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16. Abstract

The goal of this Texas Department of Transportation project was to gain a better understanding of driver performance at high speeds. Specific efforts included the following studies:

- The Closed-Course Pilot Study consisted of observing and recording the activities and actions of a series of drivers following a lead vehicle going either 60 or 85 mph.
- The Open-Road Pilot Study recorded participants driving between Odessa and Pecos, Texas, within 70- and 80-mph sections.
- The Simulator Pilot Study determined driver reactions to a looming vehicle (both passenger car and large truck) and also generated directions for how to conduct the Phase II simulator study.
- The Simulator Phase II Study collected brake reaction to a vehicle looming in the driver's view for 50 participants. Conditions varied included initial speed, lead vehicle type, lead vehicle deceleration rate, and workload level.
- The Following Distance Study used data from traffic counters to identify speed and axle gap data on freeways with 60-, 70-, and 80-mph posted speed limits.
- The Gaps at Passing Study measured gaps during passing maneuvers for daylight conditions on freeway sections.

When responding to a vehicle slowing in their lane, drivers in the Simulator Phase II Study at the 85-mph speed had a reaction time that was statistically longer than that of drivers at the 60-mph speed. In the simulator, on-road, and test track studies where researchers directly measured driver performance, performance declined when a driver was multitasking at the higher speed. The traffic counter data showed that axle clearance distance was larger for the 80-mph freeway sites as compared to the 60- and 70-mph speed limit sites, both statistically and practically. The Gaps at Passing Study found a different result; drivers used similar passing gap distances on both 70- and 80-mph sections.

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DRIVER WORKLOAD AT HIGHER SPEEDS

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CHAPTER 1

INTRODUCTION

Geometric design guidance has traditionally existed for speeds ranging from 15 to 80 miles per hour (mph). Potential values for geometric elements designed for 85- to 100-mph speeds were included in a recently completed research project conducted for the Texas Department of Transportation (TxDOT) (*1*). Design elements that were addressed in the final report included:

- sight distance,
- horizontal and vertical alignment,
- cross section,
- roadside design and hardware, and
- interchange ramps.

Recommendations have been incorporated into Chapter 8 of the Texas *Roadway Design Manual* (*RDM*), "Mobility Corridor (5R) Design Criteria" (*2*). Because of limited previous research, the project relied upon extrapolating from previous research and using engineering judgment to develop the criteria. One area that was identified as needing additional research was driver workload and visual abilities at higher speeds. The previous, most comprehensive research was based on data collected at initial speeds of 55 mph (*3*).

It is possible that driver workload could increase with higher speed, leading to a slowed reaction time to hazards. In other words, at high speeds it may be that the driver is paying so much attention to the basic task of vehicle control that he or she may be slower in responding to hazards. On the other hand, driver vigilance may increase with higher speed, leading to equal or faster reaction times. It is really an open research question. The use of cell phones and other in-vehicle distractions can also affect the answer to this question.

In addition to reaction, the driver must be able to see the object, both in the daytime and in the nighttime. The type of object that the driver would probably encounter is typically another vehicle, which may be traveling at a slower speed. On high-speed roads, there is a concern with overtaking a slower-moving vehicle. The rate of change of an image, in terms of visual angle, is very slow at far distances. The ability to perceive that a target is looming in your visual field, i.e., you are approaching a slow-moving vehicle from behind, depends on your ability to detect that the image size is changing, which does not occur until you are fairly close, so that at high speeds you will not have much time to decelerate or maneuver out of the way.

RESEARCH OBJECTIVES

The goal of this project is to gain a better understanding of driver performance at high speeds. Specific objectives include:

- determine perception-reaction time for high-speed situations,
- identify differences in driver workload at high speeds, and
- determine how operating speed affects following distance (or gap) at passing.

REPORT ORGANIZATION

This report has nine chapters. Their topics are:

- Chapter 1 **Introduction**—includes the objective of the project and the report organization.
- Chapter 2 **Literature Review**—includes a summary of previous research relevant to the subject of driver workload.
- Chapter 3 **Closed-Course Pilot Study**—includes information on the closed-course pilot study. This study consisted of observing and recording the activities and actions of a series of drivers on a closed-course track while following a lead vehicle going either 60 or 85 mph.
- Chapter 4 **Open-Road Pilot Study**—provides a summary of the methodology and findings from the open-road pilot study. The driver's actions were recorded while the participant drove between Odessa and Pecos, Texas, within a 70-mph section and an 80-mph section.
- Chapter 5 **Simulator Pilot Study**—discusses the methodology and findings from the simulator study of 12 participants. It also includes suggestions for how to conduct the Phase II simulator study.
- Chapter 6 **Simulator Phase II Study**—discusses the methodology and findings from the simulator study of 50 participants.
- Chapter 7 **Following Distance Study**—presents the findings regarding differences in following distance and time for 60-, 70-, and 80-mph posted speed limit freeways.
- Chapter 8 **Gaps at Passing Study**—discusses the methodology and findings from the study of minimum gaps during passing maneuvers.
- Chapter 9 **Summary and Conclusions**—provides the summary and key findings from each study along with a comparison of the study findings and the conclusions from the research.

CHAPTER 2

LITERATURE REVIEW

In TxDOT Project 0-5544, design criteria were identified for design speeds of 85 to 100 mph through the use of extrapolation and engineering judgments (*1*). The researchers noted that driver braking studies conducted as part of the stopping sight distance (SSD) evaluations (*3*) were performed at speeds less than 60 mph. TxDOT Project 0-5544 identified driver workload and visual abilities at higher speeds as needing additional research. Specific areas of interest are driver workload, visual acuity, and perception of time to contact.

DRIVER CHARACTERISTICS

According to the Virginia Tech Transportation Institute 100-Car Study, 93 percent of vehicle collisions and 68 percent of near collisions with a lead vehicle were found to have driver inattention as a contributing factor (*4*). Driver inattention encompassed secondary task engagement, fatigue, non-specific eye glances, and driving-related inattention to the forward roadway. Classical understanding only looked at secondary task engagement and fatigue. Task engagement and fatigue are part of a single construct referred to as driver arousal level (*5*). According to the Yerkes-Dodson law, a driver's quality of performance is based upon his or her arousal level. Driver performance level has been found to be poor at both low and high levels of arousal. Figure 2-1 shows the effect that arousal level has on quality of performance when conducting simple and complex tasks. For example, driving performance on a simple task such as staying in the lane is less affected by arousal than is a complex task such as avoiding an object that falls off the back of a lead vehicle.

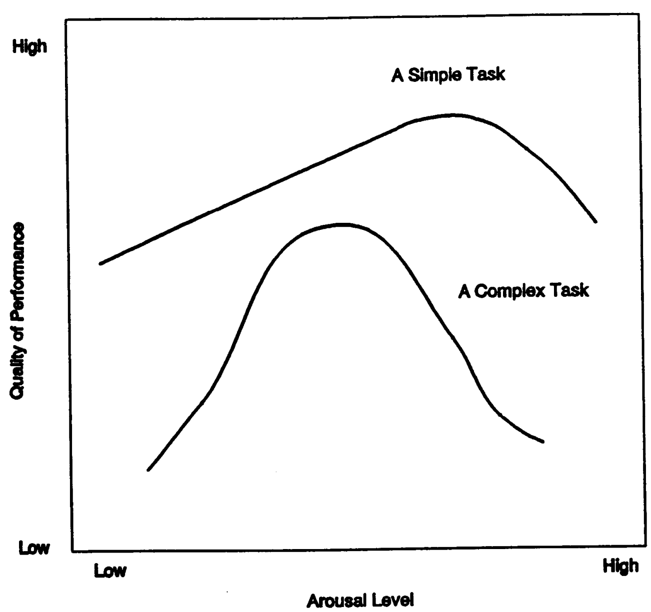


Figure 2-1. Effect on Task Performance as Arousal Level Increases.

Simonov's (*6*) Information Theory of Emotions describes a similar pattern when looking at workload. When experiencing extremely high or low levels of workload, performance declines. At intermediate levels, performance is generally at an improved level. Hancock's illustration of this phenomenon could be considered more realistic, when considering driving performance (*7*). Figure 2-2 shows Hancock's theory, which includes a wide "comfort zone" that covers a workload range found during more normative driving. As the driver becomes more or less stressed, his or her ability to adapt and perform becomes compromised. The figure also illustrates that at the extreme ends of the stress level scale, there is instability in the system so that it is impossible to accurately predict how people will perform when they are extremely under-stimulated (hypostress) and when they are extremely over-stimulated (hyperstress). At mid-levels of stress, drivers can adapt both psychologically and physiologically to deal with stress so that it does not affect their driving performance.

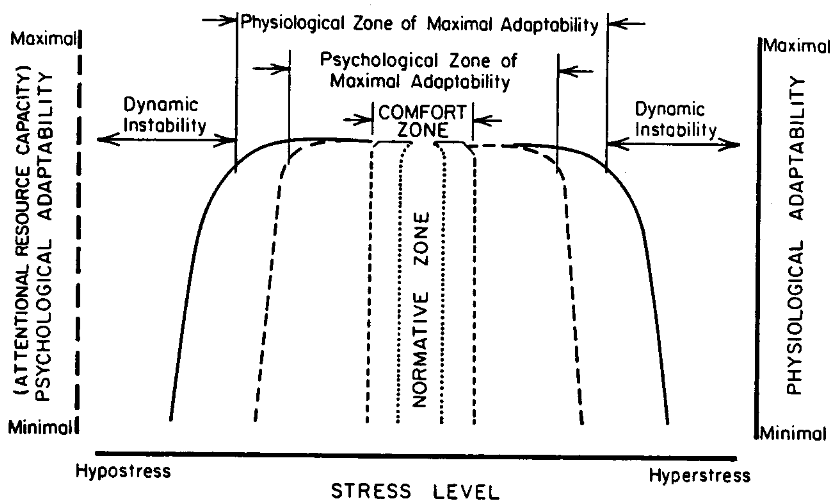


Figure 2-2. Physiological and Psychological Adaptivity as a Function of Stress (*7*).

Mental Workload

The primary method for measuring driver stress, fatigue, engagement, and arousal level is through the construct of mental workload (*8*). Mental workload refers to the amount of effort and limited processing capacity required to interpret all of the stimuli provided to perform necessary driving and non-driving tasks. Mental workload is primarily measured using subjective, performance, and psychophysiological methodologies.

Subjective Measures

These measures obtain a rating of mental workload based on the driver's assessment of the experience. The scales are primarily defined by three different approaches. First, these assessments can occur immediately, retrospectively, or at both times. Second, subjective measures are either unidimensional or multidimensional. Third, subjective measures provide either an absolute or relative measurement.

The National Aeronautics and Space Administration (NASA) Task Loading Index (TLX) and the Subjective Workload Assessment Technique (SWAT) are widely used subjective assessments. The TLX and SWAT are measured immediately, are multidimensional, and provide an absolute rating. This type of measure is extensively used in a wide range of areas (*8*). The NASA TLX is widely used when assessing mental workload (*9*). These measures are used because of their ease of use, face validity, and driver acceptance.

Performance Measures

Performance measures use deterioration or erratic performance as an indication that workload is reaching an unacceptable level (*8*). This assumes that drivers have limited workload capacity and that as driver capacity is overloaded, performance diminishes (*5*). Performance can be evaluated through the use of primary and secondary tasks. In the primary task method, the driver's ability to perform the primary task of driving is measured directly (*8*). Using the secondary task method, driver workload is measured indirectly through a secondary task. Drivers are instructed to focus on the primary task of driving and do the best they can on the secondary task. The driver's ability to perform the secondary task without jeopardizing the primary task performance provides a measure of the excess workload capacity remaining to the driver (*8*).

Secondary task measures are widely used in measuring driver workload when not using a simulator. If driver performance on the primary task of driving were to falter, then the testing environment would become dangerous. Through the use of secondary task performance measures, a safe testing environment can be maintained. The use of performance measures can be intrusive and thus change the way the task of driving is performed. The use of word games and easy-to-reach secondary controls can eliminate some of this intrusion.

With improvements in technology, two types of performance measures are becoming more prevalent in the measurement of visual workload. These measures involve the use of eye-tracking technologies and occlusion devices. These methods measure visual workload directly by looking at driver gaze patterns and visual need. These measures have been shown to be highly correlated with visual demand, and the technologies making these measures possible have made the psychophysiological measure of blink rate more viable in the natural driving environment.

Psychophysiological Measures

Psychophysiological measures look at changes in driver physiology associated with cognitive task demand (*8*). Heart rate, blink rate, and brain activity have been used and associated with certain cognitive demands. Eye blink rate has been used extensively in driver workload measures of visual demand. Heart rate and brain activity have also been used to measure workload in pilots.

Heart rate and brain activity measures have been shown to contain high variability and lag time, and the equipment is generally intrusive. This is to say the changes in heart rate and brain activity both tend to lag behind the actual increase in demand, and there seems to be large variability between subjects, making it difficult to measure. The equipment used in these measures can also interfere with the driver's ability to perform the task of driving and, in some instances, can raise the workload of participants who are not familiar with such equipment or who are uncomfortable with it.

Positive Guidance

Positive guidance is a model of the driving task that is useful for describing the three basic tasks of driving: control of vehicle, guidance, and navigation (*10*). The operation of the vehicle in terms of headway, speed, and direction falls under the control-of-vehicle task. Guidance tasks are those needed to keep the vehicle in the lane at the appropriate speed. Navigation tasks are higher cognitive tasks that involve goals and trip purpose. Vehicle control is the primary task of driving, and when mental workload increases or environmental conditions worsen, this task is preserved while guidance and navigation tasks may be shed by the driver. So, for instance, in a heavy rainstorm, a driver is using all of his or her mental capacity to concentrate on vehicle control and guidance, and will temporarily not think about navigation issues. The driver may also ask passengers to stop talking or may turn off the radio to decrease distractions in order to devote full attention to vehicle control.

Sensory Input

The five traditional senses are vision, hearing, smell, taste, and touch. Proprioception or kinesthesia describes the driver's perception of body parts in relation to each other. Simulator sickness is associated with mismatched visual and proprioception stimuli (*11*). Driver situational awareness is a function of these senses (*12*). For many years the visual sensory input level was assumed to account for 90 percent of the sensory input received by the driver. This number has been shown to have no empirical validation yet is still widely accepted (*11*). The research does suggest that visual input is the most important sensory input to the driver, but until empirical evidence is found, the value of 90 percent should not be used (*11*).

Besides visual input, hearing, touch, and proprioception are considered inputs that are used by drivers while performing the task of driving. These senses combine to provide feedback to the driver about vehicle performance and the driving environment. Drivers have high sensitivity to changes in this feedback, whether it be tactile, auditory, or vibratory (*12*). However, drivers do not seem to be aware of this sensitivity (*12*). Advances in vehicle technology could inadvertently remove situational feedback without drivers compensating for this change.

Perception-Reaction Time

Perception-reaction time is the time it takes a driver to detect a danger, recognize it as a danger, decide on a course of action, and begin to take action. These judgments are a function of perceived following distance, perceived time to contact, and driver experience (*13*, *14*). Fambro and his colleagues confirmed that a 2.5-sec perception-reaction time used in American Association of State Highway and Transportation Officials (AASHTO) SSD encompasses most of the driving population (*15*). SSD includes both the perception-reaction time and the time for vehicles to slow to a stop. The SSD studies were conducted at speeds of 55 mph or lower.

Perceived Risk and Risk Homoeostasis

Part of perception-reaction time is the driver's judgment of a dangerous situation. The driver's judgment is a result of his or her recognition of the perceived risk. Kruysse suggests a majority of dangerous judgments are made at the onset of the conflict (*16*). Risk homoeostasis theory implies that drivers have a level of risk in their driving that they are willing to accept and that as technologies improve vehicle safety, drivers perform more dangerous driving maneuvers (*17*).

While risk homoeostasis is under debate, Fuller suggests there are three basic uses of the term risk (*18*). According to Fuller, risk has been used to describe objective risk, subjective risk, and a feeling of risk (*18*). Objective risk is the statistical probability of being involved in an accident. Subjective risk is the driver's estimate of the objective risk. The driver's feeling of risk is an emotional response to threat such as a feeling of anxiety. These assessments of risk have been related to a driver's feeling of control. This feeling of control is assumed to be the inverse of the difference between the demanded ability and capability of the driver (*18*). Thus, as demand increases or capability decreases, the feeling of control decreases. This feeling of control is associated with the perceived risk of the situation.

Driver Trait and State Factors

Driver trait factors are related to the driver in general, and state factors are related to the particular driving experience in question. A strong correlation between reckless driving behavior and the trait factors of aggressiveness and sensation seeking has been found (*19*). Angry drivers are also correlated with reckless driving behavior. Adolescent boys tend to have higher ratings of sensation seeking, aggressiveness, and episodes of anger than adolescent girls (*19*). Driver age is another trait factor of concern. Drivers over the age of 65 have higher crash ratios than drivers of other ages when performing left turns, gap acceptance, and lane changes (*20*).

Speed Adaptation

As drivers experience higher speeds for longer periods of time, their estimation of lower speeds becomes less accurate (*21*). Schmidt and Tiffin found that as vehicles traveled at 70 mph for 20, 40, or 60 minutes, the driver's estimation of when the vehicle was traveling at 40 mph became less accurate. Drivers having traveled 70 mph for 20 minutes estimated a 44.5-mph speed as being 40 mph. Drivers having traveled 70 mph for 40 minutes estimated a 50.5-mph speed as 40 mph. Drivers having traveled 70 mph for 60 minutes estimated a 53.4-mph speed as 40 mph (*21*). Speed adaptation is important to consider in the design of higher-speed facilities because the effects at those speeds are unknown.

DRIVER-VEHICLE INTERACTION

The modern vehicle has many components that compete for driver attention. Radios have been in vehicles for quite some time, but MP3 players, Bluetooth technology, navigation devices, and other intelligent transportation systems are now being included in the cab. These devices compete with other components of the vehicle, such as the steering wheel and feedback instrumentation, that are necessary for proper vehicle operations. Vehicle size and driver placement within the cab can also affect the driver's ability to perform the primary task of driving, such as maintaining proper following distance.

Vision Obstruction

Drivers judge following distance based on the amount of road visible in front of the vehicle (*13*). The amount of road visible is affected by the size of the following vehicle's hood and the eye height of the driver. One study examined the effect of lead vehicle size on the judgment of following distance by having participants view driver-viewpoint still photographs of lead vehicles at different distances ahead. They found no effect of lead vehicle size on judgments of following distance. They did find that raising the driver eye height, to produce more visible roadway over the hood of the vehicle, did increase participants' ratings of following distance.

While larger vehicles may be on the conservative side of following distances, this is not true of their blind spots. Larger vehicles have larger blind spots (*22*). Blind spots are locations around the vehicle that the driver cannot view with the use of mirrors, and the driver must change his or her gaze pattern to detect the presence of a vehicle in the blind spot. Even when the driver looks, some vehicles have blind spots so large that detecting another vehicle's presence may be difficult or impossible (*22*).

Driver Hand Placement

Modern vehicles also contain more advanced devices for driver comfort, such as electronically controlled mirrors and seats. Many steering wheels now contain radio controls along with the cruise controls. While many of these features are intended to make driving more enjoyable, they are still competing for driver attention. The steering wheel is the primary method for vehicle trajectory control (*23*). A hand position of ten and two has been assumed to provide maximum vehicle controllability.

Survey data confirmed that drivers perceive a hand position of ten and two as providing more vehicle control than other hand positions (*24*). In a study comparing perceived risk and driver hand placement, it was found that in situations where there is a higher perceived risk, drivers place one or both hands on the top of the steering wheel (*24*). There does seem to be a difference between observed and reported typical hand placement. Drivers tend to overestimate themselves, having both hands on top of the steering wheel.

DRIVER-VEHICLE INTERACTION WITH THE DRIVING ENVIRONMENT

As mentioned previously, drivers' primary method for interacting with the driving environment is through vision. Vision occurs through the windows of the vehicle and the mirrors on the outside of the vehicle. Blind spots are areas surrounding the vehicle where other vehicles are difficult to detect. Through the use of frequent mirror checks, surrounding vehicles can be tracked, and their presence in blind spots can be more easily discovered. On the German autobahn, the use of the rearview mirror is strongly encouraged due to the approach of vehicles traveling at high velocities (*25*). Drivers of the autobahn are also encouraged to perform passing maneuvers quickly to limit their time next to other vehicles, and passing on the right is not allowed (*25*). The right side of a vehicle has the largest blind spot (*22*).

Mirror Check and Gaze Patterns

Mirror checks are only a portion of a driver's gaze pattern. Driver gaze patterns involve all the objects inside and outside the vehicle that the driver fixates upon. Fewer mirror checks and longer fixations are often found in instances of higher workload (*26, 27, 28, 29*). A study conducted for Transport Canada reported that drivers spend 78 percent of their time looking forward when performing no cognitive tasks. As tasks of increasing difficulty were added, the percentage of time drivers spend looking forward increased (*26*). In the same conditions the percentage of time checking mirrors decreased, indicating a drop in this secondary task as cognitive demand increases. In another study it was found that as vehicle speed increases, driver gaze patterns become narrower, indicating an increase in driver workload (*29*).

Perception of Forward Objects

Forward objects are any obstacles that present themselves in front of the driver. The first step in avoiding a collision is to recognize the presence of an object. These objects must be detectable in both daylight and nighttime conditions. In most cases this object is another vehicle (*30*). Non-object characteristics of the roadway such as signs and curvatures also need to be recognizable to the driver (*27*, *31*, *32*, *33*). The number of cues available to a driver when driving at night is relatively small compared to the amount available during the day (*31*). During the nighttime hours, sign and pavement marking reflectivity is important because these markings provide the primary cues for roadway curvature and direction for drivers (*31*).

Road Sign and Pavement Marking Retroreflectivity

Retroreflectivity is the ability of an object to reflect light back to the source. In the case of road signs and pavement markings, it is their ability to reflect the light provided by the vehicle headlights back to the driver of the vehicle (*31*). Drivers do not see reflectivity, but they do see the luminance that their vehicle headlights provide after the light is reflected by the object of concern. Past the age of 20, the amount of luminance required by the driver doubles every 13 years (*31*). Currently sign sizes are designed for below 40 mph and above 45 mph (*31*). These design standards may not be sufficient for high-speed facilities.

Visual Demand

Visual demand is a portion of driver workload related to the amount of time a driver must fixate on an object or objects. Some roadway geometries require a longer fixation and thus increase visual demand (27, *32*, *33*). There is an inverse relationship between curve radius and visual demand (*27*).

Sight Distance

As noted in AASHTO's *A Policy on Geometric Design of Highways and Streets* (commonly known as the *Green Book*) (*34*), a driver's ability to see ahead is of the utmost importance in the safe and efficient operation of a vehicle on a highway. Sight distance is the length of the roadway ahead that is visible to the driver. The available sight distance on a roadway should be long enough to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. Stopping sight distance is the sum of:

- the distance traversed by the vehicle from the instant the driver sights an object necessitating a stop to the instant the brakes are applied, and
- the distance needed to stop the vehicle.

Sight distance for curves is dependent on the height of the driver's eye and the object's height above the road surface. The 2004 *Green Book* uses values for driver's eye height and object height that were identified in a mid-1990s study (*35*). Horizontal and vertical curve designs are based upon the driver's eye height and object height along with stopping sight distance and design speed.

Time-to-Contact Estimations

When driving on a multilane highway, drivers frequently encounter other vehicles and need to make judgments on when to change lanes or slow to avoid contacting another vehicle. Time-to-contact estimation is the subjective prediction of the amount of time it will take for two objects to meet if their velocities and paths remain constant. It has been shown that drivers underestimate their time to contact and that as closing speeds increase, these estimates become more accurate (*14*, *36*). These studies paced a participant driver closely following a lead vehicle that braked suddenly. In this situation, as opposed to the studies of avoiding objects in the road, drivers chose to brake rather than maneuver in order to avoid a collision. Given a greater amount of time to choose their method of avoidance, for instance at greater following distances, drivers will exhibit uncertainty and take more time to make their decision (*14, 36*).

Perception of Speed

Olson and Farber discussed perception of speed by a driver (*37*). Driver judgment of the speed of other vehicles is generally less reliable than judgment of distance, especially when the other vehicle is moving directly toward or away from the observer. The cues drivers use to judge speed include the rate of increase or decrease in the angular size of the vehicle as it comes closer or moves farther away. Just as image size is a cue for distance, change in image size is a cue to change in distance. Stated in another manner, if the object seems to be getting larger, it means the distance is closing. Drivers have difficulty detecting changes in vehicle speed over a long distance due to the relatively small amount of change in the size of the vehicle that occurs within a given time period.

When the path of the other vehicle is almost directly away from the observer, the primary closing rate cue—and perhaps the sole cue—is rate of change of image size. That is, if the object seems to be getting larger fast, that indicates a high closing speed. As noted by Olson and Farber, the difficulty is that this cue to closing speed depends not only on closing speed but also on separation distance. At large separation distances, the apparent size changes slowly. They provide a simple example shown in Figure 2-3 to illustrate why this happens. Imagine that a vehicle first comes into view when it is 1000 ft away. Unknown to the observer initially is that it is stopped. As the distance closes by one half (i.e., from 1000 to 500 ft), the image size of the vehicle doubles and doubles again when the distance is again reduced in half, but in half the time. The relationship between viewing distance and image size is not a linear relationship. The fact that it is a nonlinear relationship adds to the difficulty drivers have in making accurate estimates of closing speed.

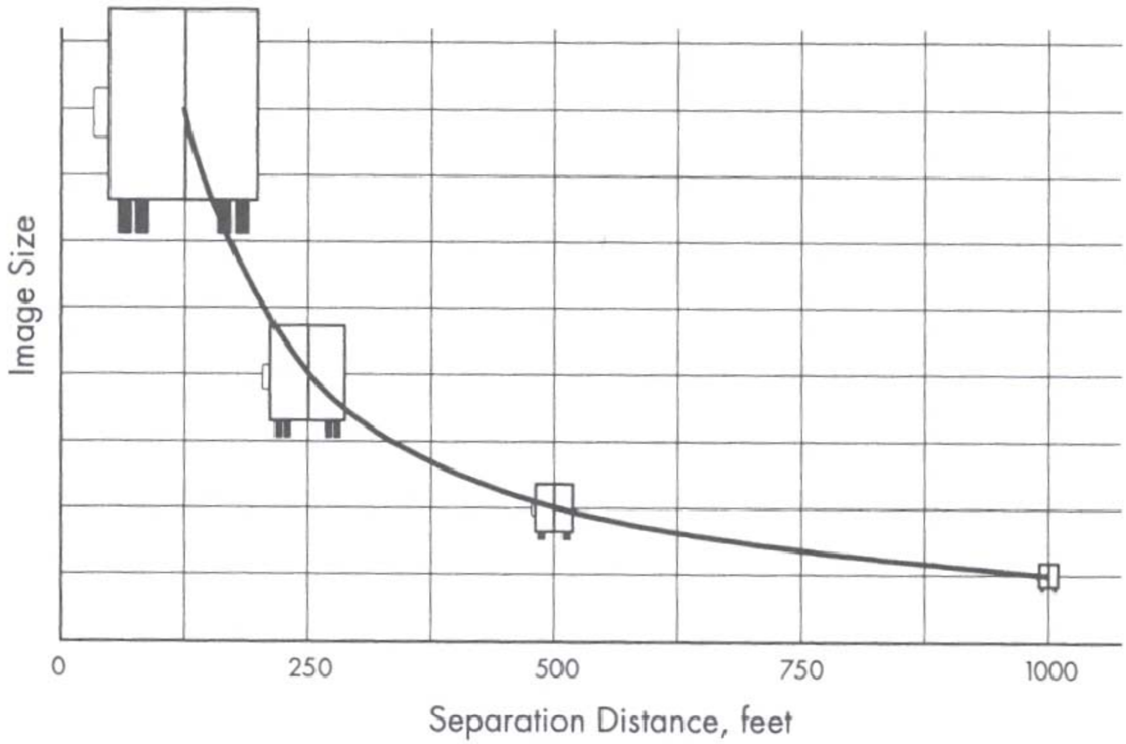


Figure 2-3. The Relationship between Viewing Distance and Image Size (*37*).

Olson and Farber provide the following equation to estimate the distance at which drivers approaching a slower-moving vehicle can first begin to sense the closing rate:

$$D_{th} = (W\,V / 0.003)^{0.5} \qquad (2\text{-}1)$$

Where:

D_{th} = threshold distance (ft),
W = width of the target vehicle (ft), and
V = closing rate (ft/sec).

Olson and Farber emphasize that the distance given by this equation is *not* the distance at which a driver can first determine that he or she is closing on a slower vehicle. The equation estimates the distance at which a driver overtaking a stationary or slower-moving vehicle first realizes how rapidly the spacing is closing, and that some response is required in the next few seconds.

Numerical examples are given in Table 2-1 for several combinations of vehicle widths and speeds. Note that the threshold distance increases with the speed but not proportionally. The time separations corresponding to the distances are also listed in Table 2-1. The result is that at higher speeds drivers have *less* time to respond even though they have more distance. Table 2-1 illustrates that by the time a driver is close enough to a slower-moving or stopped vehicle to directly appreciate how rapidly the space is closing, the driver has limited time to respond. The situation becomes worse as closing speed increases and the perceived size of the lead vehicle decreases.

Table 2-1. Distance and Time Separation at Which Drivers Can First Judge Closing Rate with a Vehicle Directly Ahead (*37*).

Target Vehicle Width (ft)	45 mph		60 mph		75 mph	
	Distance (ft)	Time (sec)	Distance (ft)	Time (sec)	Distance (ft)	Time (sec)
8 (tractor-trailer)	420	6.4	484	5.5	542	4.9
6 (passenger car, daytime)	363	5.5	420	4.8	469	4.3
5 (passenger car, nighttime)	332	5.0	383	4.4	428	3.9
2 (trailer, frame rail-mounted lights)	210	3.2	242	2.8	271	2.5

CHAPTER 3

CLOSED-COURSE PILOT STUDY

INTRODUCTION

Researchers conducted a field study of driver workload and visual capabilities at speeds of 60 mph and above. This study consisted of observing and recording the activities and actions of a series of drivers on a specified open road and a closed-course track. Each participant drove both an open-road portion and a closed-course portion. The two portions will be described in separate chapters. Chapter 3 focuses on the closed-course study where the participants drove a specified number of laps on the track. Chapter 4 focuses on the open-road study.

STUDY PARTICIPANTS

Fourteen volunteer participants participated in the study. The sample of participants was comprised of four females and ten males recruited from the Odessa, Texas, area. Participants ranged in age from 20 to 71, with a mean age of 49 (two participants did not report their age), and the average number of years with a driver's license was 33.

Participants were recruited through the use of flyers physically posted in public places and sent by e-mail to the Odessa TxDOT office as well as other local agencies that were potential generators of interested participants. As they responded to the flyers or word-of-mouth publicity by others, the participants were briefed on the nature of the study and assigned an appointment time to meet the research team in Odessa to begin their participation in the study. Participants were paid $100 at the end of their study.

STUDY VEHICLES

Study Vehicle

The instrumented vehicle used as the subject car for this experiment was a 2006 Toyota Highlander. The instrumented vehicle has a larger alternator, radiator, and fan coupling than a normal vehicle and has a greater alternator capacity to power instruments in the vehicle. The vehicle also has an eight-way power seat in order to best accommodate test participants.

The principal system within the instrumented vehicle is the Dewetron DEWE5000. Essentially a large portable computer, the DEWE5000 serves as the data acquisition device for all the peripheral systems in the vehicle. The DEWE5000 is capable of sampling at 5000 Hz. For this experiment, data were collected at 100 Hz. The DEWE5000 is mounted in a wooden equipment cabinet, which is located in the place of the driver's-side rear seat.

A Trimble DSM232 global positioning system (GPS) is used to track the position of the subject vehicle during a study. It employs a differential GPS antenna, which is mounted on the roof of the vehicle directly over the driver's seat. The GPS samples data at 10 Hz, and the receiver is mounted inside the equipment cabinet.

A Vorad radar is mounted on the front of the vehicle behind the bumper to enable the collection of headway data and to note the presence or absence of a lead vehicle. The radar has a functional range of up to 450 ft. Along with outputting the distance to up to five forward targets, the radar also outputs the differential velocity of each target as well as the azimuth of each target in order to help differentiate one forward object from another.

An AssistWare SafeTRAC package is able to track the lateral lane position of the instrumented vehicle as well as the lane width and the lateral velocity. This is accomplished through the combination of a forward-looking charge-coupled device (CCD) video camera and sophisticated image-processing software. The SafeTRAC outputs lateral lane position, lateral velocity, and lane width at 10 Hz.

A Crossbow piezoresistive accelerometer is used to collect acceleration data for three axis points of reference. It has a sensitivity of 0.6218 mV/g. The accelerometer is mounted on the cabinet behind the driver.

For this study, three potentiometers were initially used to collect data on the position of the brake pedal, gas pedal, and steering wheel; however, these systems failed during the on-road data collection for the third participant. For all subsequent participants, a video camera was mounted on the side of the driver's seat to capture the gas/brake pedal behaviors of the participants.

Video data of the experiment were collected by three cameras. One camera, facing the participant, was a 170-degree, wide-angle bullet color camera (CFC2010WA). A black-and-white bullet camera made by ProVideo was used as a forward-scene camera. It had a resolution of 420 lines. An identical black-and-white camera was used to capture the gas/brake pedal behavior for the later participants. These camera views can be seen in Figure 3-1.

Figure 3-1. Camera Views for Video Data.

Lead Vehicle

During the closed-course data collection, a confederate vehicle acted as a "lead vehicle" for the majority of this portion of the data collection. A 2007 Mitsubishi Galant was used for the lead vehicle in this study, as shown in Figure 3-2. The specific uses of the lead vehicle are described in a later section of this document.

Figure 3-2. Lead Vehicle and Instrumented Vehicle on Closed-Course Track.

TEST TRACK COURSE

The test track was a 9-mile circle track with three lanes. The experiment was conducted in the center lane to provide the most room for evasive maneuvers, to avoid grass that had grown through the pavement joints, and to avoid debris that may have collected at the edges of the driving surface. The center lane had nominal superelevation with a constant degree of curve; the track exhibited slight elevation changes throughout the complete circuit. The center area, or infield, of the circle track contained a basic West Texas landscape (level ground with small brush) with a few small buildings, but generally provided very few landmarks for the participants to use to give them information about where they were on the circle. Figure 3-3 shows a driver's view of the track.

The track was intermittently striped with broken white lane lines. Where the lane lines were absent, the pavement joints provided enough visual information to communicate where the three lanes were positioned. Participants were told that they would be driving in only the center lane.

While at the test track, each participant drove six laps while data were collected. Much of the data were associated with specific events and driving tasks that occurred at predetermined locations on the track. Table 3-1 provides a summary of the approximate relative workload for each of the events and tasks, and a summary of the six laps is shown in Figure 3-4; the specific events and tasks noted in the table and figure are described in the following sections. A researcher rode in the backseat of the instrumented vehicle with the participant driving, while a safety observer rode in the front seat.

Figure 3-3. Driver's View of Test Track.

Table 3-1. Relative Workload of Closed-Course Driving Events.

Workload	No Event (Normal Driving)	PDT Event	Brake Light Event	Decel Event	PDT with CD	Decel with HVAC
Baseline	X					
Low		X	X	X		
High					X	X
NOTES: PDT = peripheral detection task Decel = deceleration CD = compact disc task HVAC = heating, ventilation, and air conditioning (climate control) task						

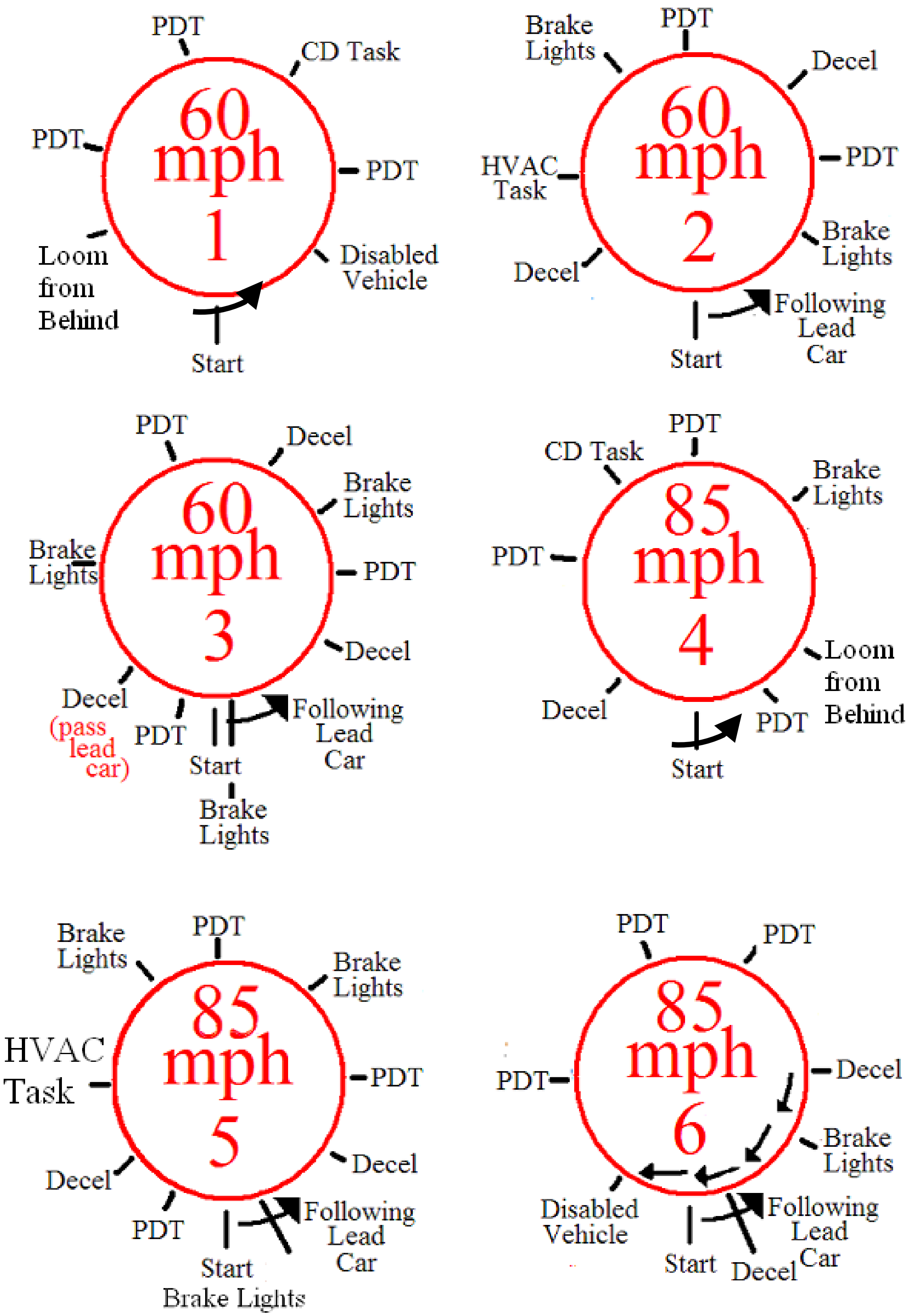


Figure 3-4. Description of Events on Six-Lap Closed-Course Study Course.

STUDY OVERVIEW

Participant Instructions

Each participant drove the first three laps at approximately 60 mph. After completing the first three laps, participants were given a short break; then they were instructed to drive the last three laps at approximately 85 mph. Participants were not allowed to use the cruise control; they were explicitly told that they would not have their speed corrected unless they were more than 5 mph away from the target speed. Participants were told that they would be looking for some events as they drove around the track. Below are the exact instructions given to the participants:

> *"Today we're going to drive six laps around the outer test track. The track is 9 miles long and three lanes wide. Today, you will be driving in the middle lane.*
>
> *"For the first three laps we will drive today, I will ask that you drive approximately 60 mph. For the last three laps we will drive at 85 mph. We ask that you not use the cruise control during the test-track portion of this experiment.*
>
> *"While this is a closed test course, I would like you to try to drive as naturally as possible. This includes scanning your surroundings for animals or other vehicles."*

Peripheral Detection Task

The peripheral detection task was implemented to study participants' mental workload at the two different driving speeds. Occasionally, at predetermined locations around the track, the experimenter in the backseat illuminated a small light-emitting diode (LED) visible to the driver in the rearview mirror. The participants were instructed to respond verbally when they noticed the light was on, at which point the light would turn off and the experimenter would record the response time on the DEWE5000 computer. Below are the exact instructions given to the participants:

> *"In order to encourage you to check your surroundings from time to time, a small light will become illuminated in your rearview mirror. This light will come on and stay on until you notice it by responding out loud with the word 'light.'"*

Lead Vehicle Events

Participants were informed that at some points during the closed-course portion they would be following another car driven by Texas Transportation Institute (TTI) researchers. When this lead car was present, they were instructed to look for two events, a brake light event and a deceleration event. This lead car was present in the parking lot while the participants were briefed on the procedure and given the instructions, so they were familiar with the appearance of the vehicle. Below are the exact instructions given to the participants:

"At some point on the track today, we will begin following another car. When the other car is present, just drive as you naturally would on public roads, maintaining a safe following distance.

"When you are following the other car, I will ask you to look for some special events."

Brake Light Event

At predetermined points around the track, the lead car driver tapped the brake pedal just enough to illuminate the brake lights for about 1 sec. Participants were asked to respond to these events by briefly tapping their brake pedal. Below are the exact instructions given to the participants:

"If you see the brake lights illuminate on the other car, I'd like you to press your brake pedal to indicate that you noticed the lights."

At the beginning of each brake light event, the passenger in the lead vehicle communicated by radio to the experimenter in the subject vehicle, to tell him the instant the lead car brakes were applied. This instant was marked in the data file on the computer. Likewise, when the participant tapped the brake pedal, this action was also recorded on the computer. This allowed brake light reactions to be scored even if the illumination of the brake lights was not visible in the forward camera of the participant's vehicle.

Deceleration Event

At predetermined points around the track, the lead car driver simply released the gas pedal and began coasting. Simultaneously, the lead car passenger radioed to the experimenter in the subject vehicle that the deceleration was beginning. As participants noticed the lead car looming closer, they indicated they were aware of the deceleration event by tapping the brake pedal. At this point, the experimenter in the back of the participant vehicle radioed the lead car, which then accelerated quickly back up to the target speed. As with the brake light events, both event times (the beginning of lead car coasting and the participant's brake activation) were recorded on the computer. Below are the exact instructions given to the participants:

"At some point the driver of the lead vehicle may let off the gas and begin slowing down. When you notice this happening, I'd like you to again respond, by pressing your brake pedal. After you indicate that you noticed the deceleration, I'll radio the driver and have him speed up again."

"Disabled Vehicle"

In addition to the two events described above, researchers also added a "disabled vehicle" event, which participants were not specifically instructed to anticipate. One time during the first lap at 60 mph and once during the last lap at 85 mph, the lead vehicle was parked along the right side of the track as the participant vehicle came upon it, simulating a stopped or disabled vehicle on the shoulder of a highway. The participants were vaguely instructed to tell the experimenter if they noticed anything unusual around the track, and all participants did indicate when they noticed the stopped car at both speeds. Below are the exact instructions given to the participants:

"Also, if you notice anything else unexpected out here, just tell me when you see it."

In-Vehicle Tasks

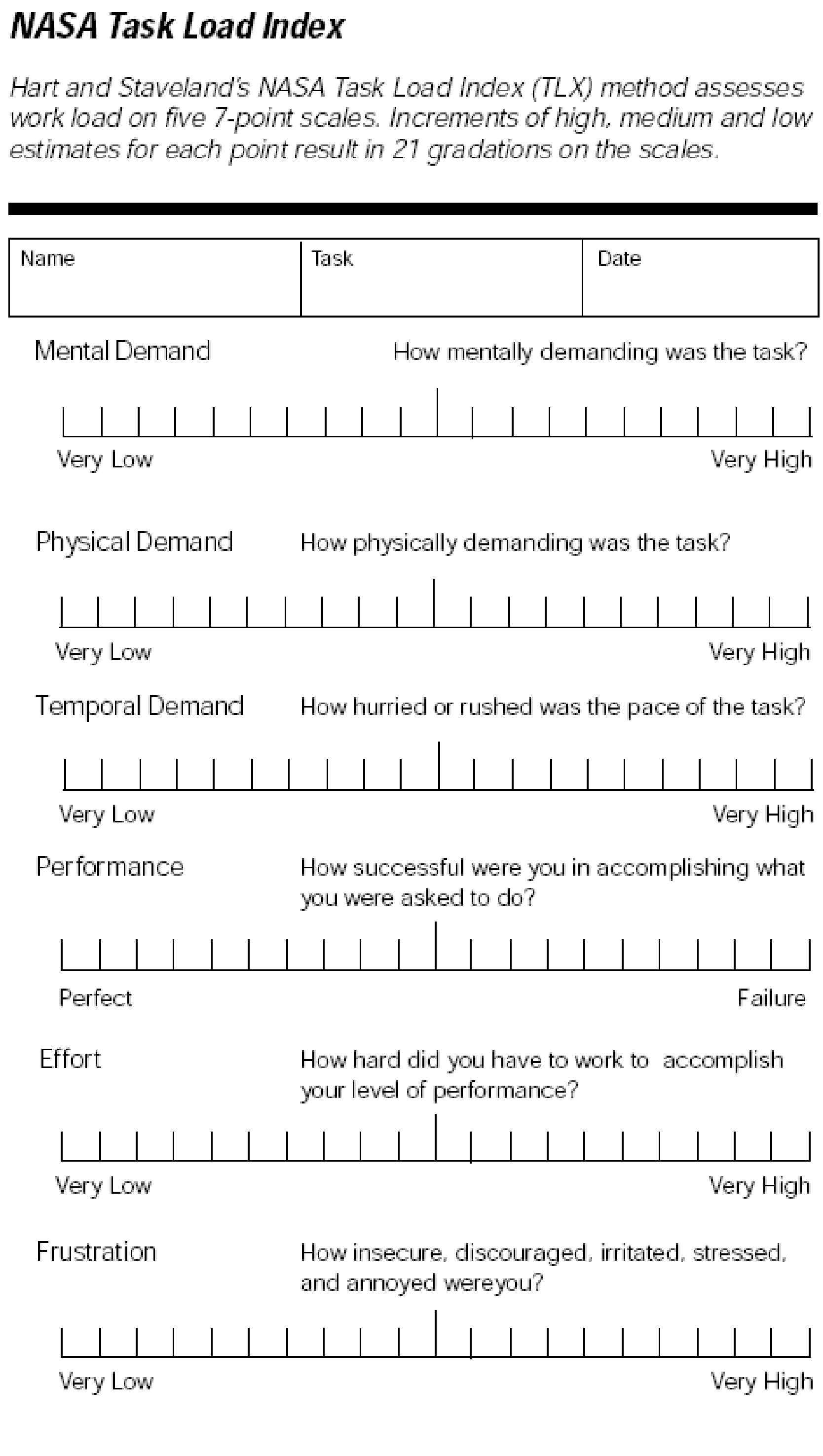
Once at 60 mph and once at 85 mph, each participant was asked to perform a "CD change" task and an "HVAC" task. In the CD task, the experimenter asked the participant to remove a specified CD from the CD holder in the windshield visor, insert the CD into the vehicle's CD player, and select a specific track to play. Once the task was completed, the safety observer turned off the CD player, and the driving experiment continued. In the HVAC task, the experimenter asked the participant to set the climate control system to a certain setting (e.g., maximum air conditioning, low fan, and output to blow on the feet). After the task was complete, the safety observer reset the climate control to the settings in effect prior to beginning the task. Each participant performed these tasks at the same locations around the track. A PDT was scheduled during the CD tasks, and a deceleration event was scheduled during the HVAC tasks. Below are the exact instructions given to the participants:

> *"Finally, we have a few tasks that we will ask you to perform while you're driving around the track today.*
>
> *"First, one time at 60 mph and one time at 85 mph, I'll ask you to select a CD from the CD visor above you and insert it in the CD player. Then I'll ask you to play a specific track. Let's practice this now…*
>
> ***"'Remove the red CD from the visor and play track 6.'***
>
> *"The other task involves adjusting the heating and cooling system (show controls). Let's practice this now…*
>
> ***"'Adjust the settings to the hottest temperature with the fan at the highest speed on your feet only.'"***

NASA Task Load Index

Drivers have some awareness of their workload while doing various tasks. Researchers chose to include a subjective rating scale of workload developed by NASA called the Task Load Index. NASA TLX produces an overall workload score based on a weighted average of ratings on six subscales (see the reproduction of the scale in Figure 3-5). These subscales include mental demands, physical demands, temporal demands, own performance, effort, and frustration. This assessment tool has been used in the human factors field for over 20 years in many different applications including aviation, automotive, workstation design, and other military applications.

During the break at the end of the third lap, after completing the 60-mph portion of the study, the participant was instructed to drive back into the staging area in the track infield. At this point the NASA TLX was administered via a laptop computer on the front passenger seat. Using the laptop's touch pad, participants indicated where they estimated their workload to be on each scale. The software converted these entries into numerical form on a scale of 1 to 100 with a higher number indicating a higher degree of workload.



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure 3-5. The NASA Task Load Index Scale (source: http://humansystems.arc.nasa.gov/groups/TLX/).

After the NASA TLX, which took approximately 5 minutes to complete, the participant drove back onto the course and accelerated to 85 mph. The three laps at 85 mph were executed very similarly to the first three laps at 60 mph. The experimenter and lead vehicle conducted the same events, but in a different order and at different locations around the track (see Figure 3-4). At the end of these three laps, the participant again drove to the staging area and was again administered the NASA TLX immediately.

DATA REDUCTION

Peripheral Detection Task Events

PDT events were evaluated by the elapsed time between the activation of the LED and the confirmation from the participants that they saw the LED, at which time the light was switched off. Therefore, the duration of the PDT event was recorded as the total time the LED was on.

The reviewer examined the Dewetron data profile for the times when the LED was switched on and switched off and input those times into a spreadsheet, along with the speed of the instrumented vehicle at the time the LED was switched on. The reviewer then calculated the difference in time between the two incidents to determine the participants' reaction times to recognize the activated LED. A sample of the spreadsheet is shown in Table 3-2.

Table 3-2. Sample of PDT Event Spreadsheet.

Participant	Lap	Location	Lap Speed (mph)	Actual Speed (mph)	LED Time On* (sec)	LED Time Off* (sec)	Reaction Time (sec)
1	2	E	60	61.7	921.1	925.2	4.1
1	2	C	60	59.5	1315.4	1317.9	2.5
1	3	F	60	60.8	1551.8	1553.1	1.3
1	3	I	60	58.5	1654.8	1667.0	12.2
1	4	A	85	84.5	1771.7	1772.9	1.2
1	4	G	85	84.8	2045.8	2047.6	1.8
*Elapse time from beginning of run							

It should be noted that the process used to gain the participants' confirmation probably added a fraction of a second to the participants' reaction times. The study required the participant to tell the experimenter that the light was on, at which time the experimenter would note the time on the computer. The process of telling the experimenter and noting the time on the computer took some additional time, generally on the order of 0.5 sec. This added time is included in the reaction times shown in Table 3-2 and used in the analysis; however, every PDT event for every participant had the same process, so the added time was consistent over the entire study.

Brake Light and Deceleration Events

Brake light events and deceleration events were reduced in similar ways. For each event researchers wanted to know the reaction time of the participant, i.e., how much time passed between the activation of the lead vehicle's brake light (or beginning of the lead vehicle's coasting action) and the participant's release of the instrumented vehicle's accelerator and activation of the brake. In addition, researchers wanted to know the distance between the lead and instrumented vehicles (i.e., gap distance) at those times.

As stated above, the lead car passenger radioed the experimenter in the instrumented vehicle when the lead vehicle brake was activated (or the lead vehicle began coasting) to begin an event. The experimenter marked this time in the data profile recorded for that participant in the Dewetron computer. The subsequent actions of the participant to release the accelerator and activate the brake were also recorded through the sensors imbedded in the instrumented vehicle. As a result, each event is displayed in the participant's data profile as an identifiable sequence of incidents.

After coding the brake light and deceleration events in the spreadsheet, the reviewer calculated the elapsed times between the incidents to determine the participants' reaction times to release the throttle and activate the brake. The gap distance (distance between the front of the instrumented vehicle and the rear of the lead vehicle) was also identified, as recorded by the instrumented vehicle's forward radar sensor. A sample of the spreadsheet is shown in Table 3-3.

Table 3-3. Sample of Brake Light Event Spreadsheet for Participant 1.

Lap	Location	Lap Speed (mph)	Actual Speed (mph)	Gap (ft)	Brake Light Time* (sec)	Release Throttle Time* (sec)	Apply Brake Time* (sec)	Reaction Time to Release Throttle (sec)	Reaction Time to Apply Brake (sec)
2	B	60	61.4	205.9	703.3	704.8	705.6	1.5	2.3
2	F	60	55.5	150.8	1022.2	1022.4	1023.1	0.2	0.9
3	D	60	61.7	184.1	1369.0	1369.1	1369.5	0.1	0.5
3	G	60	60.6	198.1	1590.1	1590.5	1590.9	0.4	0.8
4	D	85	83.5	175.7	1938.9	1939.2	1939.6	0.3	0.7
4	I	85	83.0	214.1	2086.3	2086.1	2086.4	−0.2	0.1
*Elapse time from beginning of run									

During the field study, the sensors recording the throttle and brake displacements malfunctioned for Participants 3 through 14, and the study team installed a camera in the instrumented vehicle to provide a visual record of the participants' foot activities. Therefore, for Participants 3 through 14, the data reviewer had to look at the video to determine when the participant released the throttle and applied the brake. This process was more subjective than using the Dewetron data profile, and required extra effort by the reviewer to determine the frames of the video when the participants changed positions with their foot. When those frames were determined, the reviewer then recorded the corresponding elapsed times, speeds, and gaps in the spreadsheet to produce the data in the format of Table 3-3.

The use of the video rather than the throttle/brake sensors changed the nature of the data reduction process and introduced some potential errors. Because the sensitivity was changed to a frame of data, the reviewer had to make a judgment call as to which frame represented the participant's foot movement. In the case of Participant 3, the video was above the driver's knee, which meant that the driver's feet were not visible in the video, and the reviewer had to determine which knee movement represented the driver's foot moving from throttle to brake. Because of the difficulty in ensuring accuracy, the data for Participant 3 were removed from this analysis.

For the remaining participants, there was less precision in using the video than could be obtained using the readouts from the sensors; the data stream from the sensors was capable of readings in hundredths of a second, while the video was captured at 30 frames per second. However, the time corresponding to the sensor data was still displayed in the Dewetron in increments of 0.1 sec, and the video feed was connected to the same clock. Therefore, though there were actually three frames to review in each tenth of a second, data were still reported to the tenth of a second that corresponded with the video frames that showed the movement of the drivers' feet. Thus, the use of the video instead of the sensors may have added 0.1 sec to the reaction times for some events because the reviewer needed to make sure that the participants' foot was actually moving from throttle to brake, but the effect was not evident for the entire study.

"Disabled Vehicle" Events

"Disabled vehicle" events were analyzed to determine the time and distance at which the participant recognized the parked lead vehicle ahead of him or her. The experimenter inserted a notice marker in the Dewetron data when the participant indicated that the vehicle was visible. While reducing the data, the reviewer noted the time of the notice marker and the time when the instrumented vehicle passed the vehicle in the video. The reviewer also recorded the corresponding speeds of the instrumented vehicle at those times. The average of the two speeds divided by the difference in time provided the approximate distance between the instrumented vehicle and the stopped vehicle at detection.

In-Vehicle Tasks

In-vehicle tasks were not coded and analyzed separately, but they were included as part of the analysis for the deceleration events and PDT events.

NASA Task Load Index

The answers from each participant for both speeds were downloaded from the laptop computer and placed in a spreadsheet where they were formatted and reviewed.

RESULTS

Analysis of the closed-course data focused on participants' responses to PDTs, brake light and deceleration events, and "stopped vehicle" events; the results of that analysis are presented in this section. This section also discusses the participants' responses to the NASA Task Load Index.

Peripheral Detection Task

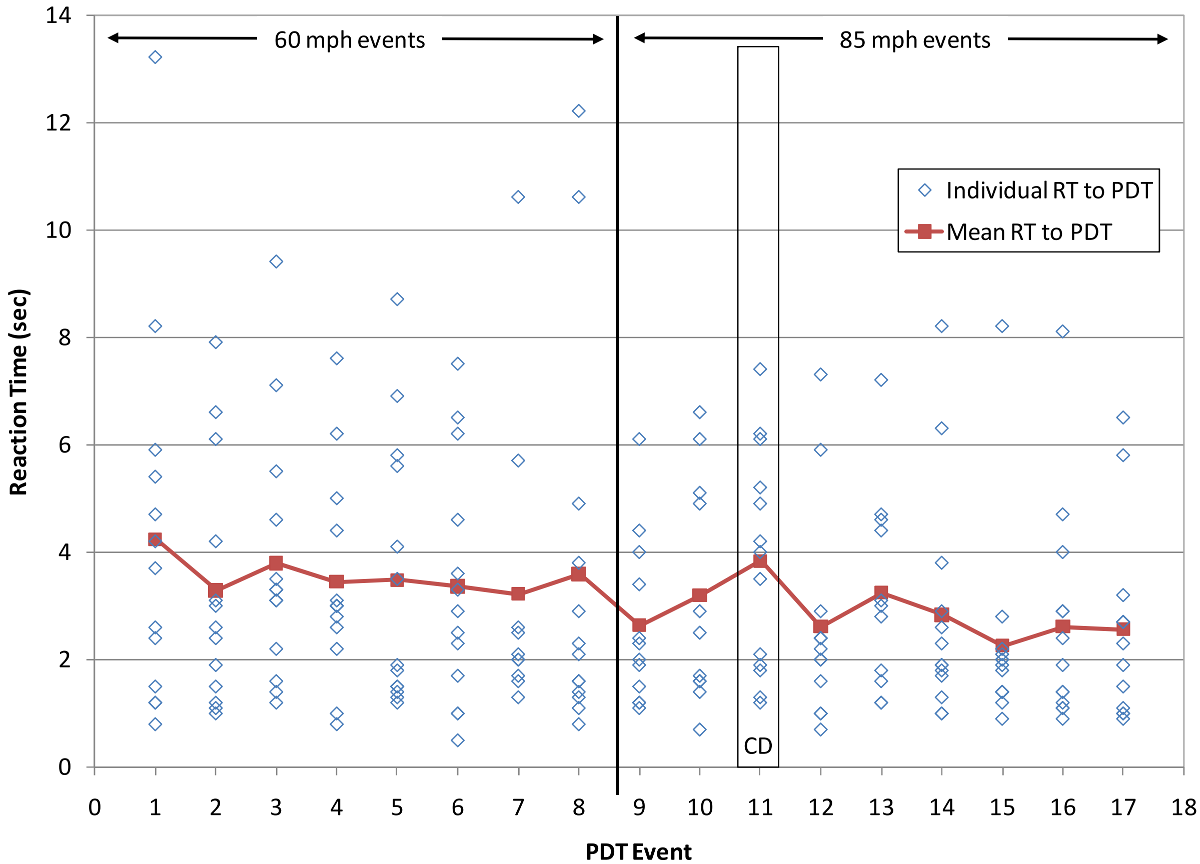
Over the entire experiment the peripheral detection task was administered 213 times, with 101 events presented at 60 mph and 112 presented at 85 mph. As many as 17 PDT events were administered to 13 of the 14 participants; the LED malfunctioned during the study for Participant 3. Each PDT event was scored for reaction time. It was intended that one PDT event at each speed would be adjacent to or overlap with a "CD change" task, but after the data were reviewed, it was determined that the CD task at 60 mph was not close enough to a PDT event to be considered as overlapping with the driver's activities for the event. PDT events were initially scored to determine if the participant failed to notice the LED after it had been illuminated for 5 sec. Data regarding the PDT events are presented in Table 3-4 and Figure 3-6.

Table 3-4. Summary of PDT Events.

Participant	Total Events	No. of Responses ≤ 5 sec	No. of Responses > 5 sec	Experimenter Error
1	17	13	3	1
2	17	12	5	0
4	17	15	1	1
5	17	15	1	1
6	17	14	1	2
7	17	10	6	1
8	17	5	11	1
9	17	16	1	0
10	17	12	5	0
11	17	16	1	0
12	17	15	1	1
13	17	15	2	0
14	17	15	2	0

Table 3-4 shows that each participant was presented with 15 to 17 PDT events, after removing those events that were canceled due to experimenter error. Most participants responded in less than 5 sec for at least 10 of those events; Participant 8 had consistently longer reaction times, providing responses greater than 5 sec in 11 of 16 events.

Figure 3-6 shows the mean reaction times and the individual responses from all of the PDT events. The PDT events numbered 1 through 17 in Figure 3-6 occurred at the same location for each participant, and each event was successfully administered between 10 and 13 times. The figure shows that the mean reaction time tended to decrease as the study progressed, indicating a potential learning effect on the task. The number of individual responses with longer response times also decreased as the study progressed; only three of the 112 events at 85 mph had response times longer than 8 sec, compared to seven events at 60 mph. The highest response time at 85 mph was 8.2 sec, while the highest at 60 mph was 13.2 sec. The figure also shows a longer mean reaction time for PDT Event 11, which overlapped with a CD task, than for the other events at 85 mph.



(RT=Reaction Time, PDT = Peripheral Detection Task)

Figure 3-6. Mean Reaction Times for PDT Events.

The reaction time data shown in Table 3-5 are organized by participant and speed. Comparison of reaction times for individual participants shows that nine of the 13 participants had slower average reaction times at 60 mph, two by as much as 2.9 sec. The four participants with faster reaction times at 60 mph did so with a difference of 1.3 sec or less. Three participants had average reaction times greater than 5.0 sec at 60 mph, and Participant 8 also had a high average reaction time at 85 mph. The results in Table 3-5 suggest that there may be a learning effect on the reaction times of the participants as the study progressed. It is possible that as they completed more of the study, the participant drivers became more accustomed to looking for and recognizing the LED in their rearview mirror and were able to react more quickly than they were earlier in the study.

Table 3-6 shows the comparison of PDT events based on the inclusion of a CD task. The table shows that, on average, reaction times were slower with a concurrent CD task than without. In comparison with all other PDT events at 85 mph, participants responded 1.1 sec slower during Event 11, and 1.2 sec slower when compared with only Event 12. The added time in Event 11 means the vehicle traveled about 140 ft further during the participants' reactions.

Table 3-5. PDT Results by Participant and Speed.

Participant	Sample Size at 60 mph	Sample Size at 85 mph	Mean Reaction Time (sec) at 60 mph	Mean Reaction Time (sec) at 85 mph	Difference in Reaction Time (sec)
1	8	8	5.6	2.7	2.9
2	8	9	4.6	3.5	1.1
4	8	8	2.1	3.1	−1.0
5	7	9	1.9	2.5	−0.6
6	7	8	3.0	2.1	0.9
7	7	9	6.0	3.1	2.9
8	8	8	6.5	5.1	1.4
9	8	9	1.8	1.9	−0.1
10	8	9	4.3	3.2	1.1
11	8	9	2.4	2.2	0.2
12	8	8	2.7	2.3	0.4
13	8	9	3.6	2.3	1.3
14	8	9	1.9	3.2	−1.3
Average of All Participants			3.6	2.8	1.2

Table 3-6. PDT Results by Participant, Speed, and CD Task.

Participant	Reaction Time (sec) for PDT Event 11, with CD	Mean Reaction Time (sec) at 85 mph, No CD	Difference in Reaction Time (sec)	Reaction Time (sec) for PDT Event 12, No CD	Difference in Reaction Time (sec)
1	1.8	2.8	−1.0	2.2	-0.4
2	5.2	3.2	2.0	1.6	3.6
4	4.9	2.8	2.1	1.0	3.9
5	6.1	2.0	4.1	2.0	4.1
6	1.2	2.2	−1.0	2.4	−1.2
7	6.2	2.7	3.5	2.9	3.3
8	7.4	4.8	2.6	7.3	0.1
9	1.9	1.9	0.0	1.0	0.9
10	4.0	3.1	0.9	2.0	2.0
11	1.3	2.4	−1.1	2.4	−0.9
12	4.2	2.0	2.2	2.4	1.8
13	3.5	2.2	1.3	0.7	2.8
14	2.1	3.3	−1.2	5.9	−3.8
Average of All Participants	3.8	2.7	1.1	2.6	1.2

Brake Light Events

Brake light events were scored by recording the participants' reaction times, both for the time at which the participant released the throttle and for the time at which the participant pressed the brake pedal. Occasionally participants noticed the slowing of the lead vehicle as the driver of the lead vehicle released the gas pedal and prepared to tap the brake pedal, so their reaction times were faster than those who did not anticipate the lead vehicle brake light. Also, Participant 10 responded to the brake light events by pressing the brake with the left foot, so no "foot-off-gas" times were recorded. Brake light events were presented as many as nine times to each participant, for a total of 117 events (50 times at 60 mph and 67 times at 85 mph), and participants missed five events (two at 60 mph and three at 85 mph). Data from the 112 successful brake light events are presented in Figure 3-7 and Table 3-7.

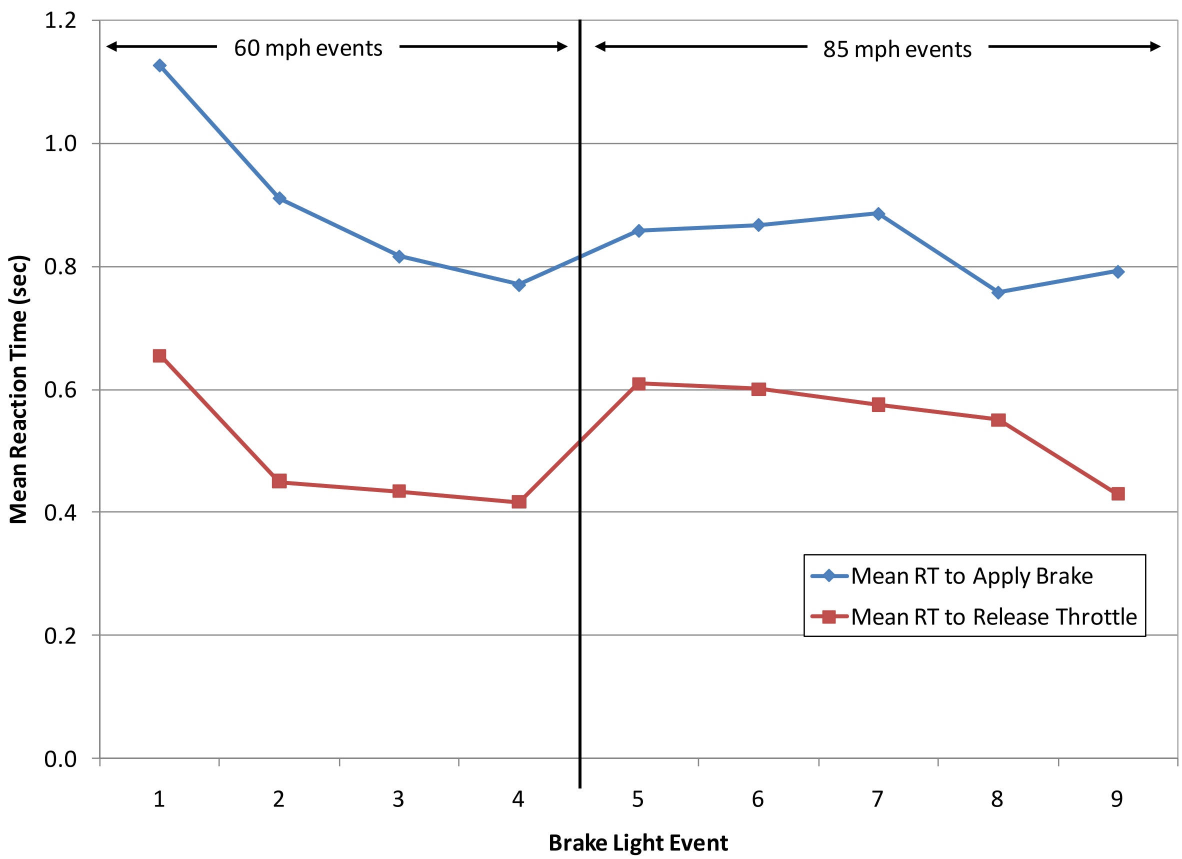


Figure 3-7. Mean Reaction Times for Brake Light Events.

The brake light events numbered 1 through 9 in Figure 3-7 occurred at the same location for each participant, and each was successfully completed between 10 and 14 times. The times to release the throttle were often slower at 85 mph, but the times to apply the brake were often as fast or faster. This indicates that it took slightly longer for the participants to recognize the brake lights on the lead vehicle at high speeds, but the participants completed their reaction more quickly to avoid additional closing on the lead vehicle. Comparing reaction times at the same speed,

Figure 3-7 suggests that participants' reaction times improved as the study progressed for both speeds.

Confirming the findings from Figure 3-7, the data in Table 3-7 suggest that reaction times to release the throttle were slightly slower at 85 mph than at 60 mph, on average, but brake times were slightly faster. This indicates that the time for participants to transfer their feet from the throttle to the brake was faster at 85 mph than at 60 mph.

Table 3-7. Brake Light Results by Participant and Speed.

Participant	Mean Reaction Time (sec) to Throttle at 60 mph	Mean Reaction Time (sec) to Throttle at 85 mph	Difference in Reaction Time (sec)	Mean Reaction Time (sec) to Brake at 60 mph	Mean Reaction Time (sec) to Brake at 85 mph	Difference in Reaction Time (sec)
1	0.5	0.2	0.3	1.1	0.6	0.5
2	0.4	0.6	−0.2	0.8	0.8	0.0
4	0.5	0.5	0.0	0.9	0.8	0.1
5	0.4	0.4	0.0	0.7	0.6	0.1
6	0.5	0.8	−0.3	0.8	1.1	−0.3
7	0.4	1.1	−0.7	0.7	1.5	−0.8
8	0.4	0.6	−0.2	0.7	0.8	−0.1
9	0.7	0.4	0.3	1.0	0.7	0.3
10	*	*	*	1.0	1.0	0.0
11	0.4	0.7	−0.3	0.7	0.9	−0.2
12	0.8	0.6	0.2	1.5	0.9	0.6
13	0.4	0.3	0.1	0.7	0.5	0.2
14	0.6	0.6	0.0	1.0	0.8	0.2
Average of All Participants	0.5	0.6	−0.1	0.9	0.8	0.1

* Participant 10 used left foot to apply the brake, so no reaction time to release the throttle could be recorded.

Deceleration Events

Because of their similarity, deceleration events were scored much like brake light events. Participants were presented with as many as 10 deceleration events, for a total of 131 events. One deceleration event at each speed was adjacent to an HVAC task. Of the 131 events, participants missed two (one at 60 mph and one at 85 mph) and never responded. In addition, sensor malfunctions prevented data collection for three 60-mph events. For the remaining 126 events, they were scored both for the time at which the participant released the throttle and for the time at which the participant pressed the brake pedal, as well as the change in the gap between the two vehicles. For one event, Participant 6 reacted only by releasing the throttle, never applying the brake. Also, Participant 10 responded to the deceleration events by pressing the brake with left foot, so no times for releasing the throttle were recorded. Data from the deceleration events are presented in Figure 3-8 and Table 3-8.

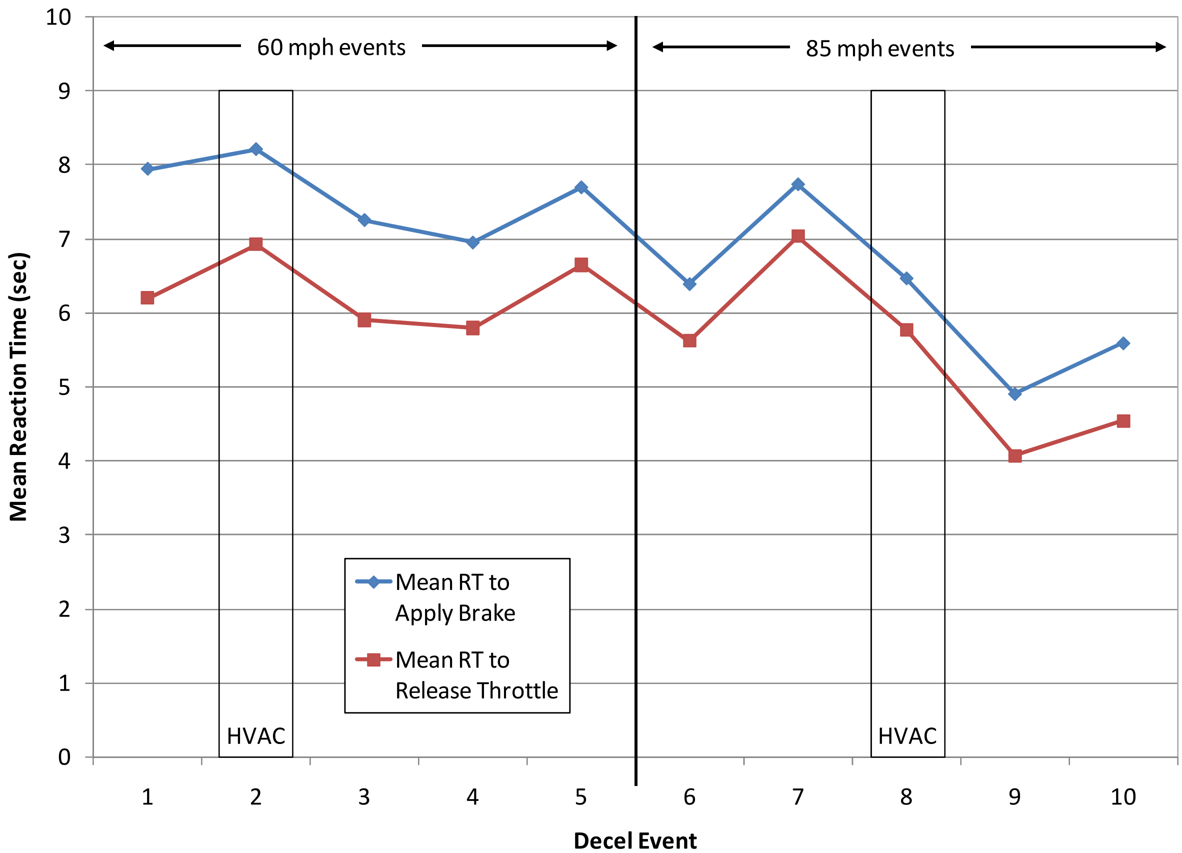


Figure 3-8. Mean Reaction Times for Deceleration Events.

The deceleration events numbered 1 through 10 in Figure 3-8 occurred at the same location for each participant, and each was successfully completed either 13 or 14 times. Figure 3-8 shows that for all but one event, drivers took at least 4.5 sec to recognize that the lead vehicle was slowing. Event 9 was the second of three deceleration events in 4.1 miles, taking place near the beginning of the final lap, and drivers may have been more attentive at this location. The results in Figure 3-8 suggest that participants reacted to a decelerating vehicle more quickly while traveling at 85 mph than at 60 mph, which may be an indication of a learning effect. Figure 3-8 also shows that drivers' reaction times in moving their foot from throttle to brake were somewhat shorter at 85 mph than at 60 mph (averages of 1.2 sec and 1.3 sec, respectively); perhaps the travel speed and/or experience with the task had some effect on the motion of the drivers' feet between pedals. Drivers may have been more casual in applying the brake at 60 mph because they were not closing on the lead vehicle as quickly. During the participants' reaction times to release the throttle, the gap between the instrumented vehicle and the lead vehicle was reduced by about 33 ft at 60 mph, compared to 25 ft at 85 mph; during the transfer from throttle to brake, the gap between vehicles remained nearly constant at 60 mph, but it declined another 13 ft at 85 mph.

When adjacent to an HVAC event, drivers reacted more slowly to the decelerating vehicle at 60 mph than at 85 mph. Compared to the non-HVAC data at the same speed, the HVAC task also appears to have a greater influence on drivers at 60 mph than at 85 mph.

Table 3-8. Deceleration Results by Participant and Speed.

Participant	Mean Reaction Time (sec) to Throttle at 60 mph	Mean Reaction Time (sec) to Throttle at 85 mph	Difference in Reaction Time (sec)	Mean Reaction Time (sec) to Brake at 60 mph	Mean Reaction Time (sec) to Brake at 85 mph	Difference in Reaction Time (sec)
1	6.5	4.9	1.6	9.0	6.5	2.5
2	4.5	3.5	1.0	7.2	4.2	3.0
4	5.1	4.4	0.7	5.6	5.3	0.3
5	6.4	5.6	0.8	7.2	6.2	1.0
6	7.3	4.7	2.6	9.1	5.3	3.8
7	4.9	4.7	0.2	6.1	5.7	0.4
8	3.9	7.2	−3.3	5.5	8.1	−2.6
9	6.8	5.8	1.0	7.6	6.5	1.1
10	*	*	*	6.9	5.2	1.7
11	7.9	6.7	1.2	8.5	7.5	1.0
12	7.2	5.3	1.9	9.5	6.6	2.9
13	5.1	4.4	0.7	5.7	5.0	0.7
14	11.1	7.2	3.9	12.4	8.3	4.1
Average of All Participants	6.4	5.4	1.0	7.7	6.2	1.5

NOTE: Reaction times include results from all events, including those with adjacent HVAC tasks.
* Participant 10 used left foot to apply the brake, so no reaction time to release the throttle could be recorded.

As shown in Figure 3-8, results in Table 3-8 indicate that throttle and brake reaction times were faster at 85 mph for all but one participant. In addition, the time for a participant to transfer from throttle to brake was about half of a second quicker at 85 mph than at 60 mph; again, this could indicate an effect of the higher speed, or it could be a result of a learning effect by the participants.

Table 3-9 shows the comparison of reaction times to release the throttle based on the inclusion of an HVAC task. The table shows that reaction times at a given speed were slower with an adjacent HVAC task, and the differences were similar at both speeds. The added time at 60 mph means the vehicle traveled an extra 70 ft while the participant was reacting, and the additional time at 85 mph translates to a difference of 62 ft in distance.

Table 3-9. Reaction Times to Release Throttle in Deceleration Events by Participant, Speed, and HVAC Task.

Participant	Mean Reaction Time (sec) at 60 mph, No HVAC	Reaction Time (sec) at 60 mph, with HVAC	Difference in Reaction Time (sec)	Mean Reaction Time (sec) at 85 mph, No HVAC	Reaction Time (sec) at 85 mph, with HVAC	Difference in Reaction Time (sec)
1	6.8	5.4	1.4	5.1	4.1	1.0
2	4.3	5.2	−0.9	4.6	0.4	4.2
4	5.7	3.5	2.2	3.5	7.8	−4.3
5	6.5	6.0	0.5	5.2	7.5	−2.3
6	7.5	6.4	1.1	5.1	3.0	2.1
7	4.2	8.1	−3.9	3.7	8.4	−4.7
8	3.4	6.0	−2.6	6.3	10.8	−4.5
9	6.9	6.5	0.4	6.0	4.7	1.3
10	*	*	*	*	*	*
11	8.2	6.8	1.4	6.6	7.1	−0.5
12	6.5	10.0	−3.5	4.4	8.2	−3.8
13	4.6	7.0	−2.4	4.2	5.2	−1.0
14	10.7	12.1	−1.4	8.5	2.0	6.5
Average of All Participants	6.1	6.9	−0.8	5.3	5.8	−0.5

* Participant 10 used left foot to apply the brake, so no reaction time to release the throttle could be recorded.

"Disabled Vehicle" Events

"Disabled vehicle" events were examined for the time and distance between the instant when the participant noticed the parked lead vehicle and when the instrumented vehicle passed the lead vehicle. Table 3-10 shows the results from this analysis.

Table 3-10 reveals that, of the 10 participants with data for both "disabled vehicle" events, six of them recognized the disabled vehicle earlier at 85 mph than at 60 mph, by an average of 3.1 sec and 1053 ft. Researchers focused primarily on two possible explanations for this finding.

1. Drivers are more alert at 85 mph and are watching more closely.
2. The conditions of the study on Lap 6 promoted earlier detection than on Lap 1.

Table 3-10. Results of "Disabled Vehicle" Events.

Participant	Lap 1 Time (sec)	Lap 1 Distance (ft)	Lap 6 Time (sec)	Lap 6 Distance (ft)	Lap 1-Lap 6 Difference in Time (sec)	Lap 1-Lap 6 Difference in Distance (ft)
1	16.5	1441	17.4	2146	−0.9	−705
2	--	--	23.5	2955	--	--
3	--	--	10.3	1302	--	--
4	29.7	2681	28.7	3456	1.0	−775
5	18.3	1625	12.9	1648	5.4	−23
6	18.2	1655	14.2	1755	4.0	−101
7	20.2	1778	31.7	3877	−11.5	−2099
8	13.4	1284	16.4	1950	−3.0	−666
9	17.8	1568	26.5	3329	−8.7	−1761
10	--	--	7.7	1020	--	--
11	9.9	926	26.0	3297	−16.1	−2371
12	14.0	1262	13.6	1685	0.4	−423
13	16.3	1585	24.9	3186	−8.6	−1601
14	19.5	--	15.7	1959	3.8	--
Average of All Participants	17.6	1581	19.3	2398	−3.1	−1053

NOTES:
Video was not recorded for Participants 2, 3, and 10 at the time of the Lap 1 event, and the velocity sensor malfunctioned for Participant 14 during the Lap 1 event, prohibiting the calculation of distance.
Time and distance differences may not be exact due to rounding.

For the former explanation, it is possible that the participants were paying greater attention to their surroundings at 85 mph than at 60 mph and thus were able to identify the stopped vehicle at a greater distance. While this would be a promising finding, more study would be needed to determine if this is actually a valid explanation.

The latter explanation takes into account the conditions of the study. The stopped vehicle event on Lap 1 was the first event the participant saw in the study, about 1 mile into the course. At this distance, it is possible the participants were still becoming accustomed to the track and the vehicle and were not as attentive as they might have been otherwise. In contrast, the stopped vehicle event on Lap 6 was the last event of the lap; the participants had become accustomed to driving the instrumented vehicle on the track and had been driving at 85 mph for 15 to 20 minutes. In addition, the participants were following the lead vehicle for the entire distance of Laps 2 through 5, but they drove most of Lap 6 alone while the lead vehicle broke formation to move into position for the stopped vehicle event. As a result, participants had an unobstructed view for most of Lap 6 leading up to the event. This may have enabled the participants to identify the vehicle earlier than they might if they were still following another vehicle.

Regardless of which is the valid explanation, a change in the study design would be in order to investigate whether the results shown in Table 3-10 are present under different conditions.

NASA TLX

Due to equipment malfunctions, the NASA TLX was administered only to the last 11 participants. The results showed slightly higher subjective workload ratings for the 85-mph driving conditions, but the differences were slight. As shown in Table 3-11, eight of the 11 participants rated the 85-mph conditions as having a higher workload than the 60-mph conditions. Table 3-12 shows the average of each participant's ratings for the 60-mph and 85-mph conditions for each of the NASA TLX subscales.

Table 3-11. Participants' Ratings for Total Workload.

Participant	Total Workload Rating for 60 mph	Total Workload Rating for 85 mph
4	45.33	52.33
5	28.67	39.33
6	52.33	68.67
7	46.00	55.67
8	32.67	46.00
9	7.67	13.00
10	72.67	71.67
11	40.33	39.67
12	42.33	34.00
13	54.00	39.67
14	52.00	52.67

Table 3-12. Comparison of Participants' Average Ratings for Workload.

NASA TLX Subscale Name	Participants' Average Ratings for 60 mph	Participants' Average Ratings for 85 mph	Difference between 85 mph and 60 mph Ratings
Mental Demand	46.36	52.73	6.36
Physical Demand	32.73	41.36	8.64
Temporal Demand	34.55	36.36	1.82
Performance	44.55	42.27	−2.27
Effort	45.91	49.55	3.64
Frustration	30.00	35.91	5.91
Total Workload	43.09	46.61	3.52

Table 3-11 shows that eight of the 11 participants rated the workload at 60 mph between 30 and 60 on the 100-point scale, with two participants lower than 30 and one higher than 60. In contrast, eight of the 11 ratings at 85 mph were between 30 and 60, with one less than 30 and two higher than 60.

Table 3-12 indicates that the mental and physical demands on the participants were most affected when the speed increased from 60 to 85 mph. The temporal demand changed very little, indicating that participants did not feel more rushed at either speed, though participants' opinion of their performance declined at 85 mph. The participants reported increased effort and frustration at higher speeds, to varying degrees. The combination of the individual subscale ratings resulted in a higher total workload rating at 85 mph, about 8 percent higher than the 60-mph rating.

CONCLUSIONS

Based on the results from the various analyses of the closed-course data, researchers drew the following conclusions:

- PDT: Participants appeared to have better reaction times to the LED in the rearview mirror at 85 mph than at 60 mph, but the differences between the two were small, and investigation of individual participants indicated that some had the opposite response. Drivers tended to have slower reaction times when a CD event was adjacent to the PDT event at 85 mph, by about 1.1 sec on average.
- Brake light: Though participants may have recognized the brake lights ahead of their vehicle more readily at slower speeds, they may have been somewhat more casual about applying the brake because their rate of closing was also lower.
- Deceleration: Participants tended to react more casually at 60 mph than at 85 mph to the lead vehicle decelerating without brake lights. Inclusion of an adjacent HVAC task resulted in somewhat slower reaction times at both speeds.
- Disabled vehicle: A change in the study design would help to address whether the study conditions contributed to the finding that participants recognized a vehicle stopped on the roadside more readily at 85 mph than at 60 mph.
- TLX: The similar workload scores in the TLX evaluation point to a possible confounding factor. For the participants who rated the workload at 85 mph higher than at 60 mph, their answers indicate that maintaining speed and gap was more taxing at higher speed, which was expected. However, for those participants with the opposite opinion, it could be an indication that their laps at 60 mph were not challenging enough, leading to boredom and a difficulty maintaining their concentration at that speed, while the added challenge of the higher speed helped them to focus their efforts on the tasks presented to them during the study.

RECOMMENDATIONS FOR FUTURE STUDIES

A major limitation to the interpretation of the speed effects in the present study is the confounding of speed and treatment order. All participants drove the test track at 60 mph for the first three laps and 85 mph for the last three laps. This treatment order was intentionally selected to improve the safety of the testing protocol. The research team was concerned that participants would not be comfortable or safe beginning their experimental drive in a new vehicle on an unfamiliar test track at such high speeds. The side effect of this treatment order is that by the time participants were asked to drive at the higher speed on the last three laps, they also were more familiar with the course, the tasks, and the vehicle. This practice effect makes it difficult to interpret some of the results. One solution to this problem in the future is to provide all participants with a practice lap at a lower speed to provide some familiarization with the protocol. The overall time required by the participants was over 3 hours due to the commute time to Odessa. The addition of a low-speed practice lap would only lengthen the experimental session time. Another solution to the problem is to counterbalance the order of treatment whereby half the participants would be asked to drive at high speed for their first laps and the other half would begin at low speed. A variant of this approach would be to intermingle the 60-mph and 85-mph laps so that practice effects are spread across the speed treatments. The same safety concerns regarding having participants drive initially at high speed would apply to this procedure.

Additional recommendations for future studies of workload on a closed course include:

- Provide additional practice on primary and secondary tasks in a parked vehicle or office setting. Results suggest that participants continued to improve on the peripheral detection task as the experiment progressed. Training should be provided until participants' response time is steady over successive trials to ensure that proficiency has been reached.
- Provide additional tasks that measure urgency. The results showed that at higher speeds participants move their foot from the throttle to the brake faster than at lower speeds. This suggests that participants may have felt a higher sense of urgency in executing their responses at the higher speeds. Such tasks may include response time to an auditory signal such as a siren or to a dashboard indicator light.
- Provide additional tasks that measure other visual driving-related tasks such as reading signs, noticing roadside objects, and noticing in-vehicle displays. The peripheral detection task showed promise as an assessment of attention and seemed sensitive to speed, particularly when a secondary task was present. Additional visual tasks such as those listed above could provide more ways to assess the effects of high-speed driving.

CHAPTER 4

OPEN-ROAD PILOT STUDY

INTRODUCTION

Researchers conducted a field study of driver workload and visual capabilities at speeds of 60 mph and above. This study consisted of observing and recording the activities and actions of a series of drivers who drove both an open-road portion and a closed-course (test track) portion. The two portions are described in separate chapters. Chapter 4 focuses on the open-road portion, while Chapter 3 focuses on the closed course.

STUDY PARTICIPANTS

Fourteen volunteer participants participated in the study. The sample of participants was comprised of four females and ten males recruited from the Odessa, Texas, area. Participants ranged in age from 20 to 71, with a mean age of 49 (two participants did not report their age), and the average number of years with a driver's license was 33.

Participants were recruited through the use of flyers physically posted in public places and sent by e-mail to the Odessa TxDOT office as well as other local agencies that were potential generators of interested participants. As they responded to the flyers or word-of-mouth publicity by others, the participants were briefed on the nature of the study and assigned an appointment time to meet the research team in Odessa to begin their participation in the study.

The participants drove a predefined route on public roads to or from a test track. A research team member was responsible for shuttling the participant in the direction he or she was not responsible for driving. The intention was to have an equal number of participants driving on public roads in both directions; however, due to cancellations, ten participants drove to the test track, and four drove the return trip.

STUDY VEHICLE

The instrumented vehicle used as the participant car for this experiment was a 2006 Toyota Highlander. The instrumented vehicle used in this study is detailed in Chapter 3.

OPEN-ROAD COURSE

All participants were met in the lobby of the hotel in Odessa. Participants were divided into two groups: those that drove the instrumented vehicle from Odessa to Pecos, and those that drove the instrumented vehicle from Pecos to Odessa. The start times of the participants were staggered in order to maximize the time of the research team at the closed-course test track and to schedule the most participants. Participants driving the instrumented vehicle to Pecos were scheduled at 8 a.m. and 1 p.m., while participants driving the instrumented vehicle from Pecos to Odessa were scheduled at 9 a.m. and 2 p.m. With this schedule, both closed-course sessions in the morning could be conducted back to back, as could the two closed-course sessions in the afternoon. This schedule also maximized the use of the instrumented vehicle since the study was designed to collect participants' data on each trip between Odessa and Pecos; the schedule was designed to eliminate any trips where data were not collected.

Drive to Pecos

Ten of the fourteen participants drove to Pecos in the instrumented vehicle. After meeting with the research team to review the informed consent documentation and complete the demographic questionnaire, the participant was escorted to the instrumented vehicle and given a "walk-through" of the vehicle's features. The participant was then provided the opportunity to adjust his or her seat and mirrors, and generally become accustomed to the controls of the vehicle. The participant, experimenter, and safety observer then left the hotel parking lot and began the drive to the Pecos Research and Testing Center (RTC). The experimenter rode in the backseat of the instrumented vehicle with the participant driving, while the safety observer rode in the front passenger seat. The first part of the drive consisted of navigating surface streets on the way to the highway; this portion took roughly 5 minutes and was considered time for the participants to acclimate themselves to the vehicle.

Participants were told not to use the radio or the cruise control, and they were instructed to drive naturally, as they would normally drive. Conversation between the participant, experimenter, and safety observer was permitted; however, it was intentionally kept light and at a pace implicitly determined by the participant. The participants were aware data were being collected, and they were shown the video camera on the dash, but they were not told specifically what data were being collected.

The vast majority of the open-road portion of the experiment took place on I-20 between Odessa and Pecos, as shown in Figure 4-1. This segment of I-20 is predominantly straight with some gentle curves and some minor elevation changes. Except when influenced by weather or darkness, sight distance in this segment is consistently near unlimited.

A route summary is shown in Table 4-1. Participants were not forewarned that there would be a change in speed limit during the drive, nor was any mention made by the research team when they passed the sign, so that drivers would react naturally to the change. After exiting the highway, participants drove on US-285, FM 1450, and a county road to the Pecos RTC. Traffic volumes on these roads, particularly FM 1450, were extremely low. The posted speed limit was 75 mph on US-285 and 70 mph on FM 1450; there was no posted speed limit on the county road. Once at the Pecos RTC, participants drove to the main building facility on the infield of the track and were given the opportunity to exit the vehicle to stretch their legs and use the restroom, and then the closed-course portion of the data collection began.

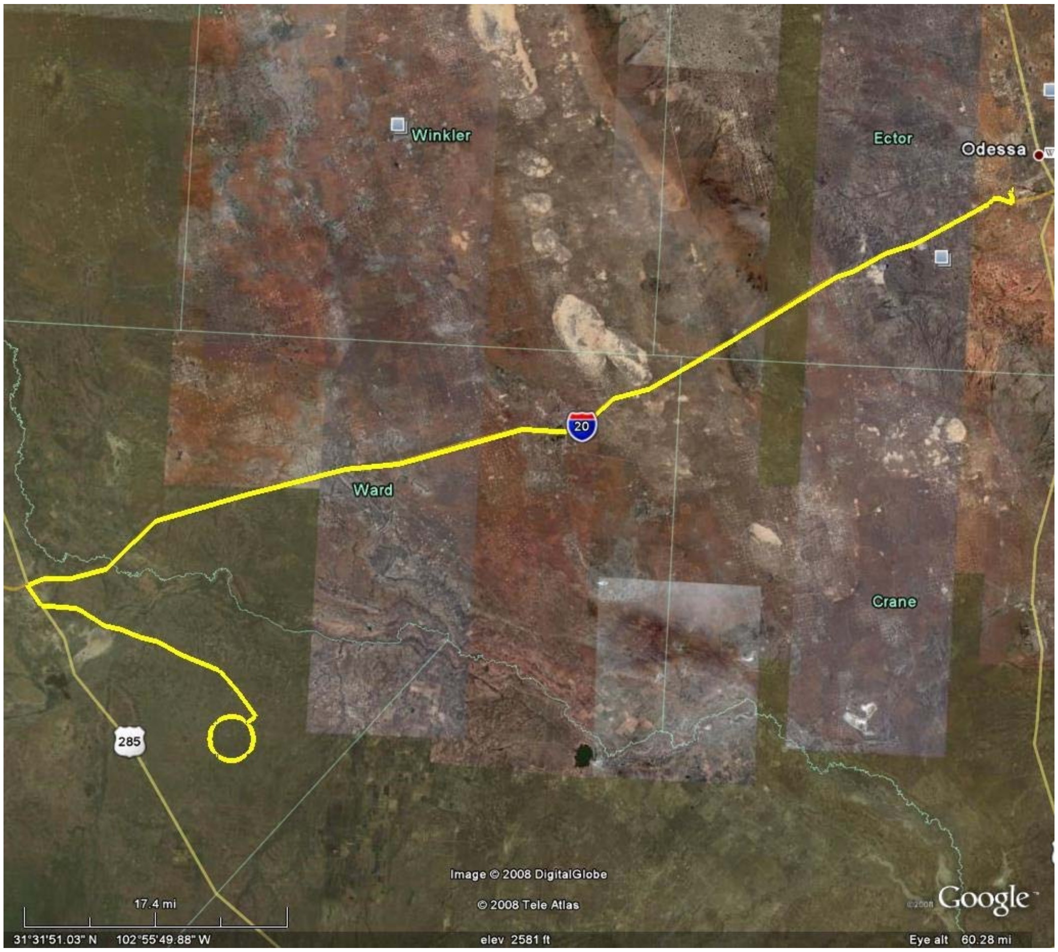


Figure 4-1. Route from Odessa to Pecos RTC (Source of Base Map: Google Earth).

Table 4-1. Summary of Route from Hotel to Pecos RTC.

Event	Location	Speed Limit (mph)	Approximate Cumulative Distance (Miles)
Start Route	MCM Grande Hotel	(various)	0
Enter Interstate	I-20 @ Loop 338 (I-20 Exit 121)	70	3
Speed Limit Change	Crane/Ward county line	80	35
Exit Interstate	I-20 @ US-285 (I-20 Exit 42)	80	82
End Route	Entrance to Pecos RTC	(various)	101

Drive to Odessa

Four of the fourteen participants drove to Odessa from the RTC, using the same route described in Table 4-1, but in the opposite direction (i.e., Pecos RTC to hotel). These participants were initially met in Odessa at the hotel lobby, where they reviewed the informed consent documentation and completed the demographic survey. They were then driven to the Pecos RTC by another member of the research team in a shuttle vehicle. Once at the Pecos RTC, these participants completed the closed-course portion of the experiment. After the closed-course portion was completed, these participants drove the instrumented vehicle back to the hotel in Odessa following the same route and the same procedures outlined above.

DATA REDUCTION

The Dewesoft software package was used to view the synchronized video, GPS, radar, and lateral offset data. The data reduced and analyzed in this study are from the open-road driving between the test track and the hotel. The primary focus of this study was driver workload and behavior at high speeds; therefore, non-interstate data were not reduced or analyzed. Two video coding runs were conducted, and computer macros were used to reduce the collected data. The following explains the video coding methods used and assumptions made during data reduction.

First Run Coding

The purpose of the first run coding was to determine the location of the instrumented vehicle on the interstate and the location of other vehicles in relation to the instrumented vehicle. The following are the event times recorded during the first run coding:

- The instrumented vehicle merges with the interstate, or the video is beginning.
- The instrumented vehicle leaves the interstate, or the video is ending.
- Other vehicles are around the instrumented vehicle.
  - When it first becomes present along with the:
    - vehicle type,
    - vehicle location, and
    - vehicle lane.
  - When the vehicle is no longer present.
- The instrumented vehicle changes lanes.

If at any time one of the above events occurred, all vehicles considered present at that time had their location, lane, and type rerecorded. For example, if a vehicle was already present and another vehicle becomes present, details about the first vehicle are recorded at the time the second vehicle arrives. In the same situation if the first vehicle were to leave the presence of the instrumented vehicle, details for the second vehicle would be recorded at the time of the first vehicle's departure.

These event times do not cover the entire event but are only usable as reference markers. This was done so that future detailed analysis could be conducted on these data using consistent reference points. These coding methods were used to maintain high inter- and intra-rater reliability. What follows is a more detailed explanation of the codes used and event definitions.

Lane Location Codes

The same lane location codes were used for both the instrumented vehicle and non-instrumented vehicles:

- 1 = vehicle located in the right lane,
- 2 = vehicle located in the left lane,
- 3 = vehicle performing a right-to-left lane change,

- 4 = vehicle performing a left-to-right lane change, and
- 5 = vehicles located on an off- or on-ramp.

Vehicle Type Codes

Vehicle codes only apply to non-instrumented vehicles and were assigned as follows:

- MOT = motorcycle,
- CAR = car,
- VAN = sports utility vehicle (SUV) or van,
- TRU = pickup truck,
- FBT = flatbed truck,
- RV = recreational vehicle (RV),
- SEMI = semi truck, and
- EMER = emergency vehicle.

Any vehicle other than a semi truck pulling a trailer was given an additional coding of a capital T after the code defined above. For example, a motorcycle with a trailer was given a code of MotT and a car with a trailer a code of CarT. All vehicles were given the codes they most closely resembled above unless they were never close enough to the instrumented vehicle to recognize. In these cases the vehicle received a vehicle code of UNK for "unknown."

Vehicle Location Codes

The location of each vehicle was recorded based on whether it was in front of or beside the instrumented vehicle:

- 1 = vehicle located in front of the instrumented vehicle and
- 2 = vehicle located to the side of the instrumented vehicle.

Vehicles behind the instrumented vehicle were undetectable and not coded.

Instrumented Vehicle Entering and Exiting the Interstate

The instrumented vehicle was considered as entering the highway when the white line to the left of the vehicle was no longer visible through the forward-viewing camera. An instance of this event can be seen in Figure 4-2. The top view shows the white line still present, and the bottom view shows the first instance where the line is no longer visible. The time where this bottom view occurs is the time recorded, and all relevant event data were also recorded, such as the SUV present in front of the instrumented vehicle in Figure 4-2.

The instrumented vehicle exiting the interstate is coded similarly. When the instrumented vehicle exited the highway, the time coded was the time when the nose of the painted gore at the exit was no longer visible. Figure 4-3 shows this occurrence. The top view shows the nose still visible, and the bottom view shows the first instance where it is no longer visible. The time where the second view occurs was recorded along with any relevant data about other vehicles.

If these events did not occur, then the first or last available synchronized video was coded to mark what was occurring at the beginning or end of the available video. Occasionally it was necessary to stop a video recording during the drive and restart it as a new video file; the beginning and ending frames of the video were recorded to indicate the times as well as the positions of all visible vehicles.

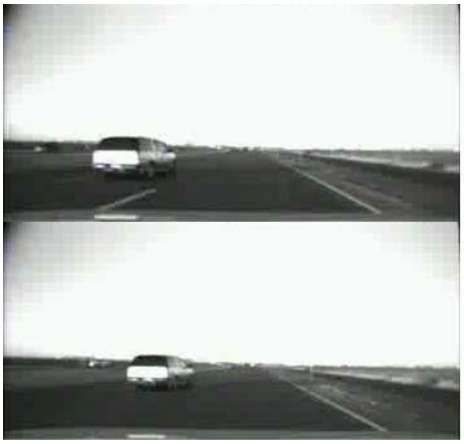


Figure 4-2. Instrumented Vehicle Entering Interstate.

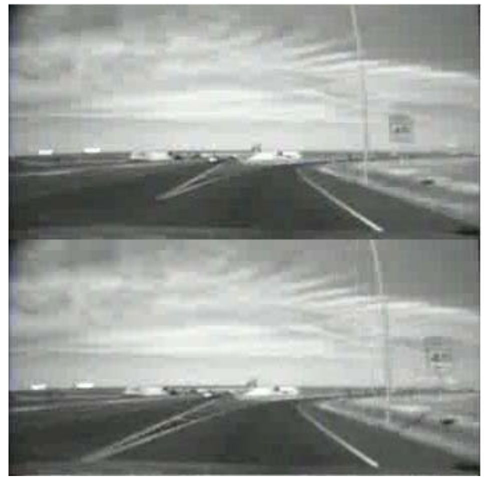


Figure 4-3. Instrumented Vehicle Exiting Interstate.

Presence of Other Vehicles

Vehicles were considered present around the instrumented vehicle if they were visible through the driver-side window, passenger-side window, or front window, or were picked up by the radar. The radar's maximum range is 500 ft; however, accurate readings normally occurred within 450 ft. When the instrumented vehicle was not in the same lane as a leading vehicle, there was a good chance, as the gap got smaller, that the radar would no longer register the lead vehicle. For this reason any vehicle within the radar range of 400 ft was considered present even if the radar was not registering it.

Vehicles were defined as being present the first instance that any of the above occurred, and times were also recorded when they changed locations around the instrumented vehicle. There are only three defined locations due to limited camera views:

- in front of the instrumented vehicle,
- beside the instrumented vehicle (left or right), and
- no longer present.

Lane changes by other vehicles were not coded. If a vehicle changed lanes, the change in location was not coded until another event occurred. Vehicles present on on-ramps were only coded if the instrumented vehicle performed a lane-changing maneuver or the vehicle on the on-ramp changed location around the instrumented vehicle. Vehicles were no longer considered present the first instant they were no longer visible through the passenger- or driver-side window or when they outdistanced the radar.

Figure 4-4 shows the instrumented vehicle passing another vehicle. In Figure 4-4(a) the car is in front of the instrumented vehicle. The instant the entire rear bumper was no longer visible to the front camera view, that vehicle was considered to the side of the instrumented vehicle. In Figure 4-4(b) the car is shown outside the passenger-side window. When no portion of the vehicle was present through that window, the vehicle was no longer considered present.

(a) Vehicle in Front of Instrumented Vehicle **(b) Vehicle out of Range of Instrumented Vehicle Cameras**

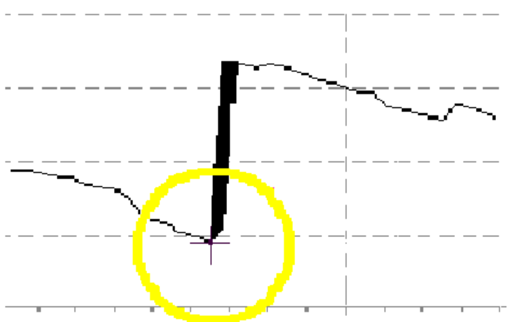
Figure 4-4. Instrumented Vehicle Passing a Car.

Vehicles approaching from the rear were considered first present when any portion of their vehicle was viewable through the passenger- or driver-side window. Vehicles are considered to be no longer to the side of the vehicle when the entire rear bumper is visible to the forward-viewing camera as seen in Figure 4-4(a). If this event occurred on the left side of the instrumented vehicle, then the lane location for both the instrumented vehicle and vehicle present were given different codes, but the qualifications for vehicle presence remained the same.

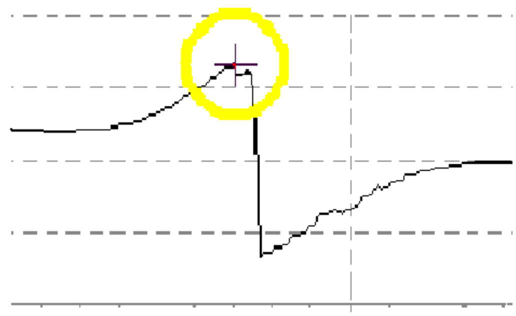
Lane Changing

Lane changes were only a coded event when the instrumented vehicle performed the lane change. Lane changes by vehicles around the instrumented vehicle were not coded. For example, if a car passed the instrumented vehicle and then changed lanes in front of the instrumented vehicle, this event was not coded. If a vehicle was changing lanes during another event being coded, that vehicle was given a code of its destination lane. For example, if a car moved from the left to right lane when another event occurred, the vehicle changing lanes was given a lane location of right. During other coded events, vehicles present have their lane location, vehicle location relative to the instrumented vehicle, and vehicle type recoded. At these times, changes in lane by other vehicles were recorded.

Lane change times by the instrumented vehicle were obtained by placing the cursor at the highest or lowest peak that occurred during a lane change event. Figure 4-5 shows lane change events demonstrated on the timeline by a spike in lateral offset and the cursor obtaining the time of this spike. The timeline shown in Figure 4-5(a) demonstrates a right-to-left lane change event, and in Figure 4-5(b) the timeline demonstrates a left-to-right lane change. These spikes occur at the point the lane tracker determines the lane of travel of the instrumented vehicle has changed.



(a) Right-to-Left Lane Change



(b) Left-to-Right Lane Change

Figure 4-5. Lane Changes Shown by Lateral Offset on Timeline.

Second Run Coding

The purpose of second run coding was to record the number and direction of non-forward glances made by drivers along with the location of their hands in 5-sec intervals. This was a very time-consuming endeavor, and for this preliminary study only two 5-minute segments were coded. The segments were all tangents located in each of the two speed conditions, allowing for comparison. These segments occurred approximately 15 minutes into each of the speed conditions.

Coding Glance Rate and Head Movement

Driver glance rates were primarily coded using driver head movement due to the video data quality. The coding of glance duration would have been difficult to achieve using these methods and thus was not sought during this preliminary study. The direction of the head movement was coded from the drivers' perspective, and each glance was given only one direction. If a driver looked down and right, it was given a code of down or right, not both. The code given was dependent on what the driver was perceived to be looking at. The following were the only movements recorded as glances during these coding runs:

- glances at one of the three mirrors,
- glances at an object in the vehicle including other passengers,
- glances at the instrumentation panel or steering column (the only event coded as down), and
- blind spot checks.

If a driver were to look at the driver-side mirror and then check the blind spot, both events were coded even if their eyes never returned to a forward view between the two events. The same was true if a driver checked the rearview mirror and then checked the passenger-side mirror in the same movement. In both cases, if the coder perceived two intentions by the driver, then two events were coded.

In some instances drivers only moved their eyes and not their head. In the cases where these movements were visible, they were given the proper coding of a head movement in that direction. In the case of drivers with sunglasses, these types of coding were not possible.

Driver Hand Placement

Driver hand placement was recorded at the beginning and end of each 5-sec segment. Each hand was coded separately, and the following four codes were given:

- A driver's hand is considered on the upper half of the steering wheel if any portion of the hand is visible above the center of the steering wheel. The center of the steering wheel is defined by the top of the uppermost spoke connected to the hub. These events were given a code of 1.
- A driver's hand is given a code of −1 if it is clearly visible in the driver-view camera and it is not grasping the steering wheel or another object.
- A driver's hand is given a code of −2 if the hand is clearly visible in the driver-view camera, and it is grasping something other than the steering wheel.
- If a driver's hand does not meet any of the above criteria, then it is given a coding of 0. A driver resting his or her hand on the shifter is given such a code because the hand is not clearly visible to the available cameras.

Dewesoft Exports

The synchronized data from the Dewesoft program were exported into spreadsheets that contained all recorded data over the duration of the recording. The data from the coding were then incorporated into these data files using the designed macros. Using the GPS coordinates from the file along with data provided by the accelerometer, researchers determined the beginning and ending of horizontal curves, and everything in between was considered a tangent segment of roadway. These geometric data were incorporated into the spreadsheet files as well. The final spreadsheets in their raw form contained more than 60 variables and 40,000 synchronized data points.

Final Data Reduction

Final data reduction was conducted using the developed macros that sorted the data file into separate worksheets by posted speed limit zones, travel lane, and roadway geometry in order to develop exploratory results for this project in the form of charts and tables. If the AssistWare SafeTRAC had a confidence of less than 90 percent, those data points were eliminated from final analysis. The remaining data were then summarized into tables and charts exploring driver hand placement, lane position, and glance rates. To eliminate some bias due to lane changing events, the following was performed:

- vehicles spending less than 30 sec in a particular lane of travel and speed condition had their data for that segment removed before final analysis, and

- vehicles spending less than 15 sec in a lane of travel within the zones where hand placement and eye coding took place had that part of the data removed before final analysis.

RESULTS

The primary data researchers reviewed for the open-road portion of the field study were lateral position of the instrumented vehicle, lane change behavior, and participants' head-hand position.

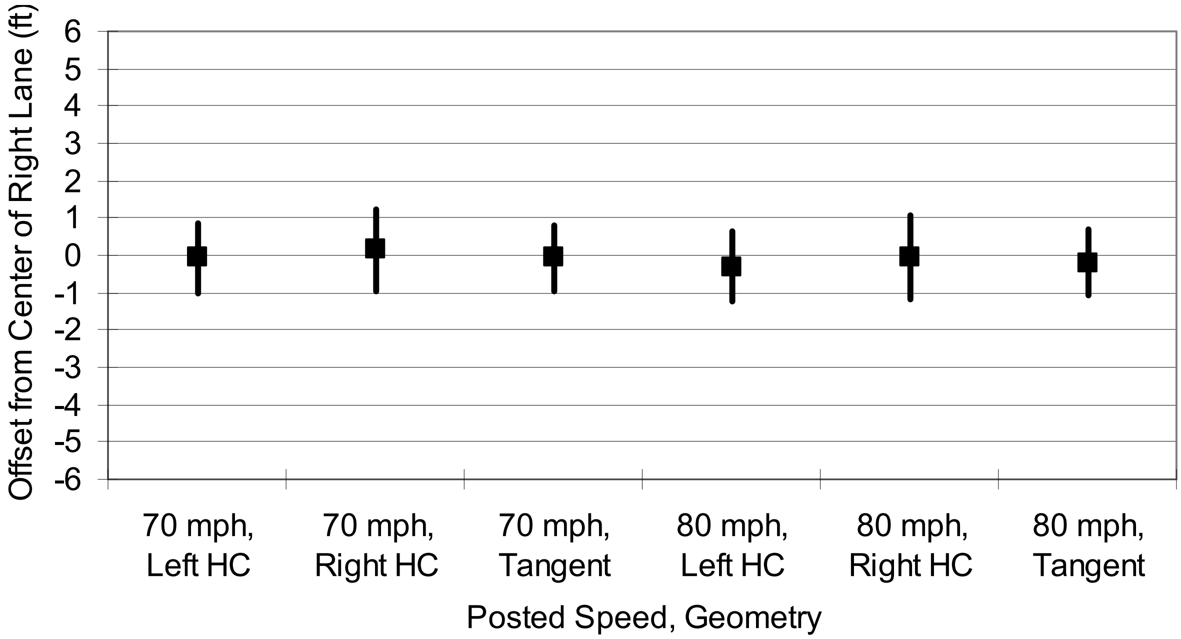
Lateral Offset

Table 4-2 contains the lateral offset associated with the three geometric characteristics being subdivided by travel lane and posted speed limit. The three geometric characteristics are horizontal curve to the left, horizontal curve to the right, and tangent section. Table 4-3 also contains the standard deviation and number of observations for each lateral offset. The first and last 5 minutes of observations were not included in these data. Figure 4-6 is a graphical representation of the data in Table 4-2. The figure could be viewed as two lanes (with each graphic being a lane) with traffic moving from right to left. The center of each lane is at zero on the y axis. The lanes widths were approximately 12 ft each. As noted previously, negative values are offsets to the left of center in the lane of travel, and positive values are to the right of center. The figure shows the average lateral offset for the lane as a black square. The black bar represents one standard deviation around the mean.

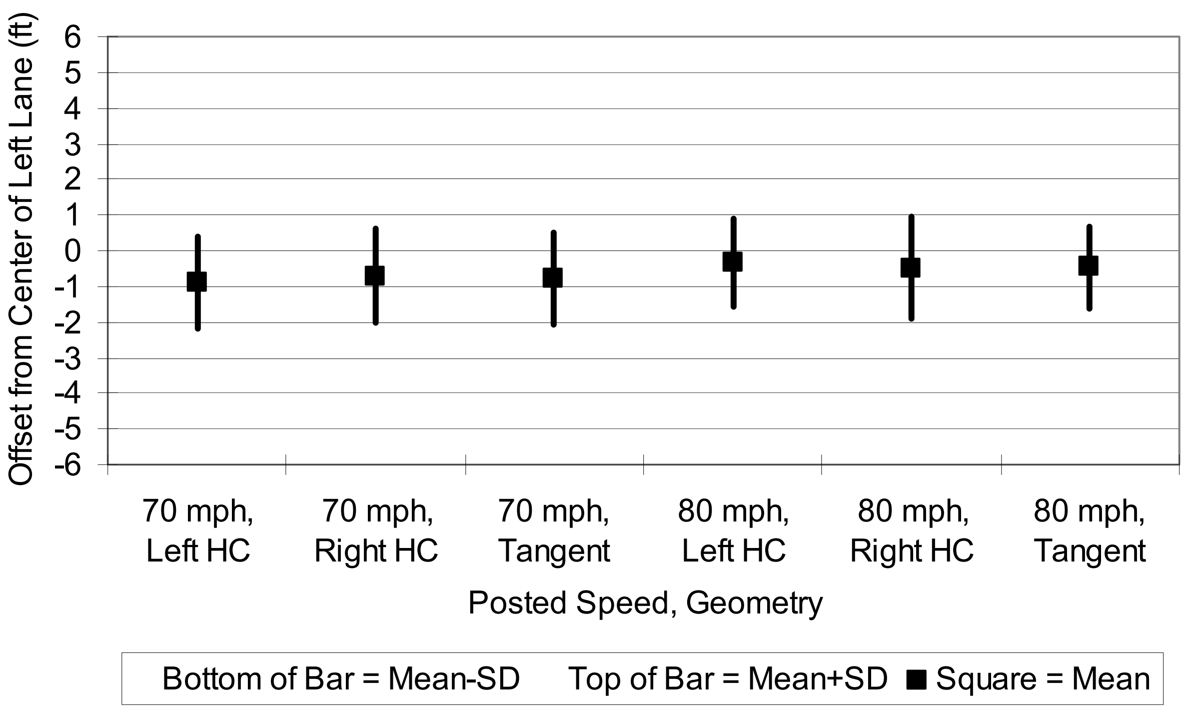
Table 4-2. Average Lateral Offset by Travel Lane, Posted Speed Limit, and Roadway Geometry.

Posted Speed Limit, Roadway Geometry	Left Lane			Right Lane		
	Average (Inches)	SD* (Inches)	n**	Average (Inches)	SD (Inches)	n
70 mph, Left HC	−10.79	15.78	4828	−0.88	11.05	10776
80 mph, Left HC	−3.99	15.08	3581	−3.55	11.22	13786
70 mph, Tangent	−9.49	15.69	33871	−0.96	10.43	104826
80 mph, Tangent	−5.71	13.62	60910	−2.34	10.75	178481
70 mph, Right HC	−8.42	16.13	4839	1.67	13.09	11045
80 mph, Right HC	−5.88	17.28	4887	−0.69	13.56	15847

* SD = standard deviation
** n = sample size
HC = horizontal curve



(a) Right Lane



(b) Left Lane

Figure 4-6. Lateral Offset by Lane, Geometry, and Posted Speed Limit.

Speed and Lateral Offset

Table 4-3 contains the average speed and lateral offset for the zones in which hand placement and head movements were coded. Table 4-3 also contains the standard deviation and number of observations for each measurement. The findings for lateral offset shown in Table 4-3 are similar to the results shown in Table 4-2 found using the larger dataset, generally being within 1 inch or less. Figure 4-7 is a graphical representation of the variability in speed by posted speed limit and travel lane.

Table 4-3. Average Speed and Lateral Offset by Posted Speed Limit and Travel Lane.

Posted Speed Limit, Travel Lane	Speed Lateral			Offset		
	Average (mph) SD	(mph)	n	Average (Inches)	SD (Inches)	n
70 mph, Left Lane	73.11	2.41	29442	−8.49	15.63	29442
70 mph, Right Lane	72.13	1.78	7462	−1.17	8.91	7462
80 mph, Left Lane	79.69	1.42	25487	−7.89	16.59	25487
80 mph, Right Lane	78.70	1.46	9075	−2.00	10.89	9075

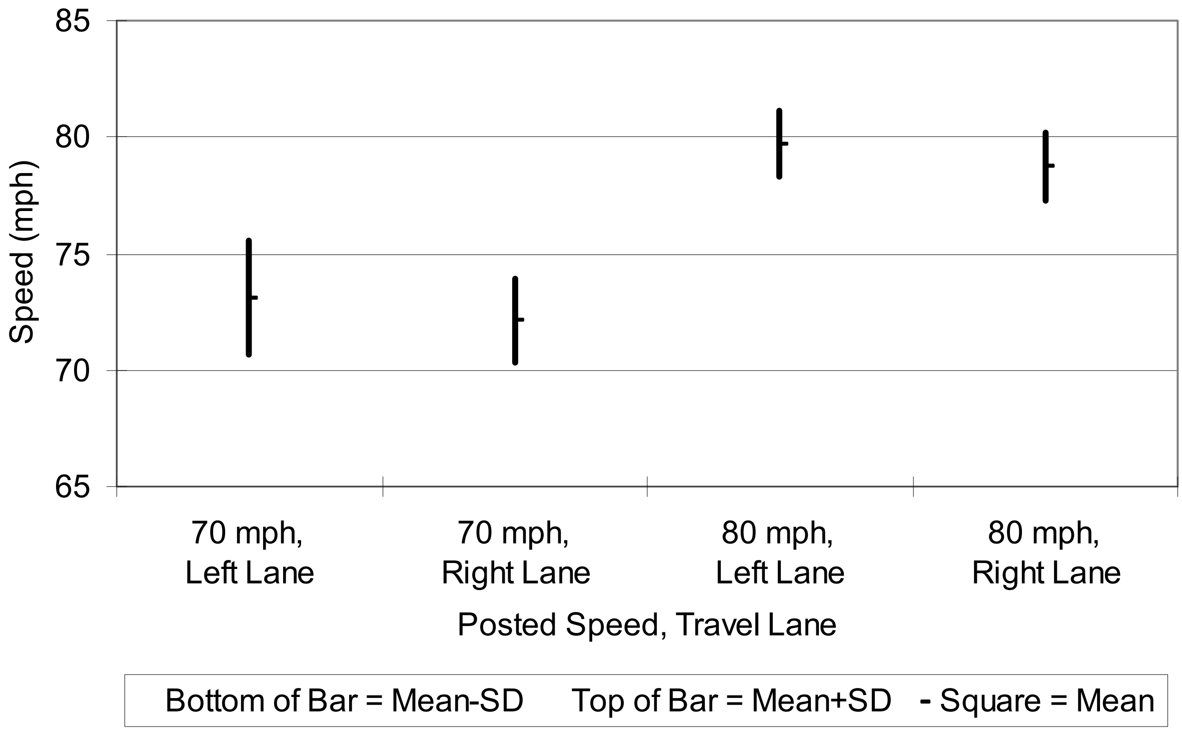


Figure 4-7. Variability in Speed by Posted Speed Limit and Travel Lane.

Driver Glance Rate

Table 4-4 contains the driver glance rate subdivided by posted speed limit and travel lane. Figure 4-8 is a graphical representation of these data. Forward glances were not taken into account in these observations.

Table 4-4. Non-forward Glance Rates by Posted Speed Limit and Travel Lane.

Posted Speed Limit, Travel Lane	Glances per Minute		
	Left	Down	Right
70 mph, Left Lane	2.85	1.32	7.85
70 mph, Right Lane	3.35	2.32	7.51
80 mph, Left Lane	2.09	1.54	7.88
80 mph, Right Lane	3.29	2.98	6.60

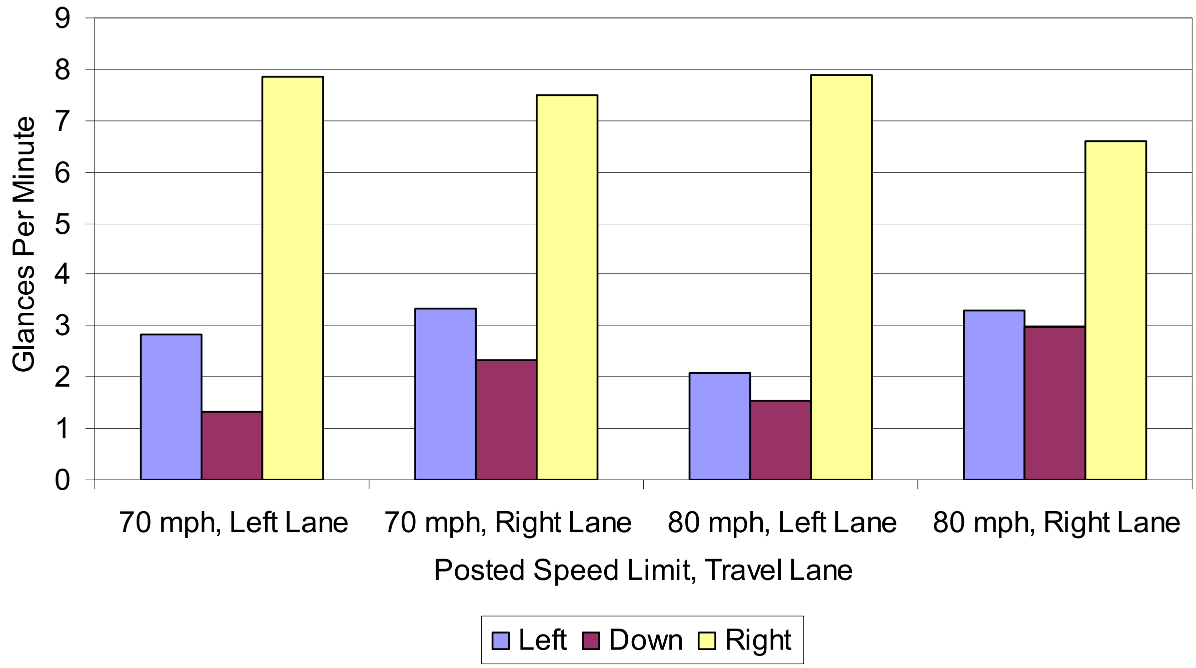


Figure 4-8. Non-forward Glance Rates by Posted Speed Limit and Travel Lane.

Driver Hand Placement

Table 4-5 contains the percentage of time drivers' hands spent at the four coding locations described previously, split by posted speed limit and travel lane. Figures 4-9 and 4-10 are graphical representations of drivers' left- and right-hand placement, respectively, as a percent of total time.

Table 4-5. Drivers' Individual Hand Placement by Posted Speed Limit and Travel Lane.

Posted Speed Limit, Travel Lane	Percent of Time (%) Hand Is Placed at…							
	Left Hand				Right Hand			
	Top	Below	Off	Object	Top	Below	Off	Object
70 mph, Left Lane	74	22	4	0	45	49	6	0
70 mph, Right Lane	78	18	4	0	30	63	7	0
80 mph, Left Lane	67	26	7	0	29	66	5	0
80 mph, Right Lane	63	31	4	2	48	46	5	1

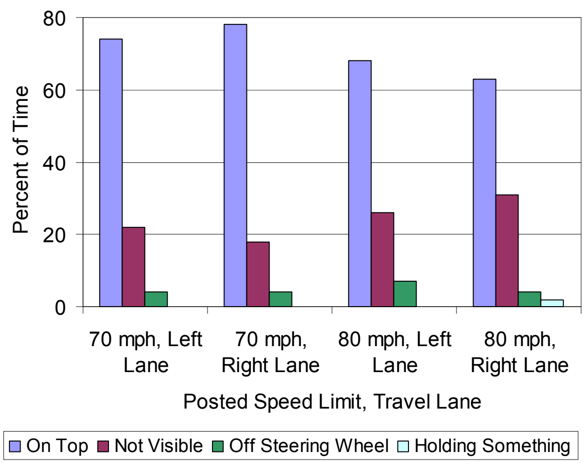


Figure 4-9. Drivers' Left Hand Placement by Posted Speed Limit and Travel Lane.

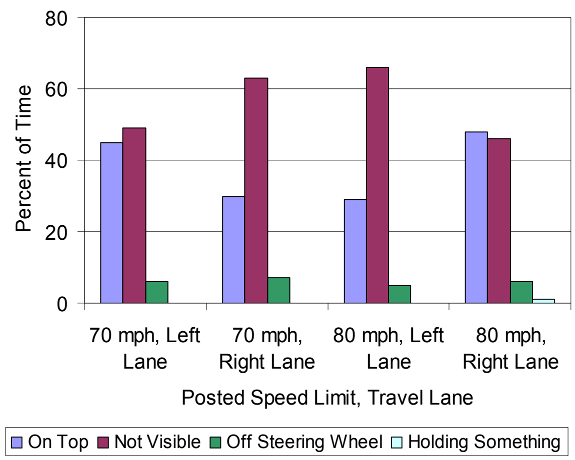


Figure 4-10. Drivers' Right Hand Placement by Posted Speed Limit and Travel Lane.

Table 4-6 contains the percent of total time that the driver had two, one, or zero hands on the top half of the steering wheel. Figure 4-11 is a graphical representation of Table 4-6.

Table 4-6. Number of Hands on Top Half of Steering Wheel by Posted Speed Limit and Travel Lane.

Posted Speed Limit, Travel Lane	Percent of Time (%) Number of Hands Were on Top of Steering Wheel		
	2 1		0
70 mph, Left Lane	36	47	17
70 mph, Right Lane	30	49	21
80 mph, Left Lane	26	44	30
80 mph, Right Lane	33	45	22

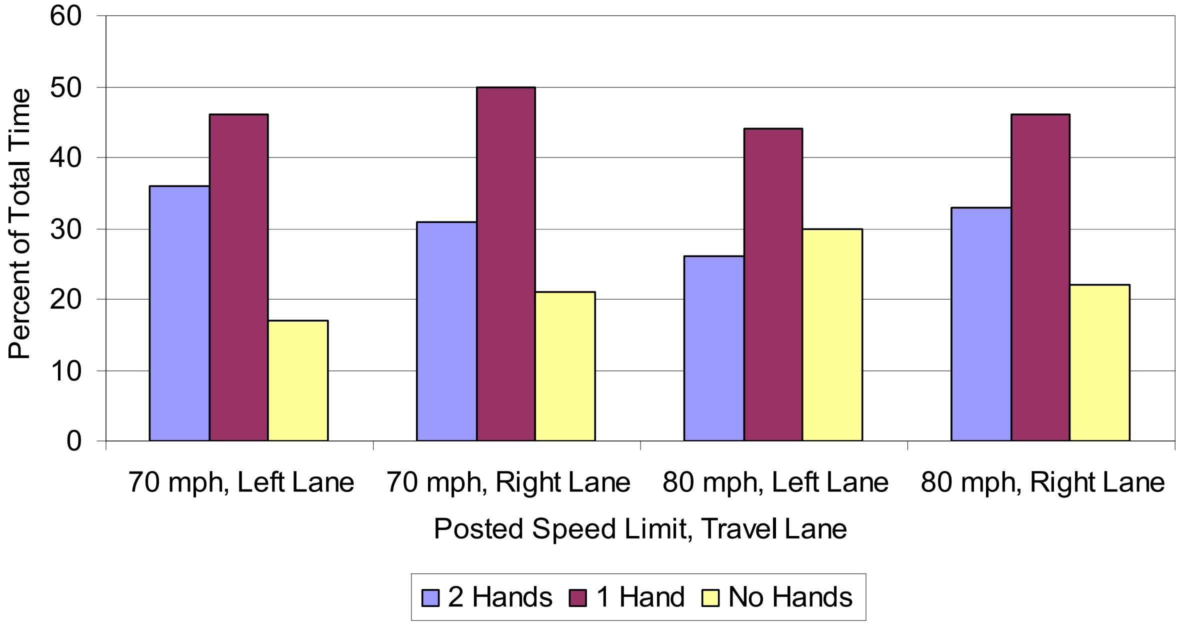


Figure 4-11. Number of Hands on Top Half of Steering Wheel by Posted Speed Limit and Travel Lane.

Gap Distance at Lane Change

The instrumented vehicle measures the distance and time to other vehicles. The gap distance between the instrumented vehicle and another vehicle was determined for each passing maneuver the participants performed while driving between Pecos and Odessa or Odessa and Pecos. This "gap distance" represents the distance between the front of the participant vehicle and the rear of the lead vehicle when the participant driver initiated the pass by crossing the lane line. Passes were removed from this evaluation if the lead vehicle's speed was not determined by the equipment or if the time to collision (TTC) was a negative value. Table 4-7 lists characteristics of the 151 passing maneuvers recorded for the 14 participants.

The average gap distance at the start of a passing maneuver was 196 ft with a 22.56-sec time to collision. The gap distances recorded ranged from as small as 46 ft up to 423 ft which is near the equipment limit of 450 ft. The time to collision values ranged between 2.97 and 419.33 sec.

Figure 4-12 shows the gap distances for each passing maneuver by the speed of the instrumented vehicle. While one may expect that larger gaps would be used at higher speeds, no pattern was identified in the data. Participants selected gap distances as low as 150 ft and below for the entire speed range of 65 to 85 mph observed. A 4-sec following interval results in following distances of 412 ft for the 70-mph speed and 470 ft for the 80-mph speed. Very few of the passing maneuvers were longer than the 412- to 470-ft following distance values.

Table 4-7. Passing Maneuvers by Participants during Drive between Odessa and Pecos.

Participant Number	Number of Passes	Gap* (ft)				TTC** (sec)			
		Average	SD	Min.	Max.	Average	SD	Min.	Max.
1	10	191	46	112	261	15.32	7.73	8.70	34.30
2	13	167	43	98	246	20.58	26.93	6.23	106.54
4	7	258	37	190	307	14.79	1.95	13.27	18.91
5	17	156	61	46	280	28.78	44.12	8.06	169.60
6	9	146	44	86	212	12.85	8.15	5.31	29.72
7	15	186	67	77	311	21.36	9.84	7.56	38.89
8	15	186	90	73	389	41.11	105.05	2.97	419.33
9	8	298	77	201	397	26.16	12.46	9.06	45.01
10	14	198	65	119	370	17.50	9.53	7.00	34.28
11	9	269	62	171	350	21.17	7.61	15.61	40.40
12	7	224	100	136	423	24.33	19.42	11.11	66.48
13	13	141	31	83	188	16.61	12.89	7.52	55.20
14	14	231	80	145	417	22.04	12.17	9.87	55.43
All Participants	151	196	76	46	423	22.56	37.80	2.97	419.33

* Gap = distance between front of participant vehicle and rear of lead vehicle (ft)
** TTC = time to collision if both vehicles maintain speed and stay in same lane (sec)

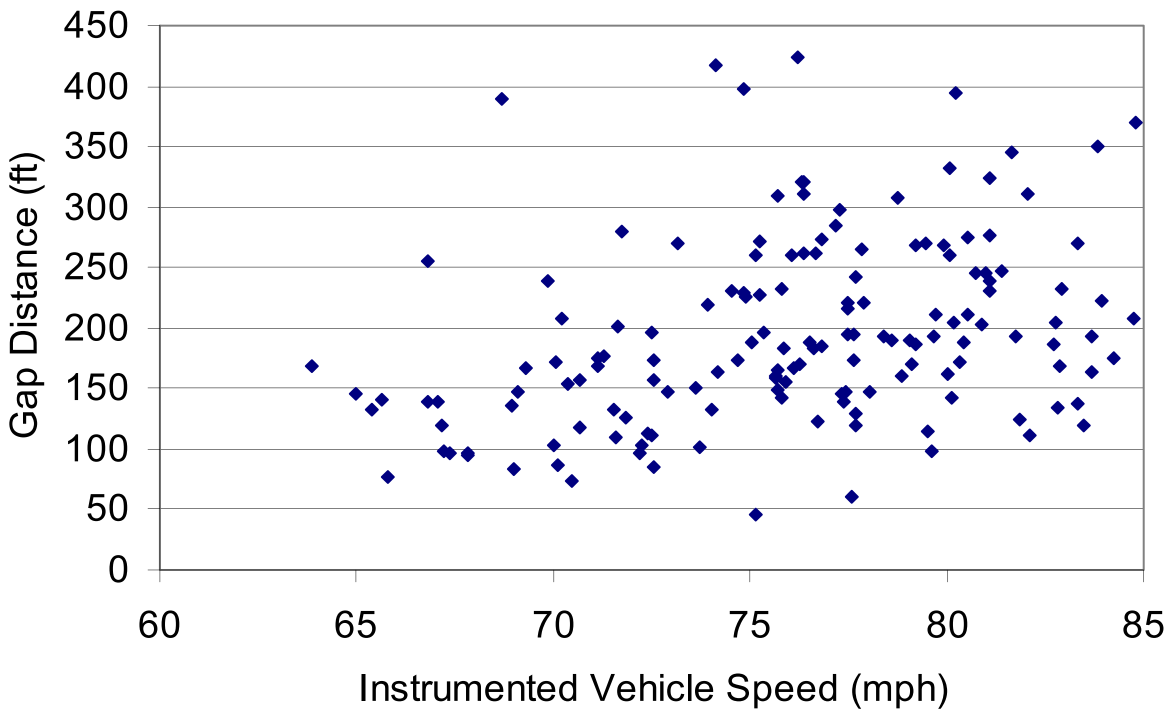


Figure 4-12. Gap Distance by Instrumented Vehicle Speed.

CONCLUSIONS

Speed results are considered to have potential practical implications if the difference in speed is greater than 2 mph. Lateral offset results are considered to have potential practical implications if the difference is greater than 6 inches. Practical implications for hand placement and glance rates will be discussed in their respective sections.

Lateral Offset Relationship with Posted Speed Limit, Travel Lane, and/or Roadway Geometry

Table 4-3 shows a practical difference of greater than 6 inches for lateral offset by travel lane. Within the 70-mph speed condition there were practical differences between vehicle lateral offset in the left lane versus that in the right lane in all geometric features investigated. For example, the offset in the left lane on a 70-mph tangent section was −9.49 inches, while it was only −0.96 inches for the right lane, a difference of about 8.5 inches.

Differences of 6 inches or more were not seen in any of the 80-mph geometries. This observation suggests that drivers going 70 mph are more likely to vary their position when traveling in the left lane than drivers at 80 mph for the roadway geometry conditions considered. These results suggest that at 70 mph drivers may be more willing to travel closer to the road's edge than at 80 mph. More detailed analysis taking into account radius of the curves and removal of transition zones is desired to verify these results. The presence of other vehicles could be a contributing factor that was not considered in the development of these results.

In addition to the practical difference by travel lane for the 70-mph sections, a practical difference of 6.8 inches was identified between different posted speed limit zones for vehicles in the left lane on horizontal curves to the left. The instrumented vehicle measured average lateral offsets for participants in the left lane of a left horizontal curve of −10.79 inches on the 70-mph section as compared to −3.99 inches on the 80-mph section. While a large sample size was available for this analysis (almost 450,000 data points), it only reflects the driving choices of the 14 participants included in the pilot study.

Speed and Lateral Offset Relationship with Posted Speed Limit and Travel Lane

While there may be statistical differences between vehicle speeds by travel lane, they are not greater than the practical threshold of 2 mph (see Table 4-3). One aspect of note is that the average traveling speed for all drivers in the 80-mph condition was under rather than over the posted speed limit as observed for the average speed in the 70-mph section. This suggests drivers may not have been driving as they normally do on such facilities. While drivers not exceeding the speed limit could be an indication of unwillingness to travel at those speeds, there are likely other reasons. They may have been driving differently because they were not driving their own vehicle. Another factor in West Texas may be an increase in enforcement of the 80-mph speed limit. A speed study along the same corridor the participants are driving would be desirable for comparison.

The lateral offset difference between travel lanes at 70 mph found for the different roadway geometry configurations (see Table 4-2 and discussion above) was also seen in the subset of sections reviewed for hand placement (see Table 4-3). The lateral offset for the left lane was −8.49 inches and only −1.17 inches for the right lane. Again, the presence of other vehicles was not considered in these results. In the 80-mph coded segment there was a 5.89-inch difference in lateral offset for the left and right travel lanes, which is near the 6-inch practical difference being used in this study. These differences suggest further evaluation of the factors that influence lateral offset would be of merit.

Driver Glance Rates Relationship with Travel Lane and Posted Speed Limit

Drivers had higher glance rates to the right for both posted speed limits and for both travel lanes. Drivers looked to the right approximately seven to eight glances per minute as compared to two to three glances per minute to the left or one to three glances per minute down. Future studies and analyses should use methods that obtain glance duration and can differentiate between a participant looking at a passenger in the vehicle and a passenger-side mirror.

Driver Hand Placement Relationship with Travel Lane and Posted Speed Limit

Some general observations about driver hand placement can be made using data from Table 4-5. The data suggest drivers prefer having their left hand on the upper half of the steering wheel rather than the right hand. The left hand was on top about 70 percent and below, off, or on an object for the remaining 30 percent. The right hand was on top for about 40 percent, below about 55 percent, and off about 5 percent of the time. These data also suggest the right hand is normally in the driver's lap or gripping the lower portion of the steering wheel. The right hand also seems to be the hand most likely to clearly not be on the steering wheel in all conditions.

A hand position of ten and two has been shown to be associated with more vehicle control. The theory is that drivers place both hands on the steering wheel if they feel the need to have greater control of their vehicle, perhaps due to traveling at higher speeds. Contrary to what may be expected, the 14 participant drivers tended to place fewer hands on the upper half of the steering column in the 80-mph condition than they did in the 70-mph condition. For the 80-mph posted speed limit, two hands were on the top of the steering wheel for about 30 percent of the time. For the 70-mph posted speed limit, two hands were on top of the steering wheel for about 33 percent of the time. This contradicts the idea that drivers feel more at risk at the higher speeds and thus try to exert more control over the vehicle.

So the question this raises is why did drivers exert less control over the vehicle in a condition that would seem to have a higher risk? One answer might be the drivers' familiarity with the vehicle. Most observations had the driver going through the 70-mph section after having driven the vehicle for 15 minutes, whereas in the 80-mph condition they had been driving for 45 minutes total. As driver familiarity with the vehicle became greater, they probably felt more comfortable in the vehicle, no matter the small change in risk they perceived between the two speed conditions measured.

Gap Distance Relationship with Operating Speed

While one may expect that larger gaps would be used at higher speeds, no pattern was identified from the 14 participants' data. Participants selected gap distances between 50 and 450 ft (limit of equipment) for the speed range observed (65 to 85 mph).

RECOMMENDATIONS FOR FUTURE STUDIES

Changes to consider if a larger open-road study is undertaken include the following:

- use of an eye-tracking device that can obtain both glance rate and duration without further coding to reduce data reduction effort;
- inclusion of a camera showing the entire steering wheel to differentiate between a hand in the driver's lap and a hand on the lower half of the steering wheel;
- possible inclusion of steering wheel grip sensors to evaluate the intensity at which the drivers grip the steering wheel as a measure of workload;
- development of more efficient computer macros to decrease data reduction effort;
- inclusion of a camera showing the roadway behind the instrumented vehicle. On high-speed facilities what is going on behind the vehicle can be just as important as what is going on in front of it;
- gathering of roadway geometry data to measure the effects of elements such as superelevation and curve radii in relation to lateral lane placement;
- use of the instrumented vehicle's GPS system to obtain an accurate GPS location for significant roadside objects such as off-ramps, on-ramps, and speed limit changes; and
- use of techniques to acquire a better balance between those participants that drive the 70-mph segment first and those participants that drive the 80-mph segment first (desirably about half of the participants should drive the 70-mph segment first and half the 80-mph segment first).

The gap distances used between vehicles just prior to passing that are available from this study do not show a difference for vehicles at 80 mph as compared to vehicles at 70 mph (see Figure 4-12). The sample size, however, only includes 14 drivers. A larger sample may provide other findings. Consider techniques for collecting gap distance between vehicles that are more efficient than hiring participants to drive TTI's instrumented vehicle. For example:

- Have a TTI researcher drive a vehicle with a rear-facing radar unit that can determine the gap distance between vehicles. An advantage of the method is that it should capture the minimum distances that occur just prior to a vehicle passing (the TTI vehicle would not pass other vehicles and would stay in the right lane). A disadvantage to the method is the number of miles that would need to be driven to capture several passing events. Researchers would need to investigate if the available speed/distance measuring technologies will activate radar detectors (which could impact driver behavior) and how best to record the data.
- Use traffic counters or video to measure speed and gap time between vehicles on 70-mph and 80-mph sections of I-20 or I-10. While this method will collect headway data between all vehicles within a lane, it may not capture the minimum distances that occur just prior to a passing maneuver.

CHAPTER 5

SIMULATOR PILOT STUDY

INTRODUCTION

Researchers conducted studies of driver workload and visual capabilities at speeds of 60 mph and above. This study consisted of observing and recording the activities and actions of several drivers in a driving simulator.

Data collection was conducted in TTI's full-size driving simulator. The driving simulator is comprised of four components: vehicle, computers, projectors, and screens. The vehicle, a complete, full-size 1995 Saturn SL automobile, is outfitted with computers, potentiometers, and torque motors connected to the accelerator, brakes, and steering. The Saturn also features full stereo audio, full instrumentation, and fully interactive vehicle components, all of which provide the realistic feel of driving. The Saturn is connected to a computer component that consists of one data-collection computer and three image-generation computers. Computer-generated driving scenes are sent to three high-resolution projectors and projected to three high-reflectance screens (see Figure 5-1). TTI's full-size driving simulator uses HyperDrive Authoring Suite™ to create the multiple test "worlds" through which the research participants drive. The roadways are created by piecing together tiles, or small segments of pre-developed roads. The world used in this study was developed by piecing together freeway tiles to create one long drive.

Figure 5-1. TTI Full-Size Driving Simulator.

DRIVING ENVIRONMENT

In designing the simulator study, researchers planned to make comparisons to the open-road and closed-course studies, so test speeds of 60 and 85 mph were selected. All testing conditions in the discussion to follow were driven by the participant at each of these two speeds.

The primary task of the participant was to follow a lead vehicle within a given target range. The participant was asked to follow the vehicle keeping a 2-sec or less spacing between them at all times. The practice world, which the participant initially drove, was designed so that a green plus sign would appear above the lead vehicle if the participant vehicle was within the 2-sec distance. This provided the participant with the opportunity to obtain a feel for when they were within the 2-sec range. For the experimental worlds, the driver was not provided any assistance and was required to determine the 2-sec range on his or her own, thereby increasing the difficulty. The recorded simulator data provided the driver's proximity to the lead vehicle.

The lead vehicle took the driver through two curves in each experimental world. Within the curves the lead vehicle performed an "Ivan," or sporadic speed change maneuver, and the participant also passed a changeable message sign (CMS). These stimuli will be explained more in the sections to follow. During the study, each participant followed both a small yellow car and a large grey truck, as shown in Figure 5-2, at speeds of 60 and 85 mph.

(a) Small Yellow Car (b) Grey Truck

Figure 5-2. Simulator Screenshots Showing the Two Varying Lead Vehicles and a CMS.

Ivans

The lead vehicle occasionally changed speed in a structured pattern that the researchers refer to as an "Ivan." One of these patterns resulted in the lead vehicle first accelerating over the speed limit and then varying speed before returning to the speed limit, while the second pattern had the lead vehicle first decelerate before varying speed. These two patterns are referred to as an Up Ivan and Down Ivan, respectively. Regardless of the speed limit, the two patterns had the same incremental speed changes each time they were repeated. They were triggered to occur at the same points in the roadway with identical geometry. Each participant saw both an Up Ivan and a

Down Ivan at each speed limit for both types of lead vehicles. Examples of both Ivans are shown in the "Data Reduction" section of this chapter.

Changeable Message Sign

Two-phase changeable message signs were also stimuli used to evaluate driver workload at the various speeds. An example of a CMS is shown in Figure 5-2(a). Along with following a lead vehicle around a curve and trying to maintain a 2-sec following distance, the participants were asked to read the CMS that they passed and then to answer questions about the sign. These CMS questions were asked by the researcher, and the researcher also recorded the driver's responses. A practice version of a CMS was built into the front of the worlds to give the participant an opportunity to acquire a feel for the types of questions they would be asked regarding the CMS's message. The responses for the practice question were not recorded. There was also a CMS on a tangent where the lead vehicle did not vary its speed in each session to serve as the baseline condition. These responses were recorded by the researcher.

Bicyclist, Lane Closure, and Lane Change Events

Another method to evaluate workload at the two different speeds was to incorporate "obstacles" into the simulator world. Figure 5-3 shows a bicyclist that weaves in and out of the driver's lane. At high speeds drivers may have a different reaction time or come into closer proximity to the bicyclist before changing lanes than they would at a lower speed. Another obstacle used was a lane closure due to construction that forced the driver into the center lane (see Figure 5-4). All of the obstacles used in this study were contained in a session before the lead vehicle became present (called the obstacle session).

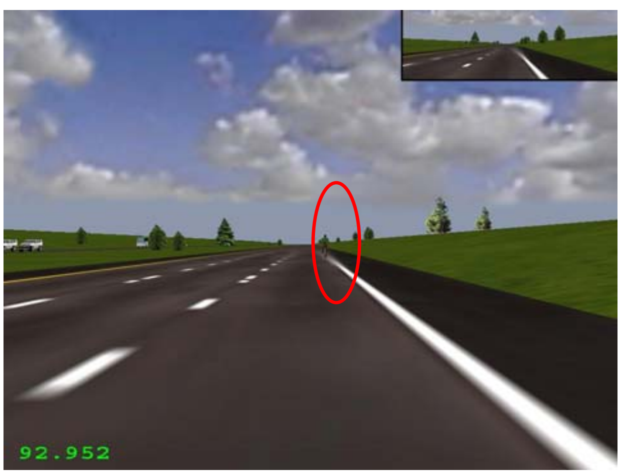


Figure 5-3. Weaving Bicyclist Obstacle.

Figure 5-4. Construction Lane Closure Obstacle.

A lane change was also included. The lead vehicle moved from the right to the center lane due to a lane closure up ahead. Before beginning the study the driver was asked to follow the lead vehicle if it made any lane changes. The driver's reaction time to make the lane change, and the proximity to the lane closure, were recorded. Details contained in the "Recommendations for

Future Studies" section of this chapter explain how this scenario could be improved for the next simulator test.

Traffic, Mirrors, and Brake Lights

Often in simulations ambient traffic is not programmed, and the rear mirrors and side-view mirrors are not used. For the purpose of this study, researchers wanted drivers to feel as if they were on a freeway, so both of these features were utilized for the experimental sessions.

Due to the limitations and flickering of the projector resolutions, the appearance of brake lights on various vehicles can be inconsistent and unpredictable. Because of this, the lead vehicle's brake lights were programmed to be off for the duration of its drive.

RESEARCH PARTICIPANTS

TTI employees recruited participants for the study through word of mouth and by contacting previous participants in TTI's consenting participant pool. Recruitment involved several prescreening questions to assess whether the recruits might experience simulator-induced discomfort (SID). If the recruits appeared to be candidates for the sickness, they were not scheduled for the study. Along with the initial sickness screening, participants completed a short, widely used questionnaire of possible symptoms they might obtain from their time in the simulator. Participants also completed an identical questionnaire at the end of their drive in the simulator.

Twelve drivers, consisting of seven women and five men, completed the driving simulation experiment. The age of two drivers was between 18 and 35, eight drivers were between 36 and 55, and two drivers were over 55, with an overall average age of 44. The participants represented a variety of education levels, driving experience, and driving frequency.

PROCEDURE

Before beginning the experiment, each participant was asked to read and sign a consent form acknowledging their rights as a research participant. The participants then completed the sickness questionnaire previously mentioned and were asked to enter the vehicle and adjust the seat and air to their comfort.

Sessions

Each participant was to complete experimental sessions with a speed of 60 or 85 mph, and with either the large grey truck or the small yellow car as a lead vehicle. Participants started the program with a practice session. Following the practice session was the obstacle session that included the bicyclist and lane closure. The obstacle session was either at 60 or 85 mph. The following is an example of the order of sessions for a participant:

- Session P: practice driving and introduction to the driving environment;
- Session O-1: obstacle events and desired speed of 85 mph;

- Session E-1: experimental events, desired speed of 85 mph, and following the large grey truck;
- Session E-2: experimental events, desired speed of 85 mph, and following the yellow car;
- break for participant;
- Session O-2: obstacle events and desired speed of 60 mph;
- Session E-3: experimental events, desired speed of 60 mph, and following the yellow car;
- Session E-4: experimental events, desired speed of 60 mph, and following the large grey truck; and
- Session C: concluding questionnaires and compensation.

The order of the CMS and Ivan events within the experimental sessions, along with the roadway characteristics, can be seen in Table 5-1. The obstacle location and the timing of the lead vehicle's lane change are also shown in the table.

Table 5-1. Event Order within Each Session.

Session	**Session Description**	**Event Order**	**Features Present during Event**				
			Tangent	**Curve**	**Up Ivan**	**Down Ivan**	**CMS**
P	Practice	Practice					
O-x	Obstacles	Bicyclist Lane closure	X				
E-x	Experimental: for a given vehicle type (car or truck) and initial speed (60 or 85 mph)	Baseline with CMS	X				X
		Up Ivan with CMS		X	X		X
		Lane change	X				
		Down Ivan without CMS	X			X	
		Down Ivan with CMS		X		X	X
		Up Ivan without CMS	X		X		
E-x	Repeat of Session E with different vehicle type or speed, total of 4 Session Es were held						
C	Concluding questionnaires, etc.						

Counterbalancing

In order to counter learning effects in driving skill or CMS comprehension, the 12 participants were split into four groups that viewed the experimental sessions in four different orders as shown in Table 5-2. Every participant began with the obstacle session (Session O) at either the 60-mph or 85-mph speed. After the break, the participant began with the obstacle session for the other speed. Half of the participants started with following the truck, while the other half followed the car.

Table 5-2. Characteristics of the Sessions by Participant Number.

Session	**Participant Number**			
	1, 5, 9	**2, 6, 10**	**3, 7, 11**	**4, 8, 12**
	Speed, lead vehicle type			
P	60 and 85 mph	60 and 85 mph	60 and 85 mph	60 and 85 mph
O-1	85 mph	60 mph	85 mph	60 mph
E-1	85 mph, truck	60 mph, truck	85 mph, car	60 mph, car
E-2	85 mph, car	60 mph, car	85 mph, truck	60 mph, truck
Break				
O-2	60 mph	85 mph	60 mph	85 mph
E-3	60 mph, car	85 mph, car	60 mph, truck	85 mph, truck
E-4	60 mph, truck	85 mph, truck	60 mph, car	85 mph, car
C	Concluding questionnaires, etc.			

Practice Session

The following was read to the participant before beginning the practice session:

> *"For the practice session your task is to get comfortable with driving in the simulator. The driving scene that will be presented to you begins with the simulator vehicle stopped on the side of the road. Once we are finished with the instructions and your questions have been answered, you may pull out onto the roadway and proceed to drive as normal in the right-hand lane. The freeway speed limit will begin at 60 mph. The vehicle is already turned on; you just need to place the car in drive to begin. Any questions? Go ahead and slowly maneuver onto the roadway and take your time getting up to a speed of 60 mph.*
>
> *"How are you doing? Once you're comfortable at this speed, practice changing lanes a couple times."*
>
> (The following was read as the participant approached the first interchange.)
>
> *"Please return back to the right lane and slowly slow down to about 60 mph.*
>
> *"In a second you will see a large grey cargo truck merge into your lane from the right. Allow this vehicle to merge ahead of you. Your task will be to follow this vehicle leaving a 2-second or shorter following distance. You will know that you are 2 seconds or closer by the green plus sign that will appear on the screen in front of you when you are in the appropriate range. When the plus sign disappears, you will need to speed up to get back in the target range. The purpose of this task is for you to get a feel of what it is like to drive in the 2-second range in the simulator. Although we realize normal driving instruction would have you follow at greater lengths on this type of roadway and at these types of speeds, we would like you to follow at 2 seconds for the purpose of this study."*

(The following was read as the participant approached the second interchange.)

"Up ahead, the truck will exit, but please continue driving straight in the right lane and adjust your speed to 85 mph. This time a small yellow car will merge in front of you from the right. Practice following this vehicle within the 2-second target range as you did before. It is okay if you must drive above the speed limit to do this. Your primary task is to remain in the target range.

"How are you doing? Do you feel you've had enough practice? Please slowly coast to a stop and place the car in park."

Experimental Session

While the experimental session world was loading, the researcher read the instructions below to the participant. Speed instructions and the lead vehicle description varied depending on which session the participant was in.

"The driving simulator you are seated in is an interactive simulator, which means the driving scenes you experience react to your steering and pedal inputs to provide a realistic driving experience. During your drive in the simulator, please drive in a normal fashion.

"The driving scene that will be presented to you begins with the simulator vehicle stopped on the side of the road. Once we are finished with the instructions and your questions have been answered, you may pull out onto the roadway and proceed to drive as normal in the right-hand lane. The freeway speed limit will begin at <u>85 mph/60 mph</u>.

"You may ask questions at any time, but other than that and answering the questions the researcher asks you during the study, please refrain from talking during this experiment. There are speakers and a microphone in the vehicle for you and the researcher to communicate when needed.

"In the initial portion of the course, make any driving maneuvers you need to, but try to stay in or return to the right-hand lane whenever possible. Several miles down the road you will also see a <u>large grey truck/small yellow car</u> merge into your lane from the right. Allow this vehicle to merge ahead of you. This will be the start of the experimental session. Your task will be to follow this vehicle, leaving a 2-second or shorter following distance as you did in the practice although this time you will not have the green plus sign as your guide. Do your best to remain in the 2-second following range. The researcher will remind you if you drift too far back. Although the vehicle will average around the speed limit, please focus on keeping in the target range rather than staying at the speed limit.

"Occasionally the lead vehicle will change lanes. Continue to follow the vehicle and change lanes along with it. You do not have to remain in the right-hand lane at this point.

"Another task you will encounter along the way is to read changeable message signs you will see alongside the road. Read the sign silently to yourself. After you pass the sign, the researcher will ask you questions about the sign such as 'What was the traffic problem?' or 'What did the sign tell you to do?' Please answer only the specific question the researcher is asking. Do not recite the entire sign that you saw to the researcher.

"At the end of the session, I will ask you to bring the vehicle to a complete stop and place it in 'park.' We will then have a 5-minute break while the next program loads. After the break, we will cover the instructions for the next experimental session. Do you have any questions regarding the procedure?"

(If "yes," the researcher answered the person's questions. If "no," the test proceeded.)

After the first experimental session was completed, the researcher read the following instructions before each of the remaining three sessions. Again, the speed instructions and the lead vehicle description varied depending on which session the participant was in.

"The remaining three sessions will be very similar to Session 1. You will begin with the simulator car parked on the side of the road. Once we are finished with the instructions and your questions have been answered, you may pull out onto the roadway and proceed to drive as normal in the right-hand lane. For Session 2/3/4 the freeway speed limit will begin at 55 mph/60 mph.

"As before, you will be following a lead vehicle within a target range. This time a small yellow car/large grey truck will merge in front of you from the right. Follow this vehicle within the 2-second target range.

"Again, you will see several changeable message signs and will be asked similar questions as before by the researcher. Continue to answer only the specific question the researcher is asking.

"At the end of the session, I will ask you to bring the vehicle to a complete stop and place it in 'park.'"

At the end of all four sessions, the participants completed an ending sickness questionnaire and a demographic and driving data questionnaire, and were compensated for their participation.

DATA COLLECTION

The experimental worlds were programmed to collect data at 30 Hz in the test condition segments and not during the filler segments. The following variables were collected:

- time (sec),
- velocity (meters/sec),
- distance (meters),
- lane position (as an offset in meters of the center of the vehicle from the centerline),
- acceleration (on a scale from 0 to 1),
- steering (in degrees),
- braking (on a scale from 0 to 1),
- distance to entity (meters), and
- entity velocity (meters/sec).

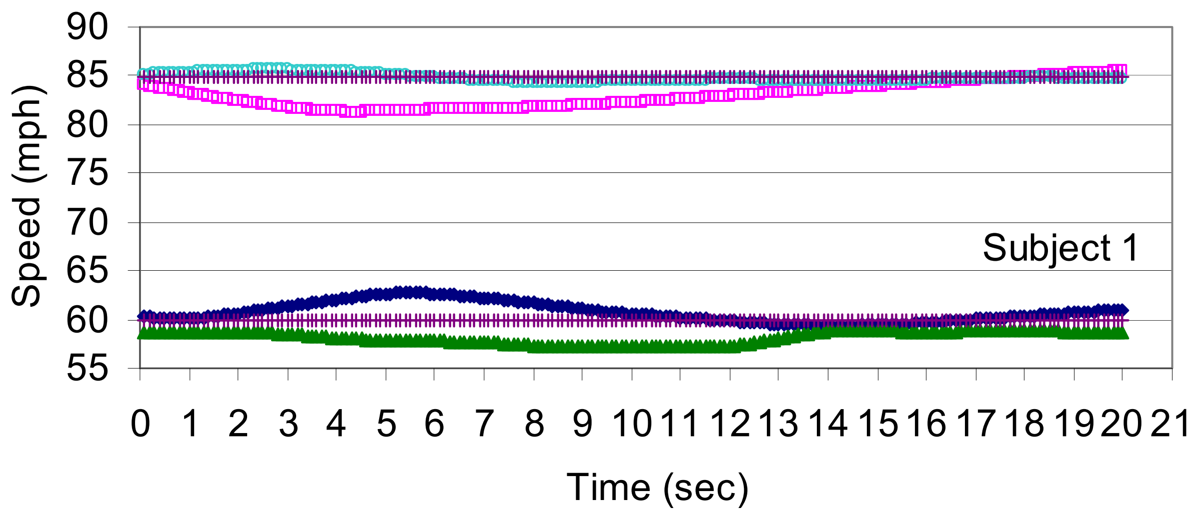
DATA REDUCTION

The data available from the simulator are in metric units. The distances and velocities were converted to U.S. standard units for evaluation. The continuous data can be used to generate speed-time plots.

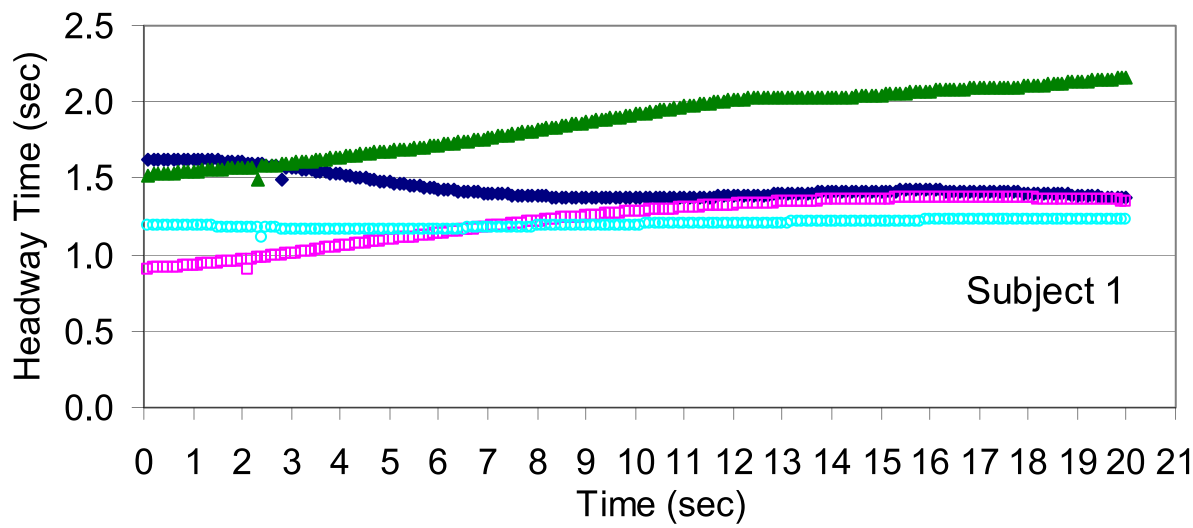
Figure 5-5 shows a sample of baseline data for Participant 1. In Figure 5-5(a) the speeds of the participant vehicle and lead vehicle are plotted for both the 60- and 85-mph scenarios. The lead vehicle has a constant speed of 85 mph or 60 mph, while the speed of the participant driver, who was told to follow the lead vehicle within 2 sec, tends to vary a few miles per hour around the lead vehicle's speed. Figure 5-5(b) shows the headway time between the lead and participant vehicles. For the 20 sec shown in the baseline profile, the headway time was between 0.9 and 2.2 sec.

Figure 5-6 shows the speed-time plot for Participant 1 during a Down Ivan with a 60-mph initial speed. It also shows the headway measured in feet between the two vehicles during the maneuver. Figure 5-7 shows similar graphs for a Down Ivan occurring during the 85-mph initial speed portion.

For the 60-mph initial speed shown in Figure 5-6(a), the lead vehicle begins the Down Ivan at time 0 sec while the participant vehicle was increasing speed. At approximately 1.5 sec, the participant vehicle stopped increasing speed. The difference between the beginning of the Ivan (at 0 sec) and when the participant was no longer accelerating was defined as the "reaction time to lead vehicle speed change" or "reaction time to decrease speed." The minimum headway for this event was 125 ft as shown in Figure 5-6(b).



(a) Speed Profile of Participant Vehicle and Lead Vehicle



(b) Headway Distance between Participant Vehicle and Lead Vehicle

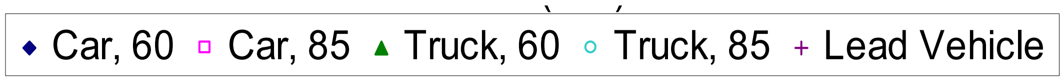
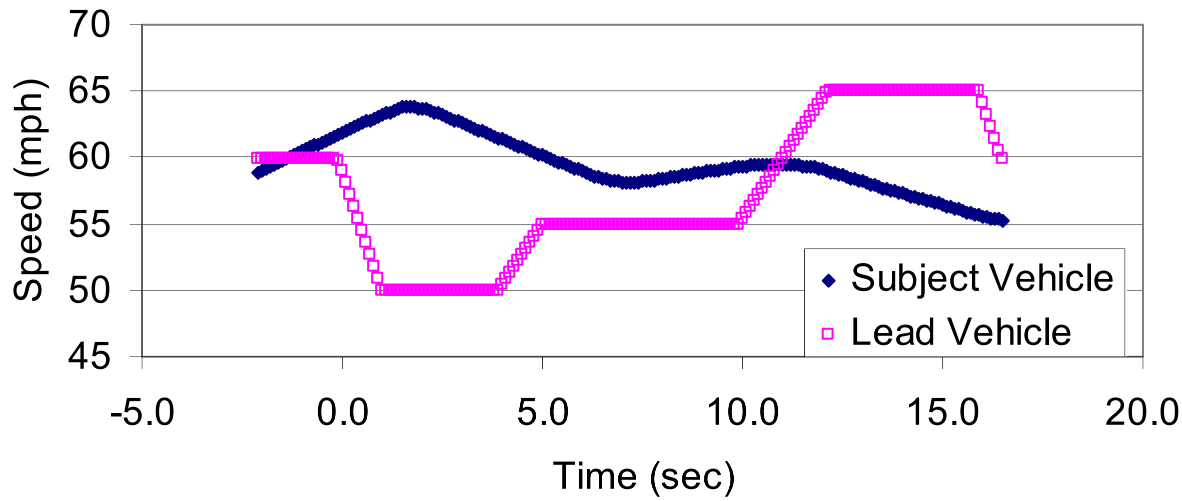
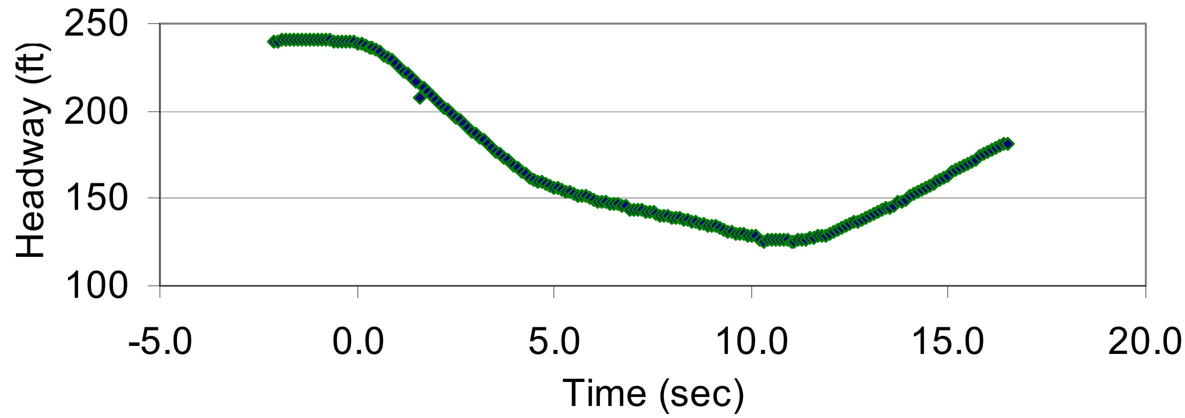


Figure 5-5. Speed Profile and Headway Distance for Participant 1 during Baseline Conditions.



(a) Speed Profile of Participant Vehicle and Lead Vehicle

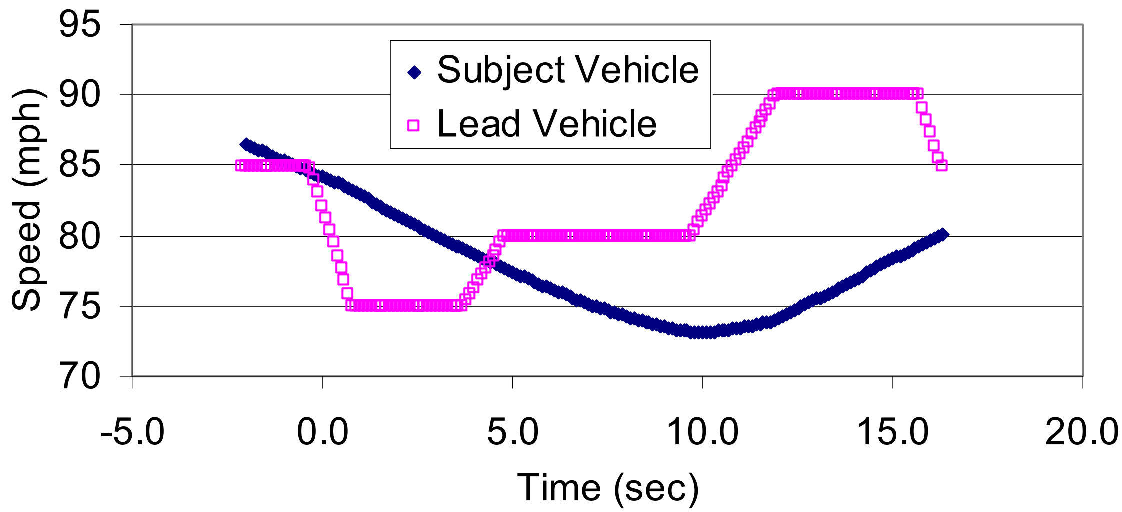


(b) Headway Distance between Participant Vehicle and Lead Vehicle

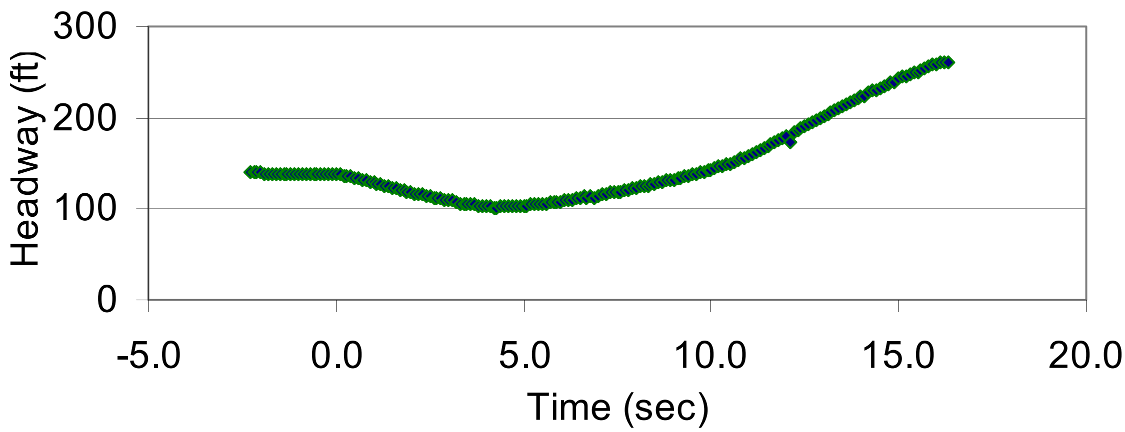
Figure 5-6. Speed Profile for Participant 1 during a Down Ivan with Initial Speed of 60 mph.

For the 85-mph initial speed shown in Figure 5-7(a), the participant vehicle was decelerating when the lead vehicle began the Down Ivan. The participant vehicle continued the deceleration during the Ivan until after the lead vehicle changed speed and began to accelerate. The minimum headway during this maneuver was 100 ft as shown in Figure 5-7(b).

An objective of using the driving simulator was to determine the driver's reaction to a looming vehicle. When the participant vehicle was accelerating, the point of reaction is easy to identify—it is the location when the vehicle's speed is no longer increasing, as shown in Figure 5-6(a). When the participant vehicle was decelerating, as shown in Figure 5-7(a), the location when the driver realized that the lead vehicle was looming into view cannot be as easily identified. Another measure that could be used is the time when the driver applied the brakes.



(a) Speed Profile of Participant Vehicle and Lead Vehicle



(b) Headway Distance between Participant Vehicle and Lead Vehicle

Figure 5-7. Speed Profile for Participant 1 during a Down Ivan with Initial Speed of 85 mph.

Figure 5-8 shows the speed profile for a Down Ivan presented to Participant 11 when following a car. The figure has a second axis that shows the use of the brake or gas pedal. In Figure 5-8, the time to when the participant vehicle began decreasing speed was at 1.0 sec. This time was determined by searching the speed values for the participant vehicle and flagging the time when the speed value decreased from the preceding value. The speed change is also reflected in the use of the gas pedal (shown with a plus symbol). Prior to 1 sec, the participant applied the gas at approximately 0.35 sec or the 35 percent level (see axis on the right side of the graph). At approximately 1 sec, the participant released the gas pedal. At 1.8 sec, the brake was applied (shown with a triangle symbol). Examining the participant's use of the brake pedal is another method to quantify driver behavior in response to the behavior of a lead vehicle.

As shown in Figure 5-5, a driver undergoes a series of speed increases and decreases as the driver attempts to stay within 2 sec of the lead vehicle. When a participant is decelerating at the start of an Ivan, the researchers cannot determine when the deceleration becomes a response to the lead vehicle's behavior as opposed to a driver's typical speed fluctuations. Researchers can determine when the driver uses the brake. Drivers may respond to an Ivan by releasing the gas pedal and coasting and, in some cases, never use the brake. Therefore, researchers determined reaction time using two methods:

- reaction time to a lead vehicle's speed reduction for each event when the participant driver was accelerating and
- reaction time to use of the brake.

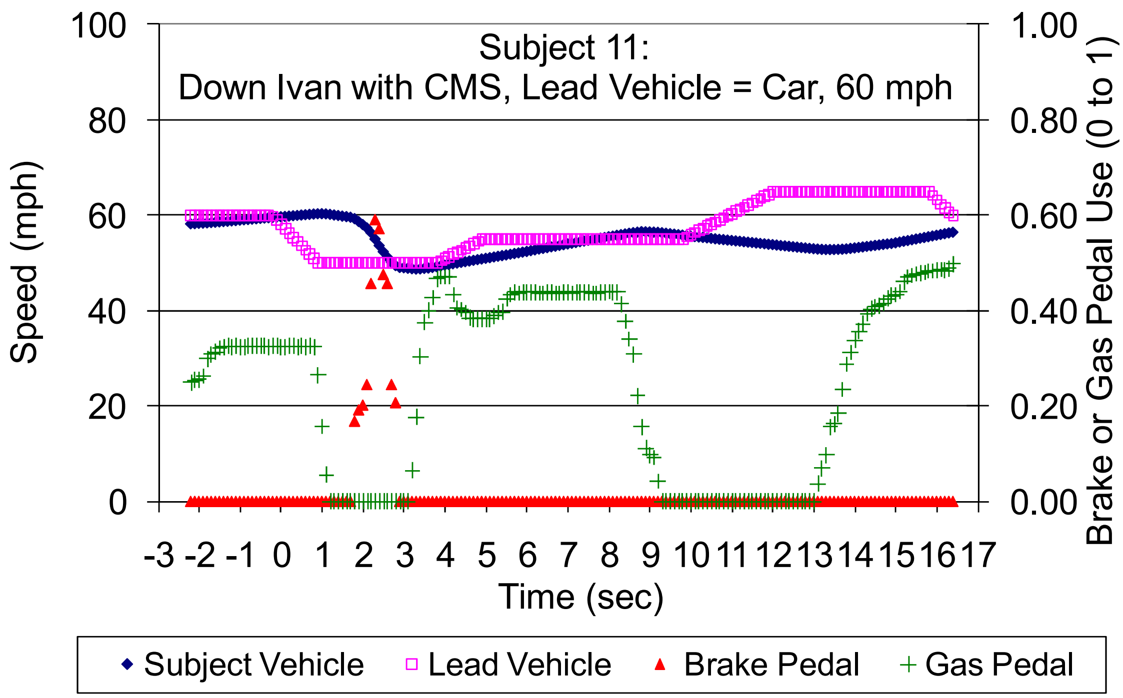
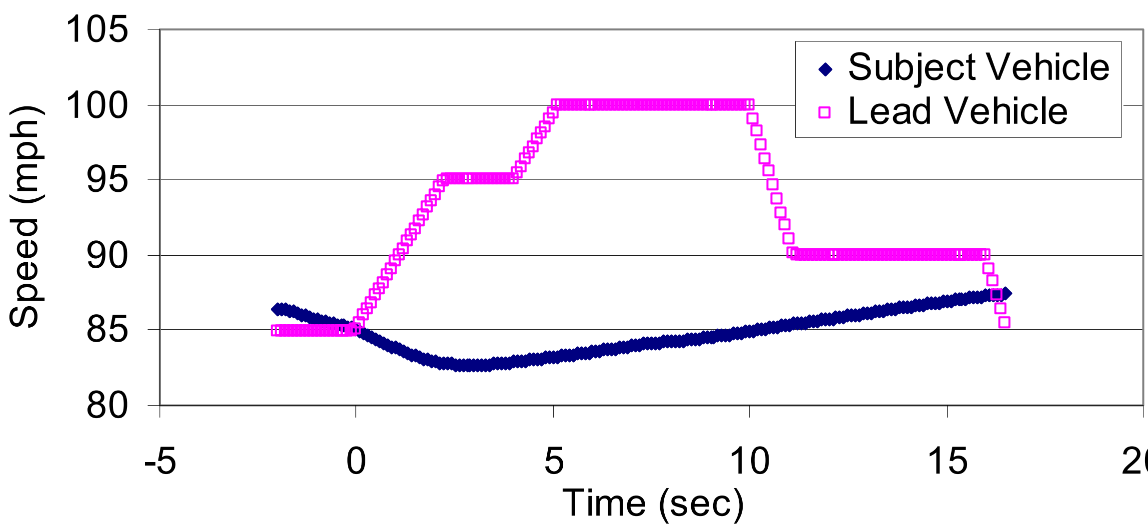


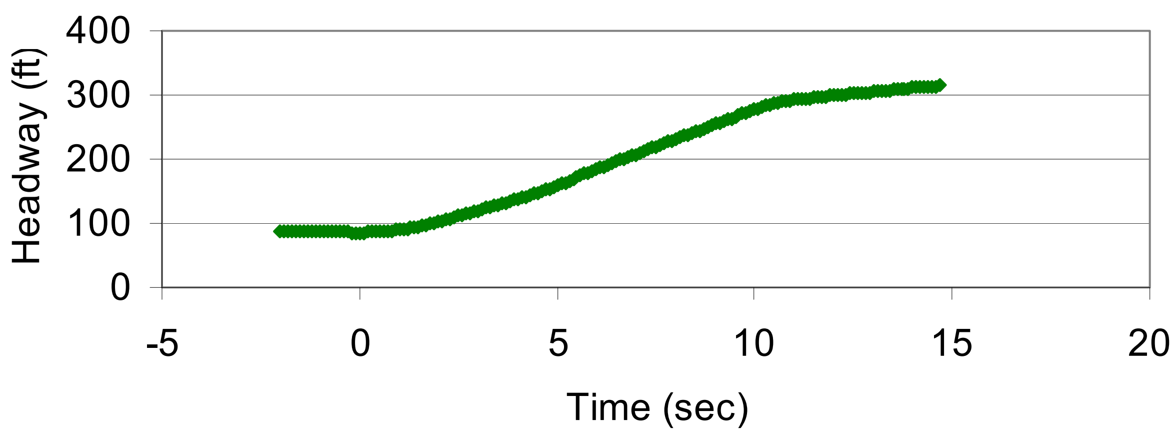
Figure 5-8. Speed Profile and Brake and Gas Pedal Use for Participant 11 during a Down Ivan with Initial Speed of 60 mph.

The reaction times were determined both for Down Ivans with a CMS and Down Ivans without a CMS. Down Ivans with a CMS occurred within a horizontal curve and while the participant was observing a CMS and responding to questions. Down Ivans without a CMS represented a speed reduction on a tangent section without a CMS.

As part of the simulated course, the lead vehicle also changed speed, with the initial change being an increase of 10 mph as illustrated in Figure 5-9. The 10-mph increase in speed was followed by a short time period of a constant speed and then an additional increase of 5 mph. After another period of constant speed, the lead vehicle reduced speed by 10 mph and then 5 mph, returning to the original speed for the segment. These initial increase speed maneuvers were included so that the participant had to react to both types of speed changes (initial deceleration and initial acceleration). Since the interest was in drivers reacting to a "looming" vehicle rather than a receding vehicle, limited evaluations were conducted for the Up Ivans.



(a) Speed Profile of Participant Vehicle and Lead Vehicle



(b) Headway Distance between Participant Vehicle and Lead Vehicle

Figure 5-9. Speed Profile for Participant 1 during an Up Ivan with Initial Speed of 85 mph.

RESULTS

Each participant experienced several combinations of the lead vehicle initially accelerating or decelerating. The participant was presented an Ivan once for each combination of lead vehicle type, initial speed, type of Ivan, and presence of CMS. Table 5-3 lists the combinations of conditions present during the Ivans. Table 5-4 shows the total number of Ivan events in the study.

Table 5-3. Number of Ivan Events per Participant.

Type of Event		Number of Events				
Ivan Type	**CMS**	**Car Truck**				**TOTAL**
		60 85		**60**	**85**	
Down	**With CMS**	1	1	1	1	4
	Without CMS	1	1	1	1	4
Up	**With CMS**	1	1	1	1	4
	Without CMS	1	1	0*	0*	2
TOTAL		4	4	3	3	14
* Missing data due to simulator error						

Table 5-4. Number of Ivan Events in Study with 12 Participants.

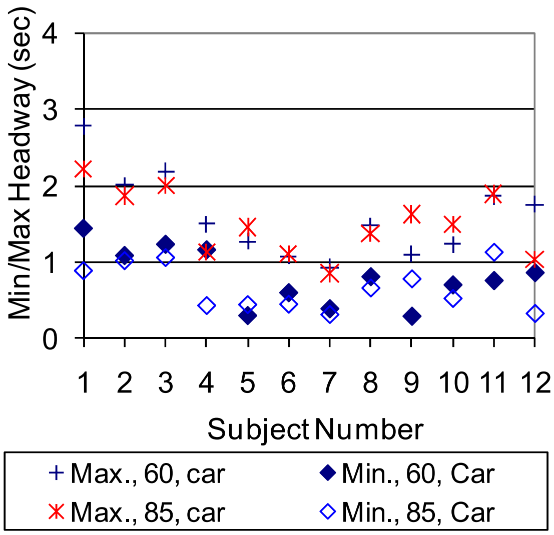
Type of Event		Number of Events				
Ivan Type	**CMS**	**Car Truck**				**TOTAL**
		60 85		**60**	**85**	
Down	**With CMS**	12	12	12	12	48
	Without CMS	12	12	12	12	48
Up	**With CMS**	12	12	12	12	48
	Without CMS	12	12	0*	0*	24
TOTAL		48	48	36	36	168
* Missing data due to simulator error						

Headway

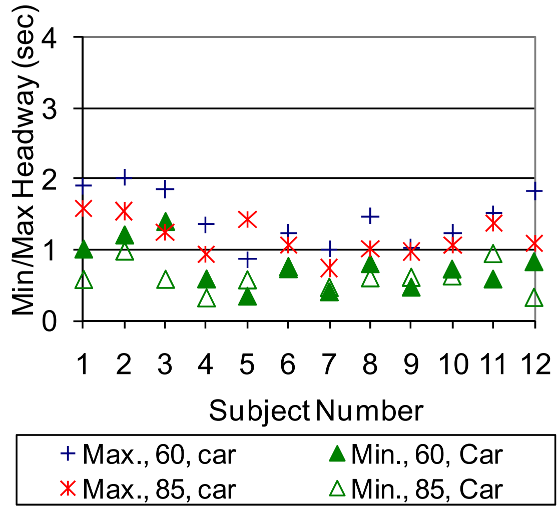
Both headway distance and headway time between the participant vehicle and the lead vehicle are available. The participants were told to stay within a 2-sec headway with the lead vehicle during the session.

Figure 5-10 shows the minimum and maximum time headway measured during the Down Ivans, while Figure 5-11 shows the minimum and maximum time headway measured during the Up Ivan. Figure 5-12 shows the minimum distance headway for the Down Ivans. Observations from Figures 5-10 through 5-12 include:

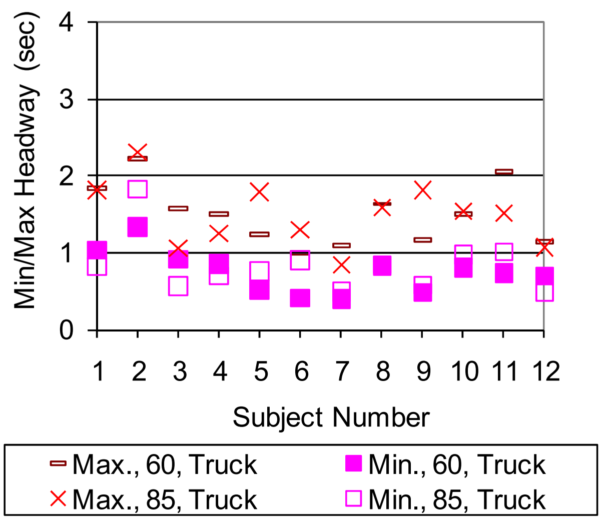
- As expected smaller headways were measured during the Down Ivans (see Figure 5-10) as compared to the Up Ivans (see Figure 5-11).
- Also as expected, the range of headways appears to be smaller during the Down Ivans.
- When minimum distances are reviewed (see Figure 5-12), distances as small as 25 ft were recorded. Of the shortest distances, most were associated with initial speeds of 60 mph rather than 85 mph.



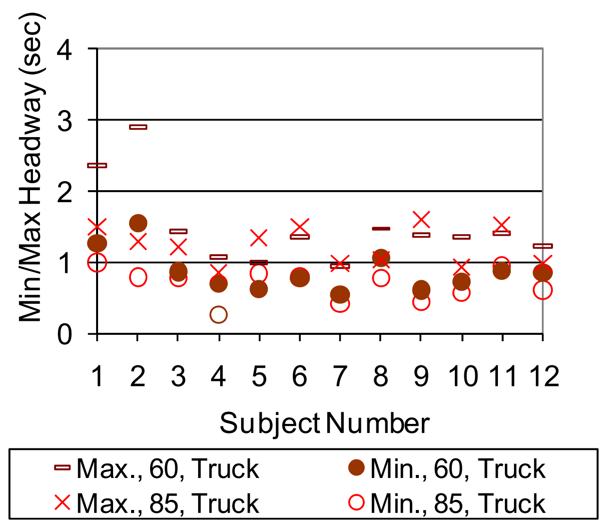
(a) Down Ivan, Car, Curve, with CMS Question



(b) Down Ivan, Car, Tangent, without CMS Question

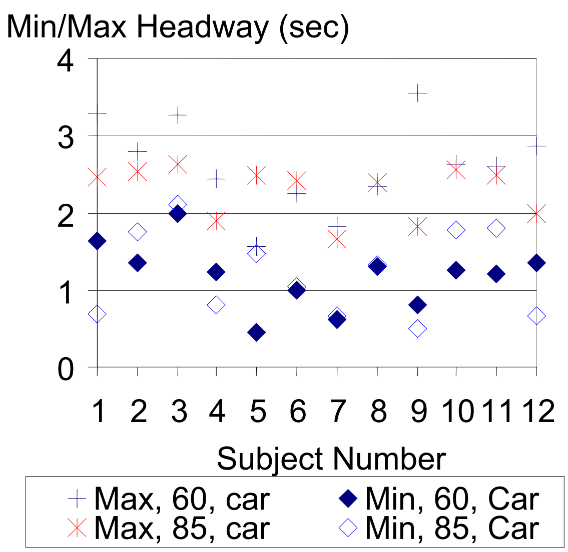


(c) Down Ivan, Truck, Curve, with CMS Question

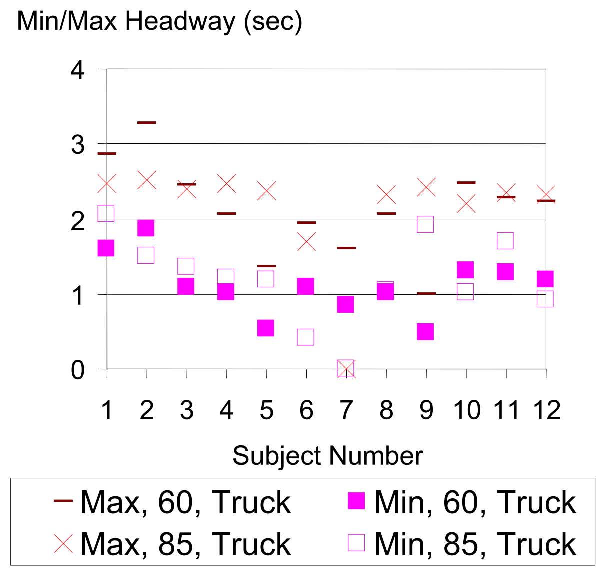


(d) Down Ivan, Truck, Tangent, without CMS Question

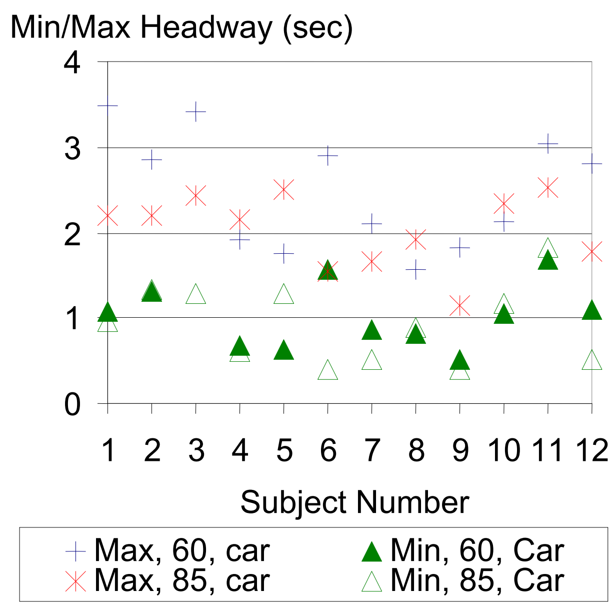
Figure 5-10. Minimum and Maximum Headways during Down Ivan Maneuvers.



(a) Up Ivan, Car, Curve, with CMS Question

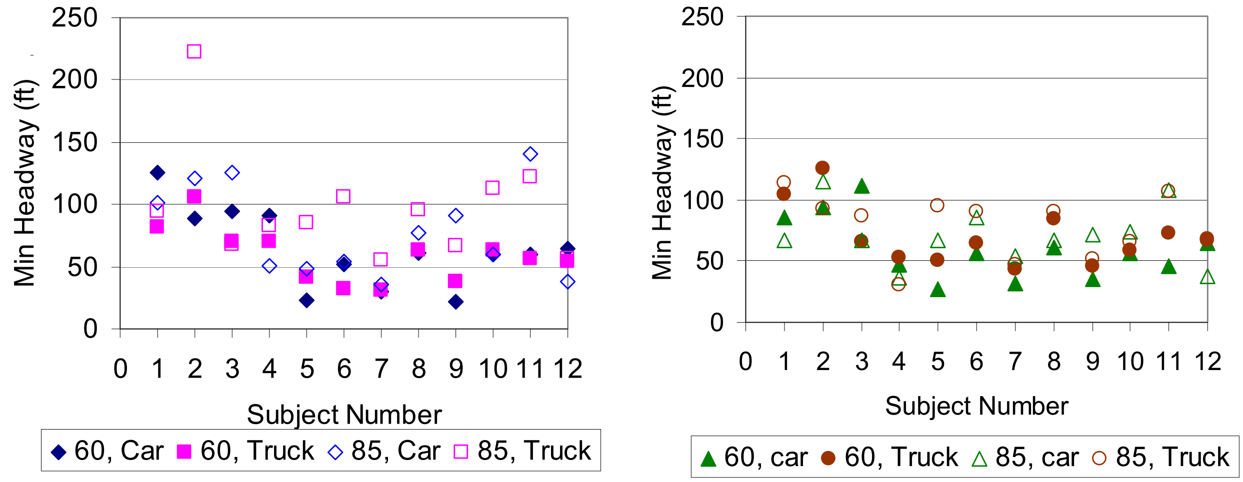


(b) Up Ivan, Car, Tangent, without CMS Question



(c) Up Ivan, Truck, Curve, with CMS Question

Figure 5-11. Minimum and Maximum Headways during Up Ivan Maneuvers.



(a) Down Ivan, Curve, with CMS Question **(b) Down Ivan, Tangent, without CMS Question**

Figure 5-12. Minimum Distance Headways during Down Ivan Maneuvers.

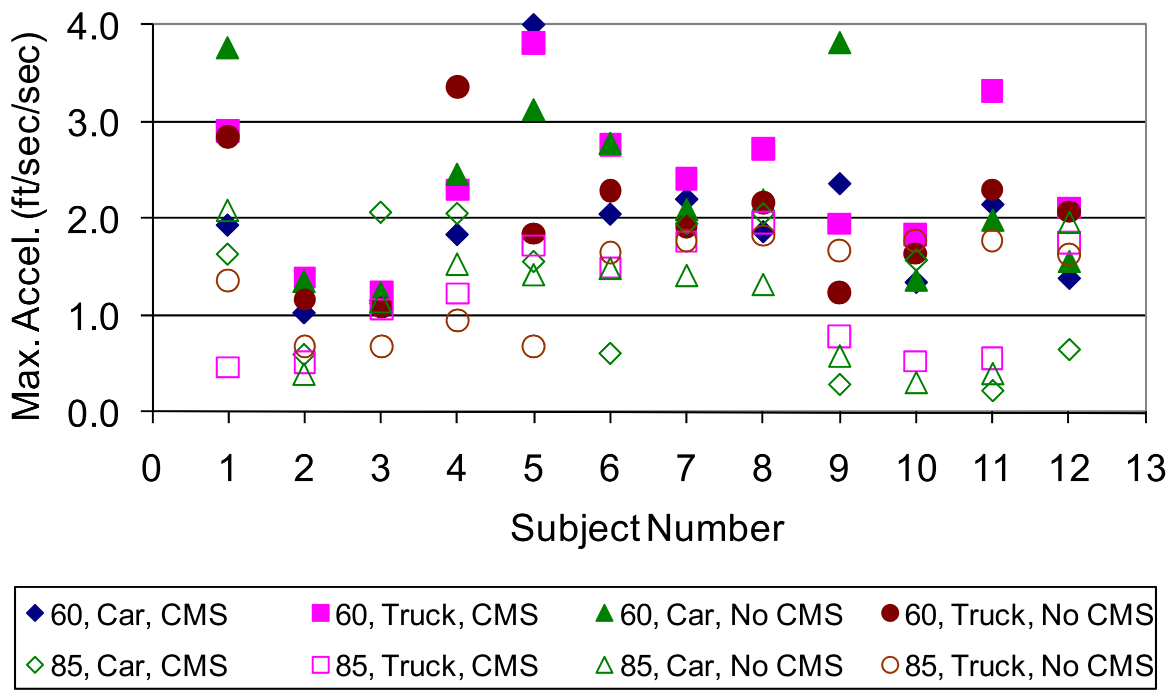
Acceleration

Maximum Acceleration

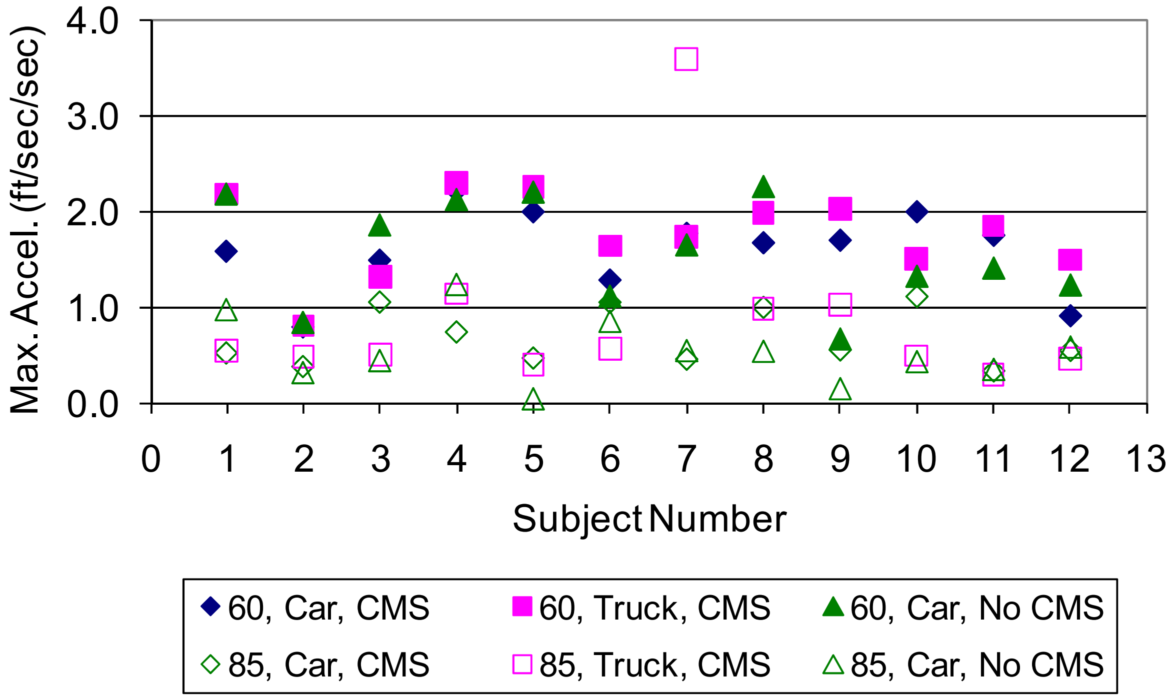
Within the Ivans, the participant vehicle accelerated in some portions of the Ivan and decelerated in others. Acceleration was determined for each constant speed increase or decrease portion. For example, if the participant vehicle increased speed for 5 sec and then decreased speed for the next 11 seconds, two acceleration values were determined—a positive acceleration for the first 5 sec and then a negative acceleration (also called deceleration) for the remaining 11 sec.

The maximum and minimum acceleration values were identified for each event. Figure 5-13(a) shows the maximum acceleration values for the Down Ivans, while Figure 5-13(b) shows the maximum acceleration values for the Up Ivans. A review of the data reveals, in general, the following:

- The maximum acceleration values were generally under 4 ft/sec^2.
- Lower maximum acceleration values are present for the events that occurred with an initial speed of 85 mph (see open symbols in the figures). The style of vehicle used in the simulator (1995 Saturn) may contribute to the lower acceleration values observed at the higher initial speed.



(a) Down Ivans



(b) Up Ivans

Figure 5-13. Maximum Acceleration Values during Ivans.

- The Down Ivans had higher maximum acceleration than the Up Ivans, which initially may appear contrary to expectations. In the Up Ivans, the lead vehicle increased speed by 10 mph followed by a 5-mph increase. The Down Ivans started with the lead vehicle decelerating 10 mph. The lead vehicle then increased speed by 5 mph, followed by another increase of speed of 10 mph. The event ended with another 5-mph decrease to return the lead vehicle to the desired speed. The Down Ivans included more speed changes than the Up Ivans, which provided the opportunity for more speed changes and differences. The participant vehicle had to accelerate more to try to keep within the 2-sec range of the lead vehicle during the Down Ivan because of the initial speed decrease.

Minimum Acceleration

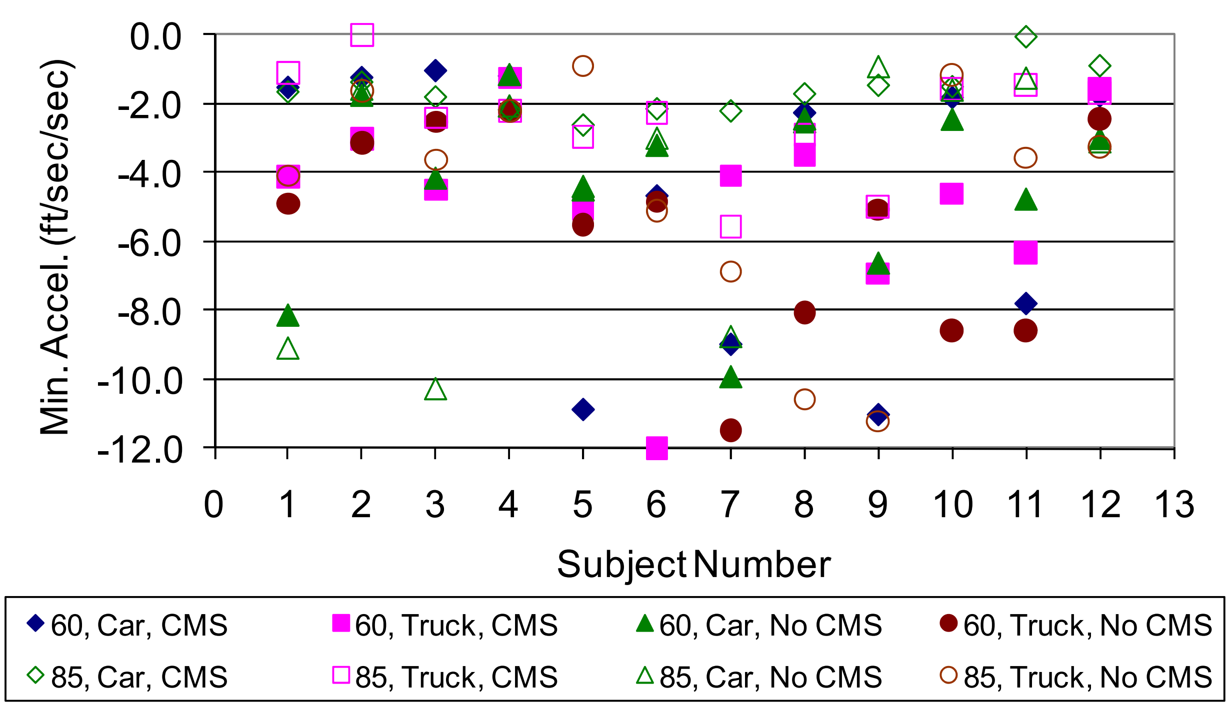
The minimum acceleration represents the maximum deceleration for a participant vehicle in response to the lead vehicle's behavior. As expected, the Down Ivans produced the largest decelerations (see Figure 5-14). In two cases, the deceleration values (11.49 and 12.0 ft/sec^2) slightly exceeded the assumed deceleration for a stopping sight distance condition (11.2 ft/sec^2). In many cases, the deceleration values were in the range of deceleration without brakes (generally about 4 ft/sec^2 for initial speeds of about 60 mph).

Headway at Speed Change Location

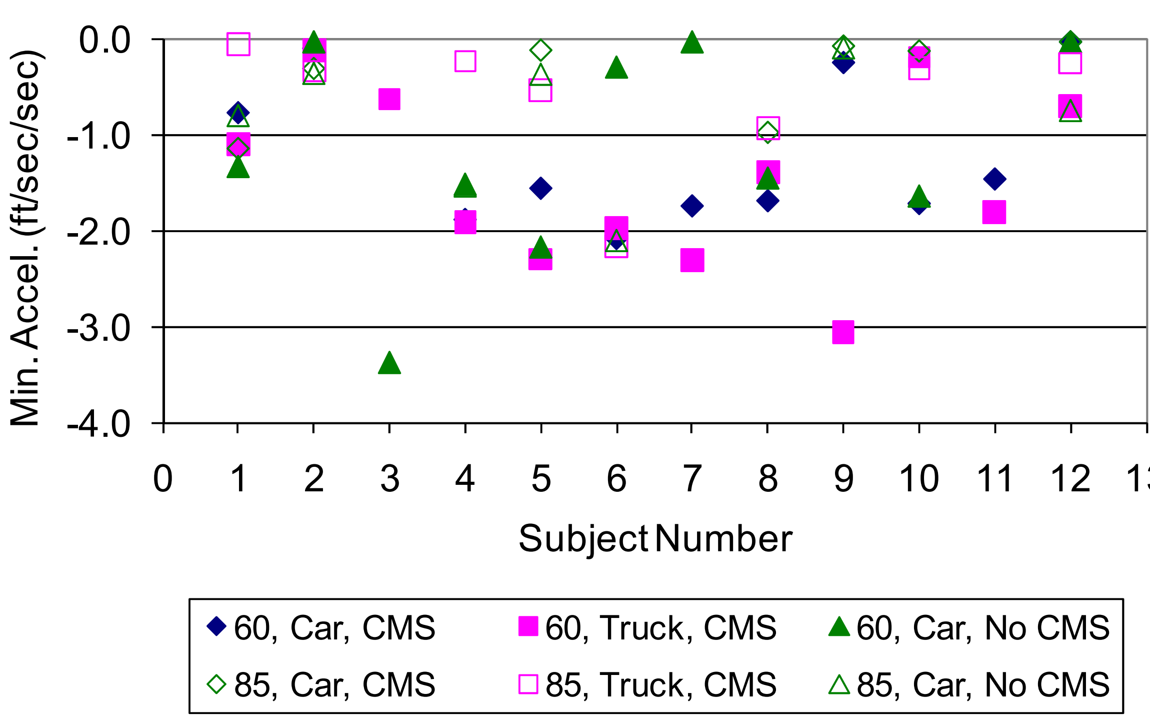
The headway value when a driver's speed changes from increasing or from decreasing may be related to the amount of acceleration selected by the driver. The headway distances when drivers changed their acceleration for the Up Ivans ranged between 50 and 300 ft for acceleration values that ranged between −3 and +2 ft/sec^2. A pattern was not obvious.

Figure 5-15 shows the relationship between deceleration and headway. Observations from the figure include the following:

- For the Down Ivan, the largest deceleration values were associated with the smallest headways.
- The smallest headways, however, were also associated with low deceleration values. Stated in another manner, high deceleration values (on the order of −6 ft/sec^2 to −12 ft/sec^2) were only selected when the participant vehicle was close to the lead vehicle (within approximately 60 ft or less).
- For the Down Ivans with a CMS, the largest decelerations were from initial speeds of 60 mph as shown in Figure 5-15(a) (acceleration values of −6 to −12 ft/sec^2 all occurred when the participant was driving 60 mph).
- When a CMS was not present as shown in Figure 5-15(b), the largest decelerations included participants at both the 60- and 85-mph initial speeds and following both cars and trucks.

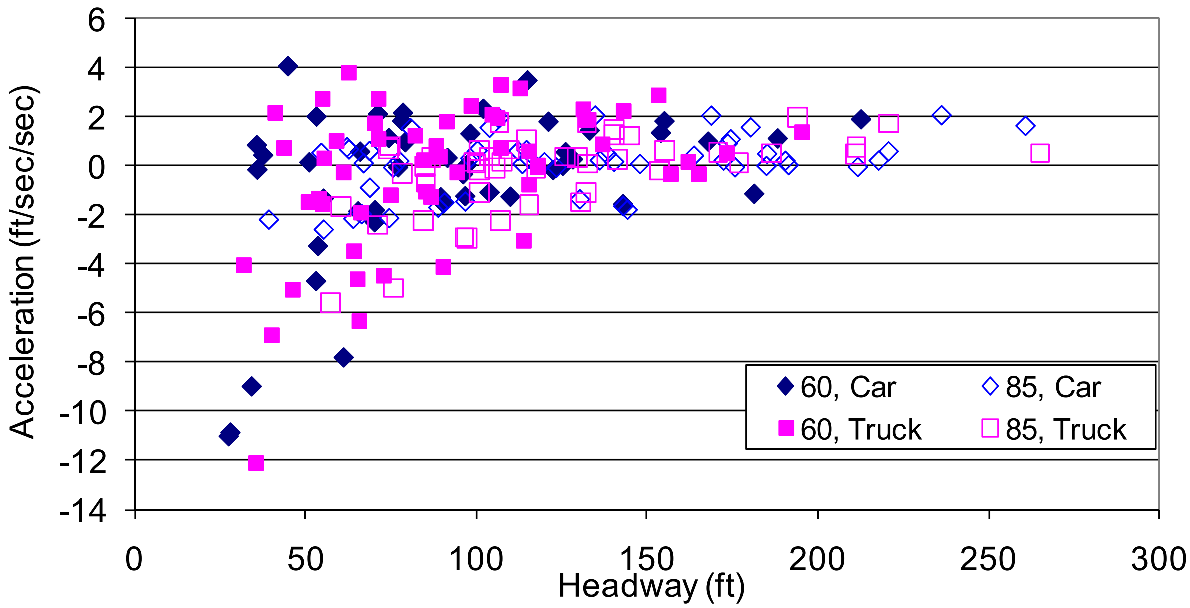


(a) Down Ivans

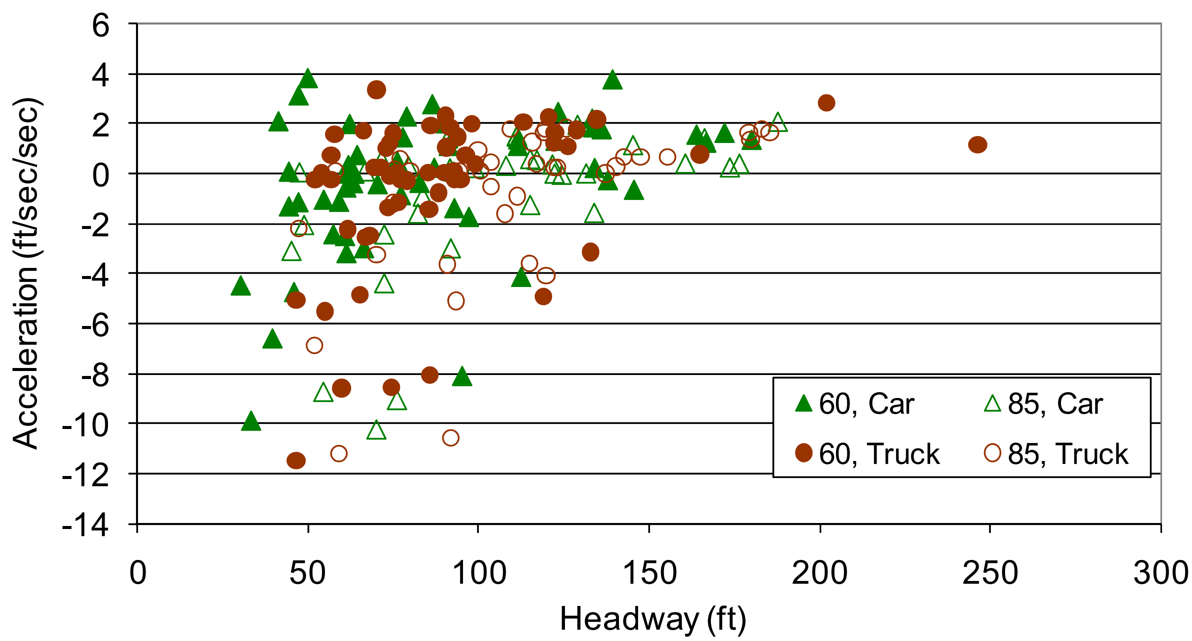


(b) Up Ivans

Figure 5-14. Minimum Acceleration (Also Called Deceleration) Values during Ivans.



(a) Down Ivans with CMS



(b) Down Ivans without CMS

Figure 5-15. Acceleration Values When Change in Speed Occurs.

Reaction Time to Initiate Speed Reduction for Down Ivans

The study included a potential of 96 reaction times to Down Ivans. Because some of the participants were decelerating when the Down Ivan occurred, the researchers cannot determine based upon the speed measurements when the participant transitioned from typical deceleration to decelerating in reaction to the lead vehicle's speed drop. Therefore, the first reaction time identified was the reaction time when the participant vehicle initiated a speed reduction in response to the lead vehicle's speed reduction. This value was determined for those events when the participant was accelerating at the start of the Ivan. The study captured 53 reaction times out of the possible 96 opportunities (about 55 percent). The number of reaction times by combination of study variables is listed in Table 5-5. Figure 5-16 shows the reaction time for each participant by combination of variables. Observations from a review of the figure include:

- Reaction times varied between almost 0 sec (which may be more of a reflection that the driver had already decided to decelerate for reasons other than the lead vehicle's deceleration) to 4.2 sec.
- The reaction times for the higher speeds (shown with open symbols) are longer in many cases than the reaction time for the lower speeds (shown with closed symbols).

Table 5-5. Number of Reaction Times to Start of Speed Reduction.

Type of Event		Number of Events				
Ivan Type	CMS	Car Truck				TOTAL
		60 85		60	85	
Down	With CMS	6	9	6	10	31
	Without CMS	4	5	8	5	22
TOTAL		10	14	14	15	53

The average reaction time per combination is listed in Table 5-6.

Analysis of variance (ANOVA) was used with the main effects (vehicle type, initial speed, and presence of CMS) and the response variable reaction time (see Table 5-7). From the effects tests, it can be seen that only initial speed is significant. Also the effect of initial speed is positive as can be seen in the effect details table. Stated in another manner, higher speed is associated with greater reaction times.

Table 5-6. Average Reaction Times (sec) for Down Ivans.

Type of Event		Average Reaction Time (sec)				
Ivan Type	CMS	Car Truck				All
		60 85		60	85	
Down	With CMS	1.07	1.70	1.12	1.50	1.40
	Without CMS	0.73	1.62	0.71	1.32	1.06
TOTAL		0.93	1.67	0.89	1.44	1.26

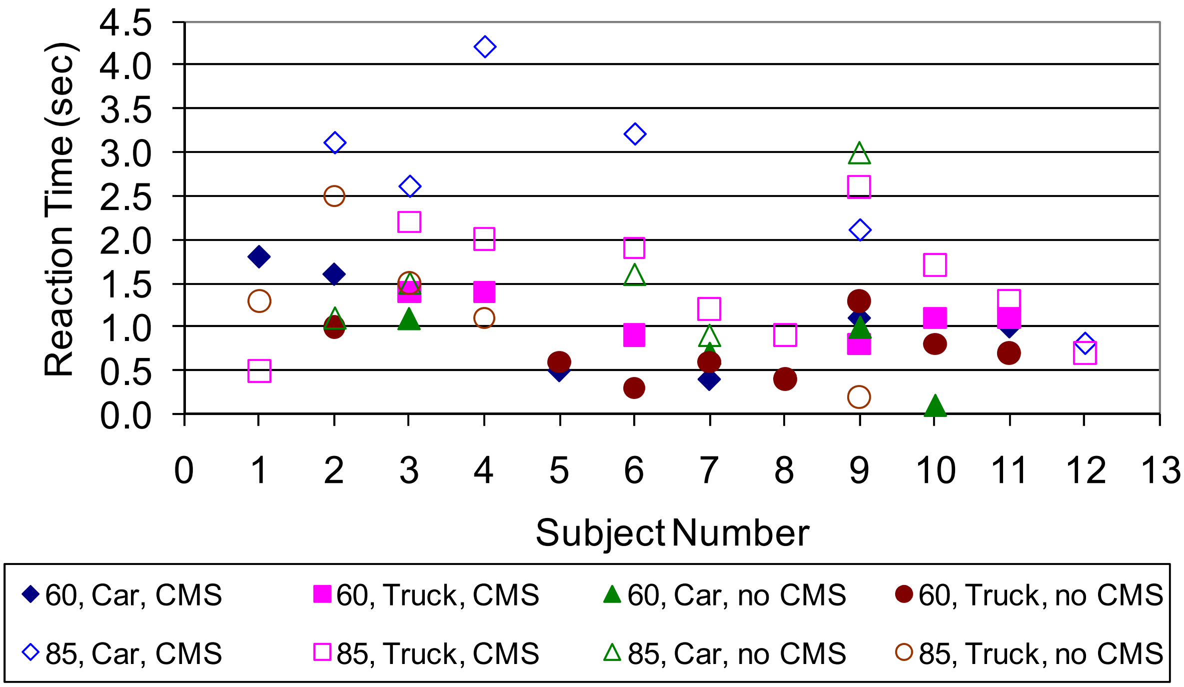


Figure 5-16. Reaction Time to Down Ivans for Each Participant by Combination of Variables.

Table 5-7. ANOVA Findings for Reaction Time.

Summary of Fit

RSquare	0.219226
RSquare Adj	0.171423
Root Mean Square Error	0.686637
Mean of Response	1.258491
Observations (or Sum Wgts)	53

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	6.486606	2.16220	4.5861
Error	49	23.102073	0.47147	**Prob > F**
C. Total	52	29.588679		0.0066

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	4	0.388156	0.097039	0.1923
Pure Error	45	22.713917	0.504754	**Prob > F**
Total Error	49	23.102073		0.9412
				Max RSq
				0.2323

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	0.9152518	0.141053	6.49	<0.0001
Lead Vehicle (Car)	0.0665108	0.095146	0.70	0.4878
CMS (Present)	0.1177987	0.097108	1.21	0.2309
Initial Speed (85-60)	0.6022076	0.192145	3.13	0.0029

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Lead Vehicle	1	1	0.2303879	0.4887	0.4878
CMS	1	1	0.6937906	1.4715	0.2309
Initial Speed	1	1	4.6311569	9.8228	0.0029

Effect Details

Lead Vehicle

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
Car	0.98176255	0.17879143	1.36250
Truck	0.84874103	0.16103177	1.17241

Ivan

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
CMS	1.0330505	0.17066645	1.40000
No CMS	0.7974531	0.17182829	1.05909

Initial Speed

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
60	0.9152518	0.14105348	0.90417
85	1.5174594	0.13110831	1.55172

The headways associated with the reaction point were also determined. Table 5-8 lists the average headways present at the point where the participant drivers reacted to the lead vehicle's Ivan. ANOVA was also used to determine if headway distance or headway time was related to the presence of the CMS, initial speed, or lead vehicle type. The result of applying ANOVA to the response variable of time headway showed that none of the factors (CMS, initial speed, or lead vehicle type) were significant. For the response variable of distance headway, initial speed was the only factor found significant (see Table 5-9). The effect of initial speed is positive as can be seen in the effect details table. Stated in another manner, higher speeds are associated with greater headway distances at the point when a decision is made to begin deceleration.

Table 5-8. Average Headways at Reaction Point for Down Ivans.

Type of Event		Average Headway				
Ivan Type	**CMS**	**Car Truck**				**All**
		60 85		**60**	**85**	
Average Headway Distance (ft)						
Down	**With CMS**	91	134	82	121	112
	Without CMS	83	106	90	107	96
	TOTAL	88	124	87	116	105
Average Headway Time (sec)						
Down	**With CMS**	1.01	1.08	0.93	0.98	1.00
	Without CMS	0.95	0.85	1.02	0.85	0.93
	TOTAL	0.98	1.00	0.98	0.94	0.97

In the previous analysis results, all three factors were included simultaneously in the model, and the effects of the factors were assessed simultaneously. On the other hand, if we are only interested in knowing if the response variables of interest are significantly different for the categories of one of the factors (just considering one factor at a time in a model), then the two-sample t-test can be employed (instead of ANOVA).

The only noticeable difference from the previous ANOVA results is that the presence of the CMS could make a difference when the one-sided test is considered, that is, if our hypotheses are:

- H_0: The average reaction time (or headway [ft] at reaction time) for Down Ivans without CMS is equal to that for Down Ivans with CMS.
- H_a: The average reaction time (or headway [ft] at reaction time) for Down Ivans without CMS is smaller than that for Down Ivans with CMS (instead of the typical two-sided hypothesis stating that H_a: The average reaction time for Down Ivans without CMS is not equal to that for Down Ivans with CMS).

The p-value of the effect of CMS is 0.0498 for reaction time (sec) and 0.0863 for headway (ft) at reaction time (see Table 5-10); therefore, we may reject the null hypothesis of no effect of the presence of the CMS.

Table 5-9. ANOVA Findings for Headway Distance.

Summary of Fit

RSquare	0.173483
RSquare Adj	0.12288
Root Mean Square Error	38.96126
Mean of Response	105.2679
Observations (or Sum Wgts)	53

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	15612.273	5204.09	3.4283
Error	49	74381.018	1517.98	**Prob > F**
C. Total	52	89993.290		0.0241

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	4	2555.706	638.93	0.4003
Pure Error	45	71825.312	1596.12	**Prob > F**
Total Error	49	74381.018		0.8074
				Max RSq
				0.2019

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	87.664514	8.003674	10.95	<0.0001
Lead Vehicle (Car)	1.9426272	5.398773	0.36	0.7205
CMS (Present)	4.9978282	5.5101	0.91	0.3688
Initial Speed (85-60)	30.955618	10.90271	2.84	0.0066

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Lead Vehicle	1	1	196.542	0.1295	0.7205
CMS	1	1	1248.848	0.8227	0.3688
Initial Speed	1	1	12237.030	8.0614	0.0066

Effect Details

Lead Vehicle

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
Car	89.607141	10.145005	108.914
Truck	85.721887	9.137284	102.250

Ivan

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
CMS	92.662342	9.6839769	111.572
No CMS	82.666686	9.7499018	96.384

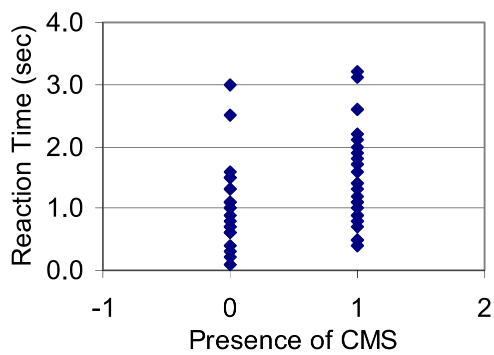
Initial Speed

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
60	87.66451	8.0036740	87.341
85	118.62013	7.4393636	120.104

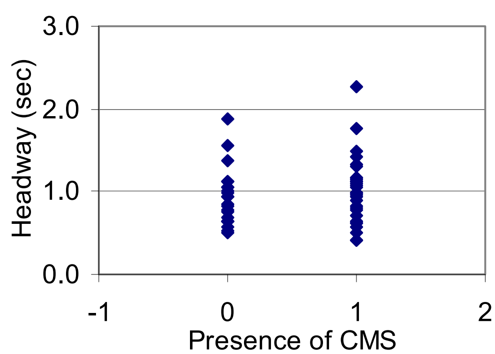
Table 5-10. Findings for Presence of CMS.

Reaction Time (sec)



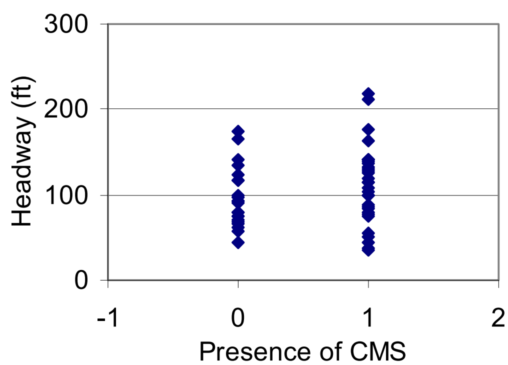
Difference	−0.34091	t Ratio	−1.67951
Std. Err. Dif	0.20298	DF	48.20642
Upper CL Dif	0.06717	Prob > |t|	0.0995
Lower CL Dif	−0.74899	Prob > t	0.9502
Confidence	0.95	Prob < t	0.0498

Headway (sec) at Reaction Time



Difference	−0.07593	t Ratio	−0.74577
Std. Err. Dif	0.10181	DF	49.00603
Upper CL Dif	0.12867	Prob > |t|	0.4594
Lower CL Dif	−0.28052	Prob > t	0.7703
Confidence	0.95	Prob < t	0.2297

Headway (ft) at Reaction Time



Difference	−15.188	t Ratio	−1.3835
Std. Err. Dif	10.978	DF	50.77855
Upper CL Dif	6.854	Prob > |t|	0.1726
Lower CL Dif	−37.230	Prob > t	0.9137
Confidence	0.95	Prob < t	0.0863

In plots, 0 = no CMS present and 1 = CMS present.
Difference: Estimates of the difference between the two group's means.
Std Err Dif: Standard error of the Difference
Upper CL Dif, Lower CL Dif: Upper and lower confidence limits for the difference
DF: Degrees of freedom
Prob > |t|: P-value for a two-sided test (i.e., when the research hypothesis states that two group means are not equal).
Prob > t: P-value for a one-sided test (with the research hypothesis that the average of the first group is larger than the average of the second group)
Prob < t: P-value for a one-sided test (with the research hypothesis that the average of the first group is smaller than the average of the second group)

Reaction Time to Applying Brakes for Down Ivans

Because some of the participants were decelerating when the Down Ivan occurred, the reaction time to the speed reduction of the lead vehicle is not as obvious as when the participant was accelerating. When the participant vehicle is reducing speed prior to the start of the Down Ivan, the researcher cannot determine when the reduction changes from a typical behavior to a reaction to the lead vehicle's speed reduction. The participant applying the brakes is a clear reaction to the lead vehicle's speed reduction, and this point can be easily identified within the data. The time to applying brakes, however, is always greater than the time to reduce speed (because the driver's initial reaction is to release the gas pedal and then coast or apply the brakes). Therefore, applying of the brakes would not reflect the driver's initial reaction to a looming vehicle in many cases. However, it may provide an appreciation of lead vehicle type, CMS presence, and initial speed influences on drivers' decisions.

The time was identified when the pressure on the brake was 5 percent or greater. These reaction times to applying brakes are listed in Table 5-11. Observations of the data in Table 5-11 include:

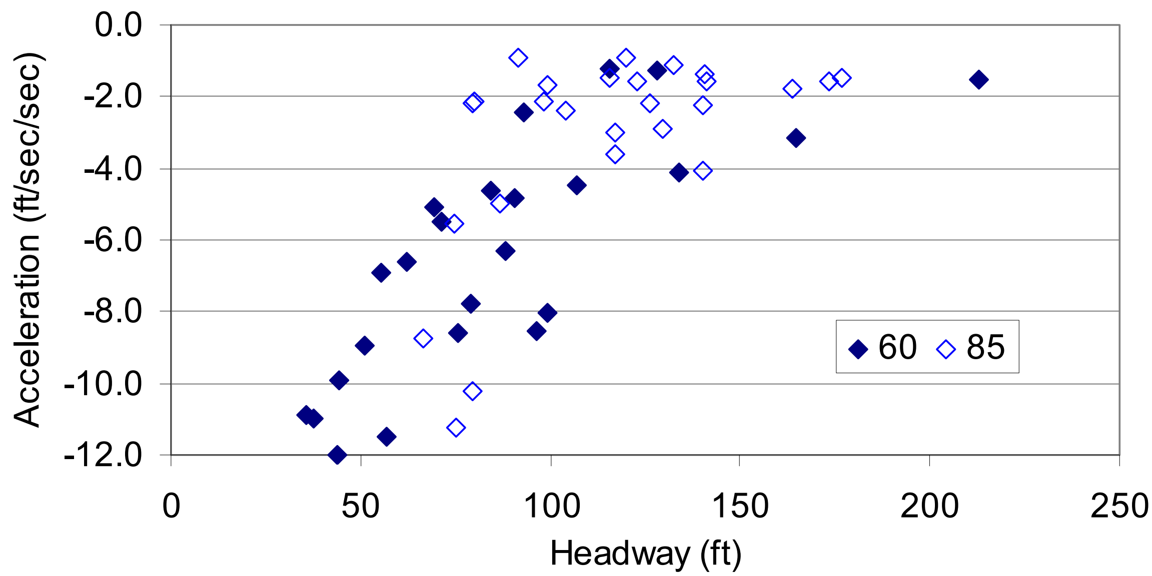
- The average reaction time to applying brakes is equal to or higher for the 85-mph condition as compared to the 60-mph condition.
- On more occasions, the participant did not apply the brakes when in an 85-mph segment as compared to a 60-mph segment.
- If the brakes were applied, they were applied within 5 sec of the start of the Down Ivan.

Deceleration Following Reaction

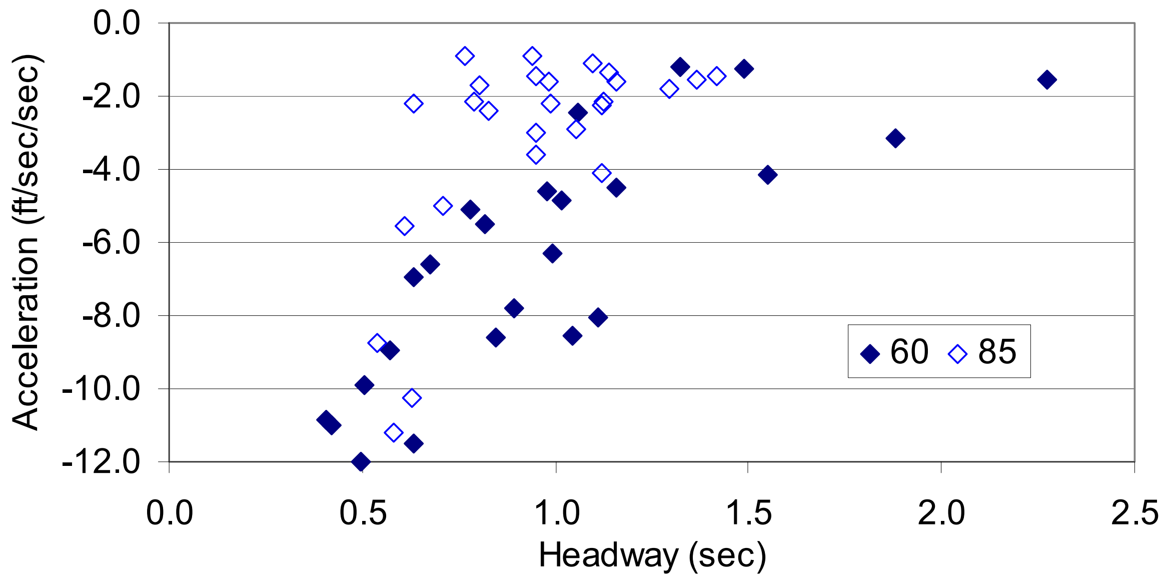
The deceleration rates selected by the driver following the decision to change speeds were determined. Figure 5-17 shows the headway at the point when the decision was made to change speed along with the deceleration used by the driver following the decision. Both headway time and headway distance show similar relationships with deceleration. When the participant driver is very close to the lead vehicle (e.g., headways below 75 ft or 0.75 sec), the participant driver applies the brake and decelerates at rates higher than about 5 ft/sec^2. For this set of data, the smallest headways were associated with the lower initial speed of 60 mph.

Table 5-11. Reaction Time to Apply Brakes.

Lead Vehicle	Participant Number	Reaction Time to Applying Brakes			
		With CMS		Without CMS	
		60 mph	85 mph	60 mph	85 mph
Car	1	NB	NB	1.6	2.4
	2	5.0	NB	3.0	NB
	3	NB	NB	1.9	1.8
	4	NB	NB	NB	3.7
	5	1.1	2.4	1.0	1.6
	6	3.5	NB	1.6	3.9
	7	1.4	NB	1.3	1.5
	8	2.3	NB	1.2	2.0
	9	1.6	NB	1.6	NB
	10	2.5	NB	2.3	NB
	11	1.8	NB	1.8	NB
	12	2.7	NB	1.5	1.6
Car	**Average**	**2.4 2.4 1.7 2.2**			
Truck	1	2.4	NB	2.5	2.5
	2	2.7	NB	3.6	4.4
	3	2.4	5.0	2.0	3.0
	4	NB	NB	2.9	4.6
	5	1.0	2.5	1.2	NB
	6	1.2	NB	1.4	2.5
	7	1.5	1.9	1.1	1.0
	8	1.2	3.4	0.7	1.1
	9	1.5	3.7	2.0	1.2
	10	1.8	NB	1.5	NB
	11	2.6	NB	1.5	2.0
	12	2.5	NB	1.3	1.8
Truck	**Average**	**1.9 3.3 1.8 2.4**			
NB = participant did not apply brakes during Down Ivan					



(a) Headway Distance



(b) Headway Time

Figure 5-17. Headway at Reaction Time and Resulting Deceleration.

Changeable Message Signs

During the Up and Down Ivans with CMS, participants were asked two questions for each CMS they passed. They also viewed a CMS during a baseline event (see Table 5-1). An example of a CMS message, the questions asked, and the three types of scoring methods can be seen in Table 5-12. Loose scoring was the most lenient scoring method, which was based on a general correct answer without the response being word-for-word correct. Moderate scoring was based on the percentage of the words in the exact message correct, and the response could be a fraction of a 100 percent score. Strict scoring was based on a word-for-word correct response. The participant could receive either 100 or 0 percent for this type of scoring.

Table 5-12. Example of a CMS Message Scored by the Three Methods.

Message	2 LANES CLOSED AT KIRBY ST MAJOR DELAY	
Question	What is the effect on traffic?	Where is the problem?
Correct Answer	Major Delay	At Kirby St
Answer Provided	"Delay"	"Kirby"
Loose Score	100%	100%
Moderate Score	50%	33%
Strict Score	0%	0%

Table 5-13 displays all of the CMS messages, questions, and answers. The table also provides the average loose, moderate, and strict scores for the 12 participants for each combination of variables. For example, all participants (100 percent) provided a generally correct answer to the first question asked on the baseline section when the participants were driving at 85 mph following a car (see "What is the effect on traffic?"). When moderate scoring was used, the average response was 83 percent. When strict scoring was used, the percent correct was 75 percent.

A few responses were missing from the averages presented in Table 5-13. In the truck lead/85 mph baseline with CMS condition, two of the twelve participant responses were missing. In the truck lead/60 mph baseline with CMS condition, three of the twelve participant responses were missing. These errors were due to experimenter error and are not believed to have occurred differentially by condition.

Table 5-13. CMS Message Percent Correct Scored by the Three Methods.

	Baseline with CMS		**Up Ivan with CMS**		**Down Ivan with CMS**	
Car Lead/85 mph						
Message	FREEWAY CLOSED AT COLLEGE ST MAJOR DELAY		MAJOR ACCIDENT AT WAYSIDE RD USE OTHER ROUTES		CONSTRUCTION AT BROADWAY ST ALL LANES CLOSED	
Question	What is the effect on traffic?	Where is the problem?	What are you told to do?	Where is the traffic problem located?	What is the traffic problem?	How many lanes are closed?
Correct Answer	Major Delay	At College St	Use Other Routes	At Wayside Rd	Construction	All Lanes Closed
Loose	100%	92%	100%	100%	92%	100%
Moderate	83%	64%	86%	53%	88%	61%
Strict	75%	25%	75%	8%	83%	33%
Car Lead/60 mph						
Message	MISSING CHILD GREEN FORD LIC 739 452		TRUCK ACCIDENT AT AIRPORT RD USE SERVICE RD		FREEWAY BLOCKED AT TIDWELL EXIT 24	
Question	What type of situation has occurred?	Did the message tell you what to look for?	What are you told to do?	Where is the traffic problem located?	What is the traffic problem?	What are you told to do?
Correct Answer	Missing Child	Green Ford	Use Service Rd	At Airport Rd	Freeway Blocked	Exit 24
Loose	100%	100%	75%	83%	92%	75%
Moderate	100%	92%	72%	64%	88%	75%
Strict	100%	83%	58%	25%	83%	75%
Truck Lead/60 mph						
Message	MISSING CHILD RED PICKUP TUNE TO RADIO		FREEWAY BLOCKED AT TIDWELL ST USE OTHER ROUTES		TRUCK ACCIDENT AT AIRPORT ALL LANES BLOCKED	
Question	What type of situation has occurred?	Did the message tell you what to look for?	What are you told to do?	Where is the traffic problem located?	What is the traffic problem?	How many lanes are blocked?
Correct Answer	Missing Child	Red Pickup	Use Other Routes	At Tidwell St	Truck Accident	All Lanes Blocked
Loose	100%	100%	100%	100%	92%	100%
Moderate	100%	89%	89%	56%	92%	61%
Strict	100%	89%	75%	8%	92%	33%
Truck Lead/85 mph						
Message	2 LANES CLOSED AT KIRBY ST MAJOR DELAY		CONSTRUCTION AT BROADWAY USE OTHER ROUTES		MAJOR ACCIDENT AT WAYSIDE RD ALL LANES BLOCKED	
Question	What is the effect on traffic?	Where is the problem?	What are you told to do?	Where is the traffic problem located?	Where is the traffic problem located?	How many lanes are blocked?
Correct Answer	Major Delay	At Kirby St	Use Other Routes	At Broadway	At Wayside Rd	All Lanes Blocked
Loose	100%	90%	100%	100%	100%	83%
Moderate	80%	58%	89%	63%	53%	42%
Strict	70%	10%	83%	25%	8%	8%

While the CMSs were added to the simulator study to increase drivers' workload during the tests of interest, the accuracy of the answers on the CMS message may provide some additional insight into drivers' capabilities at the different speeds. Table 5-14 shows the average correct responses for the different scoring techniques by type of Ivan. In some situations, the percent correct was higher for the 85-mph operating speed as compared to the 60-mph operating speed. For all of those cases, however, the difference represented 11 percent or less. Some situations had a large difference in the accuracy of the responses. For example, when the participant was reacting to a Down Ivan, his or her strict score accuracy went from 71 percent on the 60-mph section to 33 percent on the 85-mph section. The loose score accuracy showed similar percent correct for both the 60- and 85-mph sections (90 and 94 percent, respectively). Therefore, the participants understood key elements of the CMS messages regardless of their operating speed. Using the loose scoring approach, the drivers had scores more than 90 percent regardless of the type of Ivan. The largest decrease in performance from the 60-mph section to the 85-mph section was when no Ivan was present or for the Down Ivans when using strict scoring.

Table 5-14. Average Correct Response (Percent) to CMS Message by Type of Ivan.

Ivan Type	Loose Moderate						Strict		
	60 mph	85 mph	Diff.	60 mph	85 mph	Diff.	60 mph	85 mph	Diff.
Down	90%	94%	−4	79%	61%	18	71%	33%	38
Up	90%	100%	−10	70%	73%	−3	42%	48%	−6
None	100%	96%	4	95%	71%	24	93%	45%	48

Bicyclist

The first event in the obstacle session was a bicyclist on the right side of the road that begins to move down the edge line as the participant approaches it. Three possible reaction times from the start of the bicyclist's movement were measured: a sudden steer to the left, a release of the throttle (gas) pedal, and an application of the brake. All reaction times are calculated in relation to when the bicyclist begins to move. Reaction time to steer is determined as when the steering wheel is turned in the negative or counterclockwise direction. Reaction time to throttle is the time when the pressure from the participant's foot is removed. Reaction time to brake is the time when the brake is pressed.

Not every participant reacted in all three ways, and the throttle release did not always coincide with a steering movement, nor did it always happen after a steer. The higher the time value, the longer it takes the participant to react to the bicyclist and the closer the participant's car is to colliding with the bicyclist. Table 5-15 displays the average reaction times to the bicyclist split by the three types of movements. Table 5-16 shows the movements in their order of occurrence and includes the response time for the first reaction made. For the 60-mph condition, steering was the first type of maneuver for 10 of the 11 participants (91 percent) (data for the 12th participant was missing). Steering was selected by 67 percent of the participants for the 85-mph condition, with the remaining participants selecting release of the throttle as their initial reaction to the bicyclist. For 85-mph driving, the participants' average response time to the bicyclist's movement was 3.7 sec as compared to 2.5 sec at 60 mph. The change represents an approximately 1.5 sec increase in average response time for the 85-mph condition as compared to the 60-mph driving condition.

Table 5-15. Reactions and Reaction Times to Bicyclist on Right Side of Road (No Lead Vehicle Present).

Participant Number	60 mph			85 mph		
	Reaction Time (sec) to...					
	Steer	Throttle	Brake	Steer	Throttle	Brake
1	1.0	6.1	-	4.6	4.5	6.5
2	5.1	6.3	-	4.6	-	-
3	4.3	5.0	-	4.4	4.2	4.6
4	0.2	5.9	-	3.9	3.7	-
5	4.0	6.1	-	4.3	6.2	6.3
6	2.2	-	-	4.5	2.0	-
7	1.3	-	-	4.3	6.3	6.7
8	4.2	3.4	3.8	2.4	-	-
9	1.3	-	-	3.6	5.9	6.2
10	4.4	6.0	6.3	1.8	6.3	-
11	*	*	*	4.1	-	-
12	0.3	-	-	4.8	-	-
* Missing data			- Maneuver did not occur.			

Table 5-16. Reaction Orders and Reaction Time to First Reaction to Bicyclist on Right Side of Road (No Lead Vehicle Present).

Partici-pant	60 mph				85 mph				Difference in 60-mph and 85-mph First Reaction Times (sec)
	Order of Reaction			Reaction Time for 1st Reaction (sec)	Order of Reaction			Reaction Time for 1st Reaction (sec)	
	1st	2nd	3rd		1st	2nd	3rd		
1	S	T	-	1.0	T	S	B	4.5	3.5
2	S	T	-	5.1	S	-	-	4.6	−0.5
3	S	T	-	4.3	T	S	B	4.2	−0.1
4	S	T	-	0.2	T	S	-	3.7	3.5
5	S	T	-	4.0	S	T	B	4.3	0.3
6	S	-	-	2.2	T	S	-	2.0	−0.2
7	S	-	-	1.3	S	T	B	4.3	3.0
8	T	B	S	3.4	S	-	-	2.4	−1.0
9	S	-	-	1.3	S	T	B	3.6	2.3
10	S	T	B	4.4	S	T	-	1.8	−2.6
11	*	*	*	*	S	-	-	4.1	-
12	S	-	-	0.3	S	-	-	4.8	4.5
	Average ± Standard Deviation			2.5 ± 1.8	Average ± Standard Deviation			3.7 ± 1.0	1.2 ± 2.3
* Missing data				- Maneuver did not occur.				S = steer, T = throttle, B = brake	

Lane Closure

The next event in the obstacle session was construction with a lane closure that forced the participant to move left to the center lane. Since the construction was a stationary event, the reaction distance to the first construction barrel was recorded, rather than a reaction time. Similar to the bicyclist, the reaction distances of the steering, throttle release, and braking actions were determined. The lower the reaction distance, the longer it took the participant to react to the lane obstruction ahead, and the closer the participant's vehicle was to colliding with the construction barrels. Table 5-17 displays the reaction distances to the first barrel of construction, split by the three types of reactions. Table 5-18 splits the reactions into their order of occurrence and shows the average response distances for the first reaction type made.

Steering was the first type of maneuver for all drivers (100 percent) at the 60-mph speed and for most drivers (92 percent) at the 85-mph speed. At 60 mph, the average distance was 952 ft as compared to 854 ft for 85 mph.

The distance data in Table 5-18 along with the posted/instructed speed limits of 60 or 85 mph were used to calculate an estimated time to collision (see Table 5-19). The lower the time to collision, the closer the participant came to colliding with the barrels in the obstructed lane. The average time to collision for the 60-mph condition is 10.8 sec as compared to 6.9 sec for the 85-mph condition.

Table 5-17. Reactions and Reaction Distances to First Construction Barrel (No Lead Vehicle Present).

Participant Number	60 mph			85 mph		
	Reaction Distance (ft) to...					
	Steer	Throttle	Brake	Steer	Throttle	Brake
1	1122	1122	-	1220	-	-
2	974	-	-	773	-	-
3	1016	-	-	1118	837	-
4	219	69	-	720	-	-
5	847	-	-	663	-	-
6	912	-	-	614	-	-
7	979	-	-	410	501	-
8	1129	468	-	980	-	-
9	1029	-	-	1162	-	-
10	1483	979	-	1047	-	-
11	*	*	*	470	-	-
12	761	-	-	984	-	-
* Missing data	- Maneuver did not occur.					

Table 5-18. Reaction Orders and Reaction Distances for First Reaction to Construction Barrel (No Lead Vehicle Present).

	60 mph			85 mph			Difference in 60 mph and 85 mph First Reaction Distances
	Order of Reaction		Reaction Distance at 1st Reaction (ft)	Order of Reaction		Reaction Distance at 1st Reaction (ft)	
Participant	1st	2nd		1st	2nd		
1	Steer Throttle	-	1122	Steer	-	1220	98
2	Steer	-	974	Steer	-	773	−201
3	Steer	-	1016	Steer	Throttle	1118	102
4	Steer	Throttle	219	Steer	-	720	501
5	Steer	-	847	Steer	-	663	−184
6	Steer	-	912	Steer	-	614	−298
7	Steer	-	979	Throttle	Steer	501	−478
8	Steer	Throttle	1129	Steer	-	980	−149
9	Steer	-	1029	Steer	-	1162	133
10	Steer	Throttle	1483	Steer	-	1047	−436
11	*	*	*	Steer	-	470	-
12	Steer	-	761	Steer	-	984	223
	Average ± Standard Deviation		952 ± 307	Average ± Standard Deviation		854 ± 263	−62.7 ± 300
* Missing data	- Maneuver did not occur.						

Table 5-19. Throttle Reaction Distances Converted to Time to Collision at Posted Speed Limits.

Participant	Estimated Time to Collision (sec)		
	60 mph	85 mph	Difference between 60 mph and 85 mph
1	12.8	9.8	−3.0
2	11.1	6.2	−4.9
3	11.5	9.0	−2.6
4	2.5	5.8	3.3
5	9.6	5.3	−4.3
6	10.4	4.9	−5.4
7	11.1	4.0	−7.1
8	12.8	7.9	−5.0
9	11.7	9.3	−2.4
10	16.8	8.4	−8.5
11	*	3.8	*
12	8.6	7.9	−0.8
Average ± Standard Deviation	10.8 ± 3.5	6.9 ± 2.1	−3.7 ± 3.2
* Missing data			

Lead Vehicle Lane Change

For the lead vehicle lane change event, the lead vehicle was programmed to drop its speed at the same time it began to change lanes. Reaction times were measured from the time the lead vehicle dropped its speed to the moment the participant released the throttle or applied the brake. These times are shown in Table 5-20.

Table 5-20. Reaction Time to a Lead Vehicle Lane Change.

Partici-pant	Reaction Time (sec)							
	Car Lead 60 mph		Truck Lead 60 mph		Car Lead 85 mph		Truck Lead 85 mph	
	Throttle	Brake	Throttle	Brake	Throttle	Brake	Throttle	Brake
1	1.40	1.80	1.60	-	5.20	5.50	-	-
2	1.30	1.80	2.60	3.50	3.20	-	2.70	-
3	1.20	1.50	1.40	1.60	0.50	1.10	0.60	0.90
4	1.90	15.20	0.90	2.10	2.00	-	1.70	-
5	1.20	1.40	1.50	1.80	0.90	1.80	1.80	2.10
6	2.80	5.10	0.00	6.30	1.90	-	2.70	-
7	1.80	2.40	0.80	1.10	1.00	1.30	Out of Range*	
8	0.90	1.50	1.20	1.50	0.90	-	0.80	1.30
9	NA	-	1.30	2.00	1.50	1.90	0.80	1.30
10	1.50	1.80	1.20	1.60	1.80	6.70	2.10	-
11	1.00	1.60	0.10	1.80	5.00	8.10	5.60	-
12	1.70	2.10	0.80	1.20	2.20	4.80	1.40	1.70
Average	1.26	3.29	1.12	2.23	2.18	3.90	2.02	1.46
Standard Deviation	1.03	4.08	0.69	1.49	1.55	2.72	1.46	0.46

- Maneuver did not occur.
* The participant vehicle was out of the simulator's range for measuring headway when the lead vehicle began its maneuver.
NA = data not available

CONCLUSIONS

Based on the results from the various analyses of the simulator course data, researchers drew the following conclusions:

- Headway: As expected, smaller headways were measured during the Down Ivans as compared to the Up Ivans. Also as expected, the range of headways appears to be smaller during the Down Ivans. When minimum distances are reviewed, distances as small as 25 ft were recorded in the simulator.
- Acceleration: The maximum acceleration values were generally under 4 ft/sec^2. As expected, the Down Ivans produced the largest decelerations; however, in most cases, the deceleration values were in the range of deceleration without brakes (generally about 4 ft/sec^2 for initial speeds of about 60 mph).

- Headway at speed change location: For the Down Ivan, the largest deceleration values were associated with the smallest headways. However, the smallest headways were also associated with low deceleration values.
- Reaction time to initiate reduction for Down Ivans: Reaction times varied between almost 0 sec (which may be more of a reflection that the driver had already decided to decelerate for reasons other than the lead vehicle's deceleration) to 4.2 sec. The reaction times for the higher speeds are higher in many cases than the reaction time for the lower speeds. ANOVA was used with the main effects (vehicle type, initial speed, and presence of CMS) and the response variable reaction time. The evaluation showed only initial speed as being significant, with the variable being positive. Stated in another manner, higher speed is associated with greater reaction times. For the response variable headway distance, initial speed was also significant. Higher speeds are associated with greater headway distances at the point when a decision is made to begin deceleration. A t-test was also conducted using each main effect independently. The only noticeable difference from the ANOVA results is that the presence of the CMS could make a difference when the one-sided test is considered.
- Reaction time to apply brakes: The average reaction time to applying brakes is equal or higher for the 85-mph condition as compared to the 60-mph condition. On more occasions, the participant did not apply the brakes when in an 85-mph segment as compared to a 60-mph segment. If the brakes were applied, they were applied within 5 sec of the start of the Down Ivan.
- Deceleration following reaction: When the participant driver is very close to the lead vehicle (e.g., headways below 75 ft or 0.75 sec), the participant driver applied the brake and decelerated at rates of about 5 ft/sec^2 or higher. For this set of data, the smallest headways were associated with the lower initial speed of 60 mph.
- CMS: The largest decrease in performance from the 60- to 85-mph sections was when no Ivan was present or for the Down Ivans when using strict scoring. The loose score accuracy showed a similar percentage of correct responses for both the 60-mph and the 85-mph sections (90 and 94 percent, respectively).
- Time to collision: The average time to collision for the 60-mph condition is 10.8 sec as compared to 6.9 sec for the 85-mph condition.

RECOMMENDATIONS FOR FUTURE STUDIES

Reaction time did show a statistical difference depending upon the speed of the vehicle along with whether a changeable message sign was present. The initial speed was also statistically significant with respect to headway distance. Therefore, additional simulator studies should be considered.

There were many lessons learned from the beta test that should be incorporated into the design of a future simulator study, including the following:

- Data zones for data recording need to be long enough to capture both constant speed prior to and following the maneuvers.
- When looking at reaction times to entities that could be in motion, such as a deer or a bicyclist, make sure data variables are being collected on that specific entity to ease data reduction.

- Special consideration should be given to the placement of obstacles or events that should result in a reaction from the driver. If an entity is placed in a curve, it becomes much more difficult to determine the distance to that entity along a curved roadway. Also, if a change in steering is the method used to determine a reaction to an event when the vehicle is driving on a curve, there will already be a large steering displacement, and a reaction cannot be easily determined.
- When setting up a scenario that causes the driver to react, make sure there are not too many simultaneous events, or it becomes difficult to determine what the participant is reacting too. Are the participants braking because the lead vehicle slowed down or because they see the lane blocked up ahead? Are they changing lanes because they were instructed to follow the lead vehicle or because they notice the stalled car in their lane?
- When using questions such as the CMS questions as a secondary task, the questions should be of equal complexity, with the same bits of information for the driver to retain and repeat so that the response results can be compared equally.
- Finally, researchers often interact with the participant or study during the simulator drive. Many researchers cannot keep their eyes focused on the simulator screens due to the fact that motion sickness can become even more severe when one is further away from the driver's eye point. An additional cue for the researchers, whether it be a tone inaudible to the participant or a visual cue out of the eyesight of the driver, can be a helpful aid and help prevent missing data due to researcher error.

CHAPTER 6

SIMULATOR PHASE II STUDY

INTRODUCTION

The pilot study showed the following variables as being statistically different with respect to reaction time: initial speed of vehicle (60 or 85 mph) and workload (as created through the use of changeable message signs). Because the pilot study only included 12 drivers and the findings indicated that there are trends of interest, another simulator study was conducted. This Phase II study consisted of observing and recording the activities and actions of drivers in TTI's new portable driving simulator. The goal was to have a minimum of 48 drivers. Data for a total of 50 drivers were included in the evaluation.

The TTI Center for Transportation Safety is home to a desktop driving simulator that provides measurements of drivers' responses to roadway situations in a portable system. An advantage of this newer simulator is that it can be moved to different locations, thus giving the opportunity to include drivers from urban areas with more freeway driving experience than previously allowed with the older system located in College Station. The Realtime Technology system allows in-house development of roadway scenarios. It is comprised of a steering wheel, pedals, three monitors, three computers, and an audio system. For the purpose of this study, only the center monitor and computer were utilized (see Figure 6-1). The desktop setup allows testing of drivers with a wide variety of driving experience. Using this library, simulator scenarios, or "worlds," were created to represent long drives on urban freeways. The worlds were constructed such that other traffic was programmed to interact with the research participants.

Figure 6-1. TTI Driving Simulator.

DRIVING ENVIRONMENT

In designing the simulator study researchers maintained the initial speeds of 60 mph and 85 mph used in the previous simulator study (see Chapter 5), and the closed-course and open-road studies (see Chapters 3 and 4, respectively). All testing conditions in the discussion to follow were driven by the participant at each of those two speeds.

As in the pilot study, the primary task of the participant was to follow a lead vehicle within a given target range. The participant was asked to follow the lead vehicle keeping a 2-sec or less spacing between them at all times. The practice world, which the participant initially drove, was designed so that a green plus sign would appear above the lead vehicle if the participant vehicle was within the 2-sec distance. This provided the opportunity for the participant to obtain a feel for when he or she was within the 2-sec range. For the experimental worlds, the driver was only provided this assistance for approximately 2 minutes before being required to determine the 2-sec range on his or her own, thereby increasing the difficulty. The recorded simulator data provided the research team with the driver's actual proximity to the lead vehicle at each time increment.

During the study, each participant drove two initial speeds: 60 mph and 85 mph. Within each of these initial speeds, the participants followed two different lead vehicles: a small yellow car and a large blue truck as shown in Figure 6-2. Multiple combinations of these variables, called worlds, were created so that the orders of the combinations could be counterbalanced. These conditions or stimuli will be explained more in the sections to follow. The names for the experimental worlds, along with their characteristics, are listed in Table 6-1.

(a) Small Yellow Car **(b) Large Blue Truck**

Figure 6-2. Simulator Screenshots Showing the Two Varying Lead Vehicles.

Table 6-1. Speed and Vehicle Combinations for Different Worlds.

World	Initial Speed (mph)	First Lead	Second Lead
A1	60	Car	Truck
A2	60	Car	Truck
B1	85	Car	Truck
B2	85	Car	Truck
C1	60	Truck	Car
C2	60	Truck	Car
D1	85	Truck	Car
D2	85	Truck	Car

Ivans

As in the pilot study, the lead vehicle was programmed to change speed in a structured pattern that the researchers refer to as an "Ivan." The Ivans for this phase varied slightly from the Ivans of the pilot study. In the pilot study, both Up Ivans (initial speed change was an increase in speed) and Down Ivans (initial speed change was a decrease in speed) were included. In Phase II (i.e., the study reported in this chapter), only Down Ivans were included (i.e., all Ivans in Phase II began with the lead vehicle decelerating). All Phase II Ivans consisted only of a deceleration by the lead vehicle, followed by a short period at the lower speed, and then a return to the initial speed.

Half of the Ivans were programmed with a lead vehicle deceleration rate of 5.00 ft/sec^2, and half were at 9.83 ft/sec^2. The default deceleration value in the simulator is 9.83 ft/sec^2, and this value was selected for the sudden or high deceleration. For comparison, the assumed deceleration for stopping sight distance is 11.2 ft/sec^2 (*34*), and 10 ft/sec^2 is considered a "comfortable" deceleration rate in the Institute of Transportation Engineers' *Traffic Engineering Handbook* (*38*). The researchers considered using three deceleration rates; however, the overall study size needed to be kept to a manageable level, and the decision was made to retain three workload levels and two deceleration rates. The default deceleration provided a reasonably "high" deceleration rate without being in the critical deceleration range. To provide a more gradual deceleration, approximately half of the default deceleration rate was used for the "low" deceleration.

Each participant saw both a low deceleration and a high deceleration within each initial speed for both types of lead vehicles. The final variable introduced to each Ivan combination was a workload level of none, low, or high. The workload tasks will be discussed in more detail later in this section.

All of the variations created 24 different Ivan combinations: 12 experienced by the participant in a 60-mph world and 12 in an 85-mph world. Table 6-2 lists the characteristics for the Ivans.

Table 6-2. Combinations of Characteristics within Each Ivan.

Ivan Combination	Initial Speed (mph)	Lead Vehicle Type	Workload Level	Ivan Deceleration Rate (ft/sec^2)
1	60	Car	None	Low (5.00)
2	60	Car	None	High (9.83)
3	60	Car	Low	Low (5.00)
4	60	Car	Low	High (9.83)
5	60	Car	High	Low (5.00)
6	60	Car	High	High (9.83)
7	60	Truck	None	Low (5.00)
8	60	Truck	None	High (9.83)
9	60	Truck	Low	Low (5.00)
10	60	Truck	Low	High (9.83)
11	60	Truck	High	Low (5.00)
12	60	Truck	High	High (9.83)
13	85	Car	None	Low (5.00)
14	85	Car	None	High (9.83)
15	85	Car	Low	Low (5.00)
16	85	Car	Low	High (9.83)
17	85	Car	High	Low (5.00)
18	85	Car	High	High (9.83)
19	85	Truck	None	Low (5.00)
20	85	Truck	None	High (9.83)
21	85	Truck	Low	Low (5.00)
22	85	Truck	Low	High (9.83)
23	85	Truck	High	Low (5.00)
24	85	Truck	High	High (9.83)

Driving Scene

The driving scene consisted of a suburban four-lane divided freeway with a grassy median. Billboards were placed along the right-hand side of the road to encourage scanning and to keep the drivers engaged in the driving task. The participants were asked to read aloud as much of each billboard as they could. The billboards, like the one shown in Figure 6-3, were placed so that they would not coincide with an Ivan maneuver. A total of 12 billboards were placed in each of the worlds. The billboards served to keep the driver from simply staring straight ahead and to keep him or her interested in the study.

Figure 6-3. Simulator Screenshot Showing a Billboard.

Workload

Audio workload questions were used to create three workload levels. Workload was varied by asking math questions at the same time the lead vehicle performed an Ivan maneuver. The questions were prerecorded as audio files that played through the simulator's speaker system. The use of audio files ensured that the questions were asked at the same point for each participant.

A third of the Ivans had no workload, a third had a low workload, and the remaining third had a high workload. Low-workload questions were single digit plus single digit addition problems such as 7 + 5. High-workload questions were double digit plus double digit addition problems such as 15 + 28. Eight additional workload questions were added to each world where there was no Ivan maneuver. These "filler" questions were used to keep the driver's attention as well as lessen the likelihood that participants would associate the math questions with the lead vehicle braking. This workload manipulation, including the actual math questions, was taken from a previous study on driver distraction (*39*).

Traffic, Mirrors, and Brake Lights

To help drivers feel as if they were driving on a freeway, ambient traffic was included. Because the study only utilized one monitor and had limited viewing space, mirrors were not used. To be consistent with the pilot study, the lead vehicle's brake lights were programmed to be off for the duration of its drive.

RESEARCH PARTICIPANTS

The study was conducted in:

- Houston (H), Texas, and
- College Station (CS), Texas.

TTI employees recruited participants for the study through word of mouth and by contacting participants from previous studies. Recruitment involved several prescreening questions to assess whether the recruits might experience simulator-induced discomfort. If the recruits appeared to be candidates for the sickness, they were not scheduled for the study.

A total of 53 drivers were recruited. One participant found the simulation caused simulator sickness in the practice and did not complete the study. Another participant had too many difficulties driving at speeds of 85 mph in the practice and did not complete the study. Yet another participant completed the study, but after discussion about discomfort and the feeling of the unnatural simulator driving at 85 mph, the entire dataset was not used. Of the 50 remaining participants, some data for various Ivan maneuvers were missed because of the occasional loss of control of the vehicle by a participant. Additional discussion on data is in the "Data Reduction" section.

The demographic and driving information collected from the participants is shown in Table 6-3.

Table 6-3. Demographic Information and Driving Information for 50 Participants.

Demographic Information		
Number of Participants by Location	College Station	24
	Houston	26
Number of Participants by Gender	Male	25
	Female	25
Average Age (Years)		45.7
Race	White	74%
	African American	10%
	Asian, Pacific Islander	2%
	Hispanic	12%
	Other	2%
Education	Some high school	2%
	High school graduate	14%
	Some college or vocational school	40%
	College graduate	26%
	Some graduate school	8%
	Graduate degree	10%
Driving Information		
Average No. of Years Participants Have Been Driving		29.3
Number of Miles Driven per Year	Less than 12,000	25%
	Between 12,000 and 15,000	47%
	More than 15,000	28%
Percent of Time Spent Driving on Freeways	0	12%
	25-49%	28%
	50-74%	28%
	75-99%	22%
	100%	10%

PROCEDURE

Before beginning the experiment, each participant was asked to read and sign a consent form acknowledging his or her rights as a research participant.

Counterbalancing

In order to counter learning effects, the participants were split into 16 groups that viewed the experimental sessions in 16 different orders. Occasionally a participant lost control of the vehicle, and the simulation needed to be restarted. When this happened, sometimes the participant's session order would be altered in order to obtain the maximum data possible in the allotted time.

Practice Session

The following was read to the participant before beginning the practice session:

> *"The driving simulator you are seated in is an interactive simulator, which means the driving scenes you experience react to your steering and pedal inputs to provide a realistic driving experience. During your drive in the simulator, please drive in a normal fashion. You can adjust your pedals at a position that is comfortable for you. You will only be using the accelerator and brake and will not need to use the clutch on the far left. Please do not touch the paddles or buttons on the steering wheel because it may cause us to have to restart the simulation.*
>
> *"For the practice session, your task is to get comfortable with driving in the simulator. The driving scene that is presented to you begins with the simulator vehicle stopped on the side of the road (the small yellow car). See the lead vehicle parked ahead of you? Your first task will be to follow that lead vehicle with a following distance of 2 seconds or less. Go ahead and slowly maneuver onto the roadway and allow the lead to pull ahead of you. The lead is going to speed up to a speed limit of 85 mph.*
>
> *"You'll notice a green plus sign on the screen in front of you; this means you are driving within the 2-second range. When the plus sign disappears, you will need to speed up to get back in the target range. The purpose of this practice task is for you to get a feel of what it is like to drive in the 2-second range in the simulator. Although we realize normal driving instruction would have you follow at greater lengths on this type of roadway and at these types of speeds, we would like you to follow at 2 seconds for the purpose of this study.*
>
> *"How are you doing?*
>
> *"In a moment you will hear a sample math question. Please listen carefully and answer out loud clearly so that I can record your response."*

(As the driver approaches the first billboard.) *"Occasionally during the drive you will approach billboards. Please read the billboard out loud. Or, if there is a logo on the billboard and you recognize the logo, please say that out loud. Do not worry if you cannot read every bit of information on the sign; just do the best you can."*

(After passing the second practice billboard.) *"In a moment the plus sign will disappear, and I'd like you to practice remaining in the 2-second range without it."*

(After several additional minutes of practice driving.) "*How are you doing? Do you feel you've had enough practice? Please slowly coast to a stop and place the car in park."*

Experimental Session 1

While the first experimental session world was loading, the researcher read the instructions below to the participant. Speed instructions and the lead vehicle description varied depending on which session the driver was in.

"The driving scene that will be presented to you begins with the simulator vehicle stopped on the side of the road. Once we are finished with the instructions and your questions have been answered, you may pull out onto the roadway and proceed to drive as normal in the right-hand lane. The freeway speed limit will begin at <u>85 mph/60 mph</u>.

"You may ask questions at any time, but other than that and answering the questions you are asked during the study, please refrain from talking during this experiment.

"Ahead of you, you will also see a <u>large blue truck/small yellow car</u> merge into your lane from the right. Allow this vehicle to merge ahead of you. Your task will be to follow this vehicle leaving a 2-second or shorter following distance as you did in the practice although this time you will only have the green plus sign as your guide for a couple minutes before it disappears, and you must remain in the range on your own. Do your best to remain in the 2-second following range. I will remind you if you drift too far back. Although the vehicle will average around the speed limit, please focus on keeping in the target range rather than staying at the speed limit. Please remain in the right lane behind the lead vehicle; you will not need to change lanes for any reason.

"Another task you will encounter is to read billboard signs you will see alongside the road. Read the sign as you did in the practice session. The third task will be to answer the math questions that you hear. Remember, even though you have other tasks, you must also do your best to remain in the 2-second range.

"In the middle of the session, the lead vehicle will exit, and a new lead vehicle, a large blue truck/small yellow car will merge in front of you from the right-hand shoulder. As before, follow the lead within the target range. For a few minutes you will have the green plus sign as a guide before having to stay in the target range on your own.

"I will instruct you when to pull over for the end of the session. Do you have any questions?"

Experimental Session 2

While the second experimental session was loading, the researcher read the script below. Again, the speed instructions and the lead vehicle description varied depending on which session the driver was in.

"The second session will be very similar to Session 1. You will begin with the simulator car parked on the side of the road. Once we are finished with the instructions and your questions have been answered, you may pull out onto the roadway and proceed to drive as normal in the right-hand lane. For Session 2 the freeway speed limit will begin at 85 mph/60 mph.

"As before, you will be following a lead vehicle within a target range. This time a small yellow car/large blue truck will merge in front of you from the right. Follow this vehicle within the 2-second target range.

"Again, you will see several billboard signs and will be asked similar math questions as before. Continue to answer clearly out loud so that I can hear your response.

"At the end of the session, I will ask you to bring the vehicle to a complete stop. Any questions?"

At the end of the sessions, the participants completed a demographic and driving data questionnaire, and were compensated for their participation.

DATA COLLECTION

The experimental worlds were programmed to collect data at 42 Hz (or in 0.024-sec increments) for the entire session. The practice session was also recorded in case baseline driving behavior was needed. The following variables were collected:

- time (sec),
- velocity (meters/sec),
- distance (meters),
- acceleration (meters/sec^2),
- steering (in degrees),
- braking (on a scale from 0 to 300 units),

- throttle (on a scale of 0 to 90 degrees),
- distance to lead (meters),
- lead velocity (meters/sec),
- lead acceleration (meters/sec^2) , and
- headway (meters, measured from the center of the vehicle to the center of the vehicle).

DATA REDUCTION

Raw Data

The instrumented controls of the simulator record the behavior of both the participant and the lead vehicle. The lead vehicle represents the vehicle that the participant was following. Continuous data for each experimental world were obtained in three separate file formats—.dat (containing lead vehicle identification number and Ivan or filler numbers), .hdr (containing column headings for participant variables collected), and .plt (containing driving performance data/variables). The three files were matched and merged to obtain a dataset of driving performance variables with Ivan information for each world driven by the participant.

The data available from the simulator are in metric units. The distances and velocities were converted to U.S. standard units for evaluation. The continuous data were used to generate several speed-time plots to provide the researchers with an appreciation for the data. Figure 6-4 shows one sample of a speed profile, throttle use, and brake use plot of participant CS2 for the experimental world D1. Experimental world D1 has the lead vehicle at a constant initial speed of 85 mph. During the Ivans, the lead vehicle decelerated to 75 mph at a specified rate and for a specific duration before accelerating back to 85 mph. As mentioned earlier, the experimental worlds were programmed to generate 24 such Ivans (12 for each initial speed) in 16 different orders to counterbalance any learning effects that may have occurred over the course of the study session. Some Ivans included math questions to affect workload. The world also included filler math questions and billboards to keep the participants busy and to avoid making the drive monotonous.

Reaction Time Calculation

Figure 6-5 illustrates characteristics of a sample Ivan. The time at which the lead vehicle starts to decelerate is identified as the start of the Ivan. The time at which the lead vehicle accelerates back to the initial speed (85 mph or 60 mph) is identified as the end of the Ivan.

The objective of this study was to measure how long it took drivers to notice and react to the lead vehicle decelerating.

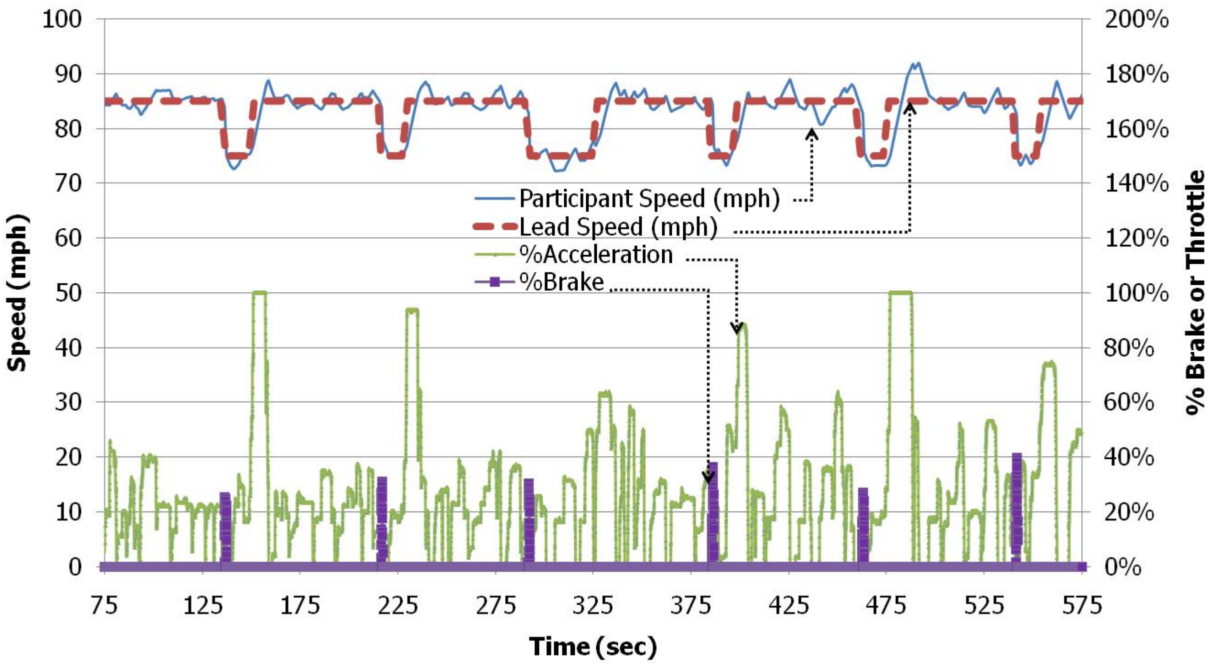


Figure 6-4. Speed Profile, Percent Throttle Use, and Percent Brake Use for Participant CS2 and World D1.

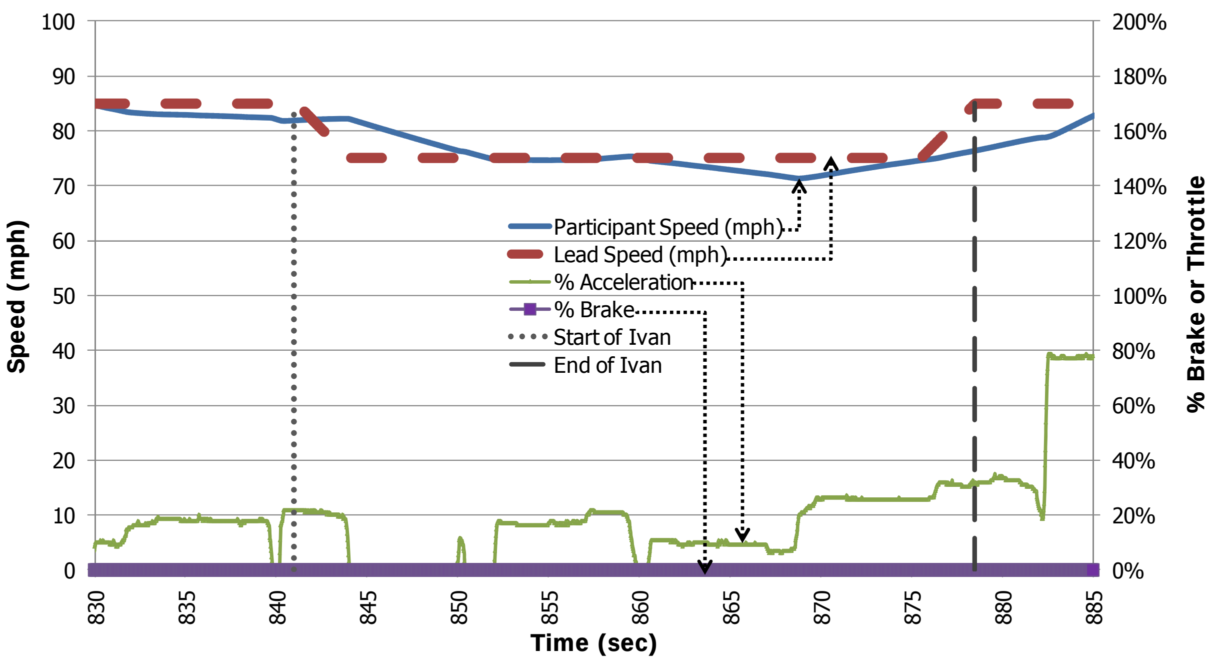


Figure 6-5. Characteristics of Sample Ivan.

Events that occurred within the Ivan time frame were considered a reaction to the change in lead vehicle speed. The reaction to a looming vehicle could vary whether the participant was accelerating or decelerating at the start of the Ivan. Four common situations observed were:

- Participant vehicle is accelerating at the start of the Ivan and releases throttle as a reaction to the looming lead vehicle.
- Participant vehicle is accelerating at the start of the Ivan and engages brakes as a reaction to the looming lead vehicle.
- Participant vehicle is decelerating at the start of the Ivan and engages brakes as a reaction to the looming lead vehicle.
- Participant vehicle is decelerating at the start of the Ivan and continues to do so without use of either brakes or throttle.

For each Ivan, the following six events (after the start of the Ivan) were noted:

- time when neither brake nor throttle is used ($T_{No\ B\ or\ G}$),
- time when brake is engaged (T_{Brakes}),
- time when participant speed is less than the average speed in the previous 1 sec ($T_{SC\_1sec\_Ave}$),
- time when participant speed is less than the average speed in the previous 5 sec ($T_{SC\_5sec\_Ave}$),
- time when participant speed is less than the average speed in the previous 55 sec ($T_{SC\_55sec\_Min}$), and
- time when the participant speed is less than the difference of initial speed (85 mph or 60 mph) and average absolute speed difference for previous 55 sec ($T_{SC\_SS\text{-}Avg\ Diff}$).

Time to engage brakes indicated a definitive reaction to the looming vehicle. It was identified when the braking force was greater than 0.00. Figure 6-6 illustrates how the reaction time was determined for participant CS1 for Ivan 1 of World A1. The participant was consistently pacing the lead vehicle speed of 60 mph for the 10 sec prior to the start of the Ivan. The driver released the throttle at 243.78 sec and then applied the brakes at 244.35 sec. The driver's reaction time to applying the brakes was 1.31 sec.

Time to no use of brakes and throttle was not always a clear indicator of reaction to the looming vehicle because drivers frequently released the throttle as they made minor adjustments to their speed in order to maintain the specified 2-sec headway. There were situations when a driver would only release the throttle and not brake as shown in Figure 6-7. Time to no use of brake and throttle was identified as when the participant throttle is less than 0.00275 degrees (minimum observed in many Ivans) and the braking force is 0.00. Stated in another manner, this event occurred when the driver's foot was "in the air." Sometimes this "foot in the air" time was followed by a re-application of the throttle, suggesting that the driver was momentarily coasting in order to maintain headway. Other times, this "foot in the air" was followed by a brake press to increase the headway distance to the lead vehicle. Figure 6-7 shows an example of the reaction time to no use of throttle and brake. In this example, the driver did not use the brakes during the Ivan.

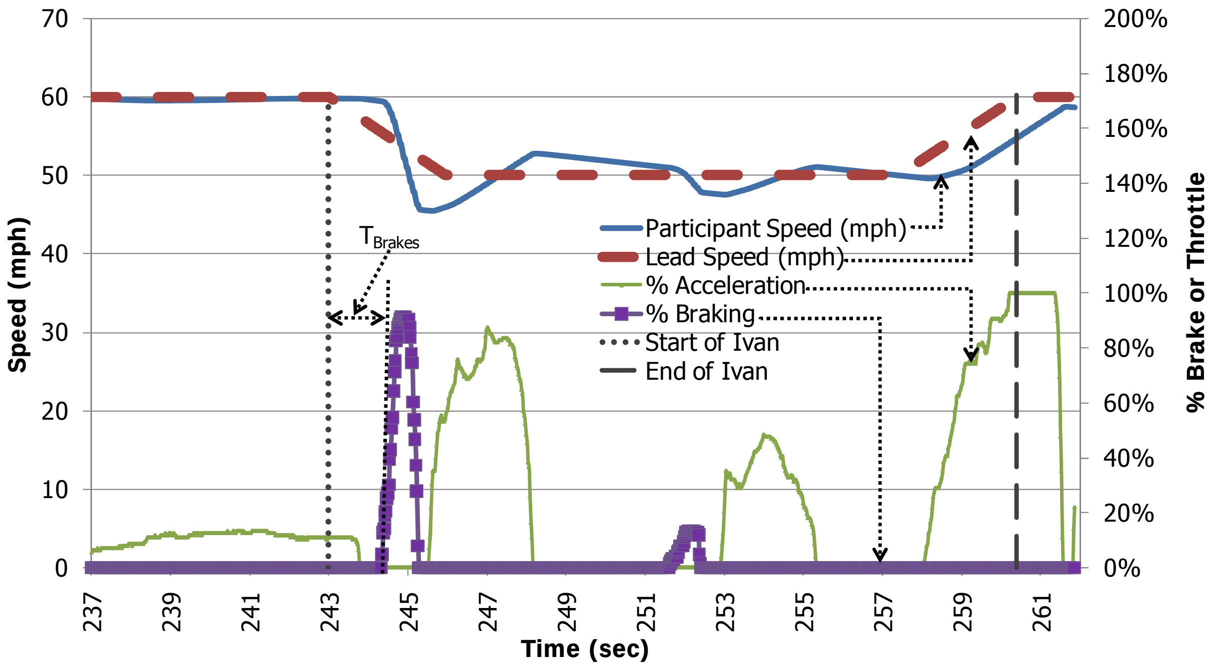


Figure 6-6. Reaction Time to Braking (CS1A1, Ivan 1).

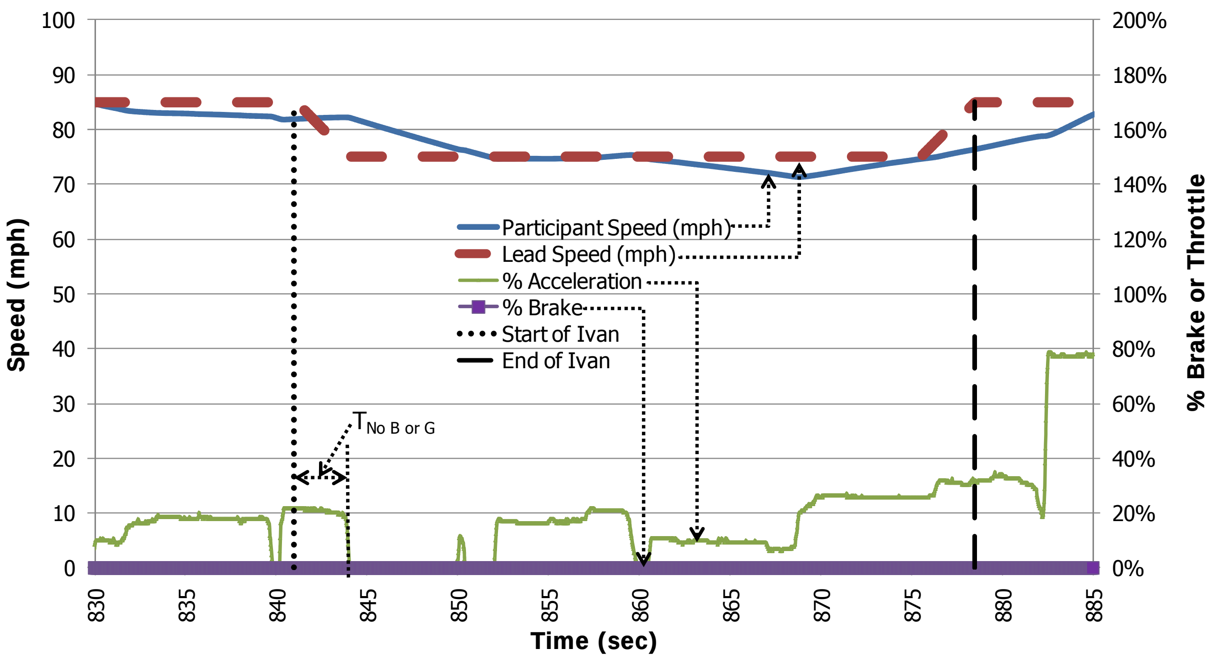


Figure 6-7. Reaction Time to No Use of Brake and Throttle (CS2D1, Ivan 17).

Participant speed change also did not always provide a clear indication of a reaction. Time-to-speed-change measures, however, are useful to identify reactions when brakes were not used and throttle use varied during an Ivan. The decrease in participant speed was considered to be a reaction if the speed at a given time (after the start of an Ivan) was lower than the average of the participant speeds in the previous 5 sec or previous 1 sec, illustrated in Figures 6-8 and 6-9, respectively. The time when the participant speed was less than the minimum speed within the previous 55 sec was also identified, as shown in Figure 6-10. Another indicator used was the time when the participant speed was less than the difference of the initial speed (85 mph or 60 mph) and the average of the absolute speed differences for the previous 55 sec for each 0.024-sec increment, as shown in Figure 6-11. The absolute differences are the difference between the initial speed and the participant speed for each increment. Table 6-4 shows the reaction times identified for the sample Ivans illustrated in Figures 6-6 through 6-11.

Table 6-4. Reaction Times for Sample Ivans.

Participant	CS1A1	CS2D1	CS1B1
Ivan Number	Ivan 1	Ivan 17	Ivan 24
Ivan Duration (sec)	17.38	37.36	15.19
Reaction Times* (sec)			
$T_{No\ B\ or\ G}$ (sec)	0.76	2.88	1.86
T_{Brakes} (sec)	1.31	No braking	No braking
$T_{SC\_1sec\_Ave}$ (sec)	5.81	2.83	1.43
$T_{SC\_5sec\_Ave}$ (sec)	0.90	2.95	2.21
$T_{SC\_55sec\_Min}$ (sec)	1.57	3.93	3.71
$T_{SC\_SS\text{-}Avg\ Diff}$ (sec)	1.40	Value beyond Ivan duration	2.36

* Reaction times:

$T_{No\ B\ or\ G}$ = time after start of Ivan when *both* brake use is 0 Newton and gas pedal use is less than 0.00275 degrees

T_{Brakes} = time to engage brakes after start of Ivan

$T_{SC\_1sec\_Ave}$ = time after the start of Ivan when participant speed is lower than the average of previous 1 sec

$T_{SC\_5sec\_Ave}$ = time after the start of Ivan when participant speed is lower than the average of previous 5 sec

$T_{SC\_55sec\_Min}$ = time after the start of Ivan when participant speed is lower than the minimum of previous 55 sec

$T_{SC\_SS\text{-}Avg\ Diff}$ = time after the start of Ivan when the participant speed is less than the initial speed (85 mph or 60 mph) − average of absolute difference for previous 55-sec speed. Absolute difference between participant speed (i.e., 85 or 60 mph) and participant speed is calculated for each time increment (approximately 0.024 sec). The average absolute difference is calculated for previous 55 sec.

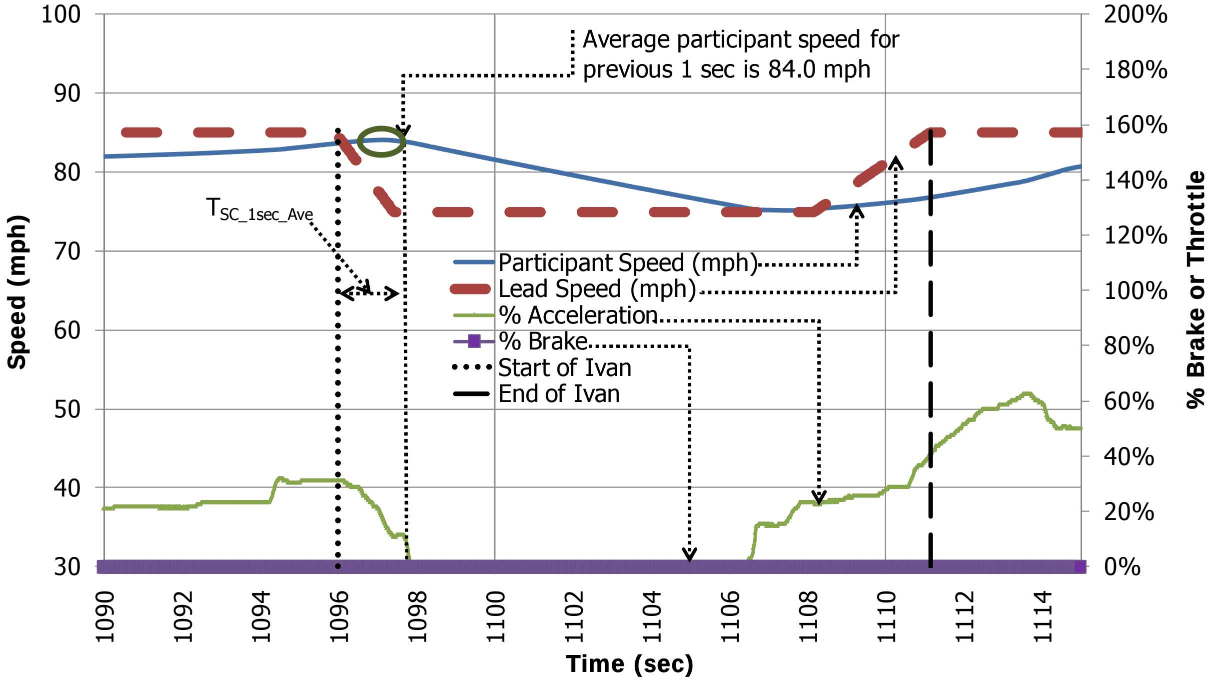


Figure 6-8. Reaction Time to Speed Change Using Average Speed of Previous 1 Sec (CS1B1, Ivan 24).

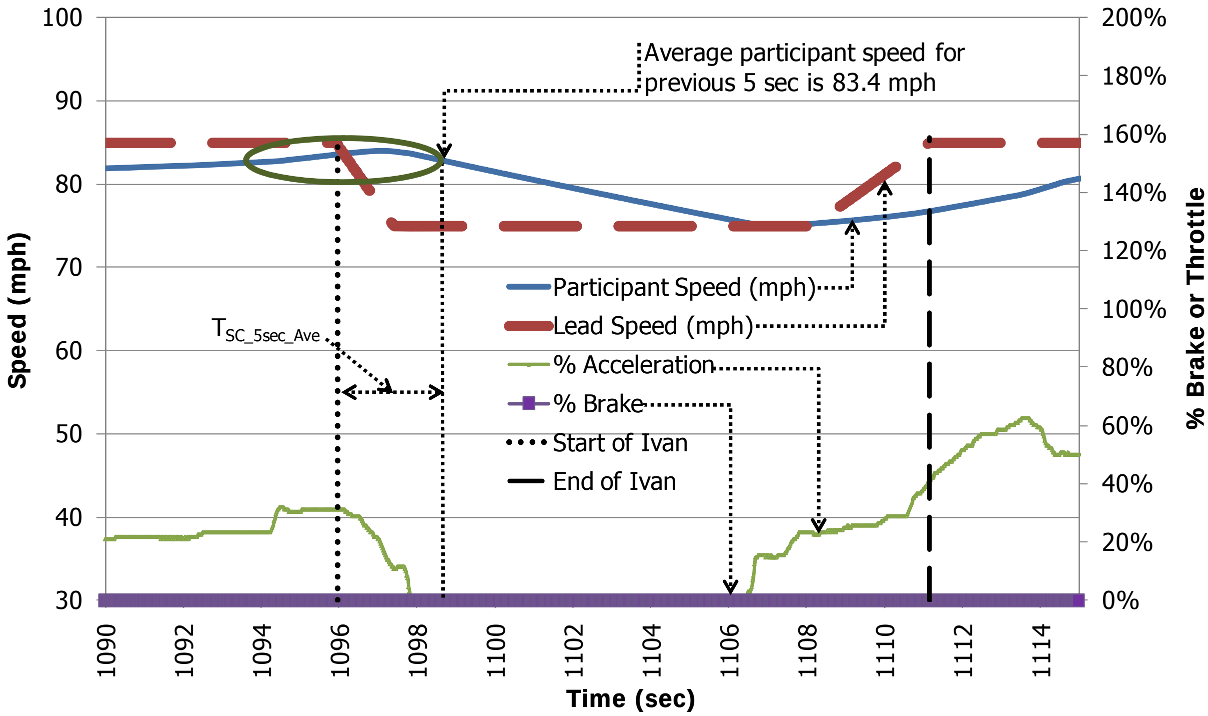


Figure 6-9. Reaction Time to Speed Change Using Average Speed of Previous 5 Sec (CS1B1, Ivan 24).

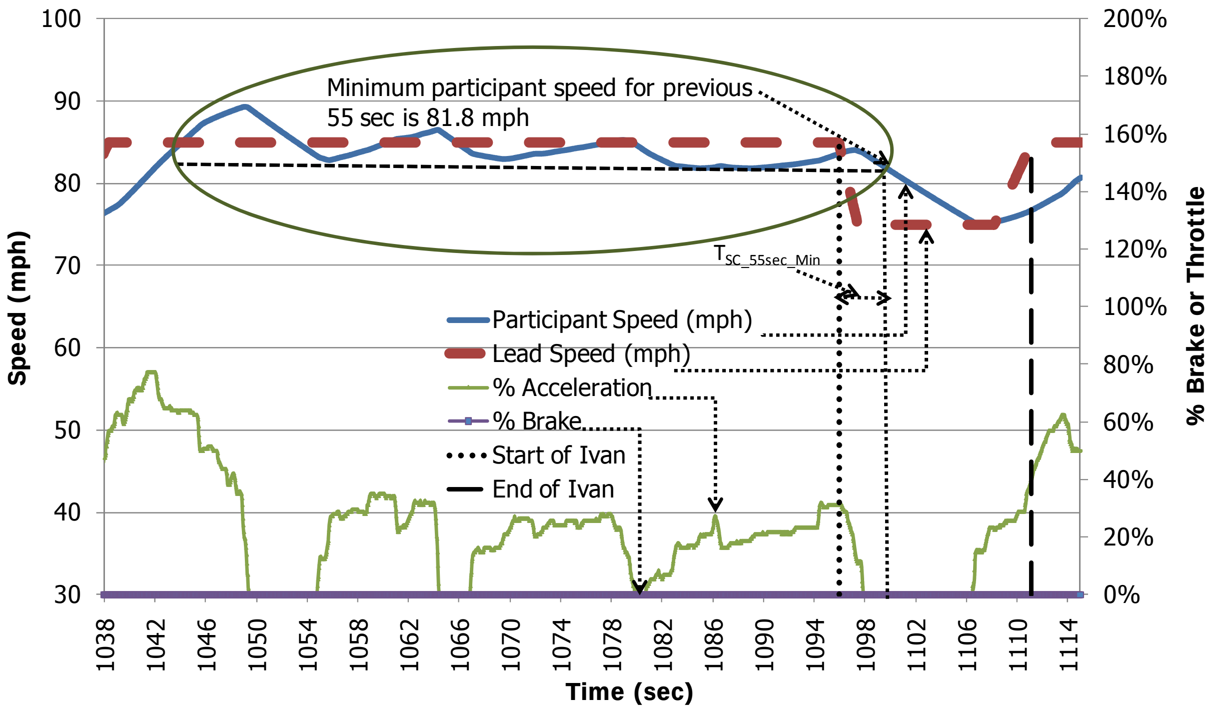


Figure 6-10. Reaction Time to Speed Change Using Minimum Speed of Previous 55 Sec (CS1B1, Ivan 24).

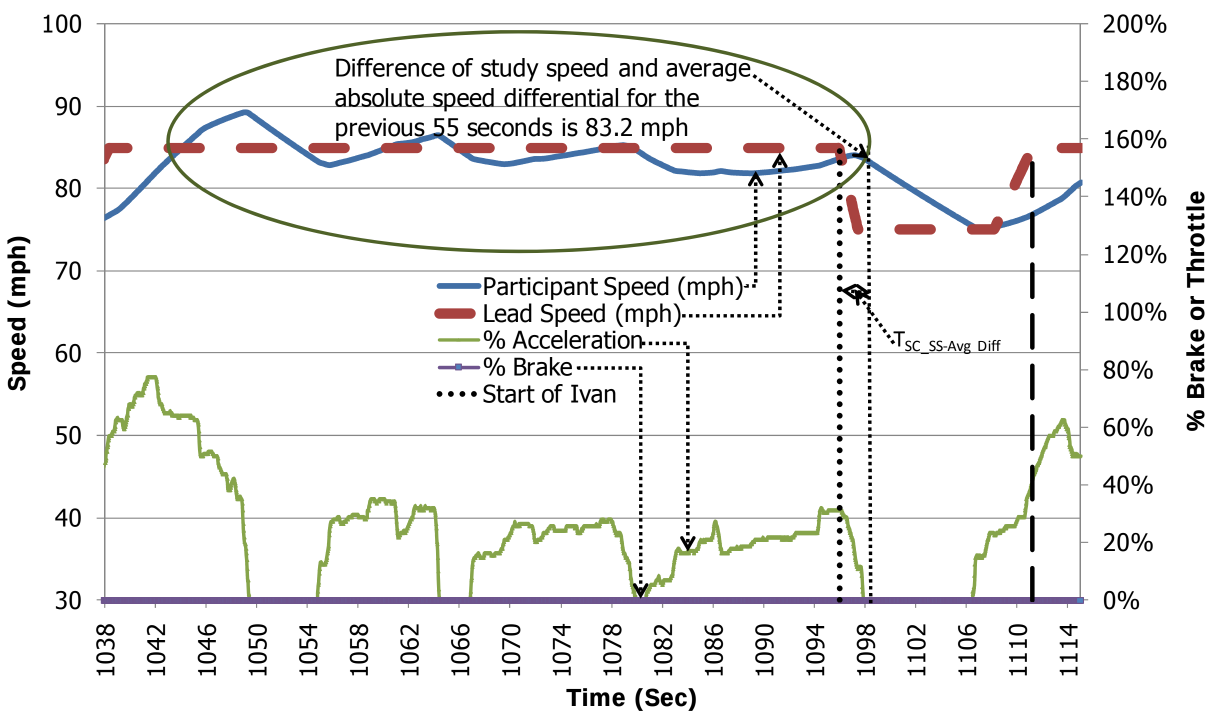


Figure 6-11. Reaction Time to Speed Change Using Average Absolute Speed Difference of Previous 55 Sec (CS1B1, Ivan 24).

Reaction Times Database

Reaction times for every Ivan were summarized into a database to identify the general pattern of participants' reaction to the looming vehicle and also to filter any discrepancies in the data. Demographic and driving data with researchers' comments on the experimental runs were added to this dataset. Researchers' comments indicated that some experimental world runs either did not have all 12 Ivans or had duplicate Ivans as a result of re-runs. The initial Ivan of a set of duplicate Ivans was discarded from the dataset.

Ivan duration is considered as the time from the start of the lead vehicle deceleration to its return to the constant speed (85 mph or 60 mph). Each world is programmed to have two Ivan durations: most at normal length and two at a longer length to provide some variation. Some Ivans were observed to have durations different than the four programmed durations (two for each speed). It was found that this was due to the interference of ambient traffic, causing the driver to follow an unintended lead vehicle. The data for each participant were evaluated to identify if such interferences had impacts on the calculated reaction times, in which case the data were eliminated from the dataset. All reaction times not occurring within the Ivan duration were also omitted from the database.

It was observed that for some Ivans, reaction to the decelerating lead vehicle occurred at the start of the Ivan (i.e., reaction time zero). Such reaction times were omitted from the database by defining the minimum reaction time as 0.25 sec. The maximum reaction time was set to 13.25 sec, and reaction times greater than that were omitted from the dataset. The 13.25 sec represent the time to contact between the lead vehicle and the participant vehicle if the participant vehicle maintained a 60-mph speed during the Ivan. Stated in another manner, the 60-mph participant vehicle would contact the lead vehicle within 13.25 sec after the lead vehicle had decelerated to 50 mph and maintained that speed. When the time to contact was investigated for the 85-mph situation, the lead vehicle had completed the Ivan and returned to 85 mph before the participant vehicle would have overtaken it. The participant vehicle would be close to but not contact the lead vehicle in the 85-mph scenario if the participant vehicle maintained the 85-mph speed. Therefore, a maximum 13.25 sec was used for both the 60- and 85-mph conditions.

A total of 53 drivers participated in the full study. All data for three of the participants were removed because of the driver's behavior during the experiment as discussed previously. Also as discussed earlier, data for a particular participant's Ivan were removed if incorrect driving was present, for example, if the driver had drifted into another lane. The study would have had 1200 data points for a given reaction time if the data for all 50 participants each reacting to 24 Ivans were available. Because of the characteristics of a reaction time, fewer than 1200 data points were available. For example, a reaction time to applying the brakes would not be available if the participant did not use the brakes within the limit of 13.25 sec. As another example, a reaction time would not be available for SC_5sec_Ave if the driver's speed within the Ivan did not go below the average speed calculated based on the previous 5 sec of speed data.

Table 6-5 lists the number of data points available for each of the reaction times explored in this study. The table starts with the maximum number of data points (1200) along with the potential number (1182) after 18 Ivans were removed based upon the researcher's observations during data collection. Along with the number of data points available for evaluations, the table lists the percentage of available data to maximum or potential. The reaction time to a speed change to below the previous 55-sec minimum speed had the largest set of data; however, the reaction to the use of the brake was similar. The reaction to the use of the brake is a stronger measure because it is easy to identify in the data stream and is clearly an identifiable reaction to the looming vehicle. This measure is used for further evaluation of the dataset. The reaction times to speed changes have limitations in that the speed change may be a continuation of the speed variation observed in typical driving behavior and the number of seconds included in generating the comparison speed is subject to debate. For example, this study used 1, 5, and 55 sec to generate the comparison speeds based on engineering judgment. Other values may be appropriate (although would probably not notably change the values found in this study).

Table 6-5. Number of Data Points Used in Evaluation.

Reaction Time to…	Number of Data Points			Percent of	
	Max.	Potential	Available for Evaluation	Potential	Max.
No Brake or Throttle Use ($T_{No\ B\ or\ G}$)	1200	1182	988	84%	82%
Brake Use (T_{Brakes})	**1200**	**1182**	**1055**	**89%**	**88%**
Speed Change to below Previous 1 sec Average Speed ($T_{SC\ 1sec\ Ave}$)	1200	1182	838	71%	70%
Speed Change to below Previous 5 sec Average Speed ($T_{SC\ 5sec\ Ave}$)	1200	1182	738	62%	62%
Speed Change to below Previous 55 sec Minimum Speed ($T_{SC\ 55sec\ Min}$)	1200	1182	1100	93%	92%
Speed Change to below Speed Determined by Subtracting Average Absolute Difference (Based on 55 sec of Previous Speed Measurements) from Initial Speed (Either 85 mph or 60 mph) ($T_{SC\ SS\text{-}Avg\ Diff}$)	1200	1182	957	81%	80%

RESULTS

Selection of Reaction Time

Table 6-6 lists the average reaction time for the given method of determining reaction times identified for the following groups:

- initial speed—60 or 85 mph;
- workload (WL)—high, low, or none;
- deceleration rate—low (5.0 ft/sec^2) or high (9.8 ft/sec^2); and
- lead vehicle type—car or truck.

Figure 6-12 provides a graphical view of the data so that patterns can be more easily shown. The data points are connected with a line; however, the presence of the line should not be interpreted as implying a relationship between the data points. The lines are only provided to demonstrate how some of the reaction time measures show a similar pattern. For example, reaction times were higher for the 85-mph condition as compared to the 60-mph condition for most reaction time events. The exceptions are reaction times determined using speed change when the participant speed is below the average speed determined based on the previous 1 or 5 sec. They had contrary relationships for initial speed, deceleration rate, and vehicle type. Preliminary evaluations were performed for each reaction time type. The preliminary investigations also demonstrated other concerns with the SC_1sec_Ave and SC_5sec_Ave reaction time values. Therefore, the SC_1sec_Ave and SC_5sec_Ave reaction times were not included in additional evaluations.

Trends were similar for the following reaction times: $T_{No\ B\ or\ G}$, T_{Brakes}, $T_{SC\_55sec\_Min}$, and $T_{SC\_SS\text{-}Ave\ Diff}$. The reaction time to use of brakes had one of the largest sample sizes as compared to the other reaction times (see Table 6-5). Reaction time to use of brakes is the most logical and clearly defined reaction time available. Therefore, the following discussion will only focus on the results associated with using reaction time to brake.

Table 6-6. Average Reaction Time per Condition.

Treatment	Condition	Reaction Time (sec)					
		No B or G	Brakes	SC_1sec_Ave	SC_5sec_Ave	SC_55sec_Min	SC_SS-Ave Diff
Speed	60 mph	1.40	2.56	4.66	4.74	2.79	2.32
	85 mph	2.28	3.16	3.85	3.83	3.87	3.21
Workload	WL-high	1.82	2.74	4.70	4.22	3.38	2.69
	WL-low	1.91	2.86	4.44	4.31	3.23	2.70
	WL-none	1.85	2.88	3.80	4.36	3.32	2.92
Deceleration Rate	5.0 ft/sec^2	2.15	3.27	4.12	3.98	3.67	3.09
	9.8 ft/sec^2	1.57	2.39	4.43	4.59	2.96	2.46
Lead Vehicle Type	Car	2.04	2.80	4.11	4.17	3.42	2.84
	Truck	1.68	2.86	4.45	4.45	3.21	2.70
Overall Average		1.86	2.83	4.28	4.30	3.31	2.77

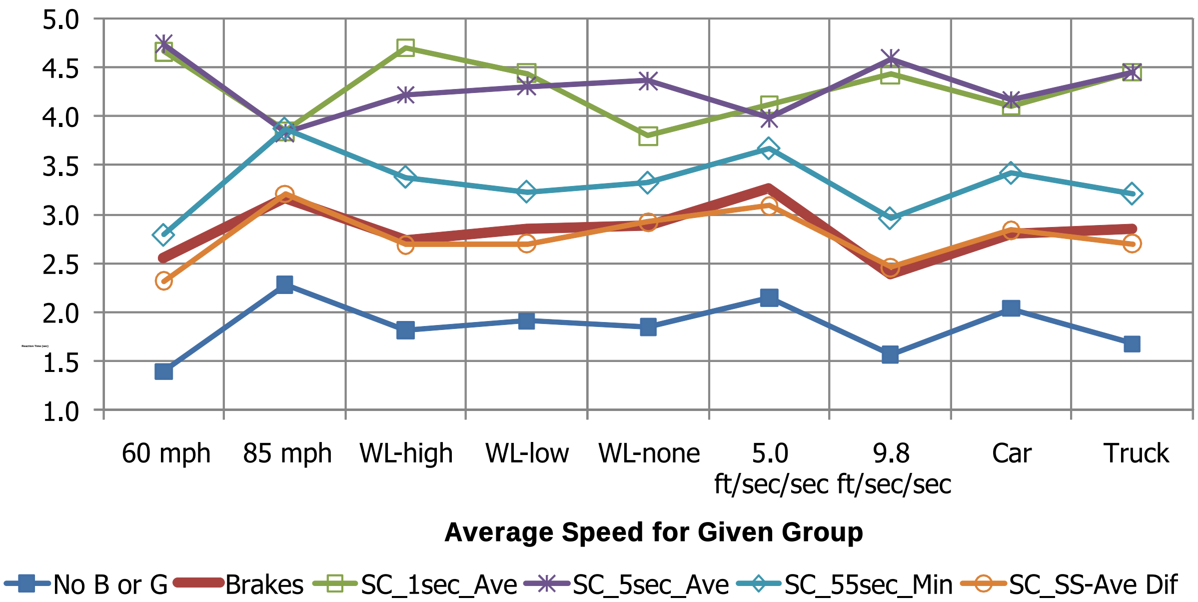


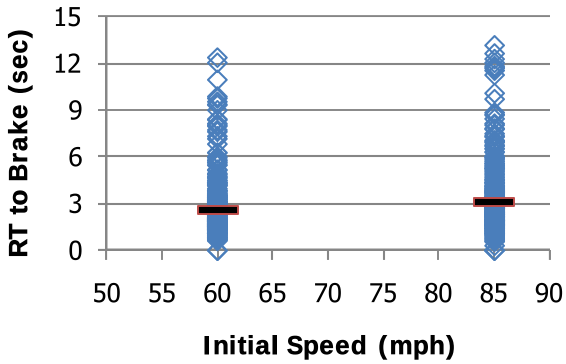
Figure 6-12. Average Speed by Initial Speed, Workload, Deceleration Rate, and Lead Vehicle Type by Type of Reaction Time.

Exploratory Analysis

The evaluation started with examining each component varied within an Ivan, assuming that there are no significant interactions among the variables, which will be assessed later:

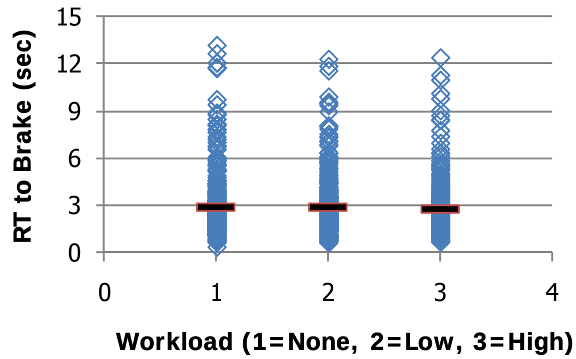
- initial speed (60 or 85 mph),
- workload level (high, low, or none),
- deceleration rate (low or high), and
- lead vehicle type (car or truck).

Figure 6-13 illustrates the distribution and average of the response data for the main effects variables. Both initial speed and deceleration rate were significant, while workload and lead vehicle type were not. Higher speeds are associated with longer brake reaction times as illustrated in Figure 6-13(a). The higher deceleration rate is associated with lower (or faster) brake reaction times as also shown in Figure 6-13(c). In other words, when the lead vehicle decelerates rapidly, the following driver brakes more quickly.



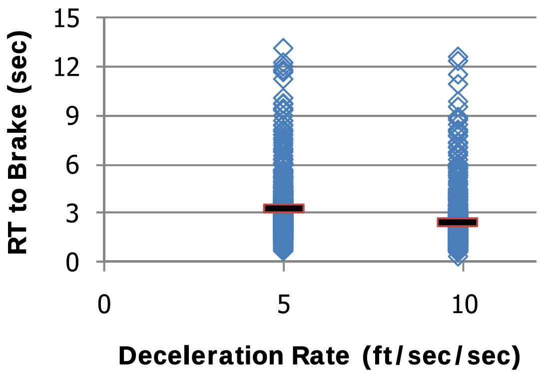
(a) Initial Speed
(Difference Statistically Significant)

Level	Number	Mean	Std. Dev.
60	583	2.56	3.36
85	427	3.16	3.04



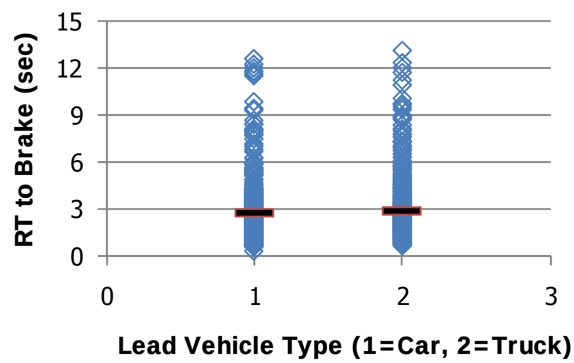
(b) Workload
(Difference Not Statistically Significant)

Level	Number	Mean	Std. Dev.
High	343	2.74	3.45
Low	352	2.86	3.45
None	360	2.89	3.45



(c) Deceleration Rate
(Difference Statistically Significant)

Level	Number	Mean	Std. Dev.
High (9.83 ft/sec^2)	522	3.27	3.26
Low (5.00 ft/sec^2)	533	2.39	3.26



(d) Lead Vehicle Type
(Difference Not Statistically Significant)

Level	Number	Mean	Std. Dev.
Car	519	2.80	3.45
Truck	536	2.86	3.45

Figure 6-13. Distributions of Reaction Time to Brake Using Findings from Exploratory Analysis of Main Effects Only.

Drivers were instructed to try to maintain a 2-sec headway throughout the study, but there was naturally some fluctuation in their actual headways. Researchers believe that reaction time may depend on the available headway at the start of the Ivan; that is, if drivers happen to be closer to the lead vehicle at the start of the Ivan, they may be more quick to apply their brakes. Figure 6-14 shows the relationship between headway at the start of the Ivan to reaction time to brake. Most headway distances were within the 2-sec goal of 176 ft for 60 mph and 250 ft for 85 mph. Although longer headway distances are clear in Figure 6-14, less than 3 percent of the headway distances exceeded 250 ft for the dataset used in the evaluation. Headway was further evaluated when examining potential interactions among the study variables, as presented in the following section.

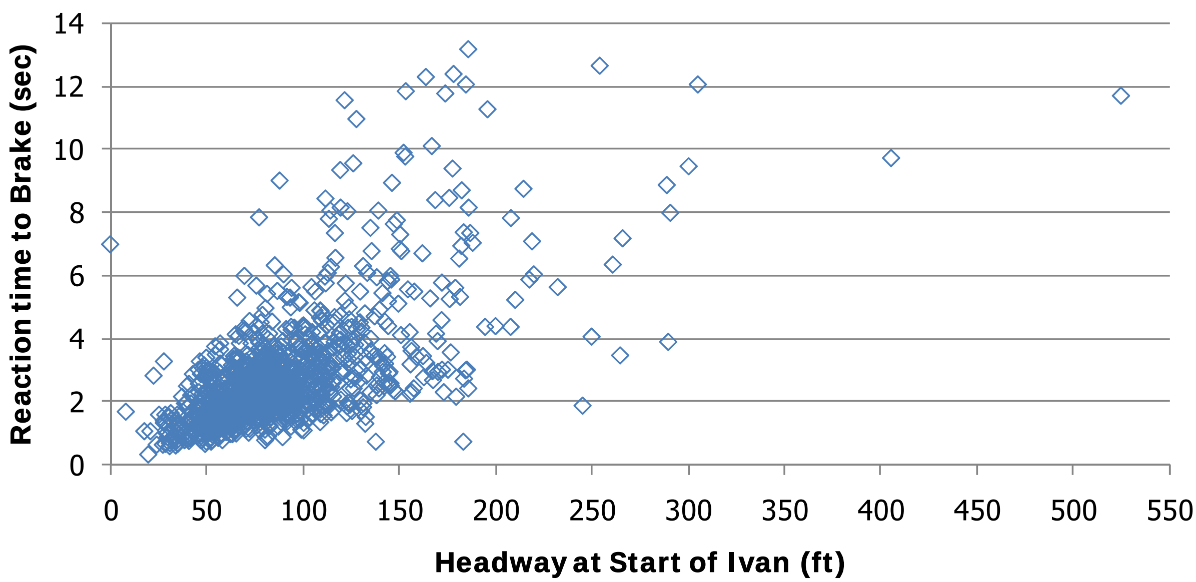


Figure 6-14. Distribution of Reaction Time to Brake by Headway at Start of Ivan.

Main Analysis

While the one-way analyses indicated that workload and lead vehicle type were not significant when considered in isolation, they could interact with other variables and affect the reaction time to when the brake is applied. The data were analyzed utilizing a randomized block design analysis with participants as random blocks to account for potential correlations in the observations (or measurements) from the same participant. The next evaluation effort considered potential interactions. Several combinations of variables (two-way interactions) were included:

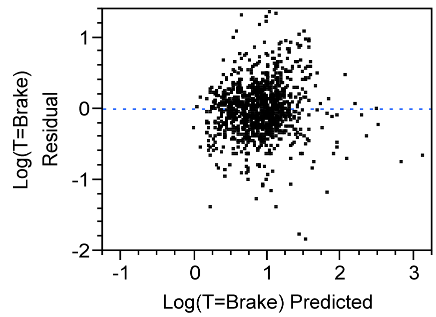
- initial speed and headway at the start of the Ivan,
- initial speed and lead vehicle type,
- initial speed and Ivan deceleration rate,
- initial speed and workload level,
- lead vehicle type and workload level,
- lead vehicle type and deceleration rate,
- lead vehicle type and headway at the start of the Ivan,
- workload level and deceleration rate,

- workload level and headway at the start of the Ivan, and
- deceleration rate and headway at the start of the Ivan.

Several of the interactions were not significant and were dropped from the models. Table 6-7 shows the results for the model that only included significant two-way interactions. Table 6-8 shows the effects details.

Table 6-7. Reaction Time to Brake Least Square Results.

Residual by Predicted Plot



Response Log(T=Brake)

Summary of Fit

RSquare	0.669252
RSquare Adj	0.665763
Root Mean Square Error	0.323689
Mean of Response	0.880377
Observations (or Sum Wgts)	1055

Parameter Estimates

Term	Estimate	Std. Error	DFDen	t Ratio	Prob>|t|
Intercept	0.2415663	0.042174	152.1	5.73	<0.0001*
Initial Speed (60)	−0.041705	0.010646	1018	−3.92	<0.0001*
Lead Vehicle Type (Car)	0.0554768	0.010369	1003	5.35	<0.0001*
Workload Level (High)	0.004975	0.014343	993.9	0.35	0.7288
Workload Level (Low)	0.0169794	0.014202	993.9	1.20	0.2322
Ivan Decel. Rate (5.0)	0.1735458	0.009998	994.3	17.36	<0.0001*
Headway (ft) at Start of Ivan	0.007462	0.000328	1017	22.77	<0.0001*
Initial Speed (60) * (Headway [ft] at Start of Ivan − 90.0405)	0.0012107	0.000264	1017	4.58	<0.0001*
Ivan Decel. Rate (5.0) * (Headway [ft] at Start of Ivan − 90.0405)	−0.001647	0.000239	1006	−6.89	<0.0001*
Initial Speed (60) * Workload Level (High)	0.013662	0.014369	994.2	0.95	0.3419
Initial Speed (60) * Workload Level (Low)	−0.038568	0.01419	993.4	−2.72	0.0067*
Initial Speed (60) * Lead Vehicle Type (Car)	0.0207448	0.010274	996	2.02	0.0437*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Initial Speed	1	1	1018	15.3463	<0.0001*
Lead Vehicle Type	1	1	1003	28.6252	<0.0001*
Workload Level	2	2	994	1.3319	0.2645
Ivan Decel. Rate	1	1	994.3	301.2731	<0.0001*
Headway (ft) at Start of Ivan	1	1	1017	518.5818	<0.0001*
Initial Speed * Headway (ft) at Start of Ivan	1	1	1017	20.9532	<0.0001*
Ivan Decel. Rate * Headway (ft) at Start of Ivan	1	1	1006	47.4205	<0.0001*
Initial Speed * Workload Level	2	2	993.9	3.8208	0.0222*
Initial Speed * Lead Vehicle Type	1	1	996	4.0770	0.0437*

Table 6-8. Reaction Time to Brake Effect Details Results.

Study Speed

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60	2.3910704	0.03155089
85	2.5990632	0.03237469

* Std. errors are on transformed Y's

Lead Vehicle Type

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
Car	2.6351047	0.03195526
Truck	2.3583666	0.03179306

* Std. errors are on transformed Y's

Workload Level

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
high	2.5053315	0.03347620
low	2.5355879	0.03331139
none	2.4387648	0.03320106

* Std. errors are on transformed Y's

Ivan Decel. Rate

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
1.524	2.9653405	0.03180121
2.999	2.0957266	0.03171005

* Std. errors are on transformed Y's

Study Speed * Workload Level

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, High	2.4360505	0.03675115
60, Low	2.3400026	0.03688518
60, None	2.3981395	0.03683814
85, High	2.5765829	0.03926363
85, Low	2.7475208	0.03857992
85, None	2.4800783	0.03824759

* Std. errors are on transformed Y's

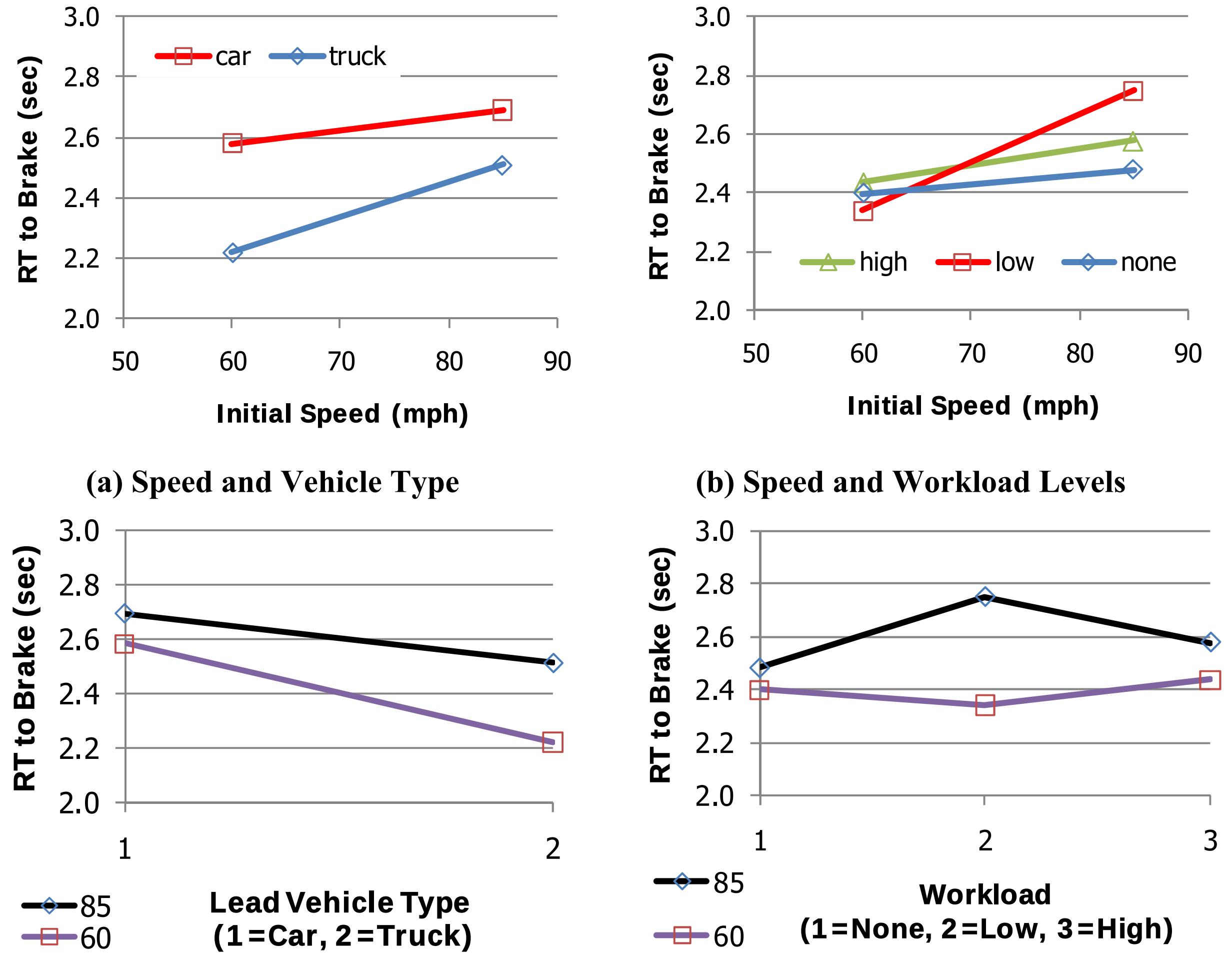
Study Speed * Lead Vehicle Type

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, Car	2.5804473	0.03492873
60, Truck	2.2155916	0.03406753
85, Car	2.6909197	0.03575859
85, Truck	2.5103422	0.03577922

* Std. errors are on transformed Y's

While workload level did not seem to be significant when it was considered by itself (see Figure 6-13), it does influence brake reaction time when considered jointly with initial speed. Figure 6-15 contains plots for statistically significant interactions, which illustrate how the effect of a variable on reaction time varies depending on the level of the other factor. Initial speed in combination with lead vehicle type shows that reaction time changes more between the two speeds when following a truck as compared to a car (see Figure 6-15[a] or [c]). Initial speed in combination with workload provided interesting findings. The low-workload tasks had an impact on reaction time but only for the higher-speed condition (see Figure 6-15[b] or [d]). Also illustrated in Figure 6-15(b) and (d) is that reaction time for all workload levels is similar at the 60-mph initial speed (between 2.34 and 2.43 sec). At 85 mph there is a 0.26-sec range (2.48 and 2.74 sec).



(a) Speed and Vehicle Type

(b) Speed and Workload Levels

(c) Speed and Vehicle Type, Rearranged

(d) Speed and Workload Levels, Rearranged

Figure 6-15. Interaction of Variables Plots.

Additional plots were generated to provide an appreciation of differences in reaction time for initial speed and deceleration rate for the relationship between reaction time and headway. Figure 6-16 is a close-up of the data with reaction times less than 8 sec and headways less than 250 ft for initial speed. Figure 6-17 is a similar graph with the division being for the deceleration rate used at the start of the Ivan. As expected, when the participant vehicle is close to the lead vehicle at the start of an Ivan maneuver (i.e., the headway distance is small), reaction times are faster. The plot showing the initial speed division does not provide clear guidance on how initial speed interacts with headway regarding an impact on reaction time. This finding is not surprising since the instructions to the participants were to try to maintain a 2-sec headway regardless of the initial speed. A 2-sec headway is 250 ft for 85 mph and 176 ft for 60 mph. The plot showing the deceleration rate division, however, does show a noticeable trend. For a given headway distance, drivers react faster to vehicles with the higher deceleration rate (see Figure 6-17).

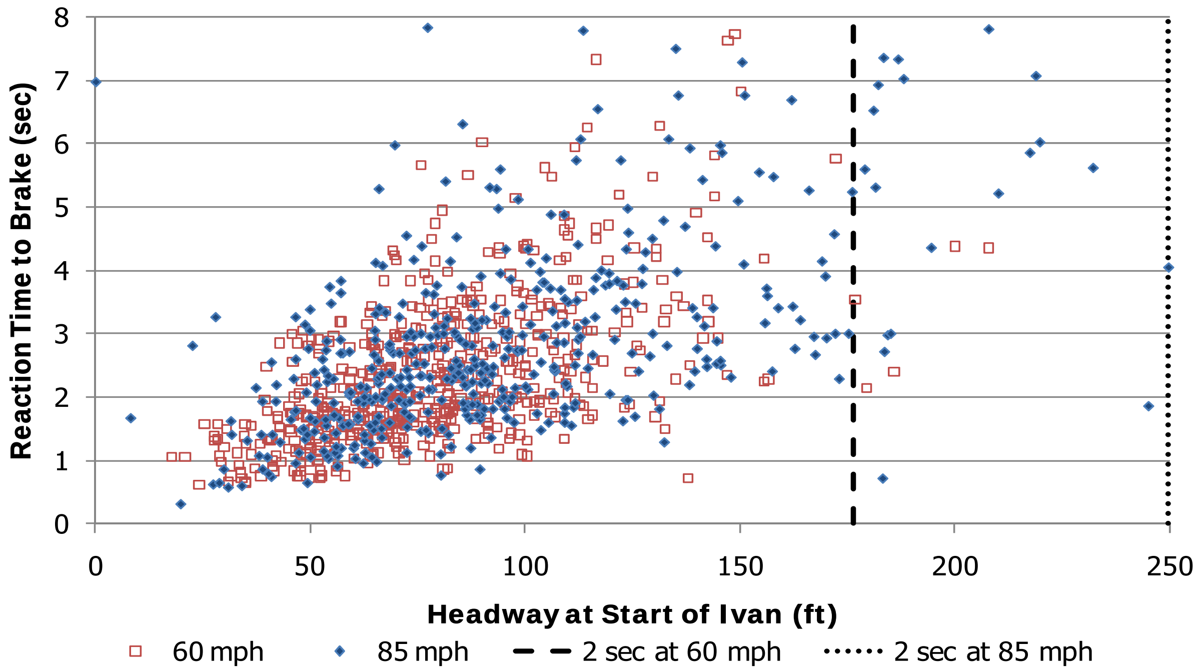


Figure 6-16. Distribution of Reaction Time to Brake by Headway at Start of Ivan and Initial Speed.

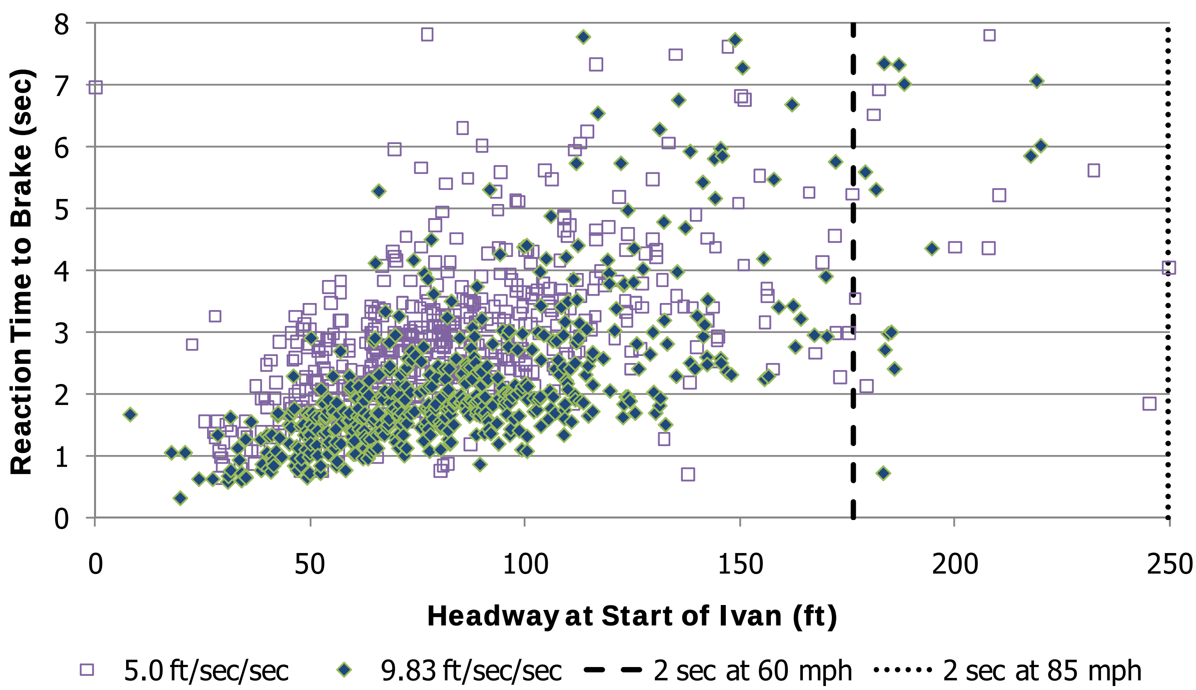


Figure 6-17. Distribution of Reaction Time to Brake by Headway at Start of Ivan and Deceleration Rate.

CONCLUSIONS

Based on the results from the various analyses of the simulator data, researchers drew the following conclusions:

- Higher initial speeds are associated with statistically significant longer reaction times. Stated in another manner, drivers were slower at responding to lead vehicle changes when at a higher initial speed. For the 60-mph condition, the predicted reaction time is 2.39 sec, while it is 2.60 sec at 85 mph, an increase of 0.21 sec. Even though the difference in values is statistically significant, one should also consider whether the difference is practically significant. A typical practical difference in reaction time is debatable. For this study, the researchers decided to use 0.15 sec, which is the time to travel 19 ft (typical passenger car length) at 85 mph. If 0.15 sec is an acceptable practical difference, then the difference found in this comparison of reaction time by initial speed is of both practical difference and statistical difference.
- The reaction times when following a smaller vehicle (a car in this experiment) are associated with longer reaction times as compared to those when following a large vehicle (truck). The predicted reaction time for following a car was 2.64 sec, while it was 2.36 sec for following a truck, a difference of 0.28 sec, which is both statistically significant and is a practical difference. This finding supports the discussion in the literature review (Chapter 2) and Table 2-1 that the looming of a wider vehicle can be detected at a greater distance.
- The two different deceleration rates of the lead vehicle tested in the study produced large differences in reaction time. When the lead vehicle had a high deceleration rate (9.8 ft/sec^2), the predicted brake reaction time was 2.10 sec. The predicted brake reaction time was 2.97 sec when the predicted rate was not as great (5.0 ft/sec^2). Drivers did not notice the slower deceleration rate as quickly as they did the faster deceleration rate, or they may have noticed but felt no urgency to respond. Note that the brake lights were not visible in any of the deceleration events; the driver needed to judge the situation based upon the lead vehicle looming in the driver's view.
- As to be expected, greater headways present at the start of an Ivan are associated with longer reaction times. Drivers have extra distance to interpret the situation with the lead vehicle and to make a decision on how best to react. The interaction of headway with initial speed and deceleration rate were both found to be statistically significant.
- Initial speed in combination with lead vehicle type shows that reaction time changes more between the two initial speeds when following a large truck as compared to a car. The increase in reaction time when following a truck was an additional 0.29 sec (2.51 − 2.22 sec) when at 85 mph as compared to 60 mph. A similar comparison for following a car only results in an increase of 0.11 sec (2.69 − 2.58 sec). This finding indicates that the advantage of the wider vehicle in terms of being able to judge closing rate is diminished at higher speeds.
- Initial speed in combination with workload provided interesting findings. Three levels of mental workload were tested in the study: none, low (easy math questions), and high (hard math questions). As discussed in the introduction, previous research has shown that peak performance occurs at moderate levels of mental arousal. If a task is too easy or too hard, performance suffers. In the case of the present study, driving at 60 mph in the simulator is an easy enough task that adding mental workload at low and high levels

does not affect reaction time performance. This is shown in Figure 6-15(d) as the flat line across the workload levels for the 60-mph initial speed condition. When the speed was raised to 85 mph, however, the driving task got a little harder, and it required more mental effort to control the steering wheel and throttle. For the no-workload condition, responding to the lead vehicle slowing is still easy, but adding the easy math problems in the low-workload condition pushes the person to have to try to multitask, and the reaction times increase. In the high-workload condition at the high speed then, why do the reaction times not continue to increase? This counterintuitive result has been seen in other studies of driver distraction, which have shown that in high-workload situations drivers adopt tunnel vision and focus only on the lead vehicle, leading to faster reaction times than in lower-workload situations. Researchers believe that in the high-workload, high-speed condition, drivers may have obtained this sort of tunnel vision.

CHAPTER 7

FOLLOWING DISTANCE STUDY

INTRODUCTION

Several factors influence a driver's decision on how close to drive to another vehicle. The amount of traffic present in the traffic stream is a major factor. Drivers may desire additional space between their vehicle and the lead vehicle when following a large vehicle, for example, because of the driver's inability to see around the lead vehicle or a feeling of being boxed in.

Speed may also influence the gap distance between vehicles. Because higher speeds may have higher workload for a driver, the driver may offset some of the workload demand by maintaining a greater following distance to the lead vehicle. Similar following distances for different speed conditions could indicate the workload is not different enough to cause a change in driving behavior.

STUDY OBJECTIVES

If following distances are found to differ based upon the operating speed of the highway, differences in driver workload may be the cause. For this reason the following research questions were investigated:

- Is there a difference in following distance between the 60-, 65-, 70-, and 80-mph daytime passenger posted speed limits (DPPSLs)?
- Does the subject vehicle size or the previous vehicle size influence following distance?
- How does traffic volume affect following distance by DPPSL?
- Does lighting condition affect the following distance?

STUDY SITES

Table 7-1 lists the characteristics for the available study sites. Table 7-2 lists the distance to upstream and downstream ramps along with the TxDOT project source of the data.

Sites were selected so that this project can explore driver workload at different speeds on Texas freeways. Approximately half of the sites included in the evaluation were from previous projects. For the other sites, counters were installed at locations of interest to this project. Typically, counters were installed in a 70-mph section for the same days counters were installed in an 80-mph section on the same freeway. This approach of using a pair of sites occurred in October 2008 (west of San Antonio) and January 2009 (east of El Paso). The approach was repeated in June 2009 for sites west of San Antonio (near Kerrville) due to concerns with the quality of the data collected in the 80-mph sections. For each of these sites, the freeway had two lanes of traffic per direction. Speed data on each lane were recorded.

Table 7-1. Characteristics of Counter Datasets.

Road	Nearest City	Lighting	Dir.	Lane	Posted Speed Limit (mph) Day/Night		Number of Vehicles	Month and Year Data Collected
					Car	Truck		
I-10	El Paso	No	EB	P	70/65	70/65	1,166	Jan. 2009
I-10	El Paso	No	EB	R	70/65	70/65	8,002	Jan. 2009
I-10	El Paso	No	EB	P	80/65	70/65	3,248	Jan. 2009
I-10	El Paso	No	EB	R	80/65	70/65	15,364	Jan. 2009
I-10	El Paso	No	WB	P	70/65	70/65	521	Jan. 2009
I-10	El Paso	No	WB	R	70/65	70/65	2,047	Jan. 2009
I-10	El Paso	No	WB	P	80/65	70/65	1,817	Jan. 2009
I-10	Kerrville	No	EB	P	70/65	70/65	14,422	June 2009
I-10	Kerrville	No	EB	R	70/65	70/65	3,977	June 2009
I-10	Kerrville	No	EB	P	80/65	70/65	4,244	June 2009
I-10	Kerrville	No	EB	R	80/65	70/65	878	June 2009
I-10	Kerrville	No	WB	P	70/65	70/65	12,793	June 2009
I-10	Kerrville	No	WB	R	70/65	70/65	4,165	June 2009
I-10	Kerrville	No	WB	P	80/65	70/65	5,269	June 2009
I-10	Kerrville	No	WB	R	80/65	70/65	1,187	June 2009
I-10	San Antonio	No	EB	P	70/65	70/65	3,313	Oct. 2008
I-10	San Antonio	No	EB	R	70/65	70/65	10,587	Oct. 2008
I-10	San Antonio	No	EB	P	80/65	70/65	962	Oct. 2008
I-10	San Antonio	No	EB	R	80/65	70/65	5,216	Oct. 2008
I-10	San Antonio	No	WB	P	70/65	70/65	3,301	Oct. 2008
I-10	San Antonio	No	WB	R	70/65	70/65	12,754	Oct. 2008
I-10	San Antonio	No	WB	P	80/65	70/65	1,322	Oct. 2008
I-10	San Antonio	No	WB	R	80/65	70/65	5,588	Oct. 2008
US-67	Dallas (Kiest)	Yes	SB	R	60	60	6,376	Sept. 2008
US-67	Dallas (Red Bird)	Yes	SB	R	60	60	55,108	Sept. 2008
I-45	Houston	Yes	NB	R	65	60	45,557	July 2008
I-635	Dallas	Yes	EB	R	60	60	45,970	Sept. 2008
SH-288	Houston	Yes	SB	R	60	60	27,638	May 2008
SH-288	Houston	Yes	NB	R	60	60	39,713	June 2008
US-59	Victoria	Yes	SB	R	70/65	70/65	13,158	June 2008
SH-6	College Station	Yes	SB	R	70/65	70/65	12,646	May 2008
I-10	Sealy (B exit)	Yes	WB	R	70/65	70/65	53,478	Oct. 2008
I-10	Sealy (P exit)	Yes	EB	R	70/65	70/65	81,445	Oct. 2008
I-10	Sealy (P exit)	Yes	WB	R	70/65	70/65	55,805	Oct. 2008
Dir: EB = eastbound, WB = westbound, NB = northbound, SB = southbound Lane: P = passing lane, R = right lane								

Table 7-2. Distance to Ramps from Counter Locations.

Site	Upstream Ramp		Downstream Ramp		Source of Data	Urban or Rural
	Distance (Miles)	Type	Distance (Miles)	Type		
El Paso, EB I-10	2.49	On	18.83	Off	0-5911	Rural
El Paso, EB I-10	2.17	On	10.13	Off	0-5911	Rural
El Paso, WB I-10	18.85	On	1.60	Off	0-5911	Rural
El Paso, WB I-10	10.11	On	2.15	Off	0-5911	Rural
San Antonio, EB I-10	1.74	On	1.93	Off	0-5911	Rural
San Antonio, EB I-10	2.85	On	3.12	Off	0-5911	Rural
San Antonio, WB I-10	1.88	On	1.76	Off	0-5911	Rural
San Antonio, WB I-10	3.04	On	2.75	Off	0-5911	Rural
Sealy (B Exit), I-10	2.50	On	0.59	On	0-6035	Rural
Sealy (P Exit), I-10	2.40	On	0.47	On	0-6035	Rural
Sealy (P Exit), I-10	1.22	On	0.52	On	0-6035	Rural
College Station, SH-6	0.25	On	0.67	On	0-6035	Urban
Dallas, EB I-635	0.22	On	0.09	On	0-5860	Urban
Dallas, SB US-67 @ Kiest	0.31	Off	0.09	On	0-5860	Urban
Dallas, SB US-67 @ Red Bird	0.52	Off	0.09	On	0-5860	Urban
Houston, NB I-45	0.50	Off	0.09	On	0-5860	Urban
Houston, NB SH-288	0.63	Off	0.09	On	0-5860	Urban
Houston, SB SH-288	0.62	Off	0.09	On	0-5860	Urban
Victoria, US-59	0.39	On	0.56	On	0-6035	Urban

Freeway data were also available from two previous TxDOT projects (0-5860 and 0-6035), which provided the opportunity to expand the evaluation into lower posted speed ranges. The added data, however, may be heavily affected by congestion since all of these sites were located in urban areas. The data may also be affected by nearby ramps. Both the 0-5860 and 0-6035 data were collected for studies that were concerned with driver behavior near ramps. For both projects, data were collected only in the right-most lane upstream of an exit ramp. Data were also collected on the exit ramp; however, only the data collected on the freeway were included in this evaluation.

PRELIMINARY FINDINGS

The data were collected using tube counters with a known distance between the tubes, generally 16 ft. The following vehicle characteristics were recorded by the traffic counters:

- vehicle speed in miles per hour,
- gap between vehicles in seconds,
- vehicle classification based upon axle spacing and number of axles using the Federal Highway Administration (FHWA) classification scheme (see Figure 7-1), and
- time of day and date when the data were recorded.

Because the minimum vehicle operating speed is 45 mph on interstates, vehicles traveling at speeds less than 45 mph were removed from the speed evaluations. Table 7-3 shows the average speed by daytime passenger car posted speed limit. Figure 7-2 shows the distributions by posted speed limit. Surprising was the minimal difference in the average speed found between the 60- and 65-mph sites and especially the minimal difference between the 70- and 80-mph sites. While there are several vehicles included in the results for the 65-mph site, it still only represents one site. Therefore, care needs to be exercised in making conclusions based on the one site. Also the site is located in an urban area and could be heavily influenced by high traffic volumes.

In previous research the average speed on arterials has been found to be near the posted speed limit (*40*). The data from the 60- and 70-mph sites in this dataset support that general finding. For the 60-mph sites the average speed was near 61 mph, a difference of 1 mph. For the 70-mph sites the average speed of 69 mph was also about 1 mph away from the posted speed limit. The data for the 80-mph sites, however, do not support the general finding of having an average speed near the posted speed limit. The average speed was 72 mph, representing an 8-mph difference with the posted speed limit.

The speeds of the trucks, which have a lower speed limit in the 80-mph section, is surely influencing the average speeds. Table 7-3 also lists the average speed by truck/car and by day/night. The lower speed limits at night and the absence of congestion will also affect the average speed. Even when examining the average speed for cars during the day, the average speed is within 1 mph of the posted speed limit for the 60-mph (60.43 mph) and 70-mph (70.04 mph) posted speed limit sites. For the 80-mph posted speed limit sites, the average speed was 5 mph away from the posted speed limit of 80 mph (75.08 mph).

The research team was concerned that the differences observed at 80 mph could represent a limitation in the speed-measuring device. Therefore, a secondary task was completed to determine the accuracy of the tube counters at a sample of 70-mph and 80-mph sites. The findings are discussed in the next section.

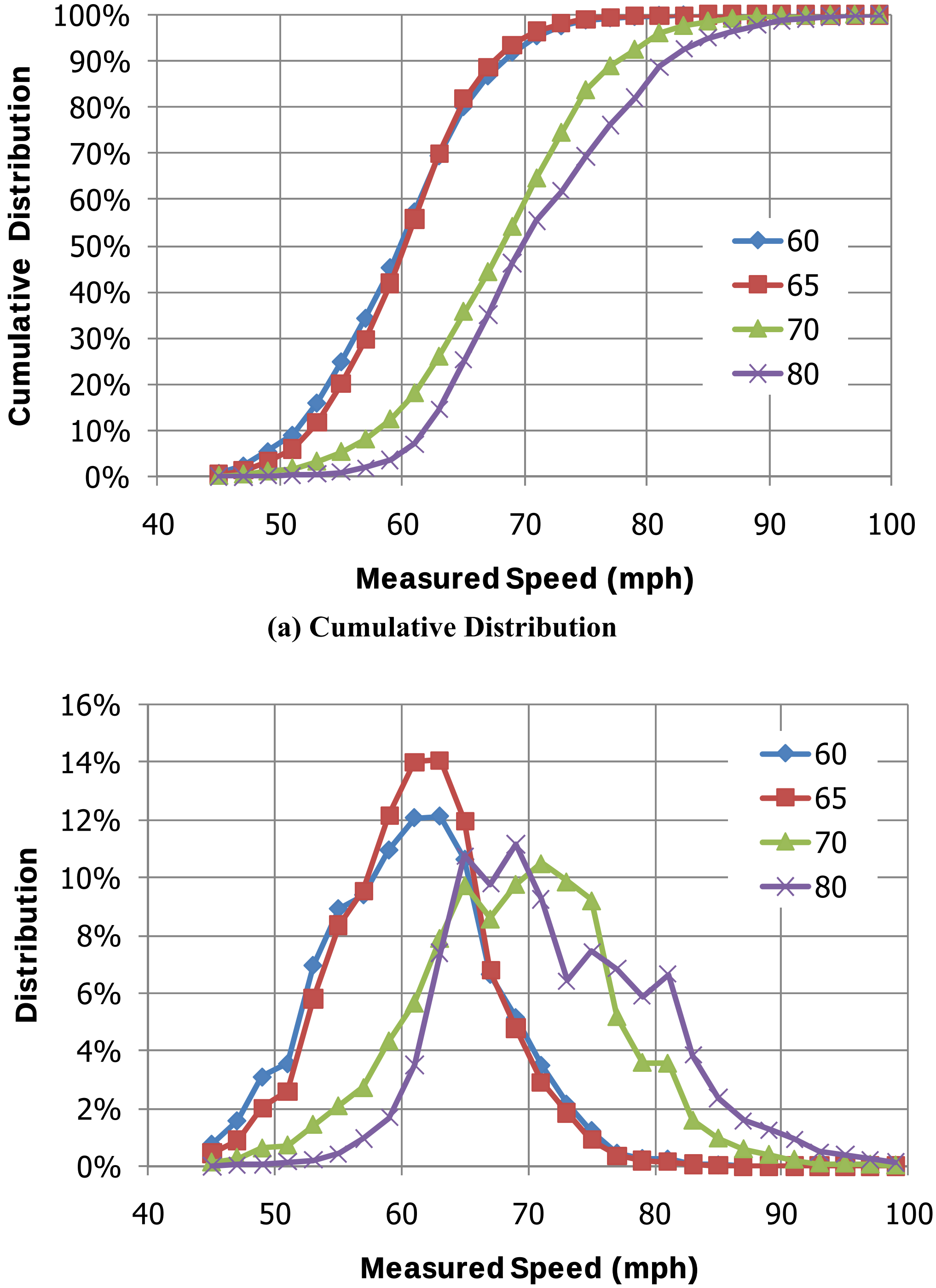
CLASS GROUP		DESCRIPTION	NO. OF AXLES
1		MOTORCYCLES	2
2		ALL CARS CARS CARS W/ 1-AXLE TRAILER CARS W/ 2-AXLE TRAILER	2 3 4
3		PICK-UPS & VANS 1 & 2 AXLE TRAILERS	2, 3, & 4
4		BUSES	2 & 3
5		2-AXLE, SINGLE UNIT	2
6		3-AXLE, SINGLE UNIT	3
7		4-AXLE, SINGLE UNIT	4
8		2-AXLE, TRACTOR, 1-AXLE TRAILER (2&1) 2-AXLE, TRACTOR, 2-AXLE TRAILER (2&2) 3-AXLE, TRACTOR, 1-AXLE TRAILER (3&1)	3 4 4
9		3-AXLE, TRACTOR, 2-AXLE TRAILER (3&2) 3-AXLE, TRUCK W/ 2-AXLE TRAILER	5 5
10		TRACTOR W/ SINGLE TRAILER	6 & 7
11		5-AXLE MULTI-TRAILER	5
12		6-AXLE MULTI-TRAILER	6
13	ANY 7 OR MORE AXLE		7 or more
14	NOT USED		
15	UNKNOWN VEHICLE TYPE		

HEAVY TRUCKS (classes 8–13)

Figure 7-1. FHWA Vehicle Classification Codes (Source: http://www.sarasota-manateempo.org/Figures/figure1.pdf).

Table 7-3. Average Speed by Daytime Passenger Car Posted Speed Limit.

	Daytime Posted Speed Limit (mph) [Number of Sites]	Average Speed (mph)	Standard Deviation (mph)	Number of Vehicles	Percent Trucks (%)
All Vehicle Types and Day/Night					
All Vehicle Types and Day/Night	60 [5]	60.73	6.62	161,567	5
	65 [1]	61.04	5.92	44,488	4
	70 [17]	68.93	7.80	291,743	19
	80 [11]	72.02	8.00	45,060	26
All Vehicle Types by Day or Night					
Daytime Only	60 [5]	60.32	6.66	130,612	5
	65 [1]	60.51	5.84	37,007	4
	70 [17]	69.37	7.87	235,792	17
	80 [11]	73.23	7.95	31,431	23
Nighttime Only	60 [5]	62.47	6.15	30,955	4
	65 [1]	63.71	5.56	7481	2
	70 [17]	67.10	7.24	55,951	28
	80 [11]	69.24	7.40	13,629	33
By Vehicle Type					
Car	60 [5]	60.84	6.64	153,316	0
	65 [1]	61.12	5.94	42,869	0
	70 [17]	69.67	7.94	236,519	0
	80 [11]	73.86	7.94	33,318	0
Truck	60 [5]	58.67	5.91	8251	100
	65 [1]	59.08	5.08	1619	100
	70 [17]	65.79	6.27	55,224	100
	80 [11]	66.81	5.44	11,742	100
By Day/Night and Vehicle Type					
Day, Car	60 [5]	60.43	6.68	123,581	0
	65 [1]	60.58	5.86	35,516	0
	70 [17]	70.04	7.95	196,471	0
	80 [11]	75.08	7.67	24,140	0
Day, Truck	60 [5]	58.40	5.94	7031	100
	65 [1]	58.77	5.04	1491	100
	70 [17]	66.01	6.45	39,321	100
	80 [11]	67.10	5.33	7291	100
Night, Car	60 [5]	62.57	6.16	29,735	0
	65 [1]	63.73	5.58	7353	0
	70 [17]	67.83	7.62	40,048	0
	80 [11]	70.65	7.75	9178	0
Night, Truck	60 [5]	60.23	5.48	1220	100
	65 [1]	62.63	4.24	128	100
	70 [17]	65.23	5.76	15,903	100
	80 [11]	66.34	5.60	4451	100



(a) Cumulative Distribution

(b) Distribution

Figure 7-2. Measured Speed Distributions for All Vehicles for Several Days by Daytime Passenger Car Posted Speed Limit.

ACCURACY OF SPEED MEASURING EQUIPMENT

Research was conducted to determine the accuracy of several different devices when used at higher speeds. Based on conversations with vendors and other traffic professionals, the general "rule of thumb" for accuracy in measuring speed is plus or minus 4 to 5 mph, or about 5 percent. A practical speed difference considered by many to be acceptable is 2 mph and in some cases 3 mph.

The devices tested included: pneumatic tube counters, a light detection and ranging (lidar) gun, and a control vehicle outfitted with devices to monitor speed and location. Data were collected near Kerrville, Texas, in both 70- and 80-mph posted speed limit sections during two days in June 2009. Device comparison involved determining the speed difference between devices for the two daytime posted speed limits.

Data Collection

Pneumatic tubes, a lidar gun, a camcorder, and the TTI instrumented vehicle captured vehicle speeds, lane presence, classifications, and other vehicle characteristics at four sites. Figure 7-3 shows photographs of the data collection techniques, while the typical layout for the sites is shown in Figure 7-4. The values for A, B, and C vary according to the site and are listed in Table 7-4.

Tube counters use hollow rubber tubes that detect the air displaced when impacted. They can collect time of impact along with speed, number of axles, axle spacing, and lane presence of the vehicles crossing the tubes. Vehicles classification is based on the number of and distance between axles. At the sites the tubes were offset 16 ft and were taped down at approximately 6-ft increments, due to the need for tube exposure at the location of tire impact.

The lidar gun works by emitting scattered light, which bounces off of the desired object and back to the device. The time elapsed during this process allows the lidar gun to determine speed and distance relative to its own location. The software used by the device also had a comment section for each reading, which allowed for vehicle classification. The lidar gun was manually operated from within a vehicle parked on the roadside. Speed profiles of vehicles for several hundred feet moving away from the instrument and approaching and crossing the tubes were collected. The speed measured closest to the tubes within this speed profile was used for the comparison. Table 7-4 lists the distances the lidar gun was located from the tubes. These distances were recorded for two reasons. One, the distance data given by the lidar gun are relative to its position, and these distances were needed to determine when the vehicle is over the tubes. Two, the laser gun's measurements need to be adjusted if recording within a certain angle. For this data collection, adjustments were not needed.

The camcorder was placed in line with the first contacted tube. It was mounted on a tripod and recorded vehicles as they crossed the tubes. It was available to verify the presence of vehicles on the tubes and to confirm notes made in the lidar files.

The TTI instrumented vehicle was used as the control vehicle. This particular vehicle is a Toyota Highlander that is outfitted with several extra features to accommodate the higher power drain due to the extra measurement devices on board. The main electronic component set up in the vehicle is the Dewetron system, used to integrate several different collection devices. Though several cameras and other devices are available, the only device that is relevant to this project is the global positioning system. This device measures location and speed through onboard devices, satellites, and communication towers. The vehicle was driven over the tubes a number of times within each study period. The number of crossings at a site was a function of the ramp spacing; longer ramp spacing required more time for the driver to complete a loop. The driver drove at different speeds during the study to provide more variability in the readings.

(a) Tube Counters

(b) Lidar Gun

(c) Instrumented Vehicle, Used as the Control Vehicle

(d) Video Camera

Figure 7-3. Examples of Data Collection Techniques.

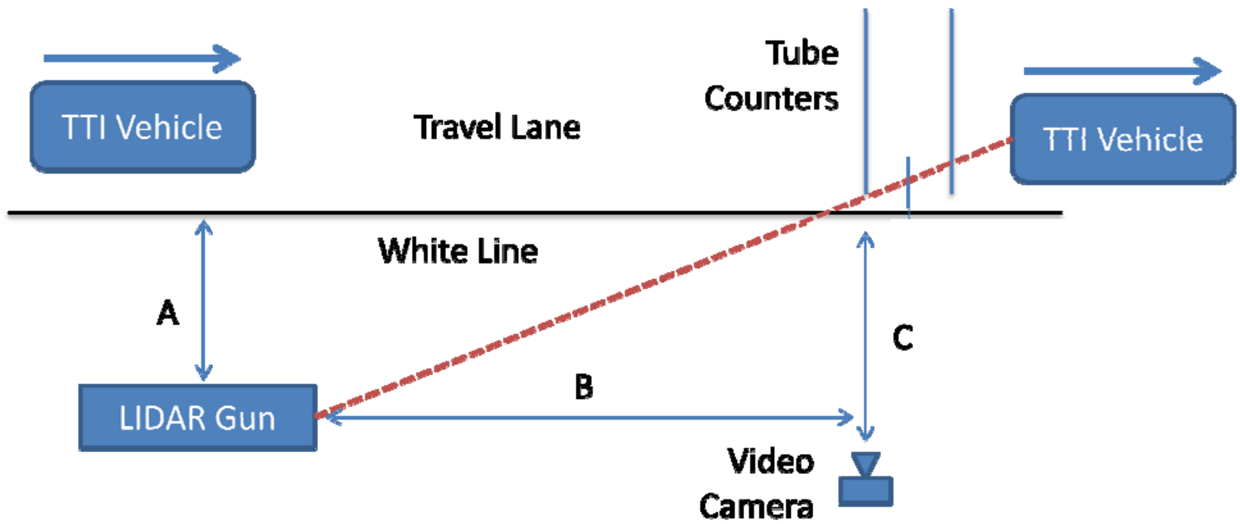


Figure 7-4. Typical Site Layout.

Table 7-4. Site Layout Distances.

Site No.	Direction	Date and Time Period	Speed Limit (mph)	Distance* (ft)			
				A	B	C	D
1	I-10 WB near Junction	6/10/09, AM	80	53	823	31	825
2	I-10 EB near Junction	6/10/09, PM	80	37	650	48	651
3	I-10 WB near Kerrville	6/11/09, AM	70	25	657	25	657
4	I-10 EB near Kerrville	6/11/09, PM	70	50	685	50	687

*Distance A, B, and C as shown in Figure 7-4.
Distance D is the distance between the lidar gun and the tubes, and was used to identify the speed measurement within the continuous speed profile closest to the tubes.

Collection Sites

Data for this study were collected at four sites near San Antonio, Texas, along I-10. Sites 1 and 2 are located near Junction, Texas, within an 80-mph daytime posted speed limit zone. Sites 3 and 4 are near Kerrville, Texas, along a 70-mph DPPSL zones. The sites were selected to be a minimum of 1 mile away from ramps to minimize the ramp effects. At Sites 1 and 2, the distance to ramps was approximately 2 miles in each direction. At Sites 3 and 4, the ramps were 8.5 miles to the west and 3 miles to the east, respectively. These distances should result in vehicles traveling at free-flow speeds and not slowing or increasing speed because of a ramp.

Collection Method and Times

After the collection site and the control vehicle's instruments were set up, data collection began. Approximately 3 hours of data were collected at each site. The videotapes could only collect 90 minutes of footage and therefore had to be changed once during each study period. The lidar gun and control vehicle were operated at the same intervals of time as the video. The control vehicle drove a loop route. Fewer recordings were available of the instrumented vehicle on the 70-mph sites because the ramps had a longer spacing. The video and lidar gun recorded the control vehicle as it crossed the tubes.

Data Reduction

Just as each of the devices was different in the variables they measured, they can be unique in how they output the information they collect. The lidar gun, tube counters, and control vehicle all output their information into a workbook format. These workbooks were merged into a single file. Vehicles were matched using the time code along with the notes, such as "TTI vehicle" or "semi truck" entered into the lidar readings. After combining the datasets, the speed differences between devices were found. The differences were then arranged to allow for the creation of cumulative distribution plots to facilitate analysis.

Speed Results

Control Vehicle

The speed difference between the control vehicle, lidar, and tube measurements for each pass of the TTI vehicle over the tubes is shown in Figure 7-5. Measurements were available for 15 passes in the 70-mph sections (eight eastbound and seven westbound). Measurements for 43 passes were available in the 80-mph sections (19 eastbound and 24 westbound). The right side of Figure 7-5 provides the data for the 70-mph sites. For most of the passes the speed measured by the lidar gun and the tubes was very similar to the speed recorded by the control vehicle. Greater differences between the tubes (shown as open squares) and the TTI control vehicle (shown as plus symbols) can be seen for the 80-mph sites (see left side of Figure 7-5).

Table 7-5 provides the averages and standard deviation for the speed measurements. The percent difference between the control vehicle and lidar was 0.9 percent and 1.2 percent for the passes in the 70-mph and 80-mph sections, respectively. The average absolute speed difference was 0.63 mph and 0.94 mph in the 70-mph and 80-mph sections, respectively. The percent difference between the control vehicle and the tubes was 1.3 percent and 3.8 percent for the passes in the 70-mph and 80-mph sections, respectively. The average absolute speed difference was 0.93 mph and 3.05 mph in the 70-mph and 80-mph sections, respectively. The comparison of lidar and tubes for this set of data provided the following differences: 0.5 percent (0.96 mph) in the 70-mph sections and 4.7 percent (3.81 mph) in the 80-mph sections.

Greater differences were observed between the tubes and the control vehicle for the 80-mph sections; however, the difference was less than 4 percent. The tubes in almost all cases under-measured the speed of the instrumented vehicle in the 80-mph section. The tubes both under- and over-measured the speed as compared to the control vehicle speed in the 70-mph sections.

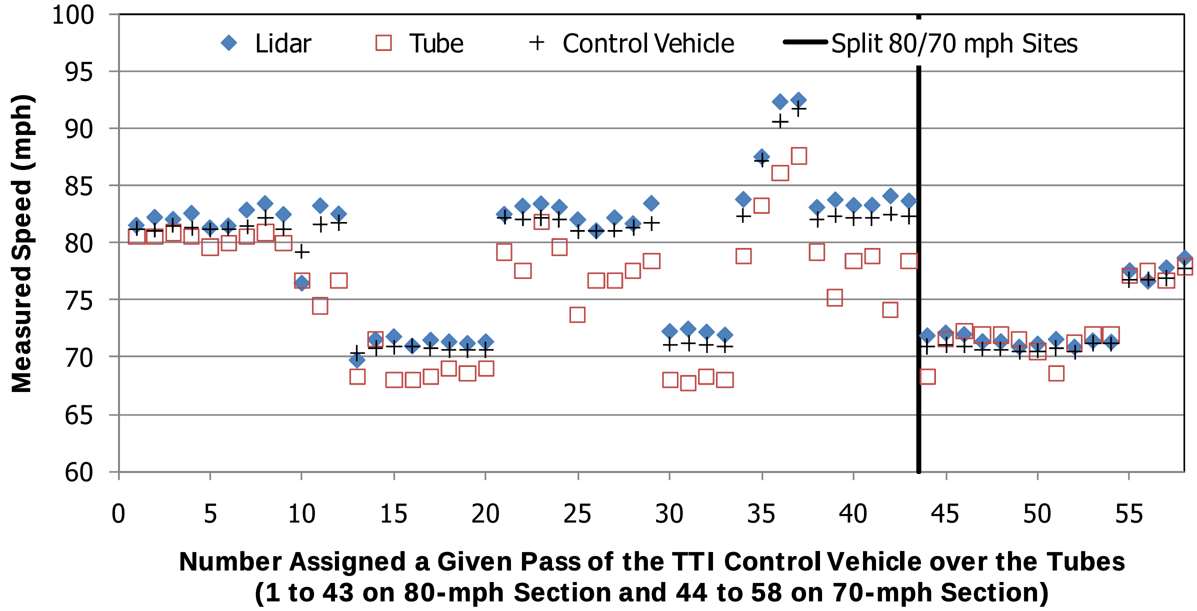


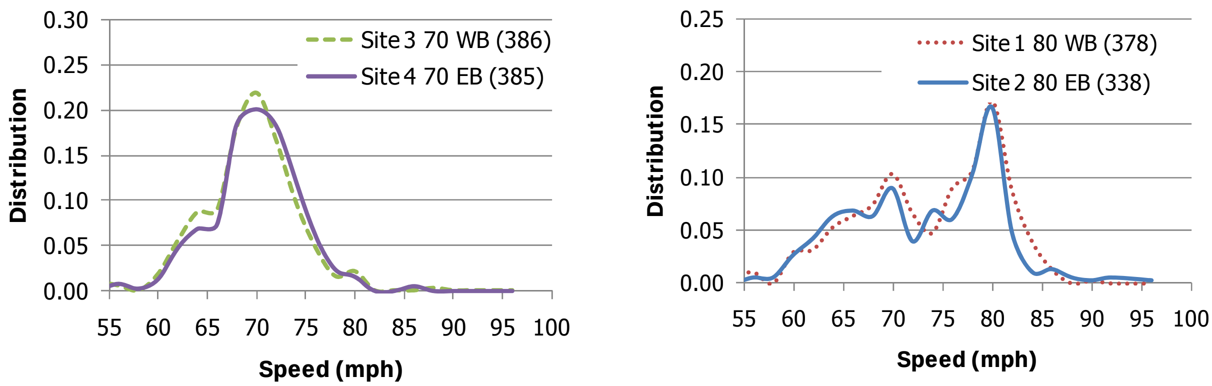
Figure 7-5. Speed Differences with TTI Control Vehicle.

Table 7-5. Differences in Speed Measurements Compared to Control Vehicle.

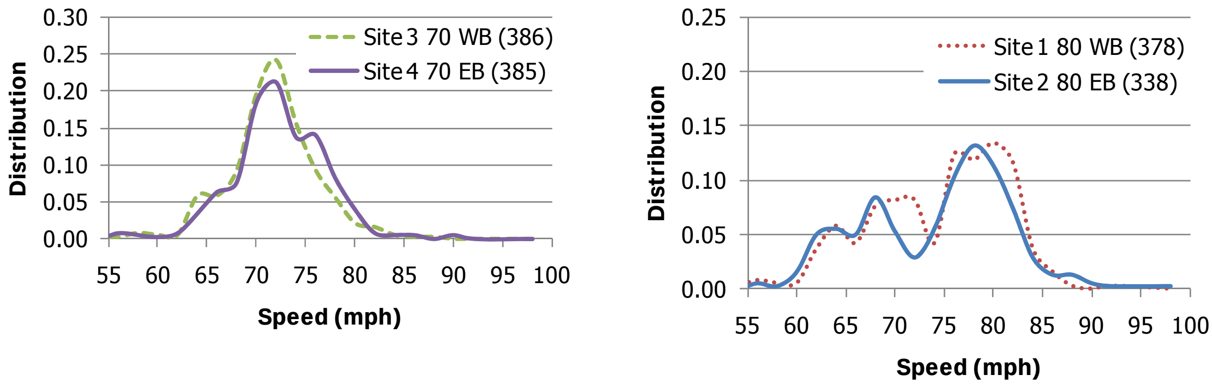
Measuring Technique	Posted Speed (mph)	Average ± Standard Deviation (mph)	Range (mph)
Control Vehicle	70	72.47 ± 2.89	70.43 to 77.81
Lidar	70	73.07 ± 2.89	70.86 to 78.62
Tube	70	72.73 ± 3.09	68.30 to 77.90
Difference Control & Tube	70	0.26 ± 1.18	−1.32 to 2.62
Difference Control & Lidar	70	0.60 ± 0.35	−1.04 to 0.20
Difference Lidar & Tube	70	0.35 ± 1.33	−0.90 to 3.54
Control Vehicle	80	79.18 ± 5.71	70.36 to 91.70
Lidar	80	79.96 ± 5.89	69.72 to 92.40
Tube	80	76.16 ± 5.47	67.70 to 87.60
Difference Control & Tube	80	−3.01 ± 1.98	−0.84 to 8.42
Difference Control & Lidar	80	0.78 ± 0.76	−1.70 to 2.79
Difference Lidar & Tube	80	3.80 ± 2.27	−0.28 to 9.94

Tubes and Lidar Measurements

Because of the nature of how the data can be collected, there was a much larger set of data for comparisons between the tube and lidar measurements as compared to the comparisons with the control vehicle. Figure 7-6 can provide an appreciation of the distribution of speed measurements from the tube and lidar techniques. The number in parenthesis on the graphs is the number of vehicles measured at the site and used in the comparisons. The patterns of speed measurements for both lidar and tubes are similar, with the lidar showing more measurements near the 80-mph value (approximately 20 percent) as compared to the tubes (approximately 15 percent).



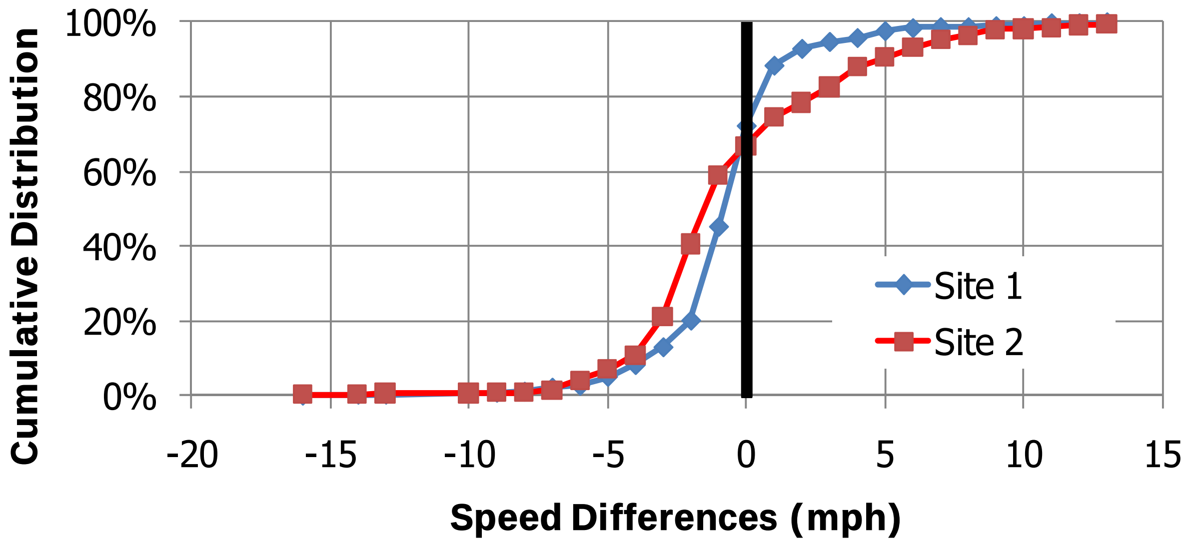
(a) Lidar



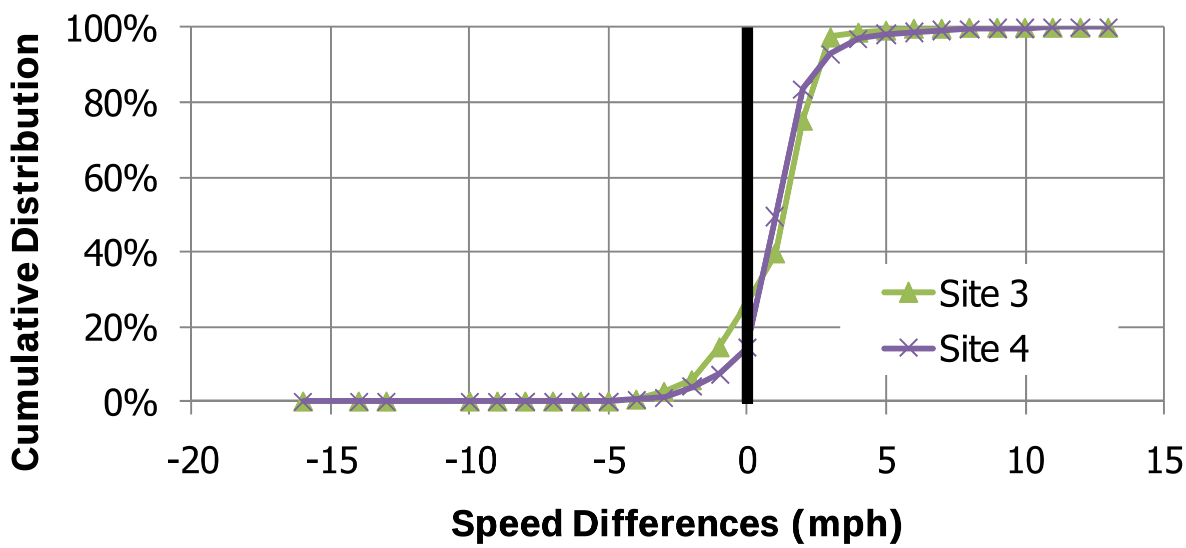
(b) Tubes

Figure 7-6. Speed Distributions.

Figure 7-7 shows the cumulative distribution of speed differences for each site, with Figure 7-7(a) showing the 80-mph sites and Figure 7-7(b) showing the 70-mph sites. For the 70-mph sites, most of the differences were positive, which means that for most of the measurements, the tubes measured a speed that was higher than the lidar speed. For the 80-mph sites the opposite was found. For most measurements the lidar speed was higher than the tube speed.



(a) 80-mph Sites



(b) 70-mph Sites

Figure 7-7. Cumulative Distribution of Speed Differences.

Table 7-6 lists the average and range of speeds measured at each site. It also provides the average and range of the difference between the lidar measurement and the tube measurement. The percent difference between the lidar and tube measurements can be calculated using the average speed difference and the average lidar speed measurement value or can be measured using the average of the individual percent differences (i.e., the percent difference identified for each individual pair of speeds). Both approaches provide a similar result for this dataset.

For the 70-mph sites, the average absolute difference is 2.2 percent or 1.51 mph. The 80-mph sites had a slightly higher absolute percent difference of 3.3 percent or 2.42 mph. These values were calculated using the absolute differences so that a negative difference will not cancel a positive difference. For example, −1.0- and 1.0-mph values average to 0 mph, while using absolute values would result in an average of 1 mph, which is a better measure of the accuracy of the equipment.

Table 7-6. Differences in Speed Measurements between Lidar and Tubes.

Posted Speed (mph)	Site Number (Sample Size)	Measuring Technique	Average ± Standard Deviation (mph)	Range (mph)
80	1 (378 matches)	Lidar	74.22 ± 7.27	50 to 90
		Tube	73.34 ± 6.96	49.3 to 90.3
		Difference Lidar & tube	−0.88 ± 2.62	−14.7 to 12.4
	2 (337 matches)	Lidar	73.88 ± 7.30	56 to 97
		Tube	73.13 ± 7.37	54.4 to 97.3
		Difference Lidar & tube	−0.75 ± 3.91	−21.0 to 12.7
70	3 (386 matches)	Lidar	69.73 ± 4.63	51 to 89
		Tube	70.62 ± 4.57	52.4 to 86.6
		Difference Lidar & tube	0.89 ± 1.64	−5.0 to 7.0
	4 (385 matches)	Lidar	70.27 ± 4.68	52 to 87
		Tube	71.28 ± 4.83	54.0 to 89.2
		Difference Lidar & tube	1.01 ± 1.57	−4.7 to 10.3

Summary and Conclusions on Accuracy of Equipment

In this effort the accuracy of measuring speed was tested using pneumatic tube counters, a lidar gun, and a control vehicle outfitted with devices to monitor speed and location. Data were collected near Kerrville, Texas, in both 70- and 80-mph posted speed limit sections during two days in June 2009.

The device comparison showed small differences in the speed measurements although not in excess of generally acceptable ranges. For tube counters the rule of thumb based on conversations with vendors appears to be about plus or minus 4 mph or 5 percent. Because lidar is used in enforcement, accuracy is more critical. For lidar guns, the rule of thumb is that measurements are accurate within 1 mph.

The following results were identified when comparing the tube and lidar speed measurements with the TTI control vehicle:

- Control vehicle and tubes:
  - 1.3 percent (0.93 mph) in 70-mph sections (15 pairs) and
  - 3.8 percent (3.05 mph) in 80-mph sections (43 pairs).

- Control vehicle and lidar:
  - 0.9 percent (0.63 mph) in 70-mph sections (15 pairs) and
  - 1.2 percent (0.94 mph) in 80-mph sections (43 pairs).
- Lidar and tubes:
  - 0.5 percent (0.96 mph) in 70-mph sections (15 pairs) and
  - 4.7 percent (3.81 mph) in 80-mph sections (43 pairs).

The following results were identified when comparing the tube to the lidar speed measurements:

- Lidar and tubes:
  - 2.2 percent (1.51 mph) in 70-mph sections (771 pairs) and
  - 3.3 percent (2.42 mph) in 80-mph sections (715 pairs).

In general, the tubes' measurements were lower than the lidar measurements but not in all cases. Therefore, an adjustment factor to shift the data, say in a higher-speed location, would not be appropriate. The differences found in this effort were within the generally accepted range for these types of devices. Some of the differences, however, do exceed a 2-mph practical limit.

FOLLOWING DISTANCES

The traffic counters provide gap values in seconds. This value represents the difference between a previous vehicle's rear axle to the following vehicle's front axle. The value called "gap" is also known as "axle gap" or "following time" within the counter's output. Columns were added to the speed dataset to identify the previous vehicle's type and speed that would be associated with a given gap value.

For the purpose of comparing following distance, the axle gap in seconds was converted to axle spacing (also known as "clearance") in feet using the subject vehicle speed as illustrated in the following equation:

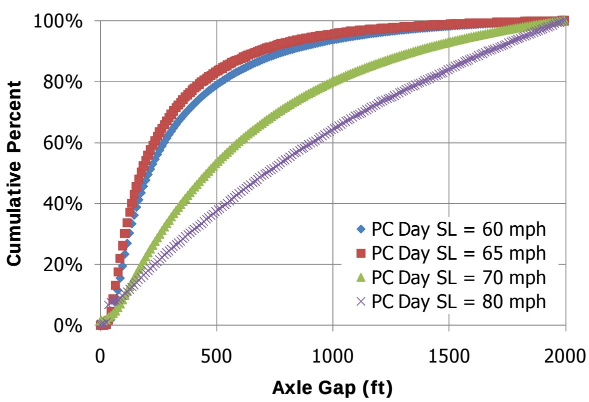
$$\text{Axle Spacing or Axle Clearance (ft)} = \text{Axle Gap (sec)} * \text{Subject Vehicle Speed (mph)} * 5280/3600 \quad (7\text{-}1)$$

The use of this equation assumes a constant subject vehicle speed over the time period between the previous vehicle's last tires striking the counter and the subject vehicle's first set of tires striking the counter. For this reason the evaluation of larger gaps using this method may not be valid, and a maximum axle gap threshold should be considered.

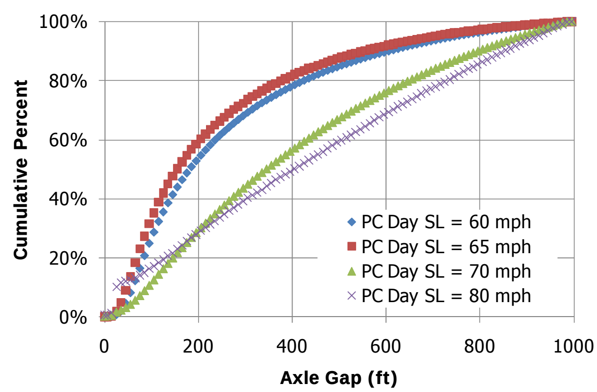
Another reason for considering a maximum axle gap threshold is the study's interest in comparing typical following distances. At a certain axle gap distance the subject vehicle is no longer following the previous vehicle; it just happens to be in the same lane as the vehicle that struck the counter previously. For the purpose of comparison, axle gap distances of 500, 750, 1000, and 2000 ft were evaluated. It was assumed that for these distances the constant speed assumption would still be valid.

As with the previous speed evaluations, data were eliminated if a vehicle speed was less than 45 mph. If either the previous vehicle speed was less than 45 mph or the subject vehicle speed was less than 45 mph, the data for the subject vehicle were removed.

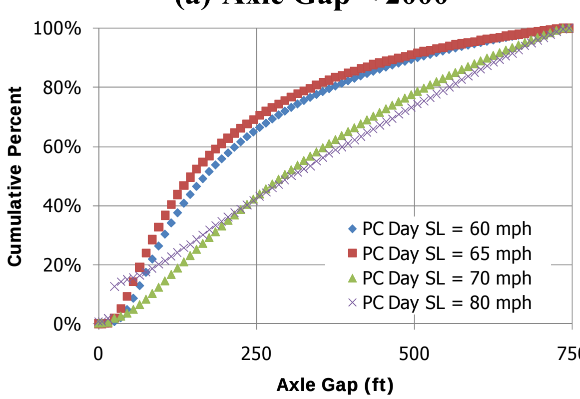
Figure 7-8 contains the cumulative distribution for each daytime posted speed limit (SL) condition when axle gaps are limited to (a) 2000 ft or less, (b) 1000 ft or less, (c) 750 ft or less, and (d) 500 ft or less. Table 7-7 contains the total number of observations for each of the conditions shown in Figure 7-8. In all four graphs we see observable differences in the distributions. The most striking differences occur when comparing the 60- and 65-mph conditions to the 70- and 80-mph conditions. The 60- and 65-mph sites have more gaps at the shorter distances than the 70- and 80-mph sites. For example, when the axle gap is limited to 1000 ft (see Figure 7-8[b]), approximately 50 percent of the gaps were at 160 ft for the 60- or 65-mph sites and about 375 to 400 ft for the 70- and 80-mph sites. Possible reasons for these differences could be the vehicle type composition, traffic volumes at the observation points, or differences in driving behavior.



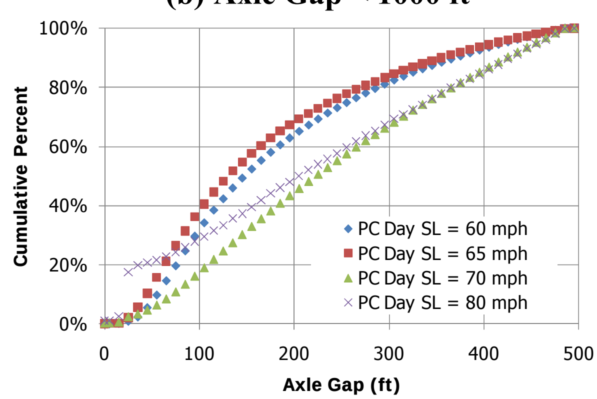
(a) Axle Gap < 2000



(b) Axle Gap < 1000 ft



(c) Axle Gap < 750 ft



(d) Axle Gap < 500 ft

Figure 7-8. Cumulative Distributions by Axle Gap Maximum.

Table 7-7. Number of Observations Contained in Each Condition for Figure 7-8 Graphs.

Daytime Posted Speed Limit	Maximum Axle Gap			
	500 ft	**750 ft**	**1000 ft**	**2000 ft**
60 mph	123,213	138,744	146,623	156,653
65 mph	36,057	39,789	41,458	43,383
70 mph	126,700	165,895	192,517	245,123
80 mph	8,275	11,458	14,218	22,200
Total	294,245	355,886	394,816	542,858

Traffic Volume Affecting Following Distance

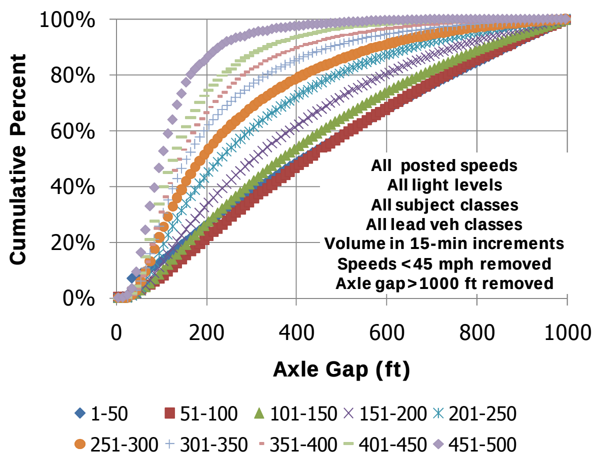
The level of congestion can have a notable influence on following distance. Figure 7-9 shows the distribution for different daytime posted speed limits. The graphs include only vehicles traveling faster than 45 mph with an axle gap less than 1000 ft. Table 7-8 lists the sample size for the different conditions. The graphs in Figure 7-9 clearly show that traffic volumes have an impact on the distribution of following distance. At the lower volumes, gaps are approximately evenly distributed as illustrated by the straight line for the lower volume ranges. As volume increases (moving from right to left within the curves), drivers are accepting shorter and shorter gaps between their vehicle and the vehicle ahead of them.

Table 7-8. Number of Observations Contained in Each Condition for Graphs.

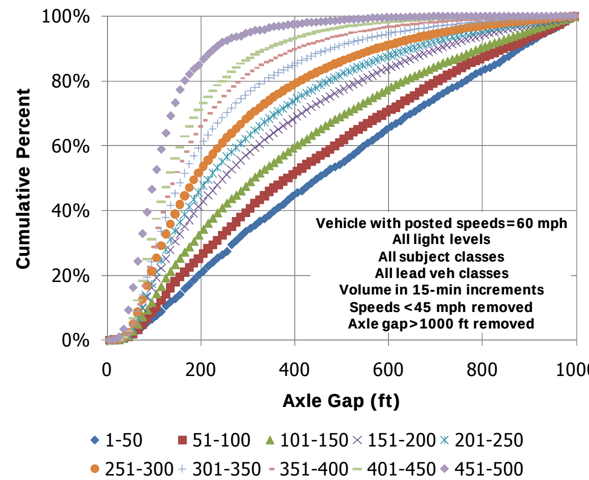
Volume (Vehicles/ 15 Minutes)	Daytime Posted Speed Limit (mph)			
	All 60		**70**	**80**
1-50	25,343	1981	10,606	2284
51-100	51,609	5981	31,497	260
101-150	70,980	9246	55,492	462
151-200	74,860	19,621	52,629	10
201-250	51,317	26,509	19,277	0
251-300	49,811	30,355	5610	0
301-350	34,042	26,025	0	0
351-400	25,863	18,284	0	0
401-450	9526	7156	0	0
451-500	1465	1465	0	0
Total	394,816	146,623	175,111	3016

A comparison of the desired or accepted axle gap for 70-mph to 80-mph highways is limited because of the lower traffic volumes on the 80-mph sites. As shown in Figure 7-9(e), the plot shows a similar distribution for each posted speed limit and volume combination. When the distributions for only the 101 to 150 vehicles/15 minutes (404 to 600 vehicles/hour) range is reviewed (see Figure 7-9[f]), a difference can be observed. Drivers are accepting smaller gaps at the lower speeds. The gaps accepted by approximately half of the drivers within the 404 to 600 vehicles/hour range are:

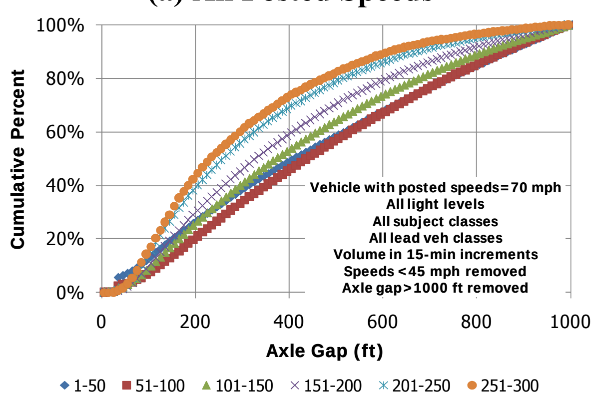
- 315-ft gap for 60-mph posted speed limit,
- 375-ft gap for 70-mph posted speed limit, and
- 425-ft gap for 80-mph posted speed limit.



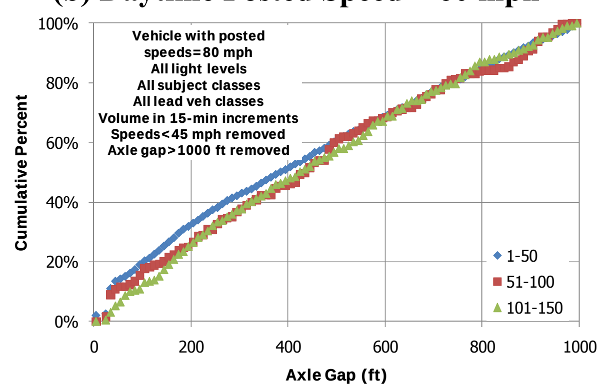
(a) All Posted Speeds



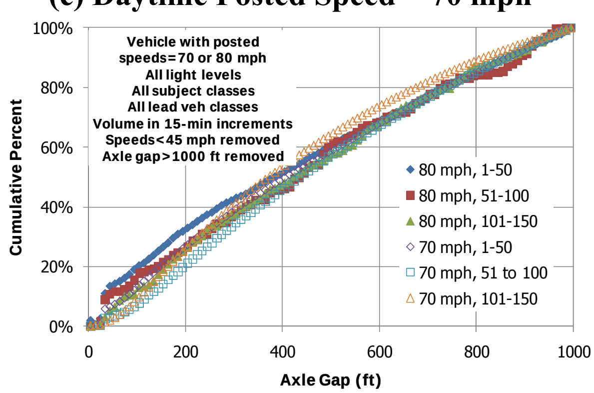
(b) Daytime Posted Speed = 60 mph



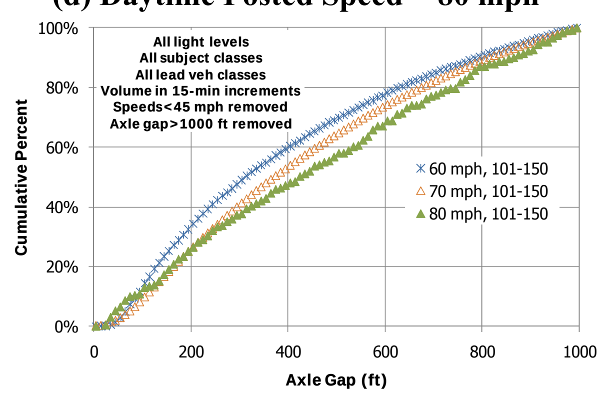
(c) Daytime Posted Speed = 70 mph



(d) Daytime Posted Speed = 80 mph



(e) Three Volume Ranges for Posted Speeds of 70 mph and 80 mph



(f) 101 to 150 Vehicles/15 Minutes Volume Range for Posted Speeds of 60, 70, and 80 mph

Figure 7-9. Distribution of Axle Gap by Volume and Posted Speed Limit.

Lighting Conditions Affecting Following Distance

Lighting condition can also influence the decisions drivers make regarding the axle gap they will accept. The time for sunrise and sunset was identified for each site. Each speed was classified as being:

- dawn (30 minutes before and after sunrise),
- day (30 minutes after sunrise until 30 minutes before sunset),
- dusk (30 minutes before and after sunset), or
- night (30 minutes after sunset until 30 minutes before sunrise).

Figures 7-10 and 7-11 show the average speed measured for day and for night for each site. Figure 7-10 shows the sites located in rural areas without roadway lighting. Figure 7-11 shows the sites with roadway lighting and other urban characteristics.

For the rural sites (see Figure 7-10) the nighttime posted speed was 65 mph, while the daytime posted speeds varied between 70 and 80 mph. For each rural site, the average speed at night was lower than the average speed during the day, which is expected since the speed limit is lower at night than during the day. Larger differences between day and night speeds can be seen for the 80-mph sites (the 80-mph sites are grouped on the right side of Figure 7-10, while the 70-mph sites are grouped on the left side).

For the urban sites (see Figure 7-11), the 70-mph sites, which have a 65-mph nighttime speed limit, also have higher daytime average speeds compared to the average nighttime speeds. For the 65- and 60-mph sites, the nighttime average speed was higher than the daytime average speed, which is the reverse of the trend seen in the rural sites. The congestion present during the daytime may be influencing the daytime average speed.

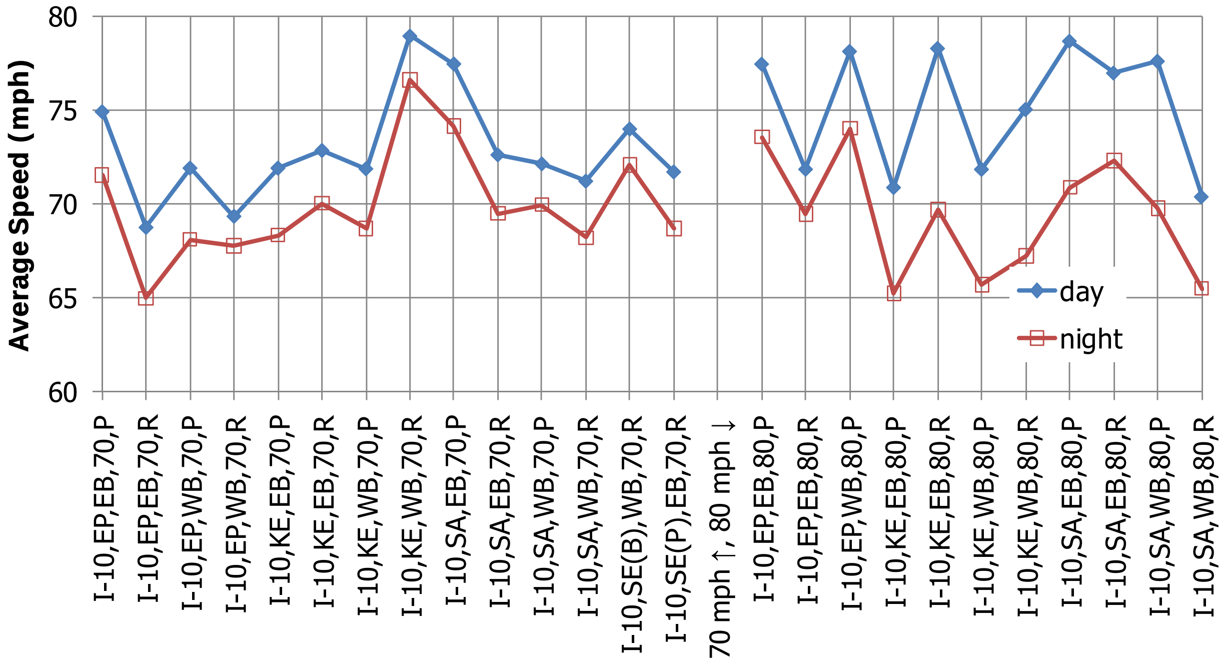
STATISTICAL ANALYSES RESULTS

While the graphs can provide a visual appreciation of the relationship between following distance and speed, a statistical analysis is needed to better understand the relationships contained within the rather large dataset.

Potential Variables Influencing Following Times and Distances

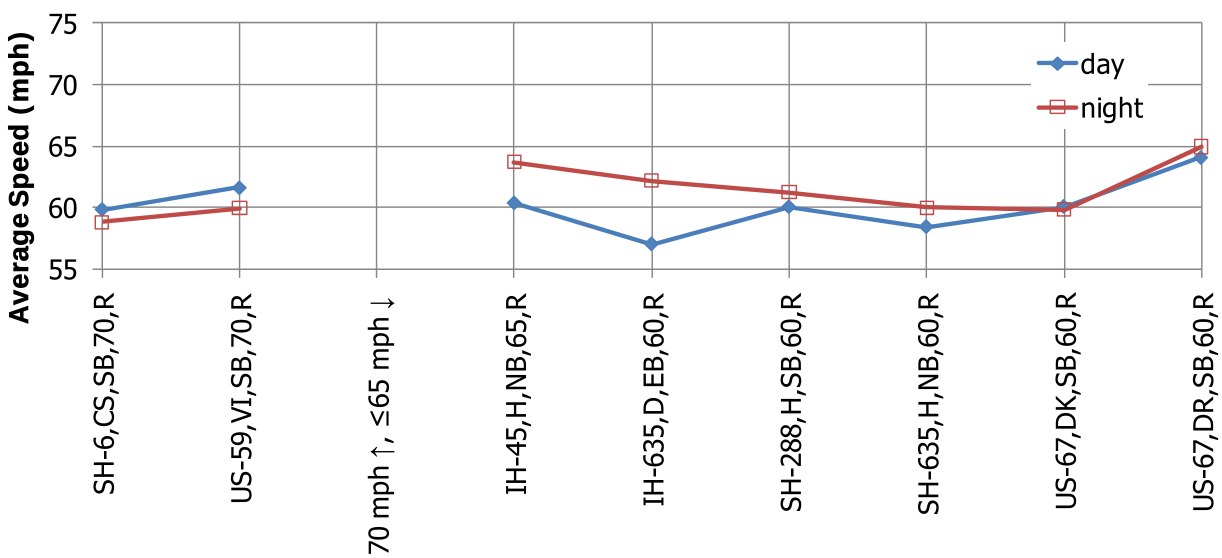
The following variables are available for investigating the influences on following gap:

- daytime passenger posted speed limit (60, 70, or 80 mph),
- previous vehicle speed (mph),
- subject vehicle speed (mph),
- previous vehicle class (passenger car or heavy truck),
- subject vehicle class (passenger car or heavy truck),
- light condition (day or night), and
- 5-minute volume (vehicles/5 minutes).



EP=El Paso, KE=Kerrville, SA=San Antonio, SE(B)=Sealy (B exit), SE(P)= Sealy (P exit)

Figure 7-10. Average Speed by Rural Site.



VI=Victoria, D=Dallas, DK=Dallas (Kiest), DR=Dallas (Red Bird)

Figure 7-11. Average Speed by Urban Site (Note That Congestion May Influence the Average Speed Values).

Initial Evaluations

Initial evaluations demonstrated the need to focus the evaluations on a smaller dataset (so that residual plots could be generated) and the need to use a transformation of the response variable. Because only one site was available for the 65-mph condition, it was removed from the evaluation. Limiting the dataset to only gaps of less than 2000 ft resulted in poor residual plots. Because researchers wanted to understand or explore the relationship between following distance and posted speed limit, they needed to control the effects of traffic volume, especially for congested conditions. Therefore, another approach was needed to manage the dataset.

A dataset was created that only included data when the 5-minute volume count was between 30 and 70 vehicles (360 to 840 vehicles/hour). This volume range was selected because it represented level of service (LOS) A conditions, which should be associated with drivers selecting a gap value that primarily reflects their comfort level rather than being affected by the number of neighboring vehicles. The spacing associated with LOS A is 480 ft and larger.

A total of 67,367 gaps were available for the investigation. The 5-minute volume range by posted speed limit is shown in Table 7-9. The average 5-minute volume was slightly higher for the 80-mph data (42.07) as compared to the 70-mph data (38.26) and lower than the 60-mph data (54.65). The level of truck traffic was notably different for the different speed limits. On the 60-mph roads, which were all urban freeways, the percent truck was 21 percent during the day and 8 percent at night. For the 80-mph freeway, the percent truck was 63 percent during the day and even higher at night—70 percent.

Table 7-10 lists average gap times and average clearance distances along with standard deviation and sample size when the 5-minute volume count was between 30 and 70 vehicles for 60, 70, and 80 mph daytime passenger posted speed limits. As shown in the final data row of Table 7-10, the average gap was 7.5 sec, and the average clearance was 722 ft.

Table 7-9. 5-Minute Volume Range.

Item	60 mph	70 mph	80 mph
Minimum to Maximum Volume	30 to 70	30 to 68	30 to 66
Average Volume ± Standard Deviation	54.65 ± 11.59	38.26 ± 8.14	42.07 ± 8.80
Percent Trucks	Day 21% Night 8%	Day 23% Night 17%	Day 63% Night 70%

Table 7-10. Average and Standard Deviation Axle Gap and Clearance by Daytime Passenger Posted Speed Limit, Light Condition, and Previous Vehicle Class When Volume Count Is between 30 and 70 Vehicles/5 Minutes (360 to 840 Vehicles/Hour).

DPPSL (mph)	Light Con-dition	Previous Vehicle Class	Axle Gap Time (sec)				Axle Clearance Distance (ft)				Count
			Ave.	SD	Min.	Max.	Ave.	SD	Min.	Max.	
60	Day	Large	5.3	5.3	0.3	64.1	487	498	18	6366	5216
		Small	5.2	5.3	0.3	66.5	464	489	21	6660	19,138
		Both	**5.2**	**5.3**	**0.3**	**66.5**	**469**	**491**	**18**	**6660**	**24,354**
	Night	Large	6.3	6.1	0.3	45.2	591	585	20	4958	1101
		Small	6.3	6.4	0.3	71.6	584	586	22	7485	11,910
		Both	**6.3**	**6.4**	**0.3**	**71.6**	**585**	**586**	**20**	**7485**	**13,011**
	Both	**Both**	**5.6**	**5.7**	**0.3**	**71.6**	**509**	**529**	**18**	**7485**	**37,365**
70	Day	Large	8.3	8.1	0.3	73.0	807	807	25	8099	4831
		Small	7.9	7.8	0.3	96.7	756	775	19	11,731	15,898
		Both	**8.0**	**7.9**	**0.3**	**96.7**	**768**	**783**	**19**	**11,731**	**20,729**
	Night	Large	5.9	6.3	0.4	35.4	210	550	30	3390	100
		Small	8.7	9.1	0.4	88.1	773	524	33	7638	534
		Both	**8.3**	**8.8**	**0.4**	**88.1**	**732**	**793**	**30**	**7638**	**634**
	Both	**Both**	**8.0**	**7.9**	**0.3**	**96.7**	**767**	**783**	**19**	**11,731**	**21,363**
80	Day	Large	14.4	15.7	0.3	359.3	1493	1710	29	44,582	3917
		Small	15.0	15.9	0.3	124.6	1647	1766	29	14,623	2254
		Both	**14.6**	**15.8**	**0.3**	**359.3**	**1549**	**1732**	**29**	**44,582**	**6171**
	Night	Large	15.1	17.3	0.3	161.9	1520	1720	25	14,149	1730
		Small	14.1	17.4	0.3	147.3	1453	1825	25	14,038	738
		Both	**14.8**	**17.3**	**0.3**	**161.9**	**1500**	**1752**	**25**	**14,149**	**2468**
	Both	**Both**	**14.7**	**16.3**	**0.3**	**359.3**	**1535**	**1738**	**25**	**44,582**	**8639**
All			**7.5**	**9.0**	**0.3**	**359.3**	**722**	**921**	**18**	**44,582**	**67,367**

DPPSL = daytime passenger posted speed limit
Ave. = average
SD = standard deviation
Min. = minimum
Max. = maximum

Statistical Analysis

When the response variable—either axle gap time or axle clearance distance—was used in its original form, the residual plot did not look randomly scattered and, in addition, had several outliers. Therefore, a log transformation was applied. Models were created using only the main effects, the main effects with all possible two-way interactions, and only those main effects and two-way interactions that were statistically significant (unless the insignificant main effect was included within one of the two-way interactions, in which case it was included in the model). Tables 7-11 and 7-12 list the results from the evaluation that included only the main effects and the significant two-way interactions for axle gap. Tables 7-13 and 7-14 list the results from the evaluations for axle clearance.

Table 7-11. Main and Two-Way Interaction Effects for Axle Gap, Part 1 of 2.

Response Log (Axle Gap[sec])

Summary of Fit

RSquare	0.12905
RSquare Adj	0.128765
Root Mean Square Error	0.982015
Mean of Response	1.496132
Observations (or Sum Wgts)	67367

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	9622.748	437.398	453.5653
Error	67344	64943.470	0.964	**Prob > F**
C. Total	67366	74566.218		0.0000*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	28516	30163.895	1.05779	1.1809
Pure Error	38828	34779.575	0.89573	**Prob > F**
Total Error	67344	64943.470		<0.0001*
				Max RSq
				0.5336

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	1.5583436	0.057785	26.97	<0.0001*
DPPSL (mph) (60)	−0.082041	0.012304	−6.67	<0.0001*
DPPSL (mph) (70)	−0.070597	0.018327	−3.85	0.0001*
Subject speed (mph)	0.0143472	0.000745	19.25	<0.0001*
Previous Vehicle Class (Large)	−0.021538	0.006045	−3.56	0.0004*
Subject Vehicle Class (Large)	0.1737733	0.006193	28.06	<0.0001*
5-Minute Volume Vehicles/5 Minutes	−0.019466	0.000618	−31.52	<0.0001*
Light Condition (day)	−0.003423	0.008239	−0.42	0.6778
DPPSL (mph) (60) * (Subject Speed [mph] − 63.5436)	−0.012991	0.001029	−12.62	<0.0001*
DPPSL (mph) (70) * (Subject Speed [mph] − 63.5436)	0.003222	0.00098	3.29	0.0010*
DPPSL (mph) (60) * Previous Vehicle Class (Large)	0.016383	0.008891	1.84	0.0654
DPPSL (mph) (70) * Previous Vehicle Class (Large)	0.0282435	0.008437	3.35	0.0008*
DPPSL (mph) (60) * Subject Vehicle Class (Large)	−0.129366	0.007758	−16.68	<0.0001*
DPPSL (mph) (70) * Subject Vehicle Class (Large)	−0.096472	0.007572	−12.74	<0.0001*
DPPSL (mph) (60) * (5-Minute Volume Vehicles/5 Minutes − 47.8368)	0.0035773	0.000661	5.41	<0.0001*
DPPSL (mph) (70) * (5-Minute Volume Vehicles/5 Minutes − 47.8368)	0.0019493	0.000817	2.39	0.0171*
DPPSL (mph) (60) * Light Condition (Day)	−0.02744	0.009623	−2.85	0.0044*
DPPSL (mph) (70) * Light Condition (Day)	0.0150128	0.01444	1.04	0.2985
(Subject Speed [mph] − 63.5436) * Subject Vehicle Class (Large)	−0.010124	0.000651	−15.55	<0.0001*
(Subject Speed [mph] − 63.5436) * (5-Minute Volume Vehicles/ 5 Minutes − 47.8368)	0.0003879	5.682e-5	6.83	<0.0001*
Previous Vehicle Class (Large) * Subject Vehicle Class (Large)	0.011084	0.005391	2.06	0.0398*
Previous Vehicle Class (Large) * (5-Minute Volume Vehicles/ 5 Minutes − 47.8368)	0.0018848	0.000518	3.64	0.0003*
(5-Minute Volume Vehicles/5 Minutes − 47.8368) * Light Condition (Day)	0.0016799	0.000442	3.80	0.0001*

Table 7-12. Main and Two-Way Interaction Effects for Axle Gap, Part 2 of 2.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
DPPSL (mph)	2	2	112.57483	58.3680	<0.0001*
Subject Speed (mph)	1	1	357.26983	370.4757	<0.0001*
Previous Vehicle Class	1	1	12.24162	12.6941	0.0004*
Subject Vehicle Class	1	1	759.17881	787.2406	<0.0001*
5-Minute Volume (Vehicles/5 Minutes)	1	1	958.00048	993.4114	<0.0001*
Light Condition	1	1	0.16643	0.1726	0.6778
DPPSL (mph) * Subject Speed (mph)	2	2	153.66175	79.6708	<0.0001*
DPPSL (mph) * Previous Vehicle Class	2	2	21.88059	11.3447	<0.0001*
DPPSL (mph) * Subject Vehicle Class	2	2	425.66265	220.6983	<0.0001*
DPPSL (mph) * 5-Minute Volume Vehicles/5 Minutes	2	2	35.68295	18.5010	<0.0001*
DPPSL (mph) * Light Condition	2	2	9.28480	4.8140	0.0081*
Subject Speed (mph) * Subject Vehicle Class	1	1	233.13333	241.7507	<0.0001*
Subject Speed (mph) * 5-Minute Volume Vehicles/5 Minutes	1	1	44.93489	46.5958	<0.0001*
Previous Vehicle Class * Subject Vehicle Class	1	1	4.07582	4.2265	0.0398*
Previous Vehicle Class * 5-Minute Volume Vehicles/5 Minutes	1	1	12.78694	13.2596	0.0003*
5-Minute Volume Vehicles/5 Minutes * Light Condition	1	1	13.95367	14.4694	0.0001*

Table 7-13. Main and Two-Way Interaction Effects for Axle Spacing, Part 1 of 2.

Response Log (Axle Gap [ft])

Summary of Fit

RSquare	0.180576
RSquare Adj	0.180296
Root Mean Square Error	0.982095
Mean of Response	6.023452
Observations (or Sum Wgts)	67367

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	23	14313.628	622.332	645.2301
Error	67343	64953.078	0.965	**Prob > F**
C. Total	67366	79266.706		0.0000*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	28515	30172.759	1.05814	1.1813
Pure Error	38828	34780.319	0.89575	**Prob > F**
Total Error	67343	64953.078		<0.0001*
				Max RSq
				0.5612

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	5.1868316	0.065711	78.93	0.0000*
DPPSL (mph) (60)	−0.084698	0.01231	−6.88	<0.0001*
DPPSL (mph) (70)	−0.079216	0.018523	−4.28	<0.0001*
Subject Speed (mph)	0.0284996	0.000913	31.22	<0.0001*
Previous Vehicle Class (Large)	−0.021797	0.006046	−3.61	0.0003*
Subject Vehicle Class (Large)	0.1739429	0.0062	28.06	<0.0001*
5-Minute Volume Vehicles/5 Minutes	−0.019396	0.000618	−31.36	<0.0001*
Light Condition (Day)	−0.004218	0.008244	−0.51	0.6089
DPPSL (mph) (60) * (Subject Speed (mph) − 63.5436)	−0.011602	0.001072	−10.82	<0.0001*
DPPSL (mph) (70) * (Subject Speed (mph) − 63.5436)	0.0031608	0.001059	2.99	0.0028*
DPPSL (mph) (60) * Previous Vehicle Class (Large)	0.0157106	0.008897	1.77	0.0774
DPPSL (mph) (70) * Previous Vehicle Class (Large)	0.0286213	0.00844	3.39	0.0007*
DPPSL (mph) (60) * Subject Vehicle Class (Large)	−0.130114	0.007784	−16.72	<0.0001*
DPPSL (mph) (70) * Subject Vehicle Class (Large)	−0.096639	0.007576	−12.76	<0.0001*
DPPSL (mph) (60) * (5-Minute Volume Vehicles/5 Minutes − 47.8368)	0.0035953	0.000662	5.43	<0.0001*
DPPSL (mph) (70) * (5-Minute Volume Vehicles/5 Minutes − 47.8368)	0.0019616	0.000819	2.39	0.0166*
DPPSL (mph) (60) * Light Condition (Day)	−0.025371	0.009696	−2.62	0.0089*
DPPSL (mph) (70) * Light Condition (Day)	0.0213065	0.014818	1.44	0.1505
(Subject Speed [mph] − 63.5436) * Subject Vehicle Class (Large)	−0.010162	0.000653	−15.56	<0.0001*
(Subject Speed [mph] − 63.5436) * (5-Minute Volume Vehicles/5 Minutes - 47.8368)	0.0003877	5.836e-5	6.64	<0.0001*
(Subject Speed [mph] - 63.5436) * Light Condition (day)	0.0015466	0.000772	2.00	0.0451*
Previous Vehicle Class (Large) * Subject Vehicle Class (Large)	0.0111782	0.005392	2.07	0.0382*
Previous Vehicle Class (Large) * (5-Minute Volume Vehicles/5 minutes − 47.8368)	0.0019034	0.000518	3.68	0.0002*
(5-Minute Volume Vehicles/5 Minutes − 47.8368) * Light Condition (Day)	0.0016991	0.000442	3.84	0.0001*

Table 7-14. Main and Two-Way Interaction Effects for Axle Spacing, Part 2 of 2.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
DPPSL (mph)	2	2	125.55133	65.0855	<0.0001*
Subject Speed (mph)	1	1	939.85547	974.4371	<0.0001*
Previous Vehicle Class	1	1	12.53555	12.9968	0.0003*
Subject Vehicle Class	1	1	759.27420	787.2114	<0.0001*
5-Minute Volume Vehicles/5 Minutes	1	1	948.79233	983.7027	<0.0001*
Light Condition	1	1	0.25246	0.2618	0.6089
DPPSL (mph) * Subject Speed (mph)	2	2	113.49962	58.8379	<0.0001*
DPPSL (mph) * Previous Vehicle Class	2	2	21.76140	11.2810	<0.0001*
DPPSL (mph) * Subject Vehicle Class	2	2	426.42105	221.0555	<0.0001*
DPPSL (mph) * 5-Minute Volume Vehicles/5 Minutes	2	2	35.97925	18.6515	<0.0001*
DPPSL (mph) * Light Condition	2	2	6.67430	3.4599	0.0314*
Subject Speed (mph) * Subject Vehicle Class	1	1	233.58925	242.1841	<0.0001*
Subject Speed (mph) * 5-Minute Volume Vehicles/ 5 Minutes	1	1	42.56132	44.1273	<0.0001*
Subject Speed (mph) * Light Condition	1	1	3.87428	4.0168	0.0451*
Previous Vehicle Class * Subject Vehicle Class	1	1	4.14538	4.2979	0.0382*
Previous Vehicle Class * 5-Minute Volume Vehicles/ 5 Minutes	1	1	13.03292	13.5125	0.0002*
5-Minute Volume Vehicles/5 Minutes * Light Condition	1	1	14.25677	14.7813	0.0001*

Significant two-way interaction effects are:

- daytime passenger posted speed limit with speed of subject vehicle,
- daytime passenger posted speed limit with previous vehicle class,
- daytime passenger posted speed limit with subject vehicle class,
- daytime passenger posted speed limit with 5-minute volume,
- daytime passenger posted speed limit with light condition,
- subject speed with subject vehicle class,
- subject speed with 5-minute volume,
- subject speed with light condition (only significant for axle clearance, not axle gap),
- previous vehicle class with subject vehicle class,
- previous vehicle class with 5-minute volume, and
- 5-minute volume with light condition.

Light condition (day or night) was not a significant main effect variable; however, it was retained in the model because of its presence in several statistically significant two-way interaction effects.

Least squares (LS) means are predicted values from the specified model across the levels of a categorical effect where the other model factors are controlled by being set to neutral values. The neutral values are the sample means (possibly weighted) for parameters with interval values and the average coefficient over the levels for unrelated nominal effects.

The evaluation found a statistically significant difference between light conditions and posted speed limit. The two-way interaction plot (see Table 7-15) illustrates how similar the spacing is during the daytime and the nighttime for each posted speed limit value (note almost horizontal lines in the graphs). Only the 60-mph sites show a potential difference between day and night. The Tukey Honestly Significant Difference (HSD) test reveals that the 80-mph spacing is different from the spacing on the 60- and 70-mph roads, with the day and night axle gap and clearance values being similar. The clearance distances (or gap times) have overlap within the 60- and 70-mph posted speed limit conditions, with 60-mph daytime conditions having the smallest gaps and clearances. Reviewing the data with consideration of practical differences results in the observation that axle gap distance is about 400 ft for 70-mph roads (regardless of light conditions) and 60-mph roads (during nighttime). The clearance during the daytime for 60 mph had a shorter spacing of 386 ft. The 80-mph roads had clearance distances of approximately 510 ft, again regardless of light condition. The time gap was approximately 4.3 sec at 60 and 70 mph, while it was a longer 5.4 sec for the 80-mph speed limit. Stated in another manner, drivers leave a greater clearance between vehicles on the 80-mph freeway as compared to the 60- or 70-mph freeways.

Table 7-15. DPPSL and Light Condition Two-Way Interaction Effects.

Effects Details, Axle Gap (sec)

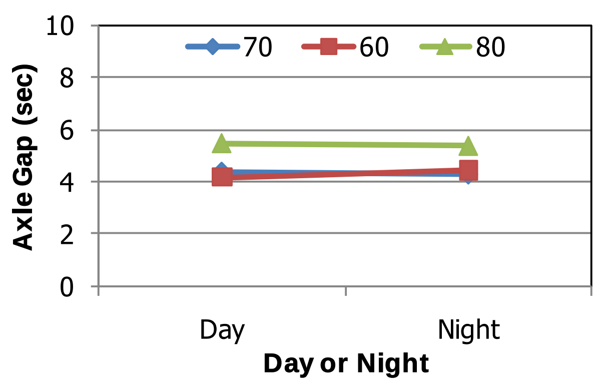
DPPSL (mph) * Light Condition

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, day	4.1616169	0.01000955
60, night	4.4265874	0.01201342
70, day	4.3920670	0.01409762
70, night	4.2914281	0.04359782
80, day	5.4764114	0.02129318
80, night	5.3786671	0.02546589

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050

Level				Least Sq. Mean
80, day	A			5.4764114
80, night	A			5.3786671
60, night		B		4.4265874
70, day		B		4.3920670
70, night		B	C	4.2914281
60, day			C	4.1616169

Levels not connected by same letter are significantly different.

Effects Details, Axle Spacing (ft)

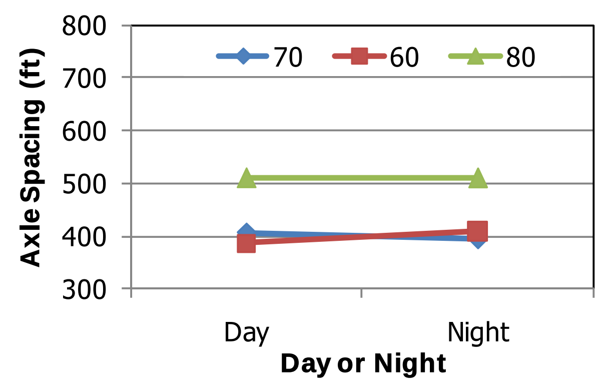
DPPSL (mph) * Light Condition

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, day	385.93985	0.01002108
60, night	409.46819	0.01208740
70, day	406.60435	0.01410465
70, night	392.94250	0.04408024
80, day	509.65203	0.02153686
80, night	509.80842	0.02625133

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050

Level				Least Sq. Mean
80, night	A			509.80842
80, day	A			509.65203
60, night		B		409.46819
70, day		B		406.60435
70, night		B	C	392.94250
60, day			C	385.93985

Levels not connected by same letter are significantly different.

The axle clearance or gaps associated with the previous vehicle class and the subject vehicle class also vary depending upon the posted speed limit (see Table 7-16). The clearance or gaps are similar when following either a car or a truck on a 60- or 70-mph freeway. The clearance is about 400 ft, and the gap is about 4.3 sec. The axle spacing and gap are statistically different on 80-mph freeways as compared to 60- and 70-mph freeways. There is also a difference between following a small vehicle (about 545 ft) as compared to following a large vehicle (about 477 ft) on the 80-mph freeway. Drivers are driving closer to the larger vehicles on the 80-mph freeways both in terms of gap time (5.8 sec compared to 5.1 sec) and clearance (477 ft as compared to 545 ft).

Table 7-16. DPPSL and Previous Vehicle Class Two-Way Interaction Effects.

Effects Details, Axle Gap (sec)

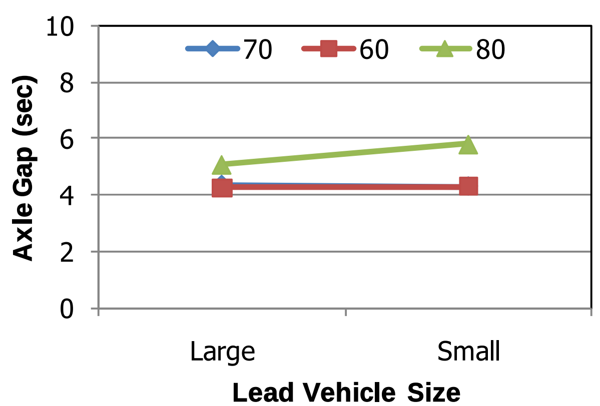
DPPSL (mph) * Previous Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, Large	4.2699878	0.01523183
60, Small	4.3142421	0.00863519
70, Large	4.3706639	0.02959265
70, Small	4.3124432	0.02406364
80, Large	5.0798436	0.02250074
80, Small	5.7985632	0.02547875

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050

Level				Least Sq. Mean
80, Small	A			5.7985632
80, Large		B		5.0798436
70, Large			C	4.3706639
60, Small			C	4.3142421
70, Small			C	4.3124432
60, Large			C	4.2699878

Levels not connected by same letter are significantly different.

Effects Details, Axle Spacing (ft)

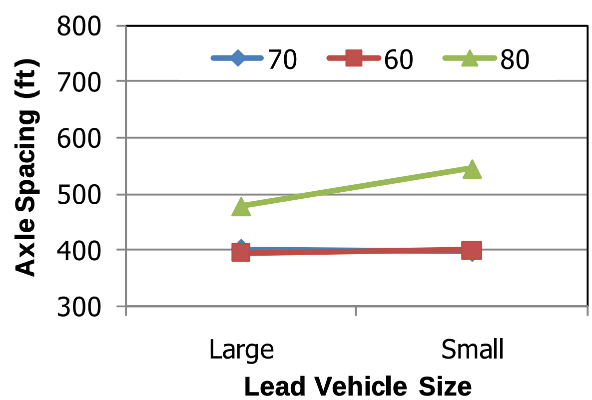
DPPSL (mph) * Previous Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, Large	395.11790	0.01525578
60, Small	399.95681	0.00863595
70, Large	402.45227	0.02978020
70, Small	396.99646	0.02432915
80, Large	477.11280	0.02256239
80, Small	544.57751	0.02552517

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050 Q = 2.84979

Level				Least Sq. Mean
80, Small	A			544.57751
80, Large		B		477.11280
70, Large			C	402.45227
60, Small			C	399.95681
70, Small			C	396.99646
60, Large			C	395.11790

Levels not connected by same letter are significantly different.

The subject vehicle class also has a significant effect on axle gap or clearance (see Table 7-17). Heavy trucks on the 80-mph freeways leave a noticeably longer spacing to the previous vehicle (761 ft) when compared to the spacing on the other freeways (432 ft or 415 ft for 70- and 60-mph freeways, respectively). Smaller vehicles use shorter spacing, between 341 and 380 ft to the previous vehicle.

Table 7-17. DPPSL and Subject Vehicle Class Two-Way Interaction Effects.

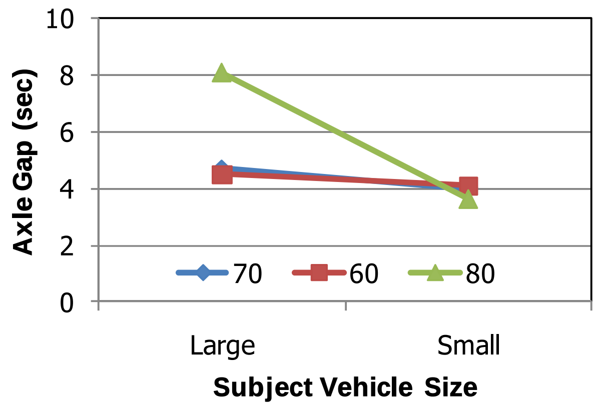
DPPSL (mph) * Subject Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, Large	4.4869523	0.01422258
60, Small	4.1056289	0.00895117
70, Large	4.6903681	0.02815052
70, Small	4.0184991	0.02434498
80, Large	8.0934629	0.02042480
80, Small	3.6394550	0.02875567

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050

Level					Least Sq. Mean
80, Large	A				8.0934629
70, Large		B			4.6903681
60, Large		B			4.4869523
60, Small			C		4.1056289
70, Small			C	D	4.0184991
80, Small				D	3.6394550

Levels not connected by same letter are significantly different.

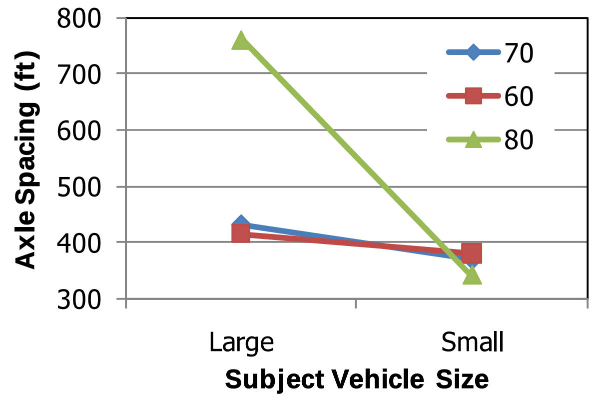
DPPSL (mph) * Subject Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
60, Large	415.34058	0.01424625
60, Small	380.48315	0.00895212
70, Large	431.84020	0.02835704
70, Small	369.97975	0.02459578
80, Large	760.95792	0.02060281
80, Small	341.44450	0.02876163

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.

α = 0.050

Level					Least Sq. Mean
80, Large	A				760.95792
70, Large		B			431.84020
60, Large		B			415.34058
60, Small			C		380.48315
70, Small			C	D	369.97975
80, Small				D	341.44450

Levels not connected by same letter are significantly different.

Table 7-18 shows the results when comparing the class of the subject vehicle and the class of the previous vehicles. Drivers in small vehicles select similar spacing as drivers in heavy trucks to heavy trucks. Drivers leave about 510 to 520 ft (or 5.5 to 5.6 sec) to heavy trucks. Drivers following small vehicles use shorter clearance (351 to 376 ft) and shorter gaps (3.8 to 4.0 sec), with truck drivers associated with the statistically significant smaller values (i.e., 351 ft and 3.8 sec).

Table 7-18. Previous and Subject Vehicle Class Two-Way Interaction Effects.

Effects Details, Axle Gap (sec)

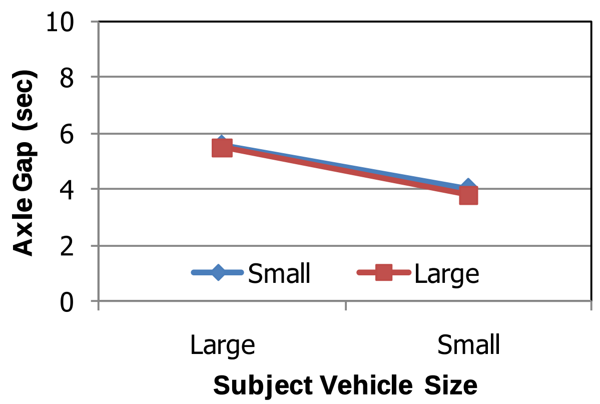
Previous Vehicle Class * Subject Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
Large, Large	5.4855982	0.01537250
Large, Small	3.7901721	0.01624298
Small, Large	5.6015022	0.01527902
Small, Small	4.0457063	0.01293201

* Std. errors are on transformed Y's.

LS Means Plot



LS Means Differences Tukey HSD

Differences are on transformed Y's.
α = 0.050

Level				Least Sq. Mean
Small, Large	A			5.6015022
Large, Large	A			5.4855982
Small, Small		B		4.0457063
Large, Small			C	3.7901721

Levels not connected by same letter are significantly different.

Effects Details, Axle Spacing (ft)

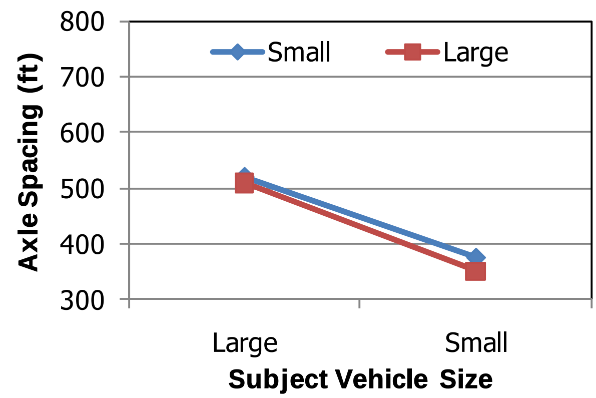
Previous Vehicle Class * Subject Vehicle Class

Least Squares Means Table

Level	Least Sq. Mean	Std. Error
Large, Large	509.42992	0.01538407
Large, Small	351.79553	0.01628199
Small, Large	520.36443	0.01528666
Small, Small	375.77858	0.01296842

* Std. errors are on transformed Y's.

LS Means Plot



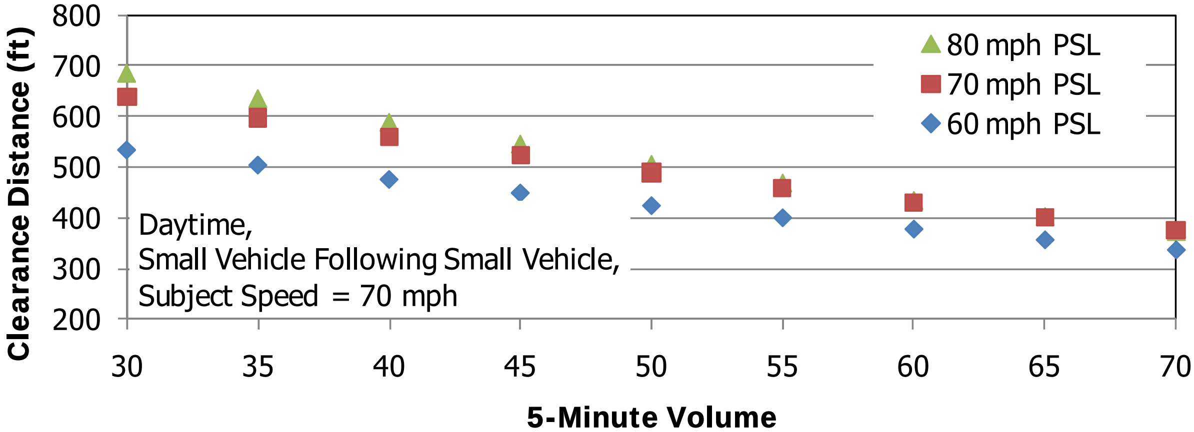
LS Means Differences Tukey HSD

Differences are on transformed Y's.
α = 0.050

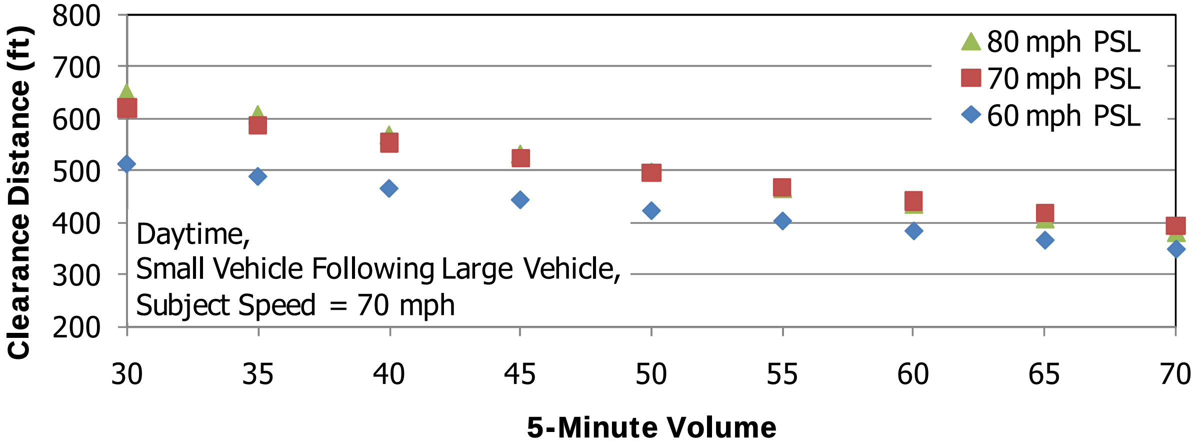
Level				Least Sq. Mean
Small, Large	A			520.36443
Large, Large	A			509.42992
Small, Small		B		375.77858
Large, Small			C	351.79553

Levels not connected by same letter are significantly different.

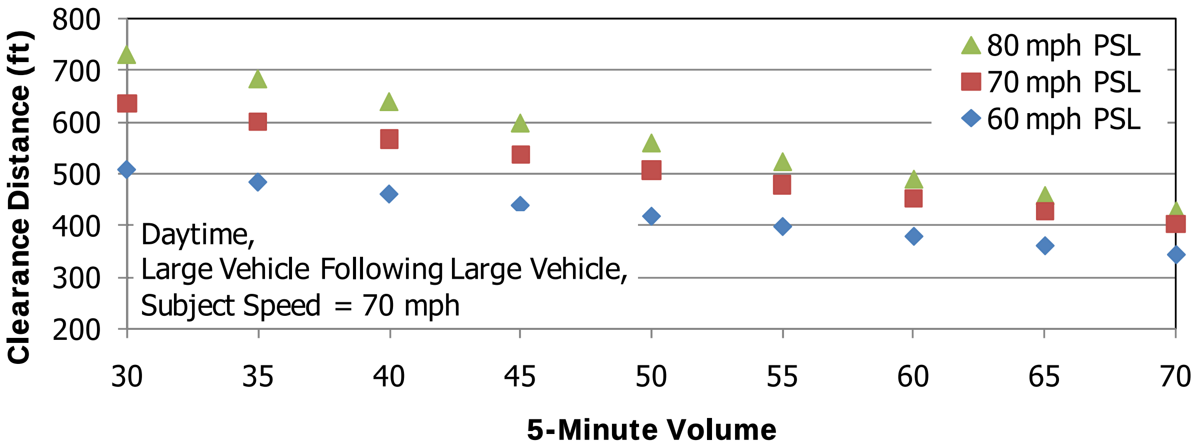
How subject vehicle speed and volume affect the axle clearance or gap is more difficult to illustrate since these parameters are continuous. A plot of the results using a set of assumptions can illustrate the impact of volume; however, such a plot only represents the assumed values for the other variables. Because of the large number of two-way interactions in the model, the slope of the lines can change depending upon the assumptions. The impact of volume is easier to illustrate than the impact of the subject operating speed. Overall, an increase in volume results in a decrease in clearance distance, generally in the range of 4 to 9 percent. Figure 7-12 illustrates clearance distance for a small vehicle traveling at 70 mph during the daytime following a small vehicle (Figure 7-12[a]) and following a large vehicle (Figure 7-12[b]). Figure 7-12(c) shows the clearance distance for a large vehicle following a large vehicle.



(a) Small Vehicle Following Small Vehicle



(b) Small Vehicle Following Large Vehicle



(c) Large Vehicle Following Large Vehicle

Figure 7-12. Illustration of Predicted Clearance Distance by 5-Minute Volume.

The operating speed of a vehicle has a large influence on the axle clearance distance or time gap. Higher operating speeds are associated with longer axle clearance distances. The influence of the subject vehicle speed is greater at higher volumes, with higher volumes associated with shorter clearance distances. The influence of the subject vehicle speed is slightly different for each of the posted speed limits, with 60-mph posted speed limit being the most sensitive. The interaction between subject speed and subject vehicle class, light condition, and 5-minute volumes also adds to a more complex relationship between operating speed and axle clearance distance or axle gap time.

CONCLUSIONS

The objectives for this chapter were to explore differences in following distances (measured using traffic counters) due to posted speed limit, subject or previous vehicle size, volume (5 minutes), subject speed, and lighting conditions. Speed data from numerous freeway sites were obtained as part of this project or from previous TxDOT projects.

Average speed was determined for each posted speed limit and by light condition and vehicle class. These speeds generated concerns for the accuracy of the data. The 60- and 70-mph sites had average daytime passenger car speeds that were within 1 mph of the posted speed limit—a trend seen in other studies on arterials. The 80-mph sites had an average speed of only 75 mph—a 5-mph difference from the posted speed limit. Therefore, investigations into the accuracy of the measuring device used to collect the speed data were conducted. Devices in the test were pneumatic tube counters, a lidar gun, and a control vehicle. Data were collected near Kerrville, Texas, in both 70- and 80-mph posted speed limit sections during two days in June 2009.

The device comparison showed small differences in the speed measurements although not in excess of generally acceptable ranges. For tube counters the rule of thumb is plus or minus 4 mph or 5 percent. Because lidar is used in enforcement, accuracy is more critical. For lidar guns, the rule of thumb is within 1 mph. In general, the tubes' speed measurements were lower than the lidar measurements but not in all cases. Therefore, an adjustment factor to shift the data would not be appropriate. Although the differences in speed were within the generally accepted range for these types of devices, some of the differences, however, do exceed a 2-mph practical value. The following results were identified when comparing the tube and lidar speed measurements with the TTI control vehicle:

- Control vehicle and tubes:
  - 1.3 percent (0.93 mph) in 70-mph sections (15 pairs) and
  - 3.8 percent (3.05 mph) in 80-mph sections (43 pairs).
- Control vehicle and lidar:
  - 0.9 percent (0.63 mph) in 70-mph sections (15 pairs) and
  - 1.2 percent (0.94 mph) in 80-mph sections (43 pairs).

The following criteria were used to generate a speed dataset for use in the evaluation to determine what influences following distance:

- subject or previous vehicle speed is greater than 45 mph (minimum speed limit for a freeway);

- daytime passenger posted speed limit was 60, 70, or 80 mph; and
- speed occurred when the 5-minute volume count was between 30 and 70 vehicles (360 to 840 vehicles/hour).

The volume restriction was selected to represent a minimal level of traffic so that drivers did have other vehicles to consider when selecting their following distance but not so large that volume would be the dominate factor of influence. The volume level represented level of service A conditions.

The analyses showed that the following factors were significant: posted speed limit, subject vehicle size, previous vehicle size, subject speed, and 5-minute volume. Several two-way interactions were also significant. Following are some of the overall findings from the evaluation:

- Axle clearance distance or gap time was larger for the 80-mph freeway sites for the lower volumes included in the dataset. The predicted mean clearance in 60- and 70-mph posted speed limit segments was around 400 ft. In the 80-mph posted speed limit segments, it was around 510 ft. The gap was approximately 4.3 sec in 60- and 70-mph segments, while it was a longer 5.4 sec for the 80-mph segments.
- Drivers of heavy trucks leave longer clearance or gaps as compared to drivers of cars. When the subject vehicle was a heavy truck, the clearance to the previous vehicle was between 415 and 761 ft, and the gap was 4.4 to 8.1 sec. It was only a 341 to 380 ft clearance (3.6- to 4.1-sec gap) when the subject vehicle was a passenger car.
- The axle distance and time are influenced by the lead vehicle type on 80-mph segments. Drivers follow more closely to large vehicles on 80-mph segments; however, the distance was still greater than the distances observed for the lower-speed facilities. Spacing to a large vehicle (heavy truck) was 477 ft, while spacing to a small vehicle was 555 ft on 80-mph segments. The gaps were 5.1 sec to a large vehicle and 5.8 sec to a small vehicle. For 60- and 70-mph segments, the clearance or gap to the previous vehicle was similar (about 400 ft or 4.3 sec) regardless of the previous vehicle type.
- The operating speed of a vehicle has a large effect on the axle clearance distance and time gap. Higher operating speeds are associated with longer axle clearance distances, with the influence of the subject vehicle speed being greater at higher volumes.
- The axle clearance distance and time gap decreased about 6 percent for each 10 vehicles per 5-minute volume increase.
- With respect to clearance distance or gap time, light conditions only had a significant effect for the 60-mph segments. During the nighttime, clearance was 409 ft, while during the day, it was 386 ft.

CHAPTER 8

GAPS AT PASSING STUDY

INTRODUCTION

An important factor in high-speed driving is the perception of the speed of a lead vehicle that is looming into the view of a driver because it is traveling slowly or is stopped. On high-speed roadways, there is greater likelihood of a faster-moving vehicle overtaking a slower-moving vehicle. Are the decisions made by a passing driver similar regardless of the speed of the lead vehicle or the speed of the passing vehicle? If not, what driver or roadway characteristics influence the passing behavior, especially if the characteristics can be managed by TxDOT?

To answer these questions, this research effort measured the distance or time gap at the point when a driver changes lanes during a passing maneuver. This “passing gap” was measured by having TTI staff record the behavior of a following vehicle during a passing maneuver. For this study passing gap was defined as being the distance between the rear of the lead vehicle and the front bumper of the following vehicle during a pass.

In the open-road study (see Chapter 4), the TTI instrumented vehicle was driven by volunteers from the general public, and passing gaps were measured via the onboard front radar unit. Passing maneuvers for only 12 participants, however, were available. Also the data were limited to 450 ft due to the capability of the radar unit. For the current effort, two instrumented vehicles of different sizes were used as probe vehicles moving in traffic. A video camera was used to record the area behind the instrumented vehicles, and lidar was used to measure distance. This permitted recording of vehicles that decided to initiate the pass at a distance greater than the limit of the previous radar device.

STUDY OBJECTIVES

This study measured passing gaps of vehicles on freeway sections with daytime posted speeds of 70 and 80 mph. If the passing gap distance is found to differ based upon the operating speed of the freeway, differences in driver workload may be the cause. For this reason the following research questions were investigated:

- Is there a difference in passing gap between 70- and 80-mph daytime posted speed limit conditions?
- Do the following variables influence the passing gap:
  - speed of the lead vehicle,
  - speed of the following vehicle,
  - size of the rear of the lead vehicle,
  - type of the following vehicle (e.g., passenger car versus large truck),
  - roadway geometry (tangent, curve to left, or curve to right), or
  - traffic conditions (restricted or not restricted)?

STUDY LOCATIONS

The route included the following parts of I-10 and I-20 in West Texas:

- I-20 between Midland and Roscoe (70-mph section),
- I-20 between west of Odessa and the interchange of I-20 and I-10 (80-mph section), and
- I-10 between Sierra Blanca and Fort Stockton (80-mph section).

The daytime posted speed limit was either 70 mph or 80 mph in the study section. For the 80-mph sections, the truck posted speed limit was 70 mph. For both sections the nighttime posted speed limit is 65 mph; however, no data were collected during dawn, dusk, or nighttime conditions.

LEAD VEHICLES

Data were collected during daylight hours using two different vehicles to assess the effect of lead vehicle size—a large-profile vehicle and a small-profile vehicle. The large-profile vehicle was a Class C RV. A sedan (Dodge Caliber) was the small-profile vehicle. Vehicle dimensions are listed in Table 8-1. A photograph of the rear of each of the study vehicles is shown in Figure 8-1.

Table 8-1. Lead Vehicle Dimensions.

Dimensions Sedan		**RV**
	2009 Dodge Caliber	**C 25 Standard Motor Home**
Length (ft)	14	25
Width (ft)	5.73	8.33
Height (ft)	5.03	12.00
Back of Vehicle Area (ft^2)	28.82	99.96
Percent of Largest Vehicle	29%	100%

(a) Sedan **(b) RV**

Figure 8-1. Rear of Lead Vehicle Profile at 20 ft.

DATA COLLECTION

Data collection consisted of a TTI technician recording the distance to a following vehicle during a passing maneuver. Pilot tests of the data collection approach revealed that the lead vehicle would need to be driven at a speed less than the posted speed limit to ensure that passes would occur. The need to drive at less than the speed limit was especially important when the passenger car speed limit is 80 mph since the heavy-truck speed limit is 70 mph on those sections. The lead vehicle was operated at approximately 20 percent below the passenger car daytime speed limit. In the 70-mph sections the lead vehicle speed was about 56 mph, and in the 80-mph section the lead vehicle speed was typically 64 mph.

The distances to the following vehicle were collected using a lidar gun, which a member of the data collection team aimed out the rear window of the lead vehicle. The lidar gun can measure continuous speeds of and distance to vehicles, with the data being recorded on a laptop computer. Comments regarding the following vehicle can be added to the file storing the data from the lidar gun. A limitation with lidar is that it does not accurately measure speeds below 5 mph. Therefore, if the relative speed between the lead and following vehicles was less than 5 mph, no speed or distance data would be obtained for the following vehicle. So to avoid losing data for vehicles with less than a 5-mph speed difference, the researchers operated the lidar gun only in distance mode, which measured distance between the two vehicles even when relative speed was less than 5 mph. The relative speed and the following vehicle speed were then calculated using the distance and time measurements from the lidar and the known speed of the lead vehicle.

A separate in-vehicle computer housed an onboard data acquisition system (DAS). The software of the DAS merged the different data streams so that the information would be visible at the same time. The DAS synchronized the lead vehicle speed and location GPS data along with video feed from a rearward facing camera positioned in the lead vehicle. Figure 8-2 shows a typical view of the visual for the system. The video was used to classify the vehicle type of the passing vehicle as passenger car or heavy truck. It was also used to determine traffic conditions and roadway geometric characteristics. The data stream from the lidar gun could not be programmed into the system in time for this study; therefore, that data stream had to be manually matched to the DAS data. Both the DAS computer and the laptop for the lidar data had their clocks synchronized each morning before data collection began to facilitate this synchronization. The video files also had the date and time captioned in text on the video frame.

Because the 80-mph sections had lower volumes, fewer passes typically occurred in an hour. Therefore, the study route was designed to spend more data collection time in the 80-mph sections. Also, to have greater opportunity to have higher volumes, and therefore more passing opportunities, data were collected on the weekends. Table 8-2 lists the number of hours of video data collected along with the number of passes per hour recorded during the data collection time periods. All data were collected during daylight hours.

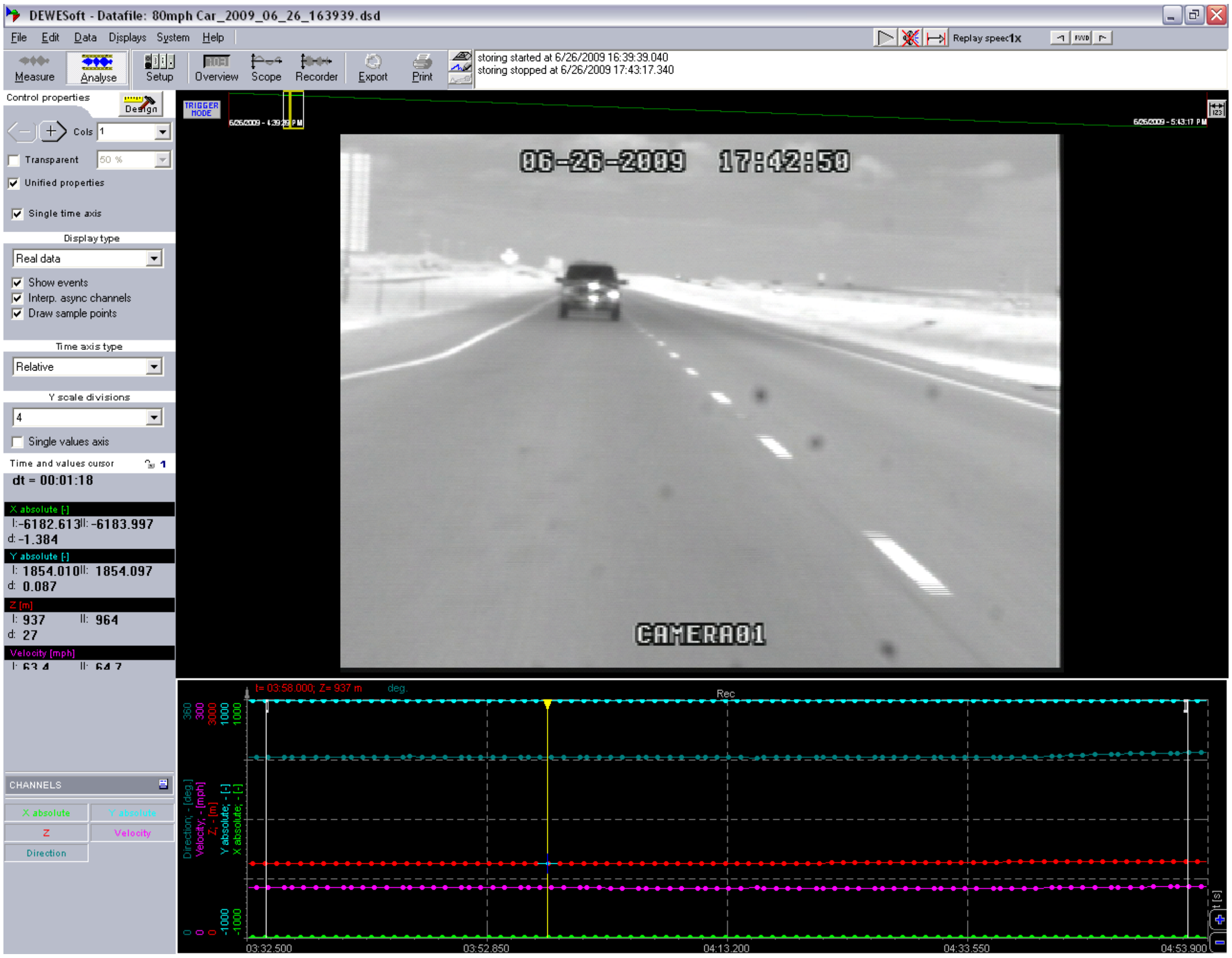


Figure 8-2. Typical View of the Data Recorded by DAS.

Table 8-2. Number of Data Points by Lead Vehicle and Posted Speed Limit.

Data	70 mph		80 mph	
	Sedan RV	Sedan RV		
Dates of Data Collection	6-28-09	7-19-09	6-26-09 6-27-09	7-17-09 7-18-09
Day of Week of Data Collection	Sunday	Sunday	Friday & Saturday	Friday & Saturday
Hours of Video Available	7	5	16	13
Passes (from Video)	358	232	317	211
Passes per Hour	51.1	46.4	19.8	16.2

DATA REDUCTION

Number of Passes

Table 8-2 lists the number of hours of video data available for each lead vehicle type and posted speed limit combination. Each vehicle that was recorded behind the lead vehicle during data collection was counted. A total of 1118 vehicles making passes were videotaped as shown in the final row of Table 8-3. Not all of the passing gaps recorded on video could be used. A few of the passing gaps distances (about 1 percent) were not available because the vehicle changed lanes beyond the typical capability of the measuring device, which was about 700 ft. Distances for approximately another 15 percent of the gaps videotaped were not available because the technician was occupied with recording information about a previous vehicle. Reviewing these passes on the video indicates that they were in the same general range as those vehicles whose distances were available. Approximately 83 percent of the passing gaps videotaped were available for the analyses, for a total of 930 passes (see data row of Table 8-3).

Table 8-3. Number of Passes Observed during Study Period.

Data	70 mph				80 mph			
	Sedan		RV		Sedan		RV	
	Number	%	Number	%	Number	%	Number	%
Passes with distance collected (typically between 50 and 700 ft)	245	69%	211	91%	293	92%	182	86%
Passes within typical distance (e.g., within 50 to 700 ft) but distance measurement missed by technician	108	30%	20	9%	17	5%	25	12%
Passes beyond reading distance (typically >700 ft) where distance was not obtained	5	1%	1	0%	4	1%	4	2%
Passes too close to lead vehicle for measurement (<50 ft)	0	0%	0	0%	3	1%	0	0%
Total passes (by daytime posted speed limit and lead vehicle size)	358	100%	232	100%	317	100%	211	100%
Passes (by daytime posted speed limit)	590				528			
Passes (all conditions)	1118							

Data from Video and Supporting Files

The following data were obtained from watching the video, reviewing the timestamp captions on the video, and searching the dataset produced by the DAS:

- time when the driver-side front tire was centered over the roadway lane line (DWPtime), used with the lidar file to determine the driver wheel passing gap distance (DWPgap);
- time when the passenger-side front tire was centered over the roadway lane line (PWPtime), used with the lidar file to determine the passenger wheel passing gap distance (PWPgap);
- lead vehicle speed;
- following vehicle type (car or heavy truck);
- traffic conditions (restrictions or no restrictions); and
- roadway geometry (curve to left, curve to right, or tangent).

Examples of the views of the video are shown in Figure 8-3(a) for when the driver-side front tire is centered over the roadway lane line and Figure 8-3(b) for when the passenger-side front tire is centered over the roadway lane line. The time from the video when the passing vehicle's tire is centered over the roadway lane line was used to identify the associated lidar distance measurement between the lead vehicle and the following vehicle.

Data from Lidar Files

The timestamp from the video when the following vehicle tire was on the lane line was used to identify the relevant lidar readings. This timestamp was presented to the nearest second. The lidar readings typically had three distance readings for each second. The distances measured within the same second were averaged to provide the gap distance. This value was used as the distance between the lead vehicle and the following vehicle. It was also used to calculate the speed difference between the lead vehicle and the following vehicle.

Following Vehicle Type

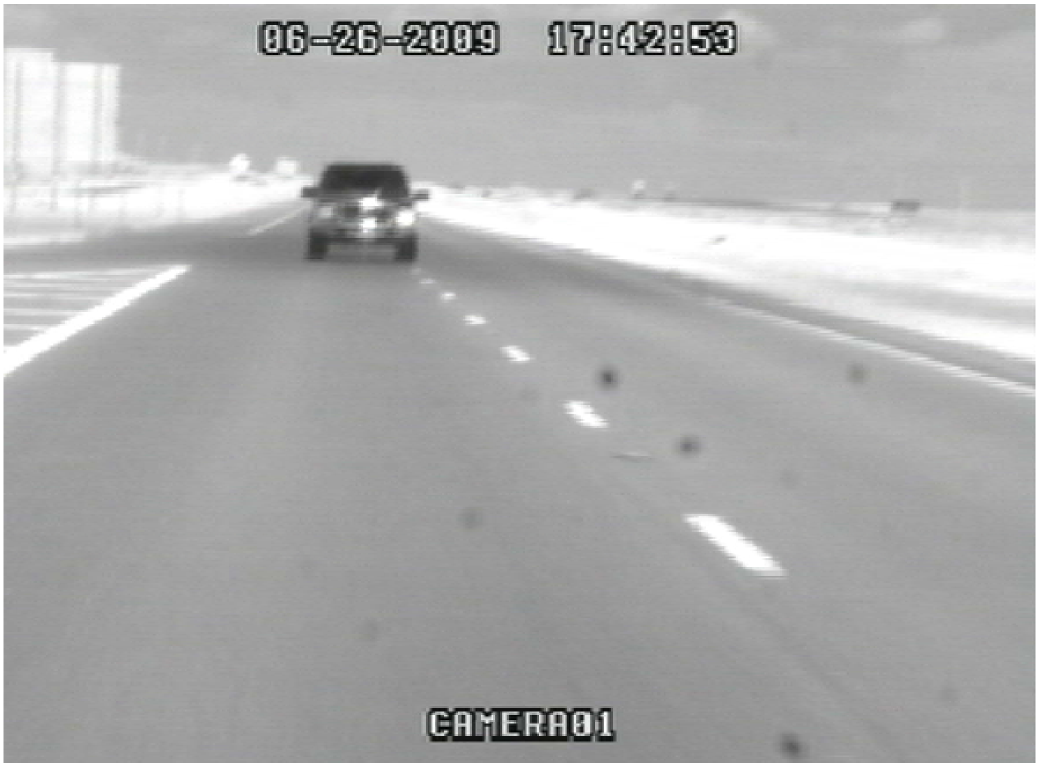
The FHWA classification scheme (see Figure 7-1) was used to classify the vehicle following the lead vehicle as either a heavy truck or a passenger car.

Traffic Conditions

Members of the research team judged whether other vehicles might have affected the decision of when to make a pass. An example of a situation when a traffic restriction was considered to be present is when vehicles are passing both the lead vehicle (i.e., the vehicle with the TTI team) along with the following vehicle (i.e., the vehicle being measured). A situation when no restrictions are present is when there are no other vehicles in either lane within approximately 1000 ft of the lead and following vehicles.

Roadway Geometry

Roadway geometry was based upon the research team member's perception of whether the following vehicle in the video was in a horizontal curve or along a tangent.



(a) Driver-Side Front Tire Centered over the Roadway Lane Line

(b) Passenger-Side Front Tire Centered over the Roadway Lane Line

Figure 8-3. Examples of Video Views.

Speed Difference between Lead and Following Vehicle

The speed of the lead vehicle was available from one of the input data streams to the DAS. The speed difference between the lead vehicle and the following vehicle was determined using the lidar readings. The calculations used the amount of time the following vehicle took to move the vehicle across the lane line during the passing maneuver, along with the distances measured by the lidar gun. The equation used to calculate the speed difference was:

$$SD = \frac{DWPgapL - PWPgapL}{PWPtime - DWPtime} \times \frac{3600\ sec/hour}{5280\ ft/mile} \tag{8-1}$$

Where:

SD	=	speed difference between the lead vehicle and following vehicle (mph),
DWPgapL	=	driver wheel passing gap measured by lidar gun (ft),
PWPgapL	=	passenger wheel passing gap measured by lidar gun (ft),
PWPtime	=	time when the passenger-side front tire is centered over the roadway lane line, and
DWPtime	=	time when the driver-side front tire is centered over the roadway lane line.

Following Vehicle Speed

The following vehicle speed was determined by adding the calculated speed difference from Equation 8-1 (between lead vehicle and following vehicle) to the lead vehicle speed available from the GPS unit.

$$FS = LS + SD \tag{8-2}$$

Where:

FS	=	speed of the following vehicle (mph),
LS	=	speed of the lead vehicle provided by the GPS unit (mph), and
SD	=	speed difference between the lead vehicle and following vehicle (mph).

Passing Gap Distance

To obtain the distance between the rear bumper of the lead vehicle and the front bumper of the following vehicle, the distance between the location of the lidar gun and the rear bumper of the lead vehicle had to be subtracted. The technician was closer to the rear bumper in the RV as compared to in the sedan. When in the sedan, the lidar gun was 3 ft from the rear bumper. It was 1 ft from the rear bumper of the RV.

$$DWPgap = DWPgapL - LtoRB \tag{8-3}$$

Where:

DWPgap	=	driver wheel passing gap (ft),
DWPgapL	=	driver wheel passing gap measured by lidar gun (ft), and
LtoRB	=	lidar gun to rear bumper of lead vehicle measurement (3 ft for the sedan and 1 ft for the RV) (ft).

RESULTS

Potential Variables Influencing Passing Gap Distances

The following variables are available for investigating the influences on passing gap:

- daytime posted speed limit (70 or 80 mph),
- following vehicle speed (mph),
- lead vehicle speed (mph),
- lead vehicle size (sedan or RV),
- following vehicle type (passenger car or heavy truck),
- traffic conditions (restricted or not restricted),
- speed difference between the lead vehicle and following vehicle (mph),
- roadway geometry (tangent, curve to left, or curve to right).

A total of 930 driver-wheel passes were available for the investigation. The minimum driver-wheel passing gap measured was 31 ft, and the maximum in the dataset was 663 ft. Table 8-4 lists by daytime speed limit the driver-wheel passing gap averages and standard deviations.

Table 8-4. Average Driver Wheel Passing Gaps by Daytime Posted Speed Limit.

Condition	70 mph		80 mph	
	Average ± Standard Deviation Passing Gap (ft)	Number of Data Points	Average ± Standard Deviation Passing Gap (ft)	Number of Data Points
All	263.8 ± 112.4	456	255.9 ± 117.9	474
Lead Vehicle Size				
RV	215.5 ± 95.7	211	270.5 ± 116.1	181
Sedan	305.4 ± 109.2	245	246.9 ± 118.3	293
Following Vehicle Type				
Car	266.9 ± 111.7	333	271.4 ± 114.0	390
Heavy Truck	255.4 ± 114.3	123	183.9 ± 109.1	84
Roadway Geometry				
Left Curve	250.3 ± 121.3	37	278.3 ± 121.1	26
Right Curve	245.3 ± 121.2	32	248.4 ± 132.6	30
Tangent	266.6 ± 110.9	387	269.3 ± 114.9	343
Traffic Conditions				
Not Restricted	273.3 ± 103.9	365	263.6 ± 116.1	413
Restricted	225.5 ± 135.5	91	203.8 ± 117.6	61

Figure 8-4 illustrates passing gap to speed data to provide an appreciation of potential relationships. Figure 8-4(a) shows the following vehicle speeds by lead vehicle speed. Recall that the lead vehicle speed was set as 20 percent below the posted speed limit via the vehicle's cruise control. Therefore, the lead vehicle speed was set at approximately 56 mph (for the 70-mph sections) or 64 mph (for the 80-mph sections). The actual speed of the lead vehicle during the passing maneuver was available from the GPS unit and was used to generate this graph. The two groups of data shown illustrate the calculated following vehicle speeds for the two different posted speed limits. The spread of following vehicle speed was similar for both posted speed limit groups—about 50 mph. Typical speeds were centered on the posted speed limit.

Figure 8-4(b) shows the passing gaps (measured when the driver-side wheel of the passing vehicle crossed the lane line) as a function of following vehicle speed. The figure shows a wide dispersion of passing gap distances with a slight trend toward longer gaps at higher speeds. Note, however, that passing gaps of less than 100 ft were recorded for following vehicle speeds of up to 75 mph.

Figure 8-4(c) shows the passing gap as a function of the speed differential between the lead and following vehicle. Again, a wide dispersion in the data is evident with a slight trend toward larger gaps at higher-speed differentials.

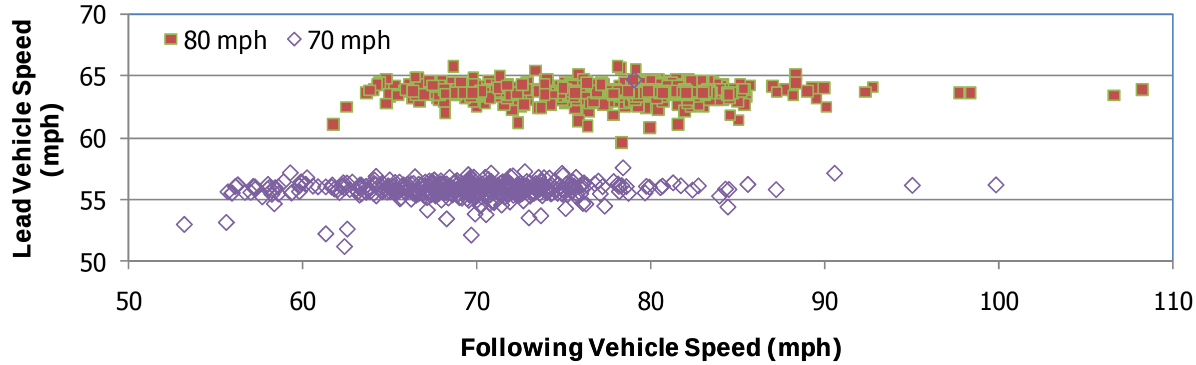
Statistical Analysis

Analyses of the passing gap data began with considering which variables to include in the models. The speed measurements—following speed, lead vehicle speed, and speed difference—were all intercorrelated since following speed and speed difference were calculated based on the measured lead vehicle speed. Therefore at most two of the measurements could be included in the model. Models were tried with either speed difference only or with lead and following vehicle speeds.

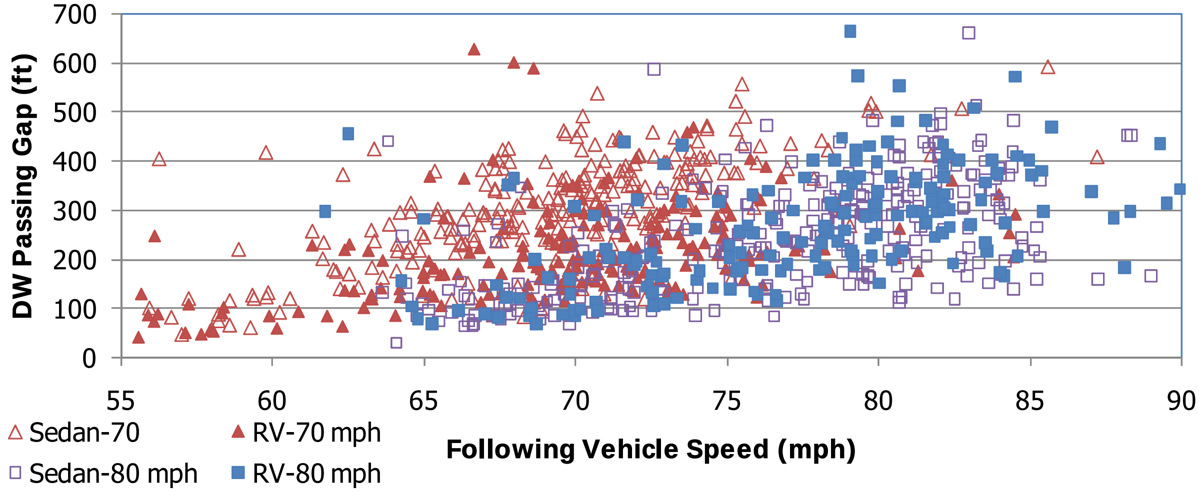
Findings with Lead and Following Vehicle Speeds

Preliminary evaluations using lead and following vehicle speeds indicated the posted speed limit variable was not statistically significant. The evaluations also indicated that relationships between other variables were different depending upon the posted speed; in other words, there were significant two-way interactions between posted speed and other variables. The patterns of passing behavior were different for the two different posted speeds. Therefore, the dataset was split into a 70-mph dataset and an 80-mph dataset. Table 8-5 shows the main-effects-only models for 70 mph. This model would only be used if two-way interaction effects were not significant because the existence of significant two-way interaction effects implies that the effect of one factor (e.g., Lead Vehicle Size) may be different for each level of the other factor (i.e., Traffic Conditions). The analysis revealed, however, that some of two-way interactions were statistically significant (even after the dataset was split by the posted speed). The following paragraphs will discuss the two-way interactions. For the 70-mph data, the following variables were observed to be significant from Table 8-5 assuming that the two-way interaction effects are practically negligible (although they may be statistically significant):

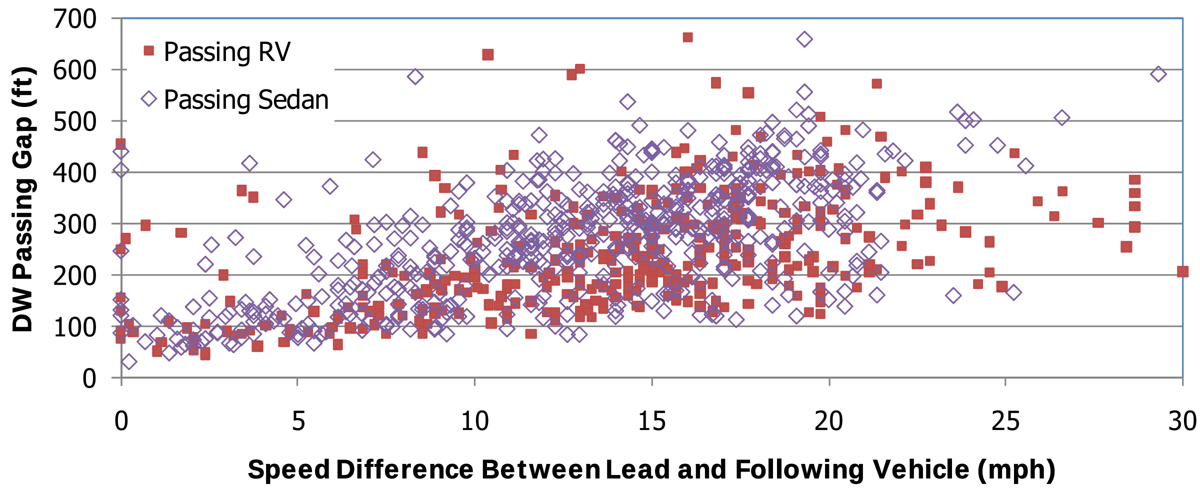
- following vehicle speed,
- lead vehicle speed,
- lead vehicle size (RV or sedan), and
- following vehicle type (car or heavy truck).



(a) Lead Vehicle Speed by Following Vehicle Speed



(b) Driver-Wheel (DW) Passing Gap by Following Vehicle Speed



(c) Driver-Wheel Passing Gap by Speed Difference

Figure 8-4. Plots of Passing Gaps by Vehicle Speed.

Table 8-5. Main-Effects-Only Models for 70-mph Data.

Response DWPgap for 70 mph

Summary of Fit

RSquare	0.407964
RSquare Adj	0.398714
Root Mean Square Error	87.16722
Mean of Response	263.8004
Observations (or Sum Wgts)	456

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	2345625.5	335089	44.1016
Error	448	3403959.4	7598	**Prob > F**
C. Total	455	5749584.8		<0.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Following Vehicle Speed	1	1	1226552.1	161.4283	<0.0001*
Lead Vehicle Speed	1	1	70717.6	9.3072	0.0024*
Lead Vehicle Size	1	1	1094881.6	144.0990	<0.0001*
Following Vehicle Type	1	1	52399.1	6.8963	0.0089*
Roadway Geometry	2	2	21657.0	1.4252	0.2416
Traffic Conditions	1	1	21285.6	2.8014	0.0949

Geometry and traffic conditions were not significant in the 70-mph model. All possible two-way interactions were also considered. Table 8-6 shows the results when significant interactions and main effects are in the model. The following two-way interactions were found to be statistically significant along with the main effects variables:

- following vehicle speed with lead vehicle size,
- following vehicle speed with traffic conditions, and
- lead vehicle size with traffic conditions.

The significant main effect of lead vehicle size means that on a 70-mph road, the findings indicate that drivers will drive closer to a large-profile vehicle (the RV) than to a small-profile vehicle (sedan). Table 8-7 provides the predicted passing gap mean of 224 ft to the RV and 311 ft to the sedan, a difference of 87 ft. The two-way interaction between lead vehicle size and traffic conditions reinforces this finding. Figure 8-5 illustrates these findings. When traffic is present in the neighboring lane (i.e., restricted traffic conditions), drivers have a shorter distance to the RV (214 ft versus 233 ft, closer by a distance of 19 ft). Drivers are a longer distance, however, to the sedan (325 ft versus 297 ft, an increase distance of 28 ft). Because the levels are not connected by the same letters (see Table 8-7), the Tukey HSD analysis indicated that the passing gap distance to the RV is significantly different than the distance to the sedan; however, the gap distances subdivided by the potential effects of traffic were not significantly different (since the levels were connected by the same letters). So even though Figure 8-5(b) shows the lines for non-restricted traffic and restricted traffic crossing, the Tukey HSD test did not find significant differences between the passing gap distances for the different traffic conditions. Given that drivers can modify their gap distance whether another vehicle is or is not located in the neighboring lane, it is logical that drivers are not adjusting their passing gap distance just because of the presence of other traffic. On the other hand, when traffic is restricted the difference in the passing gap distance between Sedan and RV is about 63 ft (297 ft versus 233 ft) while the difference is much larger (about 111 ft, 325 ft versus 214 ft) when traffic is not restricted.

Table 8-6. Model for 70-mph Data with Significant Interactions and Main Effects.

Response DWPgap

Summary of Fit

RSquare	0.446953
RSquare Adj	0.437055
Root Mean Square Error	84.34234
Mean of Response	263.8004
Observations (or Sum Wgts)	456

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	2569792.1	321224	45.1561
Error	447	3179792.8	7114	**Prob > F**
C. Total	455	5749584.8		<0.0001*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	446	3179774.8	7129.54	396.0855
Pure Error	1	18.0	18.00	**Prob > F**
Total Error	447	3179792.8		0.0401*
				Max RSq
				1.0000

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	508.73662	261.8408	1.94	0.0527
Following Vehicle Speed	10.315556	0.791687	13.03	<0.0001*
Lead Vehicle Speed	−17.16895	4.799714	−3.58	0.0004*
Lead Vehicle Size (RV)	−43.4789	5.081799	−8.56	<0.0001*
Following Vehicle Type (Car)	−10.11529	4.65739	−2.17	0.0304*
Traffic Conditions (Not Restricted)	2.1022392	5.383448	0.39	0.6964
(Following Vehicle Speed − 69.5964) * Lead Vehicle Size (RV)	−2.561884	0.697084	−3.68	0.0003*
(Following Vehicle Speed − 69.5964) * Traffic Conditions (Not Restricted)	−2.352683	0.763436	−3.08	0.0022*
Lead Vehicle Size (RV) * Traffic Conditions (Not Restricted)	−12.05865	5.187582	−2.32	0.0205*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Following Vehicle Speed	1	1	1207728.6	169.7767	<0.0001*
Lead Vehicle Speed	1	1	91022.4	12.7955	0.0004*
Lead Vehicle Size	1	1	520731.1	73.2019	<0.0001*
Following Vehicle Type	1	1	33555.4	4.7171	0.0304*
Traffic Conditions	1	1	1084.8	0.1525	0.6964
Following Vehicle Speed * Lead Vehicle Size	1	1	96081.7	13.5067	0.0003*
Following Vehicle Speed * Traffic Conditions	1	1	67557.4	9.4969	0.0022*
Lead Vehicle Size * Traffic Conditions	1	1	38437.8	5.4034	0.0205*

Table 8-7. Model for 70-mph Data Least Squares Mean Tables.

Effect Details

Lead Vehicle Size
Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
RV	223.98658	7.8175942	215.474
Sedan	310.94438	7.4441251	305.420

Following Vehicle
Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
Car	257.35019	6.0650040	266.889
Heavy Truck	277.58077	8.4545079	255.439

Traffic Conditions
Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
Not Restricted	269.56772	4.9845683	273.345
Restricted	265.36324	9.8993699	225.516

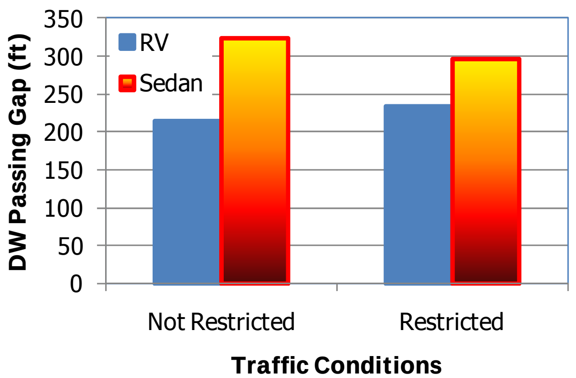
Lead Vehicle Size * Traffic Conditions
Least Squares Means Table

Level	Least Sq. Mean	Std. Error
RV, Not Restricted	214.03017	6.908830
RV, Restricted	233.94299	13.926771
Sedan, Not Restricted	325.10527	6.595450
Sedan, Restricted	296.78350	13.093616

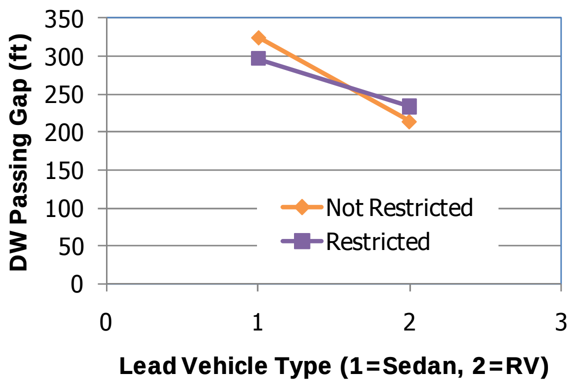
LS Means Differences Tukey HSD

Level			Least Sq. Mean
Sedan, Not Restricted	A		325.10527
Sedan, Restricted	A		296.78350
RV, Restricted		B	233.94299
RV, Not Restricted		B	214.03017

Levels not connected by same letter are significantly different.



(a) Shown as Columns



(b) Shown as X Y Scatter

Figure 8-5. Least Squares Mean Plot for Lead Vehicle Size by Traffic Conditions.

The type of vehicle doing the passing was also significant. When cars are passing the lead vehicle, the predicted passing gap mean was 257 ft. The heavy trucks had a longer passing gap predicted mean of 278 ft (see Table 8-7). This finding indicates that heavy trucks began their passing maneuvers at a greater distance upstream regardless of the type of vehicle that was being passed.

The evaluations of the 80-mph data provided a fairly different result as compared to the 70-mph results. Only two variables were significant when main effects or when all potential two-way interaction terms are considered (see Table 8-8). The significant variables when examining the 80-mph data only are:

- following vehicle speed and
- lead vehicle speed.

Table 8-8. Main-Effects-Only Model for 80-mph Data.

Response DWPgap for 80 mph
Summary of Fit

RSquare	0.386134
RSquare Adj	0.375144
Root Mean Square Error	92.14525
Mean of Response	268.3208
Observations (or Sum Wgts)	399

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	2088272.8	298325	35.1353
Error	391	3319882.1	8491	**Prob > F**
C. Total	398	5408154.9		<0.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Following Vehicle Speed	1	1	1286005.8	151.4597	<0.0001*
Lead Vehicle Speed	1	1	128562.1	15.1414	0.0001*
Lead Vehicle Size	1	1	1072.1	0.1263	0.7225
Following Vehicle	1	1	12247.6	1.4425	0.2305
Roadway Geometry	2	2	42026.0	2.4748	0.0855
Traffic Conditions	1	1	18740.6	2.2072	0.1382

Findings with Speed Difference

Investigations were also conducted using speed difference rather than the lead and following vehicle speeds as predictor variables. The speed difference variable combines these two variables into a single value. The analyses considered all possible two-way interactions along with the main effects. Variables that do not influence the passing gap distance include:

- posted speed limit (70 or 80 mph),
- following vehicle type (car or truck),
- geometry (tangent, left curve, or right curve), and
- traffic influence (restricted or not restricted).

The main effects variables that influence the passing gap include:

- speed difference and
- lead vehicle size (RV or sedan).

As shown in Table 8-9, the following two-way interactions were significant:

- posted speed limit crossed with lead vehicle size and
- speed difference crossed with lead vehicle size.

Because posted speed limit is used in a two-way interaction, it should remain in the model as a main effect. Table 8-9 shows the results of the model that contains the significant interactions and main effects. Table 8-10 lists the least square means results.

A method to gain a better understanding of the relationships revealed by the statistical analysis is to develop an equation using the coefficients for the parameters. The equation to predict the passing gap distance using the model show in Table 8-9 is:

$$P{:}DWPgap = 127.09 + 9.81 \times SD - 21.84 \times ILV - 0.73 \times IPSL - 27.32 \times IPSL \times ILV - 1.89 \times ILV \times (SD - 13.5548) \tag{8-4}$$

Where:

P:DWPgap	=	predicted driver wheel passing gap (ft);
SD	=	speed difference between the lead vehicle and following vehicle (mph);
ILV	=	indicator variable for lead vehicle size, ILV = 1 when lead vehicle size is RV, 0 otherwise; and
IPSL	=	indicator variable for posted speed limit, IPSL = 1 when posted speed limit is 70 mph, 0 otherwise.

The equation demonstrates the importance of the speed difference term. The term with the most potential to change the gap distance is speed difference. The passing gap distance increases by approximately 10 ft for each additional mile-per-hour difference between the lead vehicle and the following vehicle.

The type of the following vehicle (car or heavy truck) was not significant in this analysis. Recall, however, that following vehicle type was significant when evaluating only the 70-mph dataset.

The lead vehicle size is also influential, both as a main effect variable (coefficient of −21.84) and as part of a two-way interaction variable (coefficient of −27.32) with daytime posted speed limit. For example, passing an RV on a 70-mph section reduces the predicted passing gap by 49.89 ft (21.84 + 27.32 + 0.73 ft).

The size of the lead vehicle was a significant variable. Similar to the previous analysis, the findings were that drivers came closer to the larger vehicle (RV) as compared to the sedan. The predicted mean gap distance was 238 ft to the RV and 282 ft to the sedan. Drivers were 44 ft closer to the RV as compared to the sedan. The two-way interaction between posted speed limit and lead vehicle size reveals another interesting finding.

The posted speed limit was not significant as a main effect; however, it was significant when crossed with the lead vehicle size. Figure 8-6 contains a plot that illustrates the relationship. The passing gap to an RV or to a sedan was similar for the vehicles in the 80-mph sections (266 and 255 ft, which the Tukey HSD found to be not significantly different; see Table 8-10). A different relationship was found for the vehicles in the 70-mph sections. Drivers in the 70-mph section drove closer to the RV (predicted mean distance of 210 ft) as compared to the sedan (predicted mean distance of 308 ft).

Another interaction was between speed difference and lead vehicle size. When the lead vehicle was the RV, the regression coefficient indicates that there was a 1.89-ft change in passing gap distance for each 1-mph change in speed difference.

Table 8-9. Model with Significant Interactions and Main Effects Using Speed Difference and Both 70- and 80-mph Data.

Response DWPgap

Summary of Fit

RSquare	0.375966
RSquare Adj	0.372582
Root Mean Square Error	91.08311
Mean of Response	260.2112
Observations (or Sum Wgts)	928

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	4608372	921674	111.0969
Error	922	7649034	8296	**Prob > F**
C. Total	927	12257407		<0.0001*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	793	6613484.0	8339.83	1.0389
Pure Error	129	1035550.3	8027.52	**Prob > F**
Total Error	922	7649034.2		0.4011
				Max RSq
				0.9155

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	127.08777	7.383522	17.21	<0.0001*
Daytime Posted Speed Limit (70 mph)	−0.732899	3.03712	−0.24	0.8094
Speed Difference	9.806964	0.49091	19.98	<0.0001*
Lead Vehicle Size (RV)	−21.84217	3.047806	−7.17	<0.0001*
Daytime Posted Speed Limit (70 mph) * Lead Vehicle Size (RV)	−27.31723	3.03712	−8.99	<0.0001*
(Speed Difference − 13.5548) * Lead Vehicle Size (RV)	−1.888759	0.49091	−3.85	0.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Daytime Posted Speed Limit	1	1	483.1	0.0582	0.8094
Speed Difference	1	1	3310862.0	399.0850	<0.0001*
Lead Vehicle Size	1	1	426081.2	51.3590	<0.0001*
Daytime Posted Speed Limit * Lead Vehicle Size	1	1	671158.5	80.9002	<0.0001*
Speed Difference * Lead Vehicle Size	1	1	122807.5	14.8030	0.0001*

Table 8-10. Least Squares Mean Tables for Model with Speed Difference.

Effect Details

Daytime Posted Speed Limit

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
70 mph	259.28669	4.2852412	263.800
80 mph	260.75249	4.3200872	256.744

Lead Vehicle Size

Least Squares Means Table

Level	Least Sq. Mean	Std. Error	Mean
RV	238.17742	4.6351172	240.860
Sedan	281.86175	3.9588103	274.364

Daytime Posted Speed Limit * Lead Vehicle Size

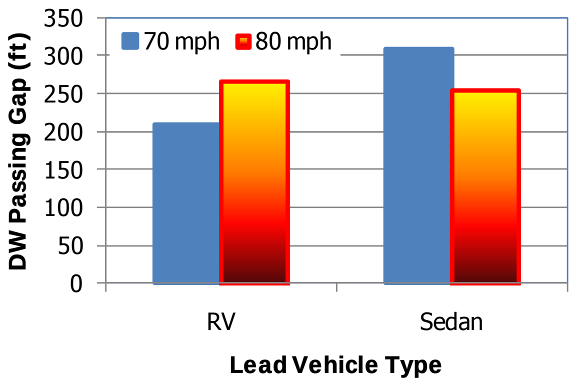
Least Squares Means Table

Level	Least Sq. Mean	Std. Error
70 mph, RV	210.12729	6.2898964
70 mph, Sedan	308.44609	5.8215437
80 mph, RV	266.22755	6.7814290
80 mph, Sedan	255.27742	5.3539549

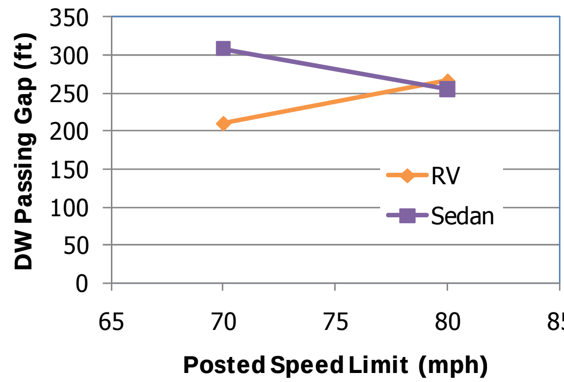
LS Means Differences Tukey HSD

Level				Least Sq. Mean
70 mph, Sedan	A			308.44609
80 mph, RV		B		266.22755
80 mph, Sedan		B		255.27742
70 mph, RV			C	210.12729

Levels not connected by same letter are significantly different.



(a) Shown as Columns



(b) Shown as X Y Scatter

Figure 8-6. Least Squares Mean Plot for Posted Speed Limit by Lead Vehicle Size.

COMPARISON WITH LITERATURE

Table 2-1 in the literature review chapter (Chapter 2) lists the distance and time separation at which drivers can first judge closing rate with a vehicle directly ahead. The values were determined based upon previous research that examined the threshold for detecting speed discrepancies in car-following studies. Table 8-11 shows the distance and time separations when typical speed differences found in this research between the lead vehicle and passing vehicle are used. The distances in Table 8-11 represent the value when drivers realize (based on previous research findings) that they need to take an action. These distances, which range from 143 to 319 ft for the recreational vehicle and 118 to 265 ft for the sedan, are generally much less than the typical passing gap distances found in this study (260 ft). In general, drivers are initiating their passing maneuvers before coming so close to the preceding vehicle that they "reach the point when they realize how rapidly the spacing is closing and that some response is required in the next few seconds" (*37*).

The evaluations of the data from this passing gap study included identifying regression coefficients that can be used to predict the passing gap for various conditions. When the coefficients presented in Table 8-9 are used, a slightly different finding is determined for specific posted speed limit and vehicle type combinations as compared to the general findings that drivers are passing before reaching the point when a response is required. Drivers passing the sedan did so within the suggested distance separation; however, when drivers were passing the RV on the 70-mph section, they were within the distance suggested by Olson and Farber as needing a response. For this study, drivers on the 70-mph sections but not the 80-mph sections came closer to the RV than the sedan. Why this was found for only the 70-mph section but not the 80-mph section needs additional research.

Table 8-11. Distance and Time Separation at Which Drivers Can First Judge Closing Rate with a Vehicle Directly Ahead Using Equation from Olson and Farber (*37*) and the Vehicle Size and Speed Differences Found in This Research.

Target Vehicle Width (ft)	Speed Difference (mph)	Using Equation from Olson and Farber		Typical Passing Gap Using Regression from This Study (ft)	
		Time Separation (sec)	Distance Separation (ft)	70-mph Posted Speed Limit Sections	80-mph Posted Speed Limit Sections
8.33 (recreational vehicle)	5	19.5	143	142	170
	10	13.8	202	182	210
	15	11.2	247	222	250
	20	9.7	285	261	289
	25	8.7	319	301	329
5.73 (passenger car, daytime)	5	16.1	118	175	176
	10	11.4	167	224	225
	15	9.3	205	273	274
	20	8.1	237	322	323
	25	7.2	265	372	372

CONCLUSIONS

Based on the results from the various analyses of the passing gap data, researchers drew the following conclusions:

- A total of 1118 passes were video recorded during 41 hours of data collection. The majority of the passes were within 663 ft of the lead vehicle. The average gap for all measurements was 260 ft.
- Evaluations that used speed difference between the lead vehicle and the following vehicle found posted speed limit to be significant as part of a two-way interaction term that consisted of posted speed limit and lead vehicle size. Figure 8-6 illustrates the findings. At 80 mph, the passing gap to either a sedan or an RV was similar. For 70 mph the passing gap was significantly different; drivers were closer to the RV than the sedan when passing. The passing gap in the 70-mph segments was less than the passing gap in the 80-mph segments for the RV, while the reverse was found for the sedan.
- The statistical analyses indicated that drivers passed more closely to the larger-profile vehicle (RV) than the smaller-profile vehicle (sedan). For example, one of the analyses found that drivers were 282 ft from the sedan and only 238 ft from the RV when they passed, a difference of 56 ft. A comparison between the passing gap values predicted using the regression coefficients shown in Table 8-9 and the values determined using the Olson and Farber equation showed that only drivers on the 70-mph section passing an RV were within the distance suggested by Olson and Farber as needing a response. The reasons drivers were passing the RV so closely within the 70-mph section needs additional investigation.
- The passing gap increases by 10 ft for each mile-per-hour increase in the speed difference between the lead vehicle and the following vehicle. Stated in another manner, the faster a driver approaches a vehicle, the greater the passing gap distance.
- The type of following vehicle (car or heavy truck) was not significant in the analysis that examined speed difference. It was significant in the evaluation of the 70-mph dataset. Drivers of cars passed approximately 20 ft closer to the lead vehicle as compared to drivers of heavy trucks.

LIMITATIONS OF CURRENT STUDY

A limitation of this study was the approach used to measure the speed of the following vehicle during the passing maneuver. The speed in this study was estimated from the distance measurements made over time rather than measured directly by available equipment. Needed is a method of measuring speed of another vehicle from within a moving vehicle at distances of up to 700 ft.

The current study only measured passing gap when both vehicles were moving at relatively high speeds. A more serious safety threat is posed on high-speed roads when a lead vehicle is moving very slowly or is stopped. The stopping sight distance for 70 mph is 730 ft and for 80 mph is 910 ft. Clearly, these values are well beyond the average 260 ft gap observed for passing in this study.

CHAPTER 9

SUMMARY AND CONCLUSIONS

SUMMARY OF RESEARCH

Geometric design guidance has traditionally existed for speeds ranging from 15 to 80 mph. Potential values for geometric elements designed for 85- to 100-mph speeds were included in a recently completed research project conducted for TxDOT (*1*). Because of limited previous research, the project relied upon extrapolating from previous research and using engineering judgment to develop the criteria. One area that was identified as needing additional research was driver workload at higher speeds. The previous, most comprehensive research was based on data collected at initial speeds of 55 mph (*3*).

It is possible that driver workload could increase with higher speed, leading to a slowed reaction time to hazards. In other words, at high speeds it may be that the driver is paying so much attention to the basic task of vehicle control that he or she may be slower in responding to hazards. On the other hand, driver vigilance may increase with higher speed, leading to equal or faster reaction times.

In addition to reaction, the driver must be able to see the object, both in the daytime and in the nighttime. The type of object that the driver is likely to encounter is typically another vehicle, which may be traveling at a slower speed. On high-speed roads, there is a concern with overtaking a slower-moving vehicle. The rate of change of an image, in terms of visual angle, is very slow at far distances. The ability to perceive that a target is looming in your visual field, i.e., approaching a slow-moving vehicle from behind, depends on your ability to detect that the image size is changing, which does not occur until you are fairly close, so that at high speeds you will not have much time to decelerate or maneuver out of the way.

Research Objectives

The goal of this project is to gain a better understanding of driver performance at high speeds. Specific objectives include:

- determine perception-reaction time for high-speed situations,
- identify differences in driver workload at high speeds, and
- determine how operating speed affects following distance (or gap) at passing.

Studies

This project used the following research approaches:

- driving simulator studies,
- instrumented vehicle research that permits accurate recording of brake activations and steering control in both open-road and closed-course environments,
- instrumented vehicle and lidar to measure gap at passing, and
- traffic counter data that provide speed and gap time between vehicles.

The specific efforts included the following studies:

- **Literature Review—**This overview of literature examined driver capabilities especially at higher speeds.
- **Closed-Course Pilot Study—**This study consisted of observing and recording the activities and actions of a series of drivers on a closed-course track while following a lead vehicle going either 60 or 85 mph.
- **Open-Road Pilot Study—**Drivers' actions were recorded while the participants drove between Odessa and Pecos, Texas, within a 70-mph section and an 80-mph section.
- **Simulator Pilot Study—**The simulator was used with 12 participants to determine driver reactions to a looming vehicle (both passenger car and large truck). The pilot study also generated directions for how to conduct the Phase II simulator study.
- **Simulator Phase II Study—**The Phase II simulator study included 50 participants. It focused on collecting driver brake reaction to a vehicle looming in the driver's view. Conditions varied included initial speed, lead vehicle type, lead vehicle deceleration rate, and workload level.
- **Following Distance Study—**Traffic counters were used to gather speed and axle gap data on freeways with 60-, 70-, and 80-mph posted speed limits.
- **Gaps at Passing Study—**Gaps during passing maneuvers were measured during daylight on freeway sections with posted speed limits of 70 and 80 mph.

Literature Review

Drivers' quality of performance is based upon their arousal, or stimulation, level. Driver performance level has been found to be poor at both low and high levels of arousal. For example, driving performance on a flat, straight road with no other traffic may actually suffer because the driver is under-stimulated by the environment and may become fatigued or mentally distracted easily. Likewise, in a highly stimulating driving environment of a winding road in poor weather, performance may suffer because of overload. The primary method for measuring driver stress, fatigue, engagement, and arousal level is through the construct of mental workload. Mental workload refers to the amount of effort and limited processing capacity required to interpret all of the stimuli provided to perform necessary driving and non-driving tasks.

The positive guidance model of driver performance proposes that drivers are first and foremost going to attend to matters of vehicle control, specifically headway and speed. Guidance tasks related to lane keeping and turning are the next most important. And lastly, tasks related to navigation receive cognitive effort. In a high-workload situation, drivers shed some of that workload by temporarily ignoring the higher cognitive tasks of navigation and guidance to concentrate solely on vehicle control. The current study investigated whether driving at high speed may result in similar mental and visual effort where higher mental functions, such as detecting objects in peripheral vision, were affected. This idea that drivers manage their workload by temporarily suspending attention toward certain tasks is referred to as "load shedding." In the current study, researchers hypothesized that driving at 85 mph was a higher-workload situation than driving at 60 mph.

Perception-reaction time is the time for a driver to detect a danger, recognize it as a danger, decide on a course of action, and begin to take action. These judgments are a function of perceived following distance, perceived time to contact, and driver experience. Fambro and his colleagues as part of a major National Cooperative Highway Research Program (NCHRP) study on stopping sight distance confirmed that a 2.5-sec perception-reaction time used in AASHTO stopping sight distance encompasses most of the driving population (*3*). The SSD studies were conducted at speeds of 55 mph or lower.

As drivers experience higher speeds for longer periods of time, their estimation of lower speeds becomes less accurate (*21*). Schmidt and Tiffin found that as vehicles traveled at 70 mph for 20, 40, or 60 minutes, the drivers' estimation of when the vehicle was traveling at 40 mph became less accurate. Drivers having traveled 70 mph for 20 minutes estimated a 44.5-mph speed as being 40 mph. Drivers having traveling 70 mph for 40 minutes estimated a 50.5-mph speed as 40 mph. Drivers having traveled 70 mph for 60 minutes estimated a 53.4-mph speed as 40 mph (*21*). Speed adaptation is important to consider in the design of higher-speed facilities because the effects at those speeds are unknown.

Visual demand is a portion of driver workload related to the amount of time a driver must fixate on an object or objects. Some roadway geometries require a longer fixation and thus increase visual demand.

When driving on a multilane highway, drivers frequently encounter other vehicles and will need to make judgments on when to change lanes or slow to avoid contacting another vehicle. Time-to-contact estimation is the subjective prediction of the amount of time it will take for two objects to meet if their velocities and paths remain constant. It has been shown that drivers underestimate their time to contact and that as closing speeds increase, these estimates become more accurate (*16, 36*).

When the path of another vehicle is directly in line of the observer (i.e., directly in front of the observer), the primary closing rate cue—and perhaps the sole cue—is rate of change of image size. That is, if the object seems to be getting larger fast, that indicates a high closing speed. The relationship between viewing distance and image size is not a linear relationship (as illustrated in Figure 2-3). The fact that it is a nonlinear relationship adds to the difficulty drivers have in making accurate estimates of closing speed. Overtaking a stationary or slow-moving 8-ft-wide tractor-trailer with a closing speed of 45 mph, a driver will first realize how rapidly the spacing is closing and that some response is required in the next few seconds at approximately 420 ft. When approaching a passenger car with the same conditions, the distance is 363 ft. The distance becomes smaller as closing speed increases or the perceived size of the lead vehicle decreases. Also, the time available to make and implement a decision becomes smaller.

Closed-Course and Open-Road Pilot Study

Overview

Researchers conducted a field study of driver workload and visual capabilities at speeds of 60 mph and above. The study consisted of observing and recording the activities and actions of a series of drivers on a specified open road and a closed-course track. Each participant drove both an open-road portion and a closed-course portion.

Fourteen volunteer participants participated in the study. The sample of participants was comprised of four females and ten males recruited from the Odessa, Texas, area. Participants ranged in age from 20 to 71, with a mean age of 49 (two participants did not report their age), and the average number of years with a driver's license was 33.

The instrumented vehicle used as the participant car for this experiment was a 2006 Toyota Highlander. The vehicle was equipped with the following for this study:

- a global positioning system to provide the speed of the vehicle;
- a radar mounted on the front of the vehicle that can collect headway data and speed for forward targets;
- a system that tracks the lateral lane position of the instrumented vehicle as well as the lane width and lateral velocity;
- potentiometers that collect data on the position of the brake pedal, gas pedal, and steering wheel; and
- video cameras that record the participant, forward scene, and gas/brake pedal behavior.

The participants drove a predefined route on public roads to or from a test track. A research team member was responsible for shuttling the participants in the direction they were not responsible for driving. The intention was to have an equal number of participants driving on public roads in both directions; however, due to cancellations, ten participants drove to the test track, and four drove the return trip.

The vast majority of the open-road portion of the experiment took place on I-20 between Odessa and Pecos. This segment of I-20 is predominantly straight with some gentle curves and some minor elevation changes.

The test track is a 9-mile circle track with three lanes. The experiment was conducted in the center lane to provide the most room for evasive maneuvers, to avoid grass that had grown through the pavement joints, and to avoid debris that may have collected at the edges of the driving surface. The center lane had nominal superelevation with a constant degree of curve; the track exhibited slight elevation changes throughout the complete circuit. The center area, or infield, of the circle track contained a basic West Texas landscape (level ground with small brush) with a few small buildings, but generally provided very few landmarks for the participants to use to give them information about where they were on the circle. While at the test track, each participant drove six laps while data were being collected. Much of the data were associated with specific events and driving tasks that occurred at predetermined locations on the track.

Findings

For the pilot field study, several observations were made on driver behavior as discussed in Chapter 3 for the closed-course portion of the study and Chapter 4 for the open-road portion of the study. With only having 14 participants to evaluate, the key value of the pilot field study was in identifying potential Phase II studies.

The closed-course findings indicated that there may be differences in reaction time at different speeds. In the open-road study, the gap distances between vehicles just prior to passing did not show a difference for vehicles at 80 mph as compared to vehicles at 70 mph. The sample size, however, only includes 14 drivers, so a larger sample may provide other findings. Collecting additional data using participants in a closed course and on the open road would require several participants to identify differences. This would represent a significant cost to conduct. The research team in agreement with the Project Monitoring Committee decided that the project funds should be spent on other data collection approaches such as:

- collecting gap distance between vehicles that is more efficient than hiring participants to drive TTI's instrumented vehicle,
- determining typical following distance for vehicles on sections with different posted speed limits, and
- conducting another simulator study.

Simulator Pilot Study

Overview

The pilot driver simulator study used TTI's full-size simulator comprised of a complete, full-size 1995 Saturn SL automobile. The Saturn is connected to one data-collection computer and three image-generation computers. Twelve drivers with an overall average age of 44, consisting of seven women and five men, completed the driving simulation experiment. The participants represented a variety of education levels, driving experience, and driving frequency.

Findings

The simulator pilot study supported the findings from the NCHRP stopping sight distance project that drivers will steer away from an obstacle in their lane rather than initiate braking (*3*). All but one of the twelve participants' initial reactions was to steer first and then to release the throttle for both the 60-mph and 85-mph speed conditions.

Based on the results from the various analyses of the pilot simulator data, researchers made several conclusions as discussed in Chapter 5. Additional simulator studies were recommended for Phase II because of the following findings:

- Reaction time did show a statistical difference depending upon whether a changeable message sign was present (the changeable message sign changed the amount of workload for a participant).
- The initial speed was also statistically significant. Higher speeds are associated with greater reaction times.

Simulator Phase II Study

Overview

The pilot study showed the following variables as being statistically different with respect to reaction time: initial speed of vehicle (60 or 85 mph) and workload (as created through the use of changeable message signs). Because the pilot study only included 12 drivers and the findings indicated that there are trends of interest, another simulator study was conducted. The Phase II study consisted of observing and recording the activities and actions of drivers in TTI's new portable driving simulator. Data for a total of 50 drivers were included in the evaluation.

In designing the simulator study, researchers maintained the initial speeds of 60 mph and 85 mph used in the previous simulator study (see Chapter 5) and the closed-course study (see Chapter 3). All testing conditions in the discussion to follow were driven by the participant at each of those two speeds. As in the pilot study, the primary task of the participant was to follow a lead vehicle within a given target range. The participant was asked to follow the lead vehicle, keeping a 2-sec or less spacing between them at all times. The recorded simulator data provided the research team with the driver's actual proximity to the lead vehicle at each time increment.

The participants followed two different lead vehicles: a small yellow car and a large blue truck. The lead vehicle decelerated (with brake lights always off) at two different deceleration rates. The driver's workload level varied between none, low, and high using math questions. Low workload questions were single digit plus single digit addition problems. High workload questions were double digit plus double digit addition problems. Multiple combinations of these variables, called worlds, were created so that the combination order could be counterbalanced.

Findings

Researchers made the following findings based on the results from the various analyses of the simulator data:

- Higher initial speeds are associated with statistically significant longer reaction times (2.60 sec at 85 mph as compared to 2.39 sec at 60 mph). Stated in another manner, drivers were slower at responding to lead vehicle changes when at higher initial speeds. In addition to being statistically significant, the 0.21-sec difference was also considered to be of practical difference.
- The reaction times when following a smaller vehicle (a car in this experiment) are associated with longer reaction times as compared to when following a large vehicle (truck). The predicted reaction time for following a car was 2.64 sec, while for following a truck it was 2.36 sec, a difference of 0.28 sec, which is both statistically significant and considered a practical difference. The looming of a wider vehicle can be detected at a greater distance, as discussed in the literature review and shown in Table 2-1.
- Initial speed in combination with lead vehicle type shows that reaction time changes more between the two initial speeds when following a large truck as compared to a car. The increase in reaction time when following a truck was an additional 0.29 sec (2.51 − 2.22 sec) when at 85 mph as compared to 60 mph. A similar comparison for following a car only results in an increase of 0.11 sec (2.69 − 2.58 sec). This finding indicates that the advantage of the wider vehicle in terms of being able to judge closing rate is diminished at higher speeds.
- The two different deceleration rates of the lead vehicle tested in the study produced large differences in reaction time. When the lead vehicle had a high deceleration rate (9.8 ft/sec^2), the predicted brake reaction time was 2.10 sec. The predicted brake reaction time was 2.97 sec when the predicted rate was not as great (5.0 ft/sec^2). Drivers did not

notice the slower deceleration rate as quickly as they did the faster deceleration rate, or they may have noticed but felt no urgency to respond. Note that the brake lights were not visible in any of the deceleration events; the driver needed to judge the situation based upon the lead vehicle looming in the driver's view.

- As expected, greater headways at the start of when the lead vehicle reduced speed are associated with longer reaction times. Drivers have extra distance to interpret the situation with the lead vehicle and to make a decision on how best to react. The interaction of headway with initial speed and deceleration rate were both found to be statistically significant.
- Initial speed in combination with workload provided interesting findings. Three levels of mental workload were tested in the study: none, low (easy math questions), and high (hard math questions). As discussed in the literature review (Chapter 2), previous research has shown that peak performance occurs at moderate levels of mental arousal. If a task is too easy or too hard, performance suffers. In the case of the present study, driving at 60 mph in the simulator is an easy enough task that adding mental workload at low and high levels does not affect reaction time performance. This is shown in Figure 6-15(d) by the relatively flat line across the workload levels for the 60-mph initial speed condition. When the speed was raised to 85 mph, however, the driving task got a little harder, and it required more mental effort to control the steering wheel and throttle. For the no-workload condition, responding to the lead vehicle slowing is still easy, but adding the easy math problems in the low workload condition pushes the person to multitask, and the reaction times increase. In the high-workload condition at the high speed then, why do the reaction times not continue to increase? This counterintuitive result has been seen in other studies of driver distraction that have shown that in high-workload situations, drivers adopt tunnel vision and focus only on the lead vehicle, leading to faster reaction times than in lower-workload situations. Researchers believe that in the high-workload, high-speed condition, drivers may have obtained this sort of tunnel vision.

Following Distance

Overview

Several factors influence a driver's decision on how close to drive to another vehicle. The amount of traffic present in the traffic stream is a major factor. Drivers may desire additional space between their vehicle and the lead vehicle when following a large vehicle, for example, because of the driver's inability to see around the lead vehicle or a feeling of being boxed in.

Speed may also influence the gap distance (also known as clearance) between vehicles. Because higher speeds may cause higher workload for a driver, the driver may offset some of the added workload by maintaining a greater following distance. Similar following distances for different speed conditions could indicate the workload is not different enough to cause a change in driving behavior.

If following distances are found to differ based upon the operating speed of the highway, differences in driver workload may be the cause. For this reason the following research questions were investigated:

- Is there a difference in following distance between 60-, 70-, and 80-mph daytime passenger posted speed limits?
- Does the subject vehicle size or the previous vehicle size have an effect upon following distance?
- How does traffic volume affect following distance by posted speed limit?
- Does lighting condition (day/night) affect the following distance?

Findings

Speed data from numerous freeway sites or from previous TxDOT projects were obtained as part of this project. Data were collected using traffic counters. The following data reduction criteria were used to generate a speed dataset for use in the evaluation of following distance:

- subject or previous vehicle speed must be greater than 45 mph (minimum speed limit for a freeway);
- daytime passenger posted speed limit was 60, 70, or 80 mph; and
- speed occurred when the 5-minute volume count was between 30 and 70 vehicles (360 to 840 vehicles/hour).

The volume restriction was selected to represent a minimal level of traffic so that drivers did have other vehicles to consider when selecting the following distance but not so much that volume would be a dominating factor. The volume level represented the level of service A conditions, so congestion should not be influencing the driver's following distance.

Analyses showed that the following factors were significant: posted speed limit, subject vehicle size, previous vehicle size, subject speed, and 5-minute traffic volume. Some of the overall findings from the evaluation are:

- Axle clearance distance or gap time was larger for the 80-mph freeway sites. The predicted mean clearance in 60- and 70-mph posted speed limit segments was around 400 ft, and in 80-mph posted speed limit segments it was around 510 ft. The gap was approximately 4.3 sec in 60- and 70-mph segments, while it was a longer 5.4 sec for the 80-mph segments.
- Drivers of heavy trucks leave longer clearance or gaps as compared to drivers of cars. When the subject vehicle was a heavy truck, the clearance to the previous vehicle was between 415 and 761 ft, and the gap was 4.4 to 8.1 sec. It was only a 341- to 380-ft clearance (3.6- to 4.1-sec gap) when the subject vehicle was a passenger car.
- The axle distance and time are influenced by the lead vehicle type on 80-mph segments. Drivers follow more closely to large vehicles as compared to small vehicles on 80-mph segments; however, the distances were still greater than the distances observed for the lower-speed facilities. Spacing to a large vehicle (heavy truck) was 477 ft, while spacing to a small vehicle was 555 ft on 80-mph segments. The gaps were 5.1 sec to a large vehicle and 5.8 sec to a small vehicle. For 60- and 70-mph segments, the clearance or gap to the previous vehicle was similar (about 400 ft or 4.3 sec) regardless of the previous vehicle type.

- The operating speed of a vehicle has a large effect on the axle clearance distance and time gap. Higher operating speeds are associated with longer axle clearance distances, with the influence of the subject vehicle speed being greater at higher volumes.
- The axle clearance distance and time gap decreased about 6 percent for each 10 vehicles per 5-minute volume increase.

Gaps at Passing

Overview

An important factor in high-speed driving is the perception of the speed of a lead vehicle that is looming into the view of a driver because it is traveling slowly or is stopped. On high-speed roadways, there is a greater likelihood of a faster-moving vehicle overtaking a slower-moving vehicle. Are the decisions made by a passing driver similar regardless of the speed of the lead vehicle? If not, what driver or roadway characteristics influence the passing behavior, especially if the characteristics can be managed by TxDOT?

To answer these questions, this research effort measured the gap at the point when a driver changes lanes during a passing maneuver. This "passing gap" was measured by having TTI staff record the behavior of a following vehicle during a passing maneuver at high speeds. For this study, passing gap was defined as being the distance between the rear of the lead vehicle and the front bumper of the following vehicle during a pass.

This study measured passing gaps of vehicles on freeway sections with daytime posted speed limits of 70 and 80 mph. Data were collected using two different vehicles to assess the effect of lead vehicle size. A large-profile vehicle (Class C recreational vehicle) and a small-profile vehicle (Dodge Caliber) were used during daylight hours. If the passing gap distance is found to differ based upon the operating speed of the freeway, differences in driver workload may be the cause. For this reason the following research questions were investigated:

- Is there a difference in passing gap between 70- and 80-mph daytime posted speed limit conditions?
- Do the following variables influence the passing gap:
  - speed of the lead vehicle,
  - speed of the following vehicle,
  - size of the rear of the lead vehicle,
  - type of the following vehicle (e.g., passenger car versus large truck),
  - roadway geometry (tangent, curve to left, or curve to right), or
  - traffic conditions (restricted or not restricted)?

Findings

Based on the results from the various analyses of the passing gap data, researchers drew the following conclusions:

- A total of 1118 passes were video recorded during 41 hours of data collection. The majority of the passes were within 663 ft of the lead vehicle. The average gap for all measurements was 260 ft. The average gap for the 70-mph sections was 264 ft, and the average gap for the 80-mph sections was 256 ft.

- Initial statistical analyses of the passing gap distances found no statistical difference for posted speed limit. Stated in another manner, drivers use similar passing gap distances on both 70-mph and 80-mph sections. Evaluations that used speed difference between the lead vehicle and the following vehicle did find posted speed limit to be significant as part of a two-way interaction term that consisted of posted speed limit and lead vehicle size. Figure 8-6 illustrates these findings. At 80 mph, the passing gap to either a sedan or an RV was similar. For 70 mph the passing gap was significantly different; drivers were closer to the RV than to the sedan when passing.
- The statistical analyses indicated that drivers passed more closely to the larger-profile vehicle (RV) than the smaller-profile vehicle (sedan). For example, one of the analyses found that drivers were 282 ft from the sedan and only 238 ft from the RV when they passed, a difference of 56 ft.
- The passing gap increases by 10 ft for each mile-per-hour increase in the speed difference between the lead vehicle and the following vehicle. Stated in another manner, the faster a driver approaches a vehicle, the greater the passing gap distance.
- The type of the following vehicle (car or heavy truck) was not significant in the analysis that examined speed difference. It was significant in the evaluation of the 70-mph dataset. Drivers of cars passed approximately 20 ft closer to the lead vehicle as compared to drivers of heavy trucks.

COMPARISON BETWEEN STUDIES

Overview

While using different approaches, portions of the studies within this project examined similar questions. Following are answers to several questions generated during the research.

Questions

Is There a Difference in the Distance (or Time) between Vehicles by Posted Speed Limit?

The traffic counter data showed that axle clearance distance or gap time was larger for the 80-mph freeway sites as compared to the 60- and 70-mph speed limit sites, both statistically and practically. The passing gap study found a different result. Drivers use similar passing gap distances on both 70-mph and 80-mph sections.

Is Drivers' Behavior Influenced by the Type of Vehicle Being Driven?

The following distance study showed that drivers of heavy trucks leave additional distance to the preceding vehicle as compared to drivers of cars. The passing gap study, however, found somewhat mixed results. The type of vehicle being driven was only significant for the 70-mph (not the 80-mph or the mixed) dataset. While the results are statistically significant, they are considered not practically different.

Does the Type of Lead Vehicle Affect Driver Behavior?

All three Phase II studies examined this question. In the passing gap study, the statistical analyses indicated that drivers passed more closely to the larger-profile vehicle (RV) than the smaller-profile vehicle (sedan). The following distance study had a similar finding for the 80-mph segments; drivers follow more closely to large vehicles as compared to small vehicles. The following distances to both large vehicles and small vehicles on 80-mph segments, however, were larger than the following distances for the 60- and 70-mph roads. The 60- and 70-mph roads had similar following distances to either a large vehicle or a small vehicle. Overall, there are some situations when drivers are closer to a large rather than a small vehicle, while in other situations there is no difference.

In the simulator, the reaction times when following a small vehicle (a car in the experiment) were associated with longer reaction times as compared to when following a large vehicle (truck). The difference in predicted reaction time is considered both statistically significant and of practical difference. This finding supports the literature that says drivers can detect speed change in a wider vehicle earlier.

How Does the Interaction between Variables Affect the Above Findings?

When the two-way interaction between posted speed limit and lead vehicle size is examined, a curious trend is revealed (see Figure 8-6[b]). The passing gap distance to the RV and sedan is similar on the 80-mph section. On the 70-mph segments, drivers passed much closer to the RV (210 ft) than the sedan (305 ft). These results may be interpreted to mean that drivers passing an RV at 80 mph recognize cognitively that such a large vehicle is likely not traveling 80 mph, so they begin their passing maneuver sooner (i.e., at a greater distance) than when traveling at 70 mph. The reasons for drivers to pass the RV within the 70-mph section so much more closely need additional investigation.

For the simulator study, initial speed in combination with lead vehicle type shows that reaction time changes more between the two initial speeds when following a large truck as compared to a car. The increase in reaction time when following a truck was an additional 0.29 sec (2.51 − 2.22 sec) when at 85 mph as compared to at 60 mph. A similar comparison for following a car only results in an increase of 0.11 sec (2.69 − 2.58 sec). This finding indicates that the advantage of the wider vehicle in terms of being able to judge closing rate is diminished at higher speeds.

How Does the Operating Speed of the Subject Vehicle Affect Driver Performance?

The operating speed of the subject vehicle had a significant impact on the distances selected by a driver both when passing and when following another vehicle. The faster drivers use longer axle clearance distances and longer passing distances. For the simulator study, higher initial speeds are associated with statistically significant longer reaction times. Stated in another manner, drivers were slower at responding to lead vehicle speed changes when at a higher initial speed.

How Does Driver Mental Workload Change with Speed?

The simulator studies were able to evaluate additional conditions since it was in a controlled environment. The results of the Phase II simulator study indicate that the driving task was more difficult for the 85-mph as compared to the 60-mph initial speed condition.

CONCLUSIONS

The goal of this project was to gain a better understanding of driver performance at high speeds on a freeway alignment. Specific objectives included determining perception-reaction time for high-speed situations, identifying differences in driver workload at high speeds, and determining how operating speed affects following distance (or gap) at passing. For these objectives the conclusions from this research are:

- Previous research as part of the NCHRP stopping sight distance study (*3*) and findings from the Simulator Pilot Study (see Chapter 5) found that drivers will steer away from an obstacle in their lane rather than engage in a panic stop situation. When responding to a vehicle slowing in their lane, the reaction time of drivers in the Simulator Phase II Study at the 85-mph speed was statistically longer than drivers at the 60-mph speed. Drivers took more time at the higher speed to respond to a lead vehicle slowing in their lane. The 0.21-sec difference was statistically significant, and the research team also considers it to be a practical difference.
- In the simulator and test track studies where researchers directly measured driver performance, evidence is present that performance declines when a driver is multitasking at the higher speeds. For tasks such as mental arithmetic in the simulator and detecting a peripheral light while changing a CD on the test track, reaction time to lead vehicle deceleration was longer at the higher speeds. Researchers interpret this to mean that driving at the higher speed was more challenging. The simulator study, in particular, showed that driving 85 mph required more mental effort than driving 60 mph, leaving less mental capacity free to do the arithmetic problems. These laboratory and controlled test track tasks are likely relatively easy compared to the type of multitasking drivers may do on actual roads. For safety reasons researchers were not able to overload drivers on the open road and test track by giving them tasks such as cell phone conversations, navigation system interactions, etc. For this reason, the results of these driver performance studies should be taken to be at the low end of a scale of driver distraction. Driving performance may decline even further in situations where drivers are engaging in other physically or mentally distracting tasks.
- The passing gap data showed that passing drivers initiated their lane change typically between 240 and 290 ft behind the lead vehicle. The predicted average gap distance for the 80-mph sections was similar to the 70-mph sections, so the posted speed limit of the facility did not influence the passing decision of the driver. The operating speed of the passing vehicle, however, did influence the passing gap. Faster drivers used larger gap distances as compared to slower drivers. The passing gap increases by 10 ft for each mile-per-hour increase in the speed difference between the lead vehicle and the following vehicle. While drivers use similar passing gap distances for the 70- and 80-mph sections, they are using larger following distances at 80 mph as compared to the 70- and 60-mph sections.

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