intersections in Maryland found that driver stopping/passing behavior and vehicle speed performance in response to a yellow-light interval were affected by multiple factors. Driver’s gender, age, and the use of cellular phones were found to be significant human factors affecting driver behavior and vehicle speed at intersections during yellow intervals. The study also concluded that the initial position of a vehicle when a yellow-light phase is displayed significantly affects drivers’ stopping/passing behavior.

This study is unique because it combines several aspects, as follows: (a) All previous studies have either been conducted in a driving simulator or gathered from the field by randomly recording driver behavior. Alternatively, this study was a controlled field study and there were no surrounding vehicles and thus driver behavior could be isolated without considering its interaction with surrounding traffic (e.g. lead or following vehicles). (b) Detailed driver information was available and the driver pool was constructed to achieve the desired driver breakdown. (c) The vehicles were equipped with a differential GPS and a Data Acquisition System (DAS), which allowed for the gathering of deci-second vehicle and brake pedal information. (d) The communication between the vehicle and traffic signal ensured that the yellow time was started when the vehicle was at pre-selected distances from the intersection and thus direct comparisons could be made and statistical tests could be conducted.

Previous studies did not conduct a systematic field controlled evaluation. The research presented in this paper attempts to address this need by conducting a controlled field evaluation of driver stop/go decision making behavior at the onset of yellow-phase transitions as a function of the vehicle’s distance from the stop bar and the driver characteristics (gender and age).

**Dilemma versus Option Zone**

A driver’s approach speed and distance from a signalized intersection at the onset of a yellow-phase indication affect his/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 (2). 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 perception-reaction time; and an acceptable
deceleration rate, is defined as the distance required for a vehicle to come to a complete stop upstream of the intersection stop bar by considering the braking, aerodynamic, rolling, and grade resistance forces as

\[ d_s = v \times t + \frac{gW}{2k_a} \ln \frac{\dot{v}}{\ddot{v}} + \frac{k_a v^2}{h_b m W + f_r W + W G} \]  

(1)

where \( d_s \) is the distance required for a vehicle to stop at the stop bar (m), \( v \) is the speed of the approaching vehicle (m/s), \( t \) is the driver perception-reaction time (s), \( \gamma_b \) 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 \((k_a = \rho / 2 C_D A_f)\) where \( \rho \) is the air density kg/m\(^3\), \( C_D \) is the drag coefficient, and \( A_f \) is the vehicle’s frontal area (m\(^2\)), \( \eta_b \) is the braking efficiency, \( \mu \) is the coefficient of roadway adhesion, \( f_r \) is the rolling coefficient \((f_r \approx 0.01(1 + v/44.73))\), and \( G \) is the roadway grade (decimal).

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

\[ d_s = v \times t + \frac{v^2}{2g(h_b m + G)} \]  

(2)

Equation (2) is typically used in the literature to compute a vehicle’s stopping distance.

A vehicle that is closer than \( d_s \) from the stop bar when the yellow is displayed will not have sufficient distance to decelerate to a stop before reaching the stop bar. 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 as

\[ d_r = v \times y \]  

(3)

where, \( d_r \) is distance required for a vehicle traveling at the approach speed \( v \) to reach the stop bar (m) and \( y \) is the duration of the yellow interval (s).

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 8 illustrates the definition of option and dilemma zones which 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.
Drivers are typically indecisive within the option zone and thus respond differently during the signal change interval. A driver approaching a signalized intersection while the traffic signal changes from green to yellow has two alternatives, either to stop at the intersection or to continue to clear the intersection before the signal turns red. A driver in such a situation is experiencing a state of uncertainty and anxiety because he/she has to evaluate many parameters before taking his/her final decision. An equation to measure the degree of uncertainty to help characterize the difficulty of choosing between different alternatives in a choice situation was proposed by Yager (9) as

$$A = 1 - \frac{\int_{0}^{a_{\text{max}}}{\frac{1}{A_{a}}}}{\int_{0}^{\infty}{\frac{1}{A_{a}}}}$$

where, $A$ is the degree of uncertainty (anxiety measure) and $A_{a}$ is the number of alternatives whose probability are greater than $a$.

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

In the case of only a two-choice situation, such as our case “stopping” or “running,” equation (4) for the measurement of uncertainty, as introduced by Kikuchi et al. (10) and Yager and Kikuchi (11), is reduced to

$$A = 1 - \max(P_{s}, P_{r}) + \frac{1}{2}\min(P_{s}, P_{r})$$

where, $P_{s}$ is the probability of stopping and $P_{r}$ is the probability of running.

The uncertainty measure is equal to 0 when one of the two probabilities is equal to one and the other is zero, and is equal to 0.75 when the value of the two probabilities are both equal to 0.5. This means that uncertainty is lowest when the probability of only one action is fully supported while the other is not, and is highest when the probability of the two conflicting actions are equal, indicating that either action is equally possible and only one has to be chosen.
EXPERIMENTAL DESIGN
The design of the field test effort involved selecting a test vehicle, the test roadway, and test subjects.

Test Vehicle
A 2004 Chevrolet Impala (FIGURE 9) was used for the intersection test bed. The instrumented vehicle was equipped with additional equipment that included a differential Global Positioning System (GPS), 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 the Virginia Tech Transportation Institute (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 9).

Roadway Layout
The Virginia Department of Transportation (VDOT) owned Virginia Smart Road at VTTI was the site of the field test. The Smart Road in Southwest Virginia 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 9) 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.

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) of the Smart Road test facility. 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 percent. The details of how the vertical profile was generated are described by Rakha et al. (12). 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.

Participants

Participants were licensed drivers recruited from the VTTI participant database, word-of-mouth, posters, and through ads in local Blacksburg (VA) newspaper. Volunteers were paid $20 per hour for a 1 to 1.5 hour session. Participants were screened through a verbal questionnaire to determine if they were licensed drivers and if they had any health concerns that would exclude them from participating in the study. Sixty drivers were recruited in two age groups, 32 of whom were under 65-years-old and the other 28 were 65 years of age or older, equal numbers of males and females were assigned to each group. The younger group consisted of 32 persons under 65-years-old with a mean age of 40 and a range of 20- to 64-years-old. The older group was 65 or older and had a mean age of 71, ranging between 65- to 82-years-old. A detailed demographic breakdown of the participants is shown in TABLE 3.

<table>
<thead>
<tr>
<th>Age</th>
<th>Group 1 (younger)</th>
<th>Group 2 (older)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age &lt; 40</td>
<td>7</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>40 ≤ Age &lt; 65</td>
<td>9</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>65 ≤ Age &lt; 70</td>
<td>8</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Age ≥ 70</td>
<td>6</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>32 (53.3%)</strong></td>
<td><strong>28 (46.7%)</strong></td>
<td><strong>60 (100%)</strong></td>
</tr>
</tbody>
</table>

Procedures

The test participants drove the entire 2.6 km (1.6 miles) test course 12 times in each direction (excluding practice runs) for a total of 24 trials. During these 24 trials the participants received a total of four green indications and 20 yellow indications that were displayed at five different distances from the stop bar (four repetitions for each distance). Each yellow-phase was triggered at five distances via a wireless communication between the test vehicle and the traffic signal controller. The distance from the signal stop bar was estimated based on the DGPS position location (accuracy of 1.5 cm). Testing was only conducted in clear weather during the daylight hours when the road was dry, ice free, and free of debris.

Upon arrival at VTTI, each participant was asked to review and sign an informed consent form. A vision test (visual acuity and color vision) was administered to each participant and only participants who had a minimum of 20/40 vision and passed the color vision test were allowed to continue with the experiment. In addition, each participant was asked to complete a medical questionnaire to verify that he/she was not under the influence of any drugs or alcohol and did not have medical conditions that would impair his/her ability to drive. Subsequently, the participant was escorted to the test vehicle. After familiarizing themselves with the test vehicle (e.g. adjusting mirrors, seat, fastening seat belts), each participant drove to the Smart Road (about a 0.5 km drive) while the experimenter read the instructions and answered any questions the test participant had. Before the first trial, the participant drove down the Smart Road to the turnaround at the other end of the test facility (2.6 km drive). During the drive to first turn-around, the test subject was asked to accelerate and brake several times to ensure that he/she was
familiar with the vehicle’s handling and braking characteristics. Each participant drove three
practice runs up and down the Smart Road test facility prior to conducting the tests. If necessary,
the participant made additional practice runs along the Smart Road.

During the test runs the participants drove a distance of 1.6 km (1 mile) going down hill
to approach the intersection followed by a 0.5 km (0.3 mile) leg to a high speed turnaround and
another 0.5 km (0.3 mile) approach going back to the intersection. The test subjects were
instructed to cruise at a speed of 72 km/h (45 mi/h) while approaching the signalized intersection
and to obey all traffic laws. Participants were reminded by the experimenter to monitor their
speed and maintain a speed of 72 km/h (45 mi/h). Further studies underway will consider other
approach speeds. No other vehicles were allowed on the test facility. A 4-second yellow phase
was triggered a total of 20 times (four repetitions at five distances). The phases were triggered
when the front of the test vehicle was 32, 55, 66, 88, and 111 m (105, 180, 215, 290, and 365 ft)
from the approach stop bar in order to cover the entire dilemma zone. An additional four green
trials were randomly introduced into the 20 yellow trials to introduce an element of surprise into
the experiment. The run sequence was generated randomly and thus was different from one test
subject 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 (FIGURE 9).

FIELD DATA RESULTS AND ANALYSIS

The data were gathered via the data recording instrumentation within the test vehicle using a
customized VTTI proprietary software package and recorded in a tab-delimited format. The data
included: an incremental counter for each trial (4–27), case number of green and yellow
indications (1–6), current state and duration of the traffic signal (s), latitude of vehicle (degrees),
longitude of vehicle (degrees), heading of vehicle clockwise from north (degrees), vehicle speed
(mi/h), acceleration (g), distance to intersection stop bar (ft), time to intersection computed as
distance/speed (s), and distance traveled in the previous 0.1 s (ft). Information on the driver
(subject number, age, gender) and run condition order were reported in the summary sheet of the
file. These data files were then downloaded to a PC and the data were analyzed in spreadsheets.

Current practice in most states is to use a driver perception-reaction time of 1 s and a
deceleration rate of 3 m/s² (10 ft/s²) as standard assumptions when calculating the yellow signal
interval time (Milazzo et al. (13)), implying braking efficiency of 0.3 on a dry pavement. In our
study, the approaching speed to the intersection was 72 km/h (45 mi/h) or 20 m/s (66 ft/s) with a
4 s yellow interval. Considering the standard assumptions and by using equation (2), the
minimum stopping distance is found to be 80.7 m (264.8 ft) while traveling on the 3% uphill
direction ($G=0.03$) and 93.9 m (308.1 ft) while traveling down hill ($G=-0.03$). The maximum
running distance for a 72 km/h (45 mi/h) approach speed and a 4 s yellow interval can be
computed using equation (3) as 80 m (262.5 ft).

Consequently, in the distance between 80.7 (264.8 ft) and 80 m (262.5 ft) going uphill
and between 93.9 (308.1 ft) and 80 m (262.5 ft) going down hill, the driver will not be able to
either stop at a deceleration rate of 3 m/s² (10 ft/s²) or proceed through the intersection without
increasing their speed above 72 km/h (45 mi/h). This represents a negligible dilemma zone of 0.7
m (2.3 ft) dilemma zone going uphill and 13.9 m (45.6 ft) going down hill with a dilemma zone
time of less than 0.7 s into the red.

Previous studies modeled the probability of stopping as a function of the approach speed,
yellow-phase trigger distance, and time to stop-line assuming a constant speed. This study
analyzes a single approach speed of 72 km/h (45 mi/h) and 5 trigger distances. The
stopping/running probability versus distance to stop bar are presented in FIGURE 10. Overall, the probability of stopping for 32, 55, 66, 88, and 111 m (105, 180, 215, 290, and 365 ft) trigger distances was 0.09, 0.59, 0.83, 0.99, and 1.00, respectively. The probability of running was 0.91, 0.41, 0.17, 0.01, and 0.00 for the 32, 55, 66, 88, and 111 m (105, 180, 215, 290, and 365 ft) trigger distances, respectively. The 0.9/0.1 probability of stopping/running laid between 66 and 88 m (3.3 and 4.4 s) from the stop bar while the 50 percent stopping/running decision point occurred when the yellow indication was triggered when the vehicle was at a distance of 51 m (2.55 s) from the stop bar.

![FIGURE 10 Probability of stopping / running](image)

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

The percentage of older drivers (65 years of age and older) who elected to stop at the short yellow-phase trigger distances was larger than the younger drivers. Older drivers were significantly less likely to clear the intersection at the 32, 55, and 66 m (105, 180, and 215 ft) trigger distances than the younger drivers. Specifically, at the 32 m (105 ft) trigger distance, the probability of stopping for the older drivers (65 years of age and older) was 0.17 compared to 0.02 for the younger drivers. Also, as shown in FIGURE 11, the probability of those stopping who were 65 years of age and older was 0.69 at the 55 m (180 ft) and 0.88 at the 66 m (215 ft) trigger distances compared to 0.50 (at 55 m) and 0.79 (at 66 m) for the younger drivers. At the longer trigger distance (88 m), 97 percent of the older drivers (65 years of age and older) stopped while all the younger drivers stopped. The Chi-square analysis demonstrated that the effect of age was highly significant at the 32m ($\chi^2 (1) = 17.66, p = 0.00003$) and the 55m ($\chi^2 (1) = 9.16, p = 0.002$) yellow-phase trigger distances, while it was marginal at the longer trigger distances of 66m ($\chi^2 (1) = 3.31, p = 0.069$) and 88m ($\chi^2 (1) = 3.52, p = 0.061$) and no significant differences
(χ² (1) = 1.13, p = 0.29) were obtained between the older and younger drivers at the 111 m (365 ft) trigger distance.

![Figure 11 Probability of stopping (function of age group)](image1.png)

Female drivers appeared to be more likely to stop when compared to male drivers. FIGURE 12 demonstrates that the probability of stopping curve for female drivers was shifted to the left when compared to male drivers in the range between the 32 to 66 m (105 to 215 ft). This shift correlates to an increase in the probability of stopping for female drivers relative to male drivers at the short yellow-phase trigger distances. The Chi-square analysis revealed that significant differences (χ² (1) = 4.6, p = 0.03) exist between male and female drivers only for the 55 m (180 ft) yellow-phase trigger distance with 52 percent versus 66 percent of the population stopping. There were no statistically significant differences for the other four trigger distances.

![Figure 12 Probability of stopping (function of distance from stop bar)](image2.png)
In addition, the data were utilized to derive the probability of stopping and compute the degree of uncertainty associated with different driver groups. The drivers were classified into the following four age groups: 20 to 39, 40 to 64, 65 to 69, and 70 years of age and older. With the probability of stopping/running obtained, the degree of uncertainty for each age group was computed using equation (5) and illustrated in FIGURE 13. The figure demonstrates that the highest degree of uncertainty occurred when the probability of stopping and running were equal. The location of the uncertainty zone and the maximum uncertainty point for the oldest group (70 years of age and older) was offset to the left demonstrating that older drivers tend to make their decisions when they are closer to the intersection. The results demonstrate that older drivers are more likely to stop in response to a yellow-phase transition and only attempt to run when they are in close proximity to the intersection. A Chi-square analysis for the four age groups demonstrated that the effect of age was highly significant at the 32 m ($\chi^2 (3) = 18, p = 0.0004$) and the 55 m ($\chi^2 (3) = 12.6, p = 0.006$) yellow-phase trigger distances, while there was no significant differences at the longer trigger distances.

![FIGURE 13 Driver uncertainty levels](image)

The driver dilemma zone can be defined as the road segment where more than 10 percent and less than 90 percent of the drivers elect to stop. FIGURE 14 presents the dilemma zone boundaries within the range of 10 to 90 percent probability of stopping when the yellow-phase is triggered at different distances from the stop bar for different age groups. The figure clearly demonstrates that the dilemma zone boundaries decrease as the driver population age increases. For example, a 30 m (1.5 s) at a 10 percent probability of stopping and 64 m (3.2 s) at a 90 percent probability of stopping are observed for the 70 years of age and older drivers compared to a 37 m (1.85 s) at a 10 percent probability of stopping to 78 m (3.9 s) at a 90 percent probability of stopping for the 20 to 39 age group. It is apparent that the driver stopping/running behavior in response to the yellow-phase trigger distance is age related, with younger drivers being approximately 20 percent more likely to attempt to run the yellow light when compared to
older drivers. Furthermore, it appears that the 70 and older age group experiences a significant reduction in the size of the dilemma zone (1.5 versus 2.0 s). In addition, the dilemma zone boundaries are significantly closer to the intersection with a change in slope in the dilemma zone boundary function. This older group tends to have a longer perception/reaction time when compared to other age groups which results in a dilemma zone that is smaller and closer to the signalized intersection.

![Graph showing dilemma zone boundaries by age groups](image)

**FIGURE 14 Dilemma zone boundaries by age groups**

**CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH**

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

It should be noted that a caveat of this study is that drivers experienced more yellow indications than green indications and thus could be more willing to stop than would be typical in a natural environment. Furthermore, the drivers were not distracted by the surrounding conditions and did not have other vehicles in close proximity to them when they made their stop/go decisions. Consequently, additional field studies are needed to characterize driver
behavior at the onset of a phase transition considering the impact of a leading vehicle, the proximity of a following vehicle, the surrounding environment, and the impact of the approach speed on driver behavior.

REFERENCES

ANALYSIS OF BRAKE PERCEPTION-REACTION TIMES ON HIGH-SPEED SIGNALIZED INTERSECTION APPROACHES

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ABSTRACT
The study used data from a field test on 60 test participants to characterize driver brake perception-reaction times at the onset of an amber phase actuation at a high-speed signalized intersection approach. The study demonstrates that the 1.0 s, 85th percentile perception-reaction time that is recommended in traffic signal design procedures is valid and consistent with field observations. Furthermore, the study demonstrates that brake perception-reaction times are impacted by the vehicle’s time-to-intersection at the onset of a phase transition. Consequently, the study recommends that time-to-intersection in the range of 2.2 to 4.4 s be considered in the characterization of brake perception-reaction time behavior. Finally, the study demonstrates that either a lognormal or beta distribution is sufficient for modeling brake perception-reaction time.

INTRODUCTION
The proper design of traffic signals requires the computation of the amber interval, which in turn entails an estimate of the driver perception-reaction time (PRT). The state-of-practice recommends a 1.0-s PRT, which is assumed to equal or exceed the 85th-percentile brake PRT. 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 (1). These studies have also demonstrated that the PRTs on high-speed intersection approaches (greater than 64 km/h) are lower, with 85th percentile PRTs in the range of 1.1 to 1.3 s. All studies, however, have measured the PRT as the time difference between the onset of the amber phase and the activation of the vehicle’s brake lights; thus PRT includes the time lag from the instant the driver presses the brake pedal until the brake lights activate.

The objectives of this paper are three-fold. First, the paper characterizes brake PRT at high-speed signalized intersection approaches in an attempt to validate the state-of-the-art field studies using data from a controlled field study. Second, the paper analyzes age, gender, and time-to-intersection impacts on PRTs. Third, the paper shows that either a lognormal or a beta distribution can be used to describe the distribution of observed PRTs for use within microscopic traffic simulation software.

Driver Perception-Reaction Times at Traffic Signals
Driver PRT is a parameter 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 (2), (3). It is also used in the calculation of the amber interval duration in traffic signal design (4).

A review of the fundamental concepts associated with reaction times will give a better understanding of the factors related to PRT. When a driver responds to a sensory input, such as the onset of an amber light at a traffic signal, the total reaction time can be split into a mental processing time (the time required for the driver to perceive the sensory input and to decide on a response) and a movement time (the time used to perform the programmed movement, such as lifting the foot from the accelerator and touching the brake). Because the mental processing time is an internal quantity that cannot be measured directly and objectively without a physical response, it is usually measured jointly with movement time (5).

In the case of a driver arriving at a signalized intersection when the phase changes from green to amber, the time interval from the onset of the amber light to the instant when the brake pedal is pressed is called the perception-reaction time (2, 6), perception response time (7), brake
reaction time (3, 5), perception-braking response time (8), or yellow response time (9). This paper will refer to it as the perception-reaction time (PRT).

Taoka (1) stresses that PRTs measured under anticipatory conditions, when drivers are aware that their perception-reaction times are recorded, should be shorter than the expected values under normal driving conditions.

In a comprehensive survey which summarizes PRT results from most studies published until 2000, Green (5) classifies PRT studies into three basic types: simulator studies, controlled road studies, and naturalistic observation. Controlled road studies and naturalistic observation differ in the sense that in the latter, the driver is unaware of the data collection effort. Each type of study has limitations in the degree to which results can be generalized to normal driving conditions. PRT measurements from driving simulators are typically shorter than those measured in vehicles because simulators have simplified visuals, smaller fields of view, no depth, no non-visual cues, and small cognitive loads. Controlled-road studies also produce shorter PRT measurements because drivers are more alert than in normal driving conditions. Both simulator and controlled-road studies create practice effects because of the many trials used to gather data for each driver. Naturalistic studies have the highest validity, but they 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.

PRTs at traffic signals also include some lag time because the onset of the amber does not always require immediate braking reaction unless the driver is close to the intersection. According to a study in which seven intersections were observed and driver PRTs (defined as “the time elapsed from the onset of the yellow until the brake light is observed”) were recorded (9), this lag should be small or nonexistent on high-speed signalized approaches because the high speed requires immediate reactions to avoid excessive deceleration or even collisions with other vehicles. The results suggest that speed effectively influences the median PRT, which stabilizes at 0.9 s at speeds equal or greater than 72 km/h (45 mph). The study also focused on the effect of the distance from the intersection at amber phase onset because, according to its authors, drivers tend to react faster as vehicles move closer to the intersection; when vehicles are farther away, the PRT might be longer because the urgency to make a decision is not as great.

A study that used a driving simulator to analyze the behavior of 77 drivers approaching signalized intersections at 70 km/h reached similar conclusions (10). The study concluded that travel time to the stop line significantly affected the PRT whereas age did not. The PRT grand mean was 0.96 s, ranging from 0.86 s for drivers closest to the intersection stop line to 1.03 s for drivers farthest from it.

In order to overcome the effect on the PRT of the distance from the intersection at amber onset, Wong and Goh (7) used a transitional zone, defined as the zone in which drivers are required to make a decision quickly or be forced to cross. Drivers before the transitional zone must stop at the intersection (because they cannot legally cross); drivers after the transitional zone must cross the intersection. The transitional zone was defined in terms of the travel time to the stop bar, measured as the actual travel time for those vehicles that crossed the intersection and as the projected travel time for those that stopped. For the three intersections analyzed in Singapore, the transitional zone was defined as lying between 2.3 and 4.2 s from the intersection stop bar. PRT was defined as the time elapsed from the amber onset until the brake lights became visible. PRT values found for the transitional zone were 0.84 s (median), 0.86 s (mean), 0.64 s (15th percentile), and 1.08 s (85th percentile), following a log-normal distribution; this finding is
consistent with other studies (1). In another paper (7), the authors reported shorter reaction times at intersections with red light surveillance cameras: 0.80 s for the median and mean and 1.00 s for the 85th percentile.

**Driver Behavior at Signalized Intersections**

The decision of stopping or proceeding through the amber light is related to the distance to the intersection, the travel time to the stop bar, and the approach speed. A study (10), which compared the performance of older and younger drivers at amber onset at high-speed signalized intersections using a driving simulator, found that older drivers (55 years or older) were less likely to stop than younger drivers and that the older drivers who decided to go through the intersection in the amber phase were more likely to be within the intersection at the onset of the red light due to their slower speeds. A naturalistic study that observed nine intersections in Maryland (11) concluded that the response to the onset of the amber phase (stop or proceed) was affected by driver’s gender, age, and the use of cellular phones as well as the position of the vehicle at the start of the amber.

**EXPERIMENTAL DESIGN**

The experiment involved having each test participant drive an instrumented vehicle along a 2.6 km private highway at approximately 72 km/h. After a practice run that allowed the participant to get acquainted with the vehicle, the participant approached a signalized intersection a number of times. The behavior of the driver was observed as the signal phases changed, and data on the participant’s responses included pressing the accelerator and brake pedals. The experiment could then be classified as a controlled-road study, according to Green’s classification scheme (5). It should be noted that the objective of the study was to analyze driver behavior in response to a red-light-running warning system and was not intended to characterize driver behavior at the onset of an amber phase. The drivers were unaware of the study’s objectives during the test runs. This section describes the instrumented vehicle, the test track, the test participants, and how the data were collected.

**Instrumented Vehicle and Signal Controller Box**

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

Signal phase data was also recorded in the data stream using a communications link between the DAS and the signal controller box installed at the intersection. This signal controller box, which was also developed at the VTTI, was used to trigger the amber phase when the front of the vehicle reached predetermined distances from the intersections. Phase changes were controlled from the instrumented car using a differential Global Positioning System (GPS) to determine the distance from the intersection and a wireless communications link to trigger the phase changes.

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

**Intersection and Intersection Approaches**

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

**Test Participants**

The test participants for the study were recruited using posters, word of mouth, local newspaper ads, and the VTTI volunteer database. Participants were paid $20/hour. Interested drivers were screened to verify that they were licensed drivers and to determine if they had any health problems that could exclude them from participating in the study. Sixty drivers were recruited, 30 in each gender; 32 drivers were younger than 65 years (50% men, 50% women) and 28 were 65 years or older, also equally divided by gender. Table 1 shows the age and gender structure of the participant sample. The age structure was designed to allow possible effects of slower response times among older drivers to be more evident. The younger group had ages ranging between 20 and 64 years, with a mean age of 40 years; the older group had a mean age of 71 years, and ages ranged from 65 to 82 years.

**TABLE 1 Age and gender structure for the participant sample**

<table>
<thead>
<tr>
<th>Age</th>
<th>Younger drivers</th>
<th>Older drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 or younger</td>
<td>40 to 64</td>
</tr>
<tr>
<td>Women</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Men</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

**Procedure**

Participants were tested individually under good conditions (daylight, good weather, dry pavement, etc.). Upon arrival at VTTI, participants were submitted to a visual acuity and color vision test. All participants selected had a minimum of 20/40 vision, passed the color vision test, and were screened by a medical questionnaire for drug/alcohol use and any medical conditions that might impair driving. Participants were then escorted to the test vehicle and asked to
familiarize themselves with the car, adjusting seat, mirrors, seat belts, etc., and to drive to the Smart Road, about 0.5 km away. Two experimenters rode in the car with the participant. During the drive to the Smart Road, one of the experimenters instructed the participant and answered questions while the other, in the back seat, used the on-board computer to control the trial conditions and the DAS. During the initial practice run, participants were asked to brake the car to a full stop from 40 km/h, 55 km/h, and 70 km/h to become familiar with the handling of the car under hard braking.

In the experiment, participants were instructed to drive the car at 72 km/h (45 mph) except in the turnarounds or when stopping at the intersection. Participants were instructed to behave normally when faced with an amber light, making the decision whether to stop or to go as they usually would. 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), composing 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 amber and, if so, at what distance from the stop bar.

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

Each participant faced phase changes from green to amber four times for each TTI. These 24 trial conditions (20 amber 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 an amber light at a given TTI on a given grade (up or down) varied between one and three times.

**PERCEPTION-REACTION TIME MEASUREMENTS**

**Field Test Data**

PRT was defined as the time elapsed between the onset of the amber phase and the instant the driver started to press the brake pedal; only the cases where the driver’s foot was on the accelerator pedal at amber onset were considered. For each participant, the average of the observed PRTs for each TTI was calculated for both grades, which provided a sample of 351 average observed PRTs ranging between 0.3 and 1.7 s, with a mean equal to 0.742 s, a median of 0.7 s, and a standard deviation of 0.189 s. The histogram for this sample is shown in Figure 1. The observed distribution can be represented by either a lognormal or beta distribution. Figure 1 shows a fitted beta distribution that passes the $\chi^2$ test. Because the observed distribution of PRTs was skewed, the median was used, instead of the mean, to avoid any bias that might have been introduced by a few very long PRTs.
FIGURE 1 Distribution of observed average PRT for all TTI (n = 351).

Table 2 shows median PRTs for the sample consisting of 351 observed PRTs, disaggregated by gender, age group, and TTI, as well as the number of observations in each case. Tables 3 and 4 show median PRT disaggregated by grade, age group, and TTI for each gender.

### TABLE 2 Medians of observed perception-reaction times (ms)

<table>
<thead>
<tr>
<th>TTI (s)</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>4</td>
<td>650</td>
<td>1</td>
<td>600</td>
<td>2</td>
<td>567</td>
<td></td>
<td></td>
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<tr>
<td>2.7</td>
<td>15</td>
<td>700</td>
<td>16</td>
<td>700</td>
<td>14</td>
<td>667</td>
<td>18</td>
<td>600</td>
</tr>
<tr>
<td>3.3</td>
<td>17</td>
<td>633</td>
<td>20</td>
<td>700</td>
<td>24</td>
<td>700</td>
<td>21</td>
<td>600</td>
</tr>
<tr>
<td>4.4</td>
<td>25</td>
<td>700</td>
<td>22</td>
<td>717</td>
<td>27</td>
<td>725</td>
<td>23</td>
<td>650</td>
</tr>
<tr>
<td>5.6</td>
<td>27</td>
<td>750</td>
<td>25</td>
<td>900</td>
<td>27</td>
<td>850</td>
<td>23</td>
<td>850</td>
</tr>
</tbody>
</table>

### TABLE 3 Medians of observed perception-reaction times, women (ms)

<table>
<thead>
<tr>
<th>TTI (s)</th>
<th>Uphill</th>
<th>N</th>
<th>PRT</th>
<th>Downhill</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
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<tr>
<td>1.6</td>
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<td>650</td>
<td>–</td>
<td>1</td>
<td>650</td>
<td>–</td>
<td>1</td>
<td>650</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>10</td>
<td>700</td>
<td>11</td>
<td>700</td>
<td>5</td>
<td>700</td>
<td>5</td>
<td>600</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>9</td>
<td>750</td>
<td>11</td>
<td>700</td>
<td>8</td>
<td>600</td>
<td>9</td>
<td>700</td>
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<tr>
<td>4.4</td>
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<td>5.6</td>
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<td>12</td>
<td>725</td>
<td>12</td>
<td>833</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### TABLE 4: Medians of observed perception-reaction times, men (ms)

<table>
<thead>
<tr>
<th>TTI (s)</th>
<th>Uphill</th>
<th>N</th>
<th>PRT</th>
<th>Downhill</th>
<th>N</th>
<th>PRT</th>
<th>N</th>
<th>PRT</th>
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<td>1.6</td>
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<td>600</td>
<td>1</td>
<td>600</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>533</td>
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<td>2.7</td>
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<td>600</td>
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<td>9</td>
<td>600</td>
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</table>
Table 2 shows that very few drivers tried to stop if the amber phase change occurred when they were close to the intersection. A series of $\chi^2$ tests was carried out to further investigate this behavior. These tests compared the number of drivers who stopped and the number of drivers who went when faced with an amber phase change when the TTI was 1.6 s. The results indicated that while there were no differences in driving behavior between uphill or downhill trips, men were less likely to stop at the amber at this short distance than women ($p < 0.01$, $\chi^2(1) = 7.460$), and younger drivers were less likely to stop than older drivers ($p < 0.01$, $\chi^2(1) = 12.668$). The test results also indicated that older women were more likely to stop than younger women ($p < 0.01$, $\chi^2(1) = 8.316$) and that there were no significant differences in behavior between younger and older men.

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

Table 2 also shows that nearly all drivers stopped when the TTI at the onset of the amber was 5.6 s and that the median PRT for this case was generally longer than those observed for shorter TTIs. Using the data presented in Tables 3 and 4, ANOVA tests were used to investigate the effects of the TTI, gender, age group, and grade on the brake PRT. Initially, a set of one-way ANOVA tests was carried out to investigate the effect on PRT of each of the following variables: age group (younger or older drivers), TTI (2.7, 3.3, 4.4 and 5.6 s), gender, and roadway grade (uphill or downhill). The medians for TTIs of 1.6 s were not included in the analysis because the results of the $\chi^2$ tests demonstrated that drivers do not try to stop at such TTIs.

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

There was a significant difference in the PRT for the up grade ($M = 696$ ms) and down grade ($M = 629$ ms) conditions ($F(1,22) = 12.288, p < 0.01$). Even if this difference is small enough to be disregarded from an engineering design point of view, it indicates that drivers are more alert when driving downhill because the deceleration needed to stop the car would be greater than when going uphill.

No significant differences were found between the men’s and women’s PRTs or between younger and older drivers. However, the data suggest that older women tended to have longer PRTs when compared to younger women and men of both age groups ($F(1,20) = 2.914$, ...
Again, the difference in PRT was so small that it may be unimportant in terms of changing design procedures.

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

**DRIVER PERCEPTION-REACTION TIME DISTRIBUTION**

The typical approach to modeling driver perception-reaction times is to consider a lognormal distribution (1). Consequently, a lognormal distribution was initially fit to the data. Subsequently, a beta distribution was considered given that it offers a bounded model between two finite limits $a$ and $b$ (12). The model is formulated as:

\[
\begin{align*}
    f_\text{lognormal}(x) &= \frac{1}{B(q,r)} \frac{(b - x)^{r-1} (x - a)^{q-1}}{(b - a)^{q+r-1}}, \quad \text{for } a \leq x \leq b \\
    &= 0, \quad \text{otherwise,}
\end{align*}
\]

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

\[
B(q,r) = \int_0^1 x^{q-1} (1 - x)^{r-1} \, dx.
\]

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

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

Figure 3 illustrates the field-observed PRTs for the entire experiment excluding data for TTIs of 1.6 and 5.6 s \( (N = 455 \) observations), in addition to two models that were fit to the data: a lognormal and a beta model. Again, as was the case for the entire dataset, there was no evidence that the field data were inconsistent with the two theoretical models \( (p < 0.001, \chi^2(6) = 32.47 \) and \( p < 0.001, \chi^2(6) = 21.46 \) for the lognormal and beta models, respectively). Based on these two distributions, the 85th percentile PRTs were 0.75 s and 0.77 s for the lognormal and beta distributions, respectively. Consequently, the field data were smoothed using an Epanechnikov kernel of bandwidth 2 \( (13) \), as illustrated in Figure 4. Again, lognormal and beta models were fit to the field data, and the results demonstrated a lack of statistical evidence to reject the hypothesis that the field data followed either a lognormal or beta distribution \( (p = 0.876, \chi^2(8) = 3.78 \) and \( p = 0.687, \chi^2(8) = 5.64 \) for the lognormal and beta models, respectively). The 85th percentile PRTs found after these changes were slightly higher, 0.79 s \( \) (lognormal) and 0.81 s \( \) (beta distribution). 

Other studies \( (1) \) have shown that the 85th percentile brake PRTs for unalerted drivers typically range from 1.1 to 1.3 s on high-speed signalized intersection approaches (greater than 64 km/h). These studies typically measure PRTs from the onset of the amber interval to the instant when the brake lights are actuated. The present study did not include the delay between the instant when the brake pedal begins to be pressed and the instant when the brake lights are activated, which is included in naturalistic observation; however, the fact that the drivers were aware that they were being observed could explain the lower PRTs observed in this study. In fact, Green \( (5) \) reports that, when drivers are fully aware of the time and location of the brake signal – as in this study –, PRTs in the range of 0.70–0.75 s have been observed. Another aspect that could explain the lower PRTs is the practice effect, given that the participants encountered more amber runs \( (20 \) out of \( 24 \) runs) during the experiment.

To estimate the impact of the practice effect, the 85th percentile PRTs were estimated only using data collected on the first trials for each driver. The PRTs were 1.1 s using data from the first trial; 1.0 s for the first two trials; and 0.9 s, if data from the first three trials are used to estimate the 85th percentile PRTs. These results clearly show that the repetitive nature of the field test affected the estimation of the 85th percentile PRT and that the estimates obtained using the fitted distributions should be used carefully, as they represent conditions that might not be fully representative of normal driving.
The study demonstrates that the 1.0 s, 85th percentile PRT that is recommended in the traffic signal design procedures is valid and consistent with field observations. Furthermore, the study demonstrates that brake PRTs are impacted by the vehicle’s TTI at the onset of a phase transition to amber. Consequently, we recommend that only TTIs of 2.2 to 4.4 s be considered in the characterization of brake PRT behavior. The study has also shown that gender and age do not affect PRTs. Even if the statistical analysis has shown that drivers have shorter PRTs when going downhill, this difference is so small that, from an engineering point of view, can disregarded. The study also demonstrates that either a lognormal or beta distribution is sufficient for modeling brake PRT. It should also be stressed that, due to the nature of the experiment, the PRTs found might not be fully representative of normal driving conditions, as drivers in this experiment were aware of the data collection effort and experienced more amber indications than green indications during the test runs.
It is recommended that these models be implemented within microscopic traffic simulation software to better capture the behavior of drivers at the onset of amber phase transitions and evaluate alternative amber timing strategies. To better understand the factors affecting PRT, it is also recommended that further studies, in which the effect of leading and following vehicles on the behavior of the subject drivers, be conducted.

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EVALUATION OF DRIVER STOPPING BEHAVIOR ON HIGH SPEED SIGNALIZED INTERSECTION APPROACHES

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ABSTRACT

The research presented in this paper characterizes driver stopping behavior at the onset of a yellow-phase on high-speed signalized intersection approaches using controlled field data gathered from 60 test subjects using an in-vehicle Differential Global Positioning System (DGPS). A total of 745 data records were available for analysis for all drivers who stopped at the onset of the yellow-phase, ranging from a minimum time to the stop bar (TTS) of 1.34 s to a maximum of 6.19 s. Statistical analyses were used to investigate the effects of the time to stop bar, grade (uphill and downhill), age (under 40-years-old, 40 to 59-years-old, and 60 years of age or older), and gender on seven dependent measures of driver performance including perception time, reaction time, perception-reaction time, braking time, stopping time, and stopping accuracy. The study demonstrates that driver perception time is not impacted by TTS while reaction time is dependent on TTS, roadway grade, and driver age. Younger drivers have longer reaction times in comparison to the older group but they are able to stop over a shorter period of time as they typically apply more aggressive braking rates. A lower perception-reaction time was found for drivers who have their foot lifted off the accelerator at the onset of the yellow-phase. Male drivers show slightly higher braking times when compared to female drivers with no significant differences between male and female drivers. Furthermore, the results demonstrate that drivers who try to stop at short TTSs are more likely to stop downstream of the stop line and that older drivers are significantly more accurate when they stopped compared to other age groups.

INTRODUCTION

At the onset of a yellow-phase transition on high-speed signalized intersections, each driver has to decide either to 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 perception-reaction time (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 \((PRT)\). 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 \((PRT)\). These studies have also demonstrated that the PRTs on high-speed intersection approaches (greater than 64 km/h) are lower, with 85th percentile PRTs in the range of 1.1 to 1.3 s.

The driver behavior during the yellow interval is a problem that has been examined in the literature since 1960 by Gazis et al. \((3)\). In their paper they examined the driver behavior in response to yellow signal phasing. That study measured the drivers braking reaction time on the basis of 87 observations and was found to have a mean of 1.14 s. Wortman and Matthias \((4)\) used a time-lapse camera to study driver behavior at six intersections in the Phoenix and Tucson, Arizona metropolitan areas. They observed a mean PRT of 1.3 s with 85th percentile times ranging from 1.5 to 2.1 s. Another study by Chang et al. \((5)\) recorded driver PRT at seven intersections (defined as “the time elapsed from the onset of the yellow until the brake light is observed”). This lag should be small or nonexistent on high-speed signalized approaches because the high speed requires immediate reactions to avoid excessive deceleration or even collisions with other vehicles. The study focused on the effect of the distance from the intersection at the onset of a yellow indication. According to its authors, drivers tend to react faster as vehicles move closer to the intersection; when vehicles are farther away, the PRT might be longer because the urgency to make a decision is not as great. The results of that study, based
on 579 stopping vehicles, showed a mean PRT of 1.3 s, median of 1.1 s, 85th percentile time of 1.9 s, and 95th percentile time of 2.5 s. However, excluding driver’s response lag time from yellow response time resulted in PRT of 1.2 s (5). In order to overcome the effect of the distance from the intersection on the PRT at the yellow indication onset, Diew and Kai (6) assumed that drivers before the dilemma zone must stop at the intersection (because they cannot legally cross); while drivers after the dilemma zone must cross the intersection. Three intersections were analyzed in Singapore and the dilemma zone was defined as lying between 4.2 and 2.3 s from the intersection stop bar whereas PRT was defined as the time elapsed from the yellow indication onset until the brake lights became visible. A mean PRT value was found to be 0.86 s with median value of 0.84 s, 15th percentile of 0.64 s, and 85th percentile of 1.08 s, which is consistent with other studies (2). However, Kai and Diew, in another study (7), reported shorter reaction times at intersections with red light surveillance cameras with mean and median times of 0.80 s and 85th percentile of 1.00 s.

Another comprehensive survey by Green (8) summarized PRT results from most studies published until 2000. It classified PRT studies into three basic types: simulator studies, controlled road studies, and naturalistic observation. Controlled road studies and naturalistic observation are both field approaches but differ in the sense that, in the latter, the driver is unaware of the data collection effort. Each type of study has limitations to the degree in which results can be generalized to normal driving conditions. PRT measurements from driving simulators are typically shorter than those measured in vehicles because simulators have simplified visuals, smaller fields of view, no depth, no non-visual cues, and small cognitive loads. Controlled-road studies may also produce shorter PRT measurements because drivers may be more alert than in normal driving conditions. Both simulator and controlled-road studies create practice effects because of the many trials used to gather data for each driver. Alternatively, naturalistic studies have the highest validity, but are also limited because it is not possible to test 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, the survey found that older female drivers respond slower than younger male ones in many cases (8). Using a moderate-fidelity driving simulator, Caird et al. (9) analyzed the behavior of 77 drivers approaching signalized intersections at 70 km/h. The study concluded that the PRT did not differ by age and was affected by time to intersection (TTI) significantly, varying from 0.86 to 1.03 s. Moreover, older drivers were found to be able to make more accurate stops at the stop-line as they approached the intersection more slowly than younger drivers. A recent study by Gates et al. (10) recorded vehicles behavior at six signalized intersections in the Madison, Wisconsin area comprising 463 first-to-go and 538 last-to-go records. The analysis of the brake-response time 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.

The literature demonstrates that there is a need to study gender and age impacts on driver behavior within the dilemma zone. This is important for consideration in the design of the yellow interval especially at locations where the driver population is older (e.g. retirement communities). Accounting for the age impact on driver behavior is critical in the design of effective and safe signal timings. Furthermore, with the deployment of Vehicle Infrastructure Integration (VII) initiatives, comes the need for in-depth understanding of age and gender impacts on driver behavior at the onset of a yellow indication.

This paper has two objectives. First, the paper characterizes the stopping behavior of drivers approaching high-speed signalized intersection at the onset of yellow. Such behavior
comprises many components such as perception time, reaction time, the summation of both times (PRT), braking time, and total stopping time in addition to the stopping accuracy in terms of distance from stop bar when the vehicle comes to a complete stop. Second, the paper investigates the significance of different factors on such behavior, e.g. roadway grade, age, and gender.

**EXPERIMENTAL DESIGN**

The design of the field test effort involved selecting a test vehicle, the test roadway, and test subjects.

**Test Vehicle**

A 2004 Chevrolet Impala was used for the intersection test bed. The instrumented vehicle was equipped with additional equipment that included a Differential Global Positioning System (DGPS), a real-time data acquisition system (DAS), and a computer to run the different experimental scenarios. The DAS, located inside the trunk, was custom built by the Center for Technology Development (CTD) at the Virginia Tech Transportation Institute (VTTI). The data recording equipment had a communications link to the intersection signal control box that synchronizes the vehicle data stream with changes in the traffic signal controller.

**Roadway Layout**

The Virginia Smart Road located at VTTI, owned by the Virginia Department of Transportation (VDOT) was the site of the field test. The Smart Road in Southwest Virginia is a unique, state-of-the-art, full-scale research facility controlled by electronic gateways for pavement research and evaluation of Intelligent Transportation System (ITS) concepts, technologies, and products. The Smart Road is a 3.5 km (2.2 mile) two-lane road with one four-way signalized intersection, a high-speed banked turnaround at one end and a medium speed flat turnaround at the other end. 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 percent. The details of how the vertical profile was generated are described by Rakha et al. (11). 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.

**Participants**

Participants were licensed drivers recruited from the VTTI participant database, by word-of-mouth, posters, and/or through ads in local Blacksburg, VA newspapers. Volunteers were paid $20 per hour for a 1 to 1.5 hour session. Participants were screened through a verbal questionnaire to determine if they were licensed drivers and if they had any health concerns that would exclude them from participating in the study. Sixty drivers were recruited in three age groups, 16 of whom were under 40-years-old with a mean age of 28, 12 drivers between 40 and 59-years-old with a mean age of 49, and the third group were for 32 drivers of 60 years of age or older with a mean age of 70. Note that near equal numbers of males and females were assigned to each group. The age structure was designed to allow possible effects of slower response times among older drivers to be more evident.

**Procedures**

The participants drove the entire 2.6 km (1.6 miles) test course 12 times in each direction (excluding practice runs) for a total of 24 trials. During these 24 trials the participants received a total of four green indications and 20 yellow indications that were displayed at five different
distances from the stop bar (four repetitions for each distance). Each yellow-phase was triggered at five distances via a wireless communication between the test vehicle and the traffic signal controller. The distance from the signal stop bar was estimated based on the DGPS position location (accuracy of 1.5 cm). Testing was only conducted in clear weather during the daylight hours when the road was dry, ice free, and free of debris.

Upon arrival at VTTI, each participant was asked to review and sign an informed consent form. A vision test (visual acuity and color vision) was administered and only participants who passed the vision test were allowed to continue with the experiment. In addition, each participant was asked to complete a medical questionnaire to verify that he/she did not have any medical conditions that would impair his/her ability to drive. Subsequently, the participant was escorted to the test vehicle. Each participant drove three practice runs (2.6 km each way) up and down the Smart Road test facility prior to conducting the tests. If necessary, the participant made additional practice runs along the Smart Road.

During the test runs the participants drove a distance of 1.6 km (1 mile) going down hill to approach the intersection followed by a 0.5 km (0.3 mile) leg to a high speed turnaround and another 0.5 km (0.3 mile) approach going back to the intersection. The participants were instructed to cruise at a speed of 72 km/h (45 mi/h) while approaching the signalized intersection and to obey all traffic laws. No other vehicles were allowed on the test road. The phases were triggered when the front of the test vehicle was 32, 55, 66, 88, and 111 m (105, 180, 215, 290, and 365 ft) from the approach stop bar in order to cover the entire dilemma zone. An additional four green trials were randomly introduced into the 20 yellow trials. The run sequence was generated randomly and thus was different from one participant to another.

FIELD DATA RESULTS AND ANALYSIS

The data were gathered via the data recording instrumentation within the test vehicle using a customized VTTI proprietary software package and recorded in a tab-delimited format. Information on the driver (subject number, age, gender) and run condition order was reported in the summary sheet of the file. The data gathered included but was not limited to: current state and duration of the traffic signal, heading of the vehicle clockwise from north (deg), vehicle speed (mi/h), acceleration (g), distance to intersection stop bar (ft), time to stop bar (TTS) computed as distance/speed (s), and the percentage of brake and throttle application (1/100 sec for each value). These data files were then downloaded to a PC and the data were analyzed in spreadsheets.

The experiment could be classified as a controlled-road study, according to Green’s classification scheme (8). Although the drivers were instructed to drive at a speed of 72.4 km/h (45 mi/h), the approach speeds at the yellow interval onset varied considerably from 54.7 to 88.4 km/h (34 to 55 mi/h), with a mean equal to 73.6 km/h (45.7 mi/h), a median of 73.9 km/h (46 mi/h), and a standard deviation of 3.4 km/h (2.1 mi/h), as illustrated in FIGURE 15. The histogram of the approach speed appears very close to a normal distribution. The average approach speed tends to be slightly higher than the instructed speed because there was no leading or following vehicles in the controlled-road study.
Because of the variation in the responses of different drivers when the yellow-phase was triggered at the signalized intersection, further analysis of various parameters that affect the driver behavior and characteristics for those who stopped at the onset of the yellow-phase was considered. The present study investigated seven dependent measures of driver performance including perception time, reaction time, cruising PRT, overall PRT, braking time, stopping time, and stopping accuracy. Drivers who were not cruising at the onset of the yellow-phase (had their foot lifted off the accelerator in advance of the yellow-phase) were removed from the perception, reaction, and cruising PRT analyses, but were included in the overall PRT, braking, stopping, and stopping accuracy analysis.

A total of 745 data records were available for analysis, for all drivers who stopped at the onset of the yellow-phase, ranging from a minimum time to stop line (TTS) of 1.34 s to a maximum of 6.19 s with a mean equal to 3.96 s, a median of 4.14 s, and a standard deviation of 1.08 s. Only 482 data records (of the 745 data records) were for those who were cruising at the onset of the yellow-phase ranging from a minimum TTS of 1.34 s to a maximum of 6.19 s with a mean equal to 3.97 s, a median of 4.15 s, and a standard deviation of 1.09 s. The data were sorted based on the driver’s TTS, at the yellow-phase onset, into equal sized bins (equal number of observations) and the average of the various parameters (perception time, reaction time, cruising PRT, overall PRT, braking time, stopping time, and stopping accuracy) for each bin was computed. The average value for each parameter was computed as the summation of all trials divided by the total trials within the bin considering a bin size of 50 observations, sorted by TTS, for the cruising drivers data set and bin size of 75 observations for the all drivers data set as shown in TABLE 4.

Using the data presented in TABLE 4(a) for the cruising drivers data set and in TABLE 4(b) for the all drivers data set, a four-factor analysis of variance (ANOVA) was conducted using the general linear model procedure (GLM) of the SAS software to investigate the effects of the TTS, grade, age group, and gender on each dependent variable (perception time, reaction time, cruising PRT, overall PRT, braking time, stopping time, and stopping accuracy). Initially, a set of F-statistics generated from ANOVA tests were used to investigate the effect of the following
independent variables on each of the seven dependent variables: TTS, roadway grade (uphill and downhill), age group (under 40-years-old, between 40 and 59-years-old, and 60 years of age or older), and gender (male and female).

TABLE 4 Average Parameters Statistics at Different Yellow-Phase Onset

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time to stop bar (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.38 2.75 3.05 3.21 3.93 4.24 4.50 5.19 5.40 5.66</td>
</tr>
<tr>
<td>Number of stopping drivers</td>
<td>29 32 29 33 28 34 34 33 33 27</td>
</tr>
<tr>
<td>Average perception time (sec)</td>
<td>0.40 0.41 0.40 0.39 0.37 0.42 0.38 0.38 0.36 0.42</td>
</tr>
<tr>
<td>Average reaction time (sec)</td>
<td>0.24 0.27 0.29 0.32 0.36 0.37 0.37 0.55 0.52 0.46</td>
</tr>
<tr>
<td>Average cruising PRT (sec)</td>
<td>0.64 0.68 0.69 0.71 0.73 0.79 0.75 0.93 0.88 0.88</td>
</tr>
</tbody>
</table>

(a) Cruising Drivers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time to stop bar (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.35 2.75 3.05 3.18 3.81 4.21 4.36 5.06 5.32 5.59</td>
</tr>
<tr>
<td>Number of stopping drivers</td>
<td>34 39 40 41 39 42 41 42 48 43</td>
</tr>
<tr>
<td>Average overall PRT (sec)</td>
<td>0.64 0.66 0.65 0.68 0.67 0.74 0.72 0.82 0.83 0.84</td>
</tr>
<tr>
<td>Average braking time (sec)</td>
<td>4.58 5.17 5.74 6.04 7.28 7.96 8.55 9.54 9.91 10.5</td>
</tr>
<tr>
<td>Average stopping time (sec)</td>
<td>5.13 5.76 6.29 6.64 7.87 8.63 9.19 10.2 10.7 11.3</td>
</tr>
<tr>
<td>Average Stopping accuracy (m)</td>
<td>-3.3 -0.4 -0.1 0.2 1.0 1.1 1.2 1.7 1.2 1.8</td>
</tr>
</tbody>
</table>

(b) All Drivers

**Perception-Reaction Time Analysis**

A review of the fundamental concepts associated with reaction times will give a better understanding of the factors related to PRT. When a driver responds to a sensory input, such as the onset of an yellow light at a traffic signal, the total reaction time can be split into a mental processing time (the time required for the driver to perceive the sensory input and to decide on a response) and a movement time (the time used to perform the programmed movement, such as lifting the foot from the accelerator and touching the brake) (δ). In the case of a driver arriving at a signalized intersection when the phase changes from green to yellow, the processing time (time interval from the onset of the yellow light to the instant the accelerator released) is called the perception time while the movement time (time interval when the accelerator released to the instant the brake pedal pressed) is called the reaction time.

PRT measurements (which is the time interval from the yellow-phase onset to the instant the brake pedal is pressed) from driving simulator and controlled-road studies can also be computed as the summation of both the perception and reaction times. In naturalistic studies, it is not possible to measure the perception and reaction times separately and also to differentiate between the drivers who were pressing the accelerator from those who had their foot lifted off the accelerator in advance of the yellow-phase onset.

In our study, perception time, reaction time, and PRT were only calculated for those who stopped. Participants who lifted their foot off the accelerator in advance of the amber change were removed from the perception, reaction, and cruising PRT analyses, but were included in the Overall PRT analysis.
Perception Time

The perception time (time required by the driver to perceive the yellow indication and make his/her decision either to stop or to go) was measured from the time of the yellow-phase onset to the instant in time at which the driver released his/her foot from the accelerator.

Mean perception times to the 4-sec yellow-phase as a function of the yellow-phase change trigger time are shown in FIGURE 16(a). For each participant, the observed mean perception times for each TTS was calculated for both grades, which provided a sample of 482 average observed perception times ranging between 0.11 to 1.29 s, with a mean equal to 0.39 s, a median of 0.39 s, and a standard deviation of 0.14 s.

The ANOVA model was not significant for the perception time at the 0.05 level. The ANOVA analysis showed that TTS (F (9,482) = 1.03, p = 0.42), roadway grade (F (1,482) = 0.74, p = 0.39), age group (F (2,482) = 0.06, p = 0.94), and gender (F (1,482) = 0.3, p = 0.58) had no significant effect on the average perception time.

Reaction Time

The reaction time, which is the time required by the driver to react after his/her perception of the yellow indication, was measured from the time the driver lifted his/her foot from the accelerator pedal until the brake was first depressed. Reaction times as a function of the yellow-phase change trigger time, shown in FIGURE 16(b) ranged between 0.09 to 1.3 s, with a mean equal to 0.37 s, a median of 0.3 s, and a standard deviation of 0.19 s.
FIGURE 16 Mean perception and reaction time as a function of TTS, age, and gender
The ANOVA model for the reaction time was significant ($P < 0.0001$) at the 0.05 level. The ANOVA analysis showed that the reaction time increases as the TTS increases ($F (9,482) = 19.8, p < 0.0001$). FIGURE 16(b) shows mean reaction times to onset of the yellow-phase from both approaches (i.e., uphill and downhill). Mean reaction time for drivers going downhill ($M=0.33$) was shorter than going uphill ($M=0.39$) where drivers may have delayed the start of their brake application. The F-statistic generated from the ANOVA test for the roadway grade demonstrated that significant differences ($F (1,482) = 10.9, p = 0.0010$) exist between the uphill and downhill approaches. The data were utilized to analyze the reaction times associated with different drivers’ age groups. The mean reaction time of drivers between 40 and 59-years-old (0.34 s) were significantly lower than those of the age group under 40-years-old (0.41 s) and 60 years of age or older (0.38 s). It is not clear why this is observed; however one can speculate that younger drivers were being less cautious and more willing to accept a higher deceleration rate. The F-statistic generated from the ANOVA test for the three age groups demonstrated that significant differences ($F (2,482) = 4.61, p = 0.0104$) exist between the driver age groups while no significant differences ($F (1,482) = 0.44, p = 0.51$) exist between male and female drivers.

**Perception-Reaction Time**

PRT, which is defined as the time elapsed between the onset of the yellow-phase and the instant the driver starts to press the brake pedal, was measured from the time of the yellow-phase onset to the initiation of braking and also can be computed by the summation of both the perception and reaction times. As mentioned earlier, cruising PRT will be considered only for those drivers with their foot already on the accelerator pedal at the yellow-phase onset, while overall PRT will be considered for all stopping drivers. Observed PRT for each driver was calculated, which provided a sample of 482 cruising PRT in the range of 0.38 to 2.4 s, with a mean equal to 0.76 s, a median of 0.69 s, and a standard deviation of 0.21 s. Overall PRT (745 observations) ranged between 0.14 to 2.4 s, with a mean equal to 0.73 s, a median of 0.69 s, and a standard deviation of 0.22 s.

The ANOVA model for both the cruising PRT and overall PRT was significant ($P < 0.0001$) at the 0.05 level and the ANOVA analysis confirmed the trend that cruising PRT ($F (9,482) = 13, p < 0.0001$) and overall PRT ($F (9,745) = 12, p < 0.0001$) increase as the TTS increases. FIGURE 17 shows the mean cruising PRT and overall PRT from both approaches (uphill and downhill). Mean cruising PRT and overall PRT for drivers going downhill (0.71 and 0.66 respectively) were shorter than going uphill (0.77 and 0.78 respectively). The F-statistic generated from the ANOVA test demonstrated that roadway grade had a significant effect on both cruising PRT ($F (2,482) = 12.4, p = 0.0005$) and overall PRT ($F (2,745) = 74.3, p < 0.0001$). No significant differences were found in the mean cruising PRT ($F (2,482) = 2.9, p = 0.06$) and overall PRT ($F (2,745) = 2.09, p = 0.12$) for the driver age groups, and also no significant differences ($F (1,482) = 0.04, p = 0.84$ for cruising PRT and $F (1,745) = 0.54, p = 0.46$ for overall PRT) exist between male and female drivers.
FIGURE 17 Mean perception-reaction time as a function of TTS, age, and gender
Mean perception-reaction times in both cases (cruising PRT and overall PRT) were compared as shown in FIGURE 18. The figure demonstrates that the mean cruising PRT curve was shifted up compared to the overall PRT over the entire TTS range except for less than 2.75 s. This shift correlates to a lower perception-reaction time for those drivers who have their foot lifted off the accelerator at the onset of the yellow interval. The results, however, indicate a similar trend and thus the gathering of PRT data when driver foot information is not available should be valid.

![FIGURE 18 Cruising PRT and overall PRT as a function of TTS](image)

**Braking Time Analysis**

The braking time, which is the time required by the vehicle to come to a complete stop, was calculated from the time the brake exceeded 1.67 percent depression after the onset of the yellow-phase transition until the vehicle came to a complete stop (speed < 0.1 km/h). Mean braking times as a function of the yellow-phase change trigger time are shown in FIGURE 19(a). For each participant, the observed mean braking times for each TTS was calculated providing a sample of 745 observed braking times ranging between 2.9 to 13.9 s, with a mean value of 7.5 s, a median of 7.5 s, and a standard deviation of 2.2 s. The ANOVA model for the braking time was significant (P < 0.0001) at the 0.05 level. The ANOVA analysis showed that the TTS had a significant impact on the average braking time (F (9,745) = 345.9, p < 0.0001). No significant differences were found in the mean braking time for the uphill (M = 7.5 s) and downhill (M = 7.52 s) conditions (F (1,745) = 0.5, p = 0.48). The results show that braking times on either approach (i.e., on upgrade or downgrade) were about the same and there were no significant differences (p < 0.05).

The F-statistic generated from the ANOVA test for the three age groups demonstrated that significant differences (F (2,745) = 6.22, p = 0.002) exist between the driver age groups. In FIGURE 19(a), the mean braking time of those under 40-years-old (7.33 s) was significantly lower ranging between 2.75 to 5.32 s than those of the age group between 40 and 59-years-old.
(7.65 s) and 60 years of age or older (7.54 s). These results demonstrate that the younger driver population while having a longer reaction time compared to the 40 to 59 age group had a shorter brake time. Consequently, it appears that these drivers were either aware of their braking capabilities and thus were not obliged to react quickly, or alternatively braked more aggressively to recuperate the lost time during their longer reaction time. The results also demonstrate that male drivers show slightly higher braking times when compared to female drivers while the F-statistic generated from the ANOVA test revealed that no significant differences (F (1,745) = 2.23, p = 0.14) exist between male and female drivers.

**Stopping Time Analysis**

Stopping time, which is defined as the time required by the driver to come to a complete stop after the onset of the yellow-phase, was measured from the time of the yellow-phase onset until the vehicle came to a complete stop and also can be computed as the summation of both the PRT and braking time. Stopping times as a function of the yellow-phase change trigger time, shown in FIGURE 19(b), ranged between 3.4 to 15.1 s, with a mean equal to 8.14 s, a median of 8.1 s, and a standard deviation of 2.24 s.

The ANOVA model for the stopping time was significant (P < 0.0001) at the 0.05 level. The ANOVA analysis confirmed the trend that the stopping time increases as the TTS increases (F (9,745) = 420.3, p < 0.0001). No significant differences were found in the mean stopping time for the uphill and downhill conditions (F (1,745) = 1.19, p = 0.28), and also no significant differences (F (1,745) = 1.96, p = 0.16) exist between male and female drivers. In FIGURE 19(b), the mean stopping time of those under 40-years-old (7.89 s) were significantly lower in the range between the 2.75 to 5.32 s than those of the age group between 40 to 59-years-old (8.22 s) and 60 years of age or older (8.19 s). The F-statistic generated from the ANOVA test for the three age groups demonstrated that significant differences (F (2,745) = 7.2, p = 0.0008) exist between the driver age groups. Consequently, while the less than 40 age group had longer reaction times in comparison to the 40 to 59 age group, they were able to stop quicker because they braked more aggressively.
FIGURE 19 Mean braking and stopping time as a function of TTS, age, and gender
Stopping Accuracy Analysis

Stopping accuracy was measured from the front of the car bumper to the inside line of the stop bar (the side closest to the approaching vehicle) after the driver came to a complete stop. A negative number indicated that the participant crossed the stop bar and stopped inside the intersection.

The ANOVA analysis showed that TTS (F (9,745) = 24.9, p < 0.0001), roadway grade (F (1,745) = 5.8, p = 0.016), and age (F (2,745) = 4.56, p = 0.011) are significant factors while gender (F (1,745) = 0.45, p = 0.5) was not significant. In FIGURE 20, the two age groups under 40-years-old and 40 and 59-years-old was merged into a single age group (under 60-years-old) and compared with the older age group (60 years of age or older) because no differences were observed between these two age groups. The results demonstrated that the older age group (60+) was more accurate when they stopped than the younger age group, probably due, in part, to their reduced approach speed. The results demonstrate that drivers that attempt to stop at TTSs less than 3 s are more likely to stop downstream of the stop bar.

FIGURE 20 Mean stopping accuracy as a function of TTS, age, and gender

CONCLUSIONS AND RECOMMENDATIONS

The study used data from a controlled field test on 60 test participants to characterize driver stopping behavior at the onset of a yellow interval at high speed signalized intersection approaches. Specifically, the study characterizes driver brake perception times, reaction times, perception-reaction times, brake times, and stopping accuracy at the onset of a yellow indication on a high-speed signalized intersection approach. The findings of the study can be summarized as follows:
Driver perception time is not impacted by TTS at the onset of the yellow interval, driver gender, driver age, or roadway grade and has a mean value of 0.4 s and a standard deviation of 0.14 s.

The driver reaction time is dependent on the driver age and TTS at the onset of the yellow interval.

The mean reaction time of drivers in the 40 to 59 age group (0.34 s) is significantly lower than those of the less than 40 age group (0.41 s) and 60+ age group (0.38 s).

While the less than 40 age group have longer reaction times in comparison to the 40 to 59 age group, they are able to stop over a shorter period of time because they typically apply more aggressive braking rates.

Overall PRT ranges between 0.14 to 2.4 s with a mean value of 0.73 s and a standard deviation of 0.22 s. Driver age and gender has no impact on the driver PRT while the PRT increases as the TTS at the onset of the yellow interval increases.

The elimination of scenarios where a driver is not pressing the accelerator at the onset of a yellow-phase has no impact on the study conclusions.

The results demonstrate that drivers who attempt to stop at TTSs less than 3 s are more likely to stop downstream of the stop bar.

These findings should be incorporated in the design of the yellow interval especially at locations where the driver population is older (e.g. retirement communities). Accounting for the age impact is critical in the design of effective and safe signal timings. Furthermore, with the deployment of Vehicle Infrastructure Integration (VII) initiatives, comes the need for in-depth understanding of age and gender impacts on driver behavior at the onset of a yellow indication.

It should be noted that a caveat of this study is that drivers experienced more yellow indications than green indications and thus could be more willing to stop than would be typical in a natural environment. Furthermore, the drivers were not distracted by the surrounding conditions and did not have other vehicles in close proximity to them when they made their stop/go decisions. Consequently, additional field studies are needed to characterize driver behavior at the onset of a phase transition considering the impact of a leading vehicle, the proximity of a following vehicle, the surrounding environment, and the impact of the approach speed on driver behavior.

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Modeling Driver Behavior within a Signalized Intersection Approach Decision/Dilemma Zone

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ABSTRACT

The study uses data gathered in a field test on 60 test participants to develop models that characterize driver brake perception-reaction times, brake times, and stop-go decisions at the onset of a yellow indication at a high-speed signalized intersection approach. The study demonstrates that driver perception-reaction times (PRTs) are only influenced by the driver’s time-to-intersection (TTI) at the onset of the yellow indication. The driver PRT is found to increase linearly with TTI and is not impacted by the vehicle speed (in the range of 54 to 88 km/h), driver gender, or driver age. In the case of stop-go behavior, the older driver (≥ 65 years of age) dilemma zone is wider, ranging from a TTI of 4.81 to 1.66 s versus 4.90 to 2.87 s for the younger age group. Female drivers are more likely to stop when compared to male drivers and tend to have a dilemma zone that is closer to the intersection. Finally, the study demonstrates that dilemma zone control systems should consider a dilemma zone from 5.0 to 1.5 s instead of the current state of practice of 5.5 to 2.5 s in order to capture all potential driver age and gender groups.

INTRODUCTION

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

Several research efforts have attempted to address the dilemma zone problem using various Intelligent Transportation System (ITS) strategies. These strategies include basic green-extension systems, enhanced green-extension systems, and green-termination systems [1-4]. More recently, researchers [5, 6] developed the Detection-Control System (D-CS), which uses two loop detectors in a speed trap configuration installed about 300 m upstream of the intersection on the main approach to detect the presence and 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 m distance. The system assumes a constant dilemma zone, defined by TTIs ranging between 5.5 and 2.5 s. The D-CS implements a 2-step gap-out (maximum gap size between consecutive vehicles) strategy to reduce the probability of max-out (reaching the maximum green time) and thus reduce the probability of trapping vehicles in the dilemma zone. During the first step, the D-CS holds the green indication until the dilemma zone is clear of any vehicles. If the dilemma zone is not cleared after a certain time, the D-CS applies a second-step relaxed criterion that allows the green to end when there is only one car in the dilemma zone (but not a truck). This two-stage operation mimics the operation of the LHOVRA and SOS systems, developed in Sweden [1, 2].

The current dilemma zone mitigation systems assume that the driver dilemma zone is fixed (ranges between 5.5 to 2.5 s from the intersection) considering a 1.0 s perception-reaction time (PRT). However, it is not clear how driver PRTs and corresponding dilemma zones vary as
a function of drivers’ characteristics and their time-to-intersection. A number of studies have demonstrated that brake PRTs may be much longer than 1.0 s and that the 85th percentile PRT is more in the range of 1.5 to 1.9 s [7]. These studies have also demonstrated that PRTs on high-speed intersection approaches (greater than 64 km/h) are lower, with 85th percentile PRTs in the range of 1.1 to 1.3 s. All studies, however, have measured the PRT as the time difference between the onset of the yellow phase and the activation of the vehicle’s brake lights; thus, the PRT estimates include the time lag from the instant the driver presses the brake pedal until the brake lights are displayed.

The objectives of this paper are four-fold. First, the paper develops models for estimating driver perception, reaction, and PRT times considering the vehicle’s instantaneous speed and TTI at the onset of the yellow interval. Second, the paper compares the controlled field study driver behavior to naturalistic field driver behavior. Third, the paper develops data transformation procedures to adjust controlled field study data to reflect naturalistic field driver behavior. Fourth, the paper evaluates gender and age impacts on driver perception-reaction times and stop-go decisions. It is anticipated that the models that are developed in this paper can be incorporated within microscopic traffic simulation software to enhance the modeling of driver behavior at the onset of a yellow interval.

In terms of the paper layout, a brief background of the problem is presented followed by a brief description of the data gathering procedures. Subsequently, driver perception, reaction, and perception-reaction times are characterized. Next, driver stop-go decisions and dilemma zone boundaries are studied. Finally, the conclusions of the paper are presented.

BACKGROUND

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

In the case of a driver arriving at a signalized intersection when the indication changes from green to yellow, the time interval from the onset of the yellow light to the instant when the brake pedal is pressed is called the perception-reaction time [9, 10], perception response time [11], brake reaction time [8, 12], perception-braking response time [13], yellow response time [14], or brake-response time [15]. This paper will refer to it as the perception-reaction time (PRT).

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

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

PRTs at traffic signals also include some lag time because the onset of the yellow does not always require immediate braking reaction unless the driver is close to the intersection. In a study by Chang et al. [14], seven intersections were observed and driver PRTs (defined as “the time elapsed from the onset of the yellow until the brake light is observed”) were recorded, this lag should be small or nonexistent on high-speed signalized approaches because the high speed requires immediate reactions to avoid excessive deceleration or even collisions with other vehicles. The study focused on the effect of the distance from the intersection at the onset of a yellow indication because, according to its authors, drivers tend to react faster as vehicles move closer to the intersection; when vehicles are farther away, the PRT might be longer because the urgency to make a decision is not as great. Accordingly, the study produced curves demonstrating significant variability in driver PRT as a function of the vehicle speed (different lines represent speeds in km/h) and distance to intersection at the instant the traffic signal turned yellow, as illustrated in Figure 21. We demonstrate that if the x-axis were replaced with the time-to-intersection instead of distance-from-intersection, the lines approach one another. Consequently, it appears that TTI would be a better explanatory variable because it combines two explanatory variables, as will be demonstrated later in the paper. Similar behavior is observed for vehicle decelerations, as demonstrated in Figure 21. However, in the case of vehicle deceleration levels the effect of speed still appears to be significant. The results of Chang et al. study suggest that speed effectively influences the median PRT, which converges to 0.9 s at speeds equal to or greater than 72 km/h (45 mi/h). Other research efforts have also considered the use of TTI as an explanatory variable [16, 17].

![Figure 21: PRTs at Traffic Signals](image-url)
A study that used a driving simulator to analyze the behavior of 77 drivers approaching signalized intersections at 70 km/h made similar conclusions [18]. The study concluded that the TTI significantly affected the PRT whereas age did not. The PRT grand mean was 0.96 s, ranging from 0.86 s for drivers closest to the intersection stop line to 1.03 s for drivers farthest from it.

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

A very recent study by Gates et al. [15] evaluated the behavior of vehicles trapped in the dilemma zone; defined by the authors to be between 2.0 and 5.5 s. The study can be classified as a naturalistic observation study that recorded vehicles behavior at six signalized intersections in the Madison, Wisconsin area comprising 463 first-to-go and 538 last-to-go records. The analysis included brake-response time and deceleration rate for first-to-stop vehicles, and probability of vehicle stopping/non-stopping. The 15th, 50th, and 85th percentile brake-response times were 0.7, 1.0, and 1.6 s, respectively. Regarding the vehicle stopping/non-stopping probability, the time-to-intersection was found to be, by far, the strongest variable affecting the stop/go decision among all other factors. Drivers were found to be more likely to stop rather than to go with greater time-to-intersection. A comparison is to be made between the calibrated model by Gates et al. (University of Wisconsin (UWn) model) [15] and our calibrated model (Virginia Tech (VT) model) will be presented later in this paper.

**DATA DESCRIPTION**

The experiment involved having each test participant drive an instrumented vehicle along a 2.6 km private highway at approximately 72 km/h. After a practice run that allowed the participant...
to get acquainted with the vehicle, the participant approached a signalized intersection a number
of times. The behavior of the driver was observed as the signal phases changed, and data on the
participant’s responses included the vehicle speed, the signal indication, and the measurements
of the pressing of the accelerator (throttle value) and brake (brake value) pedals. It is worth
mentioning that the latter two measurements; throttle and brake values, are used to determine the
perception and reaction times as will be explained later. The experiment could then be classified
as a controlled-road study, according to Green’s classification scheme [8]. It should be noted
that, while the drivers were not informed of the specific objectives of the study, they might have
inferred these objectives as a result of the multiple runs they made at the signalized intersection.

This section describes the instrumented vehicle, the test track, the test participants, and
how the data were collected.

Instrumented Vehicle and Signal Controller Box

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

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

Intersection and Intersection Approaches

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

Test Participants

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

**Procedure**

Participants were tested individually under good conditions (daylight, good weather, dry pavement, etc.). Upon arrival at VTTI, participants were submitted to a visual acuity and color vision test. All participants selected had a minimum of 20/40 vision, passed the color vision test, and were screened by a medical questionnaire for drug/alcohol use and any medical conditions that might impair driving. Participants were then escorted to the test vehicle and asked to familiarize themselves with the car, adjusting seat, mirrors, seat belts, etc., and to drive to the Smart Road, about 0.5 km away. Two experimenters rode in the car with the participant. During the drive to the Smart Road, one of the experimenters instructed the participant and answered questions while the other, in the back seat, used the on-board computer to control the trial conditions and the DAS. During the initial practice run, participants were asked to brake the car to a full stop from 40 km/h, 55 km/h, and 70 km/h to become familiar with the handling of the car under hard braking.

In the experiment, participants were instructed to drive the car at 72 km/h (45 mi/h) except in the turnarounds or when stopping at the intersection. The participants were told about the objectives of the study. 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), composing 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 bar.

The yellow duration was 4 s and was initiated when the front of the car was at the following distances from the stop bar: 32 m (105 ft), 55 m (180 ft), 66 m (215 ft), 88 m (290 ft), or 111 m (365 ft). Considering an approach speed of 72 km/h (45 mi/h) speed, these distances correspond to TTIs of 1.60 s, 2.75 s, 3.30 s, 4.40 s, and 5.55 s, respectively. Each participant faced phase changes from green to yellow four times for each distance. 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. In other words, the experimental design ensured that a driver had at least one of the four yellow light encounters on each of the two approaches.

**DRIVER PERCEPTION-REACTION TIME ANALYSIS**

Prior to describing the results of the analysis, the various parameters that were measured and a description of how they were measured are presented. Three response parameters were recorded: these included the perception time, reaction time, and brake time. It is worth mentioning here that this analysis is conducted only on the stopping drivers at the onset of yellow. The identification of the start and the end of the different response parameters is not feasible in case of non-stopping drivers given that there is no tangible action to be measured. Accordingly, the perception time was defined as the time required by the driver to perceive the yellow indication and make his/her decision, either to stop or to go. It was measured from the time of yellow indication onset to the instant in time at which the driver lifted his/her foot from the gas pedal (throttle value $\leq 6\%$). Alternatively, the reaction time was defined as the duration of time required by the driver to react after his/her perception of the yellow indication. It started from the
instant the driver lifted his/her foot from the gas pedal (throttle value \( \leq 6\% \)) until he/she pressed the brake pedal (brake value \( \geq 1.67\% \)). Finally, the braking time was defined as the duration of time required by the vehicle to come to a complete stop starting from the moment the brake pedal was pressed (brake value \( \geq 1.67\% \)) until the vehicle came to a complete stop (speed < 0.1 km/h). The perception reaction time was computed as the sum of both the perception and reaction times, whereas the stop time was computed as the sum of the three parameters; perception, reaction, and brake times. A total of 745 data records were available for analysis ranging from a minimum TTI of 1.34 s to a maximum of 6.19 s. The PRT ranged from 0.139 s to 2.400 s, while the brake time ranged from 2.9 to 14.4 s.

Although the drivers were instructed to drive at a speed of 72 km/h (45 mi/h), the approach speeds at the yellow interval onset varied considerably from 54 to 88 km/h (34 to 52 mi/h), as illustrated in Figure 22b (top right distribution). Consequently, an initial model considering the time-to-intersection (TTI) and approach speed at the yellow interval onset \( (u) \) was formulated as

\[
 t = b_0 + b_1TTI + b_2u , \tag{1}
\]

where \( b_0, b_1, \) and \( b_2 \) are model constants. A robust linear regression was applied to the data to derive the model parameters. The robust linear regression fit uses an iteratively re-weighted least squares algorithm, with the weights at each iteration calculated by applying the bisquare function to the residuals from the previous iteration. This Matlab algorithm gives lower weight to points that appear to be outliers. Data that should be disregarded are given a weight of zero. Consequently, the regression model is less sensitive to outliers in the data as compared with ordinary least squares regression.

The speed coefficient was found to be insignificant in the case of the PRT, brake, and total stop time, with \( t \)-statistic probabilities (p-values) of 0.37, 0.76, and 0.48, respectively. Given that the speed was not found to be a statistically significant explanatory variable, the analysis did not consider the approach speed any further.
Having identified the critical independent variables, the next step in the analysis was to fit a single linear model and test for normality of the residual error. Unfortunately, a Kolmogrov-Smirnov test revealed that there was insufficient evidence to conclude the data were normal ($p<0.05$), as is evident in Figure 22a (top left distribution). Different data transformations were considered including logarithmic and square root transformations; however these did not result in normal PRT data. Finally, the data were sorted and aggregated based on their TTI into equal sized bins (equal number of observations) and the average parameter for each bin was computed. Using a bin size of 3 observations or greater the PRT, brake, and stop residual errors passed the K-S normality test with p-values of 0.73, 0.12, and 0.15, respectively. An illustration of the PRT and initial speed distribution following the data aggregation is also presented in Figure 22c and d considering a bin size of 3 observations. Again a robust linear regression was applied to the data to derive the model parameters (only a single observation was excluded from the analysis using the robust regression). The estimated model parameters and Root Mean Square Error for each of the response variables is summarized in Table 5. All models and variables were statistically significant, demonstrating that the PRT, deceleration (brake) time, and total stop time increase linearly as the TTI increases.
Table 5: Summary of Model Parameters

<table>
<thead>
<tr>
<th>Measure</th>
<th>K-S Prob.</th>
<th>RMSE</th>
<th>$b_0$</th>
<th>$b_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRT (s)</td>
<td>0.73</td>
<td>0.0886</td>
<td>0.4784 (&lt;0.0005)</td>
<td>0.0577 (&lt;0.0005)</td>
</tr>
<tr>
<td>Brake Time (s)</td>
<td>0.12</td>
<td>0.5156</td>
<td>0.2008 (0.033)</td>
<td>1.8297 (&lt;0.0005)</td>
</tr>
<tr>
<td>Stop Time (s)</td>
<td>0.15</td>
<td>0.4606</td>
<td>0.6022 (&lt;0.0005)</td>
<td>1.8845 (&lt;0.0005)</td>
</tr>
</tbody>
</table>

The model predictions appear to be consistent with the field data, as illustrated in Figure 23. It should be noted that the model is valid for a TTI range of 1.5 to 6.0 s and should not be used outside this range.

Interestingly, the slope of the PRT is significantly less than the slope of brake and total stop times demonstrating that the PRT is less sensitive to the TTI in the 1.5 to 6.0 s range. Furthermore, the summation of the PRT and brake time coefficients approximately equals the stop time coefficients, as expected given that the stop time equals to the summation of both times. Interestingly, an earlier field study by Chang et al. [14] found that the PRT was more sensitive to the TTI, as illustrated in Figure 24.

![Figure 23: Parameter Variation as a Function of TTI](image)

Interestingly, the results presented here are identical to the Chang et al. study at a TTI of 2.77 s (the lowest TTI considered in the Chang et al. study). It appears that in the controlled field study (Smart Road study), given that drivers encountered more yellows than greens they were more alert and thus less sensitive to the TTI. A correction factor for the PRTs was computed in which the coefficients of the correction factor equal the difference in model coefficients, as illustrated in Figure 24. In this case the PRT correction factor equals

$$CF_{PRT} = -0.6049 + 0.2189 \times TTI. \quad [2]$$
A sensitivity analysis considering different data aggregation levels was conducted. The results demonstrate that overall the model coefficients are marginally impacted by the level of aggregation considered in the model development (differences in the third decimal place).

In an attempt to quantify potential differences in driver behavior as a function of driver age and gender, the data were divided into two age groups (group 1: < 65 years of age and group 2: ≥ 65 years of age). A full model for the PRT of the form

\[ t = b_0 + b_1 TTI + b_2 + b_2 TTI , \]

was fit to the data where \( z \) is a binary variable that is equal to 1 for group 1 and 0 for group 2. A statistical comparison of the full model to the partial model of form

\[ t = b_0 + b_1 TTI \]

revealed no statistical difference using an \( F \)-test (\( p << 0.0005 \) for \( F(2,727) \)). Similarly, no statistical differences were found in PRTs associated with the driver gender. Consequently, the results reveal no statistical differences in PRTs associated with driver age and gender. Similarly, gender and age was found to have no impact on the brake (deceleration) time (\( p << 0.0005 \)). These findings are consistent with an earlier study that were conducted using the distance to intersection as opposed to TTI [19].

**MODELING DRIVER STOP-GO BEHAVIOR**

A total of 1186 stop-go decisions were available for the analysis. The data included, the driver age, gender, TTI, vehicle speed at the onset of yellow, and a binary (0 or 1) driver stop decision variable to indicate whether a driver stopped or proceeded through the intersection. Using the data a Generalized Linear Model (GLM) of the logistic type was fit to the data considering a binomial distribution of the form

\[ \ln \frac{P_r}{1 - P_r} = \ln \frac{P_s}{1 - P_s} = c_0 + c_1 TTI , \]

where \( P_r \) is the probability of running, \( P_s \) is the probability of stopping, and \( c_0 \) and \( c_1 \) are model constants. The model calibrated parameters were 4.486 and -1.806 for parameters \( c_0 \) and \( c_1 \), respectively (\( p << 0.0005 \)). The model produced a 13.66% prediction error (a total of 162 wrong decisions out of the 1186 trials). The field observed data and model fit are illustrated graphically in Figure 25. In order to illustrate the field data graphically, the probability of stopping (\( P_s \)) was computed considering a bin size of 20 observations sorted by TTI (\( P_s \) was computed as the number of stopped trials divided by the 20 total trials within the bin). The field data, as is the case with previous field studies, clearly demonstrates a decrease in the probability of stopping as the TTI decreases. The figure also demonstrates a good match between the VT
model estimates and field observations with some outlier field observations at the 5.5 and 6.1 TTI.

Figure 25: Smart Road Field Data and Model Predictions of Probability of Stopping

Because drivers experienced more yellow than green indications (20 yellows versus 4 greens), it appeared that drivers were more willing to stop at shorter TTIs when compared to uncontrolled field test results reported in the literature, as illustrated in Figure 25 (comparing the controlled smart road VT Model to uncontrolled field test UWn Model). As mentioned earlier, a study conducted by the University of Wisconsin reported a model with $c_0$ and $c_1$ coefficient values of 6.34 and -1.69, respectively [15]. Consequently, a data transformation of the Smart Road TTI observations was applied to adjust for the higher propensity for vehicle stopping in the controlled field test versus uncontrolled field test; while maintaining the advantage of tracking the subject driver in the controlled test versus an uncontrolled field test. The computation of the data transformation parameters can be derived considering the adjusted TTI (TTI') as

$$TTI' = a_0 + (1 + a_1) TTI.$$  \[6\]

A data transformation from the VT model to the UWn model parameters can be computed considering that

$$c_0 + c_T TTI' = c_0 + c_T TTI,$$  \[7\]

where $c'_0$ and $c'_1$ are the desired model parameters (6.34 and -1.69, respectively). Solving Equation [7], the TTI adjustment factors $a_0$ and $a_1$ can be computed as

$$a_0 = \frac{c_T - c_0}{c_1},$$ and
After deriving the data transformation parameters, the Smart Road field data were transformed and the logistic model was fit to the transformed data to produce a model similar to the UWn model, as illustrated in Figure 26. The optimized model parameters are estimated at 5.82 and -1.62 (p<<0.0005) with a prediction error rate of 12.8% and a dispersion parameter of 1.01. This model is statistically equivalent to the UWn model given that the parameter standard errors are 0.41 and 0.10, respectively.

The next step in the analysis was to consider potential differences in driver behavior associated with driver gender or age.

In the case of age impacts, the data were grouped into two groups: ages <65 and ages ≥65. A full model of the form

\[ \ln \frac{P}{P_s} = c_0 + c_1 TTI + c_2 z + c_3 z TTI, \]  

was fit to the data, where \( z \) is a flag indicating the driver age group (0 for <65 and 1 for ≥ 65). The error for the full model and the partial model were then compared to identify differences in driver behavior associated with age. The computed F statistic \( (F_c) \) was estimated as

\[ F_c = \frac{(SSE_r - SSE_f)/DF_1}{SSE_f/DF_2}, \]
where $SSE_r$ is the sum-of-squared error for the reduced model (all ages), $SSE_f$ is the sum of squared error for the full model (considering two age groups), $DF_1$ is the number of parameters being tested (in this case 2), and $DF_2$ is the degrees of freedom for the full model (in this case $n-4=1182$). Given that the computed $F$-statistic (32.1866) exceeds the tabulated 95th-percentile $F$-statistic ($F(2,1182) = 3.0033$), we conclude that the difference between the two age groups is statistically significant. In the case of gender the $F$-statistic is 3.31 which is slightly greater than 95th-percentile $F$-statistic (3.00). Consequently, we can conclude that the gender difference is statistically significant.

The results demonstrate that the dilemma zone for older drivers ($\geq 65$ years of age) is larger (ranges from a TTI of 4.81 to 1.66 s) compared to the younger driver population (ranges from 4.90 to 2.87 s), as summarized in Table 6. Female drivers tend to delay their stop-go decision compared to male drivers (i.e. dilemma zone is closer to the intersection). In terms of the design of dilemma control systems, the study demonstrates that the dilemma zone should be expanded and shifted from the current range of 2.5 to 5.5 s range to 1.5 to 5.0 s.

Table 6: Summary Results of Dilemma Zone Boundaries

<table>
<thead>
<tr>
<th></th>
<th>Raw a</th>
<th>Transformed a</th>
<th>Raw b</th>
<th>Transformed b</th>
<th>Raw P(0.10)</th>
<th>Transformed P(0.10)</th>
<th>Raw Width</th>
<th>Transformed Width</th>
<th>Raw E (%)</th>
<th>Transformed E (%)</th>
<th>All E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 65</td>
<td>&gt;= 65</td>
<td>&lt; 65</td>
<td>&gt;= 65</td>
<td>Male</td>
<td>Female</td>
<td>Raw</td>
<td>Transformed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>5.198</td>
<td>3.988</td>
<td>8.381</td>
<td>4.511</td>
<td>4.783</td>
<td>4.208</td>
<td></td>
<td></td>
<td>1.55</td>
<td>1.01</td>
<td>2.32</td>
</tr>
<tr>
<td>b</td>
<td>-1.930</td>
<td>-1.781</td>
<td>-2.157</td>
<td>-1.396</td>
<td>-1.861</td>
<td>-1.759</td>
<td></td>
<td></td>
<td>-1.86</td>
<td>-1.66</td>
<td>-1.80</td>
</tr>
<tr>
<td>P(0.10)</td>
<td>1.55</td>
<td>1.01</td>
<td>2.87</td>
<td>1.66</td>
<td>1.39</td>
<td>1.14</td>
<td></td>
<td></td>
<td>2.32</td>
<td>2.16</td>
<td>1.27</td>
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<tr>
<td>P(0.90)</td>
<td>3.83</td>
<td>3.47</td>
<td>4.90</td>
<td>4.81</td>
<td>3.75</td>
<td>3.64</td>
<td></td>
<td></td>
<td>5.08</td>
<td>4.60</td>
<td>3.70</td>
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<tr>
<td>Width</td>
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<td>2.47</td>
<td>2.04</td>
<td>3.15</td>
<td>2.36</td>
<td>2.50</td>
<td></td>
<td></td>
<td>2.77</td>
<td>2.64</td>
<td>2.43</td>
</tr>
<tr>
<td>E</td>
<td>13.27%</td>
<td>13.20%</td>
<td>13.27%</td>
<td>13.20%</td>
<td>14.53%</td>
<td>13.30%</td>
<td></td>
<td></td>
<td>13.35%</td>
<td>11.95%</td>
<td>13.66%</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Regarding driver perception-reaction, brake, and stop times, the following is concluded.

a. Driver perception-reaction times (PRTs) are only influenced by the driver’s time-to-intersection (TTI) at the onset of the yellow indication.

b. The driver PRT is found to increase linearly with TTI and is not impacted by the vehicle speed (in the range of 54 to 88 km/h), driver gender, or driver age.

Furthermore, in terms of driver stop-go decisions, the study demonstrated the following.

a. The study demonstrated that the use of a controlled field testbed is suitable for gathering driver behavior within the traffic signal dilemma zone. Data transformations may be required to replicate naturalistic field data; however these transformations are simple. Specifically, the paper develops mathematical formulations for such transformations.

b. Drivers in the $\geq 65$ years of age group tend to have a wider dilemma zone in comparison to the younger age group (3.15 versus 2.03 s).

c. Drivers in the $\geq 65$ years of age group have a dilemma zone that is closer to the intersection (ranges from a TTI of 4.81 to 1.66 s) versus 4.90 to 2.87 s for the younger age group.

d. Female drivers are more likely to stop when compared to male drivers and tend to have a dilemma zone that is closer to the intersection.

e. The study demonstrated that dilemma control systems should consider a dilemma zone from 1.5 to 5.0 s instead of the current state of practice of 2.5 to 5.5 s.
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