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16. Abstract

This project recognizes the disparity in the relationship between truck and passenger car speeds and current advisory speed signing practices. The results of this project provide a mechanism that traffic engineers may use to provide enhanced differential warning to trucks and passenger vehicles at freeway connector ramps. Considering the strong evidence that there is a significant differential between speeds that cars and heavy trucks can comfortably and safely traverse freeway connector ramps, there was a need for further research to investigate current advisory speed signing practices and examine whether a dual-advisory speed signing scheme, one that provides different recommended advisory speeds for trucks and passenger vehicles, can safely address this differential. Based on the results of the analysis of average and 85th percentile speeds at the midpoint of each study curve, the dual-advisory warning signs generally had a positive impact on reducing speeds at the point of curvature on the curve and/or having an accompanying reduction in speed-related crashes at the study sites.

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GUIDELINES FOR DUAL-ADVISORY SPEED SIGNING ON FREEWAY-TO-FREEWAY CONNECTORS IN TEXAS

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Anthony P. Voigt, P.E., #84845.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1. INTRODUCTION

Freeway interchanges have proven to be particularly hazardous for large trucks, especially for those truck drivers that tend to travel at higher speeds on connector ramps. Previous studies have recognized that crashes, particularly truck crashes, tend to cluster at freeway interchange off-ramps and direct connector ramps. Many of these truck crashes are single-vehicle crashes where truck and driver performance, driver expectations, and roadway geometry interact, sometimes quickly and forcefully with negative results.

While many studies have examined the relationship between truck crashes and ramp geometry, this report recognizes the disparity in the relationship between truck and passenger car speeds and current advisory speed signing practices. The results of this report provide a mechanism that traffic engineers may use to provide enhanced differential warning to trucks and passenger vehicles at freeway connector ramps. Considering the strong evidence that there is a significant differential between speeds that cars and heavy trucks can comfortably and safely traverse freeway connector ramps, there was a need for further research to investigate current advisory speed signing practices and examine whether a dual-advisory speed signing scheme, one that provides different recommended advisory speeds for trucks and passenger vehicles, can safely address this differential.

BACKGROUND

This research builds on a previous study that quantified the differences in vehicle operations on freeway-to-freeway connectors *(1)*. The previous research found that the non-truck-driving motoring public (drivers in passenger cars, light trucks, and sport-utility vehicles, etc.) generally exceeds the posted advisory speed on freeway-to-freeway connectors in great numbers (with violation rates from 95 to 99 percent) and often exceeded that speed by more than 10 miles per hour (mph). That same research indicated that there is a 5 to 10 mph higher difference between a passenger car driver's maximum comfortable speed on a freeway-to-freeway connector ramp and when compared to drivers of larger vehicles.

This research project is founded on experiences in the Houston urban area where truck rollover crashes frequently occur on some freeway-to-freeway connector ramps. Truck rollovers are typically high impact and high visibility incidents that can bring traffic on freeway facilities to a halt during any time of the day. These incidents tend to require several hours for cleanup and removal, often result in injuries or fatalities, and traffic impacts from the incident can result in extraordinary traffic delays on affected freeway systems.

OVERVIEW

The State of Texas serves as an economic gateway between the east and west coasts of the United States (U.S.), as well as to Canada, Mexico, and Central America. As a crossroads of sort, the state has experienced an increasing amount of truck traffic on its highways. The Texas Department of Public Safety states on its website that as a result of the North American Free Trade Agreement (NAFTA), commercial truck traffic has increased dramatically in Texas. Commercial motor vehicle miles traveled in Texas increased 47 percent from 1993 to 1999, and according to TxDOT, approximately 16 percent of all trucks traveling in Texas are NAFTA-related and nearly 80 percent of the overland trade between Mexico and the U.S. comes through Texas. According to figures from the U.S. Customs Service, about 69 percent of the commercial truck traffic from Mexico comes through Texas. This ever-increasing number of trucks on these facilities has various impacts on traffic operations including increasing the potential for truck crashes and conflicts.

As the trucking industry continues to grow and employs new and less-experienced drivers, the number of truck drivers with limited knowledge of Texas freeway facilities will increase. These unfamiliar truck drivers must rely on the signing and pavement marking techniques that the Texas Department of Transportation and other state Departments of Transportation (DOTs) use to convey the appropriate speeds to motorists while negotiating freeway-to-freeway connector ramps.

Previous data collected in the Houston region on freeway-to-freeway connector ramps indicated that all types of vehicles are exceeding the posted limits by varying amounts ranging from 5 mph to more than 15 mph *(1)*. Speeds in excess of the posted advisory speeds may be acceptable for driver comfort and vehicle physics a majority of the time, but there are situations where inexperienced or inattentive drivers (especially drivers of large truck-trailer combinations with high centers of gravity) may exceed the posted advisory speed limit on some connectors and rollover crashes may sometimes result. Transporting high loads can be especially challenging for less experienced truck drivers, who may not fully understand the physics of the trailer and its cargo. This lack of driver experience may be compounded during inclement weather when tire/pavement friction supply may be reduced or during periods of high-volume traffic when vehicle headways may be less than desirable.

The national authoritative reference for the geometric design of horizontal curves is the American Association of State Highway and Transportation Officials' (AASHTO) Green Book *A Policy on the Geometric Design of Highways and Streets (2)*. The objective of the AASHTO policy on horizontal curve design is to select a curve radius and superelevation rate such that the unbalanced lateral acceleration remains within "comfortable" limits. These "comfortable" limits are based on research conducted in the 1930s and 1940s using vehicle passengers that were unbelted, blindfolded, and sitting on bench seats, primarily in passenger cars. These early studies established that the maximum "comfortable" unbalanced lateral acceleration ranged from a maximum of 0.17 g (g = gravitational constant) at 20 mph to 0.10 g at 70 mph.

However, over the last few decades many studies have questioned if these limits are still relevant today considering the advances in roadway construction, pavement ride, and vehicle dynamics. There is an obvious difference in the operating and handling characteristics for all classes of motor vehicles between those from the 1940s and current vehicle designs. The current design procedure is assumed to leave a significant factor of safety between the level of comfort and that of skidding or rollover (as it does for current passenger vehicles) but may cause issues for larger, heavier vehicles – especially on lower design speed curves.

The driver that traverses a curve at a speed higher than used for design will experience a level of lateral acceleration that may make the driver uncomfortable but may not necessarily create a safety problem with potential to cause a crash. In this situation, most drivers are unaware that the traversed curve design's factor of safety, which is founded on driver comfort and not vehicle dynamics, is reduced. This holds especially true for larger and heavier vehicles. One concern with this phenomenon is that less experienced truck drivers may not realize that the level of discomfort due to lateral acceleration forces brought on by speed are not equivalent to those forces acting on their attached load. Less experienced truck operators may chose operating speeds based on personal comfort, not completely considering the physics of their load, thereby increasing the risk of vehicle skidding or rollover. AASHTO curve design policy is based on the tenet that side friction factors used for design are based on driver comfort levels and not necessarily on vehicle physics. These guidelines do not explicitly address the physics of heavy vehicles and especially the physics of trailers pulled by trucks where the dynamics of the cargo load should be considered.

The relationship between design speed and the margin of safety for trucks traversing curves is especially interesting. Consider a semi-trailer combination with a rollover threshold of 0.35, the margin of safety for skidding or rolling increases as the design speed increases. For example, for four different curves designed to AASHTO standards with a superelevation of 0.04, truck rollover speeds would be 27 mph for a 20 mph design speed curve and 40 mph for a 30 mph design speed curve. However, the failure mode changes to skid (before rolling over) at 54 mph on a 40 mph and 67 mph on a 50 mph curve. These factors appear to indicate that considering the current design criteria, the more critical situations are created for trucks on the lower design speed curves, typical of many freeway connector ramps.

The point-mass equation that forms the basis for curve design as shown in the AASHTO policy is:

$$e + f = \frac{v^2}{15R} \qquad \text{(Eq. 1)}$$

where:

e = superelevation rate (decimal),
f = side friction factor,
v = speed (mph), and
R= radius of curve (feet).

This equation is theoretically as applicable to trucks as it is to passenger cars. However, studies have shown that there are significant differences in the physical, handling, and suspension characteristics between trucks and cars. These studies have also stated that side friction is distributed differently among tires for cars and trucks *(2)*. The result of this finding was that trucks typically demand 10 percent more side friction than passenger cars, which indicate that there may be a reduced factor of safety built in for large trucks while applying the standard method of curve design.

Another known weakness of the point-mass equation with respect to trucks and passenger cars is the assumption made that the driver holds a constant radius through the curve. Drivers commonly violate this assumption when they oversteer, causing the side friction demand to increase past the design-assumed levels. While this assumption is generally overlooked because of the perceived margin of safety in the AASHTO recommended guidelines, no definitive data exist to verify if oversteering by drivers of trucks is different from that of the drivers of passenger vehicles. The consequences of critical oversteering (or corrective) movements may be much more critical for trucks than it may be for passenger cars, especially if a truck is exceeding the posted advisory speed.

The AASHTO curve design criterion does not specifically consider vehicle rollover thresholds. Typical passenger vehicles will skid before they roll over, with the rollover thresholds for cars at 1.2 g or higher. In comparison, tractor-trailers can have low rollover thresholds, sometimes as low as 0.24 g. When the assumptions for design are treated as a whole, the margin of safety for trucks with high centers of gravity is quickly reduced when operational parameters such as oversteering and excessive speed meet with vehicle parameters (loading characteristics, suspension characteristics, etc.), roadway geometry, and surface condition.

In response to the above factors and findings from previous research, there was an identified need to determine if providing advisory speed warning signing that differentiated between passenger vehicles and trucks would be effective. This research attempted to determine if a dual-advisory speed warning concept was viable and, if so, what impact could be observed if the concept was to be implemented in a real-world test environment.

CHAPTER 2. METHODOLOGY

This chapter briefly summarizes each of the work tasks of this research project. The project sought to complete a comprehensive review of existing advisory signing practices on freeway connector ramps, develop and implement an acceptable dual signing option, and quantify any affects on operating speed. The general methodologies used in developing new dual-advisory speed signs and the implementation and testing of prototype signs on six freeway-to-freeway connectors in Houston, Dallas, Mesquite, and Fort Worth, Texas, are also described.

TASK 1. LITERATURE REVIEW

Researchers conducted a comprehensive literature search to identify publications on existing methods and practices on differential advisory speed signing for trucks and passenger vehicles on freeway-to-freeway connectors. This search used all available bibliographic resources including the Internet and various catalogs and databases including Texas A&M University's Sterling C. Evans Library local library database, Online Computer Library Center (OCLC) database, National Technical Information System (NTIS), and Transportation Research Information Service (TRIS).

Researchers selected key words and word combinations to conduct a systematic search of the above databases. Key words and key word combinations used in the search included: freeway ramp, trucks, signing, advisory speed, ball-bank indicator, and lateral acceleration, among others. After identifying potential literature sources, researchers acquired abstracts and reviewed those abstracts for applicability to the project. Those documents identified as of interest were obtained for incorporation into the literature review. Chapter 3 of this report summarizes the literature review.

TASK 2. IDENTIFY TEXAS SIGNING METHODS AND ATTITUDES

This task facilitated the identification and documentation of methods used for installation of truck-specific warning signing on connector ramps within the state of Texas. Transportation operations engineers for each of the 25 TxDOT districts were contacted to determine if they have implemented differential speed advisory signing or were in the process of considering differential signing on connector ramps. In general, the primary questions included in the mail-out survey were:

- Do you have freeway-to-freeway connectors that have problematic histories for trucks?
- If so, what countermeasures have you tried to mitigate those problems?
- What criteria does your district use to set advisory speeds on freeway connectors?
- Have any non-standard truck-specific signing been used in your district to convey advisory speeds on freeway connectors?

Chapter 4 of this report presents details of the state DOT survey. Researchers used data received during this task on problematic freeway connectors to develop a list of potential candidate field study sites for prototype sign testing.

TASK 3. DEVELOP A PROFILE OF EXISTING PRACTICE AND ISSUES FROM OTHER STATES

The research team conducted survey interviews of other state departments of transportation regarding alternative advisory speed warning signs on freeway connectors. The chief traffic engineer of each state transportation agency was the primary source of contact. The basic categorical questions asked included:

- Has your agency encountered safety problems for trucks on freeway connectors?
- What is the nature of these problems, and what actions have been taken to mitigate them?
- Has your agency used truck-specific warning signs for freeway connectors?
- Has your agency used signing that has different advisory speeds for trucks and cars?
- What methods and criteria does your agency use to set advisory speeds on curves?

Researchers contacted some states that responded to the survey again by telephone to get more information on survey responses, especially in cases where the researchers determined that such a follow-up would provide benefit to the project. Chapter 4 of this report presents details of the nationwide survey.

TASK 4. DEVELOP PROTOTYPICAL CURVE WARNING AND ADVISORY SPEED SIGNING

After reviewing the practices throughout Texas as well as those of other states, several candidate dual-speed advisory speed signing concepts were developed. Sign development incorporated known existing signing practices (whether standard or non-standard) and relied upon the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) as a guide for development. This task focused on development of both graphics and text that were perceived to most efficiently give drivers meaningful advisory speed curve warning information. These candidate signs were reviewed by traffic engineering professionals (members of TxDOT staff, Texas Transportation Institute [TTI] researchers, and others) to determine each sign's suitability and application to *Manual on Uniform Traffic Control Device* (MUTCD) principles. Researchers tested driver comprehension of the selected signs by interviewing known drivers of passenger cars, sport-utility vehicles (SUVs), light trucks, and heavy trucks. Task 5 provides further explanation.

TASK 5. CONDUCT DRIVER OPINION AND UNDERSTANDING INTERVIEWS

Researchers evaluated signs developed in Task 4 using focus groups and individual interviews. Four focus groups were conducted, two with a subset of the general driving population and two with groups of professional truck drivers. This task provided good insight into driver understanding of a dual-advisory speed signing scheme and served to ensure that the goal of the research was comprehensible to the motoring public.

TASK 6. SIGNING IMPLEMENTATION AND OPERATIONAL ANALYSIS

Researchers evaluated the effectiveness of implementing the signing scheme, finalized in Task 5, at a limited number of sites throughout the state. The evaluation included the review of 57 potential candidate sites identified from the TxDOT District Survey (Task 2). Of those 57 sites initially noted by survey respondents, TTI evaluated 18 sites for candidacy by collecting volume, speed, and classification data using automated tube counters.

Working with the project advisory committee, researchers chose six sites for implementation of the signing scheme. While the signs were being manufactured and installation plans were being made by TxDOT, researchers collected speed and classification data at each of the six sites. After TxDOT installed signs at each test freeway connector ramp, researchers collected additional data to assess the impact of the signing technique used. In addition to the operational data, researchers sought crash data for each of the study sites by requesting reports from local law enforcement agencies.

Based upon the results of each of the tasks above, and with special attention to the results of the studies conducted in Task 6, the researchers have developed guidelines and recommendations for applying the concept of deploying dual signing on freeway-to-freeway connector ramps throughout the state. Chapter 9 of this research report presents the guidelines.

Volume, Speed, Gap, and Classification Data Collection

TTI researchers and staff collected, reduced, and analyzed vehicle speed and classification data at six freeway-to-freeway connector ramps in Texas. TTI collected data for three time periods: "before," "early-after," and "late-after" the installation of the dual-advisory speed warning. The "early-after" time period was generally within two to three weeks of installation of the sign, while the "late-after" was typically several months after the deployment of the signs. Researchers completed investigations for six sites in Dallas (3), Houston (2), and Fort Worth (1) as identified in Table 1.

Table 1. Final Dual-Advisory Speed Warning Sign Study Site Locations.

TxDOT District (City), Site Designation	Location
Dallas (Mesquite), "Dallas 1"	IH 635 Northbound to US 80 Eastbound
Dallas (Mesquite), "Dallas 2"	US 80 Westbound to IH 635 Northbound
Dallas (Dallas), "Dallas 3"	IH 635 Westbound to IH 35E Northbound
Fort Worth (Fort Worth), "Fort Worth 1"	IH 35W Northbound to IH 820 Westbound
Houston (Houston), "Houston 1"	IH 610N Eastbound to IH 45N Northbound
Houston (Houston), "Houston 2"	US 59N Southbound to IH 610N Eastbound

Data Collection and Analysis

TTI researchers sought to obtain volume, speed, and vehicle classification measurements at multiple locations on each connector ramp to measure any operational impacts of the dual-advisory speed signs. TTI deployed automatic data collection devices to measure vehicle speeds and classifications at three locations on each study curve:

- *upstream* of each connector ramp (denoted as "US"),
- at the *point of curvature* (denoted as "PC") on each connector, and
- at the *midpoint* of the curve (denoted as "PI").

Once speed data were collected, the researchers completed a thorough quality control and analysis of the data for each site. The analysis steps included the following:

- segmentation of free flowing vehicles;
- categorization and aggregation of vehicles by classification;
  - passenger vehicles (denoted as "PV");
  - rigid trucks (denoted as "RT" or rigid vehicles);
  - heavy trucks (tractor-trailer combinations; denoted as "HT" or heavy vehicles);
- volume, speed, classification dataset processing, and quality control;
- speed data analysis;
  - calculation and analysis of the general statistics for each study curve by curve location (US, PC, and PI), vehicle class (PV, RT, and HT), and study period (before, early-after, and late-after);
  - before-after comparison of the 85th percentile speed and mean speed for each study curve by curve location, vehicle class, and study period;
  - Analysis of Variance (ANOVA) for mean speeds at each curve and vehicle type;
  - before-after comparison of in-curve speed reductions (US to PC, US to PI, and PC to PI) by vehicle type and study period (before, early-after, and late-after);
  - before-after comparison of driver compliance of the classification-specific advisory speed;
- effectiveness of the dual-advisory speed warning sign on vehicle crashes;
  - crash data collection; and
  - crash data analysis.

Chapter 8 of this report provides more detail on each of these steps.

CHAPTER 3. LITERATURE REVIEW

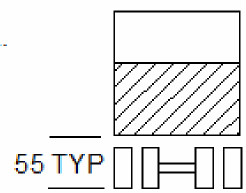
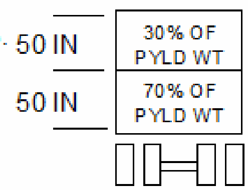
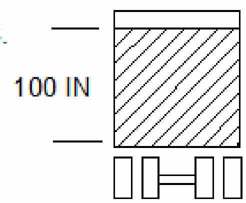
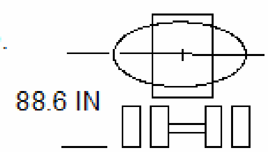
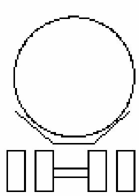
Of the geometric elements that characterize our freeway systems, freeway-to-freeway direct connector ramps can be considered as some of the more complicated with many variable features that drivers must negotiate. The combination of horizontal and vertical curvature often limited sight distance, and selection of an appropriate speed can be problematic to some drivers. Several studies have focused on freeway-to-freeway connector ramps over the past few decades. Two particular aspects mentioned most often are the freeway connector's impact on truck operations and recognition that the current advisory speed setting guidelines may result in the posting of seemingly unrealistic advisory speeds when compared to field observed operating speeds. This section reviews the current available literature that addresses these concepts.

Heavy trucks and truck-trailer combinations, as compared to lighter, more maneuverable passenger cars, light trucks, and sport-utility vehicles, have limitations on the vehicle's ability to traverse horizontal curves on freeway-to-freeway connectors. These limitations include size and weight characteristics, mechanical performance parameters, and dynamics of the cargo loading to name a few. Excessive speed when entering or traversing a horizontal curve causes many truck rollover incidents.

There are likely several reasons why truck drivers exceed the posted advisory speed on a freeway-to-freeway connector. The most prominent reasons include the desire of the driver to hold speed for merging into freeway mainlanes and inadequate deceleration distance entering the connector. In addition, as discussed earlier, drivers may also lack understanding of the many geometric limitations of freeway connectors. It is also typical for drivers of passenger vehicles to exceed the posted advisory speeds on freeway-to-freeway connector curves for some of the same reasons as truck drivers. Although this is true, the consequences of a passenger vehicle crash on a freeway connector may have less of an impact on the freeway system than crashes involving larger and heavier vehicles. Truck crashes on freeway-to-freeway connectors can have significant impacts on the capacity and mobility of freeway facilities, especially during peak traffic periods.

The basis for geometric design of freeways and freeway-to-freeway connectors in the United States is AASHTO's Green Book *A Policy on the Geometric Design of Highways and Streets (2)*. Over its history, the AASHTO Green Book has provided design guidance based primarily on passenger vehicle representations and not necessarily from a perspective of heavy trucks. As a result, many freeway-to-freeway ramps may not adequately accommodate the different operational parameters of trucks, and the AASHTO guidelines may be out of date in terms of setting the advisory speeds for modern passenger vehicles. Highway alignments depend on developing a preferred design based on trade-offs between several mitigating factors. The trade-off often involves the cost for right-of-way and the cost of construction against vehicle operating costs and safety. The horizontal alignment features that govern a given vehicle's performance on a curve include radius (or degree of curvature) and pavement width. Other factors necessary to define the design include design speed, superelevation rate, and side friction factor. All of these factors work together during the design process to determine a safe and efficient freeway-to-freeway connector ramp curve alignment.

As a truck travels through a curve, speed combined with ramp curvature and superelevation creates lateral acceleration *(3)*. For every truck and cargo loading circumstance, there is a maximum lateral acceleration threshold that, if exceeded, will cause the truck to roll over *(4)*. The University of Michigan Transportation Research Institute (UMTRI) developed typical rollover threshold values for various trucks and loading conditions using various static and dynamic testing *(5, 6)*. Figure 1 presents these thresholds values.

CASE	CONFIGURATION	WEIGHT (lbs) GVW	PAYLOAD CG HEIGHT (IN.)	ROLLOVER THRESHOLD (g's)
A.	 FULL GROSS, MEDIUM-DENSITY FREIGHT (34.0 LB/CF)	80,000	83.5	0.34
B.	 TYPICAL LTL FREIGHT LOAD	73,000	95.0	0.28
C.	 FULL GROSS, FULL CUBE, HOMOGENEOUS FREIGHT (18.7 LB/CF)	80,000	105.0	0.24
D.	 FULL GROSS, GASOLINE TANKER	80,000	88.5	0.32
E.	 CRYOGENIC TANKER (He_2 and H_2)	80,000	100.0	0.26

Source: *(5)*

Figure 1. Rollover Thresholds for Various Heavy Vehicles.

Side friction factors recommended for design are based on driver comfort levels and not necessarily on the physics of passenger cars or trailers pulled by trucks. For example, with a semi-trailer combination with a rollover threshold of 0.35, the margin of safety for skidding or rolling increases as the design speed increases *(7)*. Additional examples of this can be illustrated using four curves with the same superelevation of 0.04.

- Truck rollover speeds would be:
    - 27 mph for a 20 mph curve (margin of safety: 7 mph), and
    - 40 mph for a 30 mph curve (margin of safety: 10 mph).
- But the truck would skid at:
    - 54 mph on a 40 mph curve (margin of safety: 14 mph), and
    - 67 mph on a 50 mph curve (margin of safety: 17 mph).

While the mode of failure changes from rollover to skid as speeds increase, there appears to be much less margin for error on lower speed ramps when designed to current design criteria. These factors indicate that the most dangerous situations for trucks, given current design criteria, are on the lower-design speed curves, typical of many freeway connector ramps. This condition may also indicate the need for additional truck-specific warning devices for these types of curves.

HORIZONTAL CURVES AND THE BALL-BANK INDICATOR

The most commonly used tool for selecting a posted advisory speed on horizontal curves is the ball-bank indicator. A study by Fitzpatrick et al. presented a survey indicating that 88 percent of states, cities, or counties that responded use the ball-bank indicator to set advisory speeds on curves *(8)*. The ball-bank indicator measures relative lateral acceleration that drivers and passengers sense while traversing a curve.

Merritt, in his *Safe Speeds on Curves: A Historical Perspective of the Ball-bank Indicator*, gave a general history of the use of the ball-bank indicator *(9)*. In 1935, the need for a consensus method to determine safe speeds on curves lead the Bureau of Public Roads to issue instructions for measuring superelevation and curvature and defined the maximum safe speed under normal driving conditions. The maximum safe speed was set at the minimum speed where the centrifugal force caused a driver or passenger to feel a "side pitch outward." The thought was that there would be a significant factor of safety between the higher speed at which an out-of-control skid would take place and the lower comfort threshold. This comfort feeling was curiously termed the "driver's judgment of incipient instability." After many driving experiments with test vehicles during the 1930s, researchers found that a 10-degree ball-bank reading was about equal to a side friction factor or 0.14 or 0.15, depending on the body roll of the vehicle *(10)*.

The mid-1930s testing indicated that the maximum side friction that a driver would accept before discomfort was about 0.14 or 0.15; therefore, the 10-degree ball-bank limit was deemed a close fit to the side friction at discomfort for higher speeds *(9)*. For lower speeds, it was found that drivers would accept higher levels of side pitch due to the perceived lessened consequences of a mistake, thus using the 12-degree reading for curves of 30 mph and 14 degrees for curves of 20 mph or less became more accepted. These recommendations were promulgated throughout many publications over the next several decades and were included in AASHTO policies in the late 1930s and early 1940s. These recommendations are also stated in various handbooks and guidelines, including the Institute of Transportation Engineer's (ITE) *Transportation and Traffic Engineering Handbook*, *Traffic Control Devices Handbook*, and some older federal and state versions of the *Manual on Uniform Traffic Control Devices*. Merritt does note that since these guidelines were produced, there have been significant improvements in roadway and vehicle characteristics. However, he states that the criteria based on 1930s' technology remains an accepted method to determine maximum safe speed on curves. He later explains that attitudes about these guidelines have changed recently to use higher ball-bank readings to set advisory speeds.

The ball-bank test studies are typically made with a driver and an observer. After checks of calibration to ensure that the ball-bank indicator is calibrated on "zero" when the vehicle is in a horizontal position and at rest, the vehicle is driven on the subject curve at a constant speed parallel to the center of the curve *(9)*. The criterion for setting the advisory speed on the curve is the speed associated with a ball-bank reading of 14 degrees for speeds below 20 mph, 12 degrees for speeds between 20 and 35 mph, and 10 degrees for speeds of 35 mph or greater. The decision to provide an advisory speed sign is made when the safe operating speed as determined by the ball-bank indicator study is less than the prevailing speed on the roadway. The value posted on the sign usually corresponds to the lowest speed (to the nearest 5 mph) obtained during trial runs that created a target ball-bank reading within the suggested speed ranges *(10, 11)*.

The physics that explain the mathematical relationships involved in depicting motion around a horizontal curve can be described using several equations *(2, 12)*. Given that a vehicle is moving at a constant speed *v* on a curve or constant radius *R*, the acceleration is directed toward the center of the circle, perpendicular to the velocity at any instant. This phenomenon is termed *centripetal acceleration* (or *lateral acceleration* in highway engineering) and is represented by Equation 2:

$$a_{per} = \frac{v^2}{R} \qquad \text{(Eq. 2)}$$

where:

a_{per} = centripetal acceleration (ft/s^2),
v = velocity of vehicle (ft/s), and
R = radius of curve (ft).

As a vehicle generates this measure of lateral acceleration as it traverses a curve of constant radius, each is counterbalanced by the vehicle weight, roadway superelevation, and side friction development between the tires and pavement surface.

The AASHTO Green Book uses a point mass model to determine the minimum radius of curvature for a superelevation rate and design speed such that the lateral acceleration may be kept at a desirable maximum level based on driver and passenger comfort. When combined with the second law of physics, the point mass model equation used to represent vehicle motion on a horizontal curve is:

$$e + f = \frac{v^2}{15R} \quad \text{(Eq. 3)}$$

where:

e	= superelevation rate (decimal),
f	= side friction factor,
v	= speed (mph), and
R	= radius of curve (feet).

Equation 3 should be thought of as a supply-demand equation. The left side of the equation represents the amount of lateral acceleration supplied, while the right side represents the lateral acceleration that is demanded for the vehicle to safely travel around the curve.

Traffic engineers to determine a threshold operating speed that causes discomfort for drivers and passengers on curves have historically used the ball-bank indicator. The ball-bank unit consists of a steel ball enclosed in a glass tube. The ball moves freely, with the exception that the movement is dampened by the liquid that fills the tube *(2)*. The ball-bank reading can be expressed by the following equation:

$$\alpha = \theta - \varphi + \rho \quad \text{(Eq. 4)}$$

where:

α	= ball-bank reading,
θ	= body roll angle,
φ	= centrifugal force angle, and
ρ	= superelevation angle.

Moyer and Berry recommended overlooking the body roll term of Equation 4 as long as the observers understood its impact *(10)*. Carlson and Mason examined this assumption further and confirmed that the knowledge of the body roll of the passenger car vehicle (using a Ford Taurus) was unnecessary to calculate safe speeds on curves, as it was found to be statistically insignificant *(12)*. Carlson and Mason concluded that ball-bank indicators could be correlated directly with driver comfort and lateral acceleration values used in curve design; however, no further studies to examine the validity of the AASHTO values of lateral acceleration were recommended.

At the time of the Carlson and Mason study (1999), the following AASHTO guidelines for setting advisory speeds on curves were in effect:

- maximum 14 degrees for speeds 20 mph or less,
- maximum 12 degrees for speeds 25 or 30 mph, and
- maximum 10 degrees for speeds 35 to 50 mph.

Again, these criteria were based on tests conducted in the 1930s and were intended to represent the 85th to 90th percentile curve speed. These limits correspond to side friction values of 0.21, 0.18, and 0.15, respectively. Chowdhury et al. argue that these side friction values reflect an average comfortable speed and that modern cars on dry pavement are capable of reaching side friction coefficients of 0.65 and higher before skidding *(13)*. These guidelines resulted from the Moyer and Berry study of vehicles in the 1940s *(10)*.

Over the past few decades, various research efforts have presented arguments that these criteria may no longer be appropriate given the changes in vehicle stability and driver comfort levels. A Transportation Research Board paper by Chowdhury, Warren, Bissell, and Taori suggested that the existing criteria be changed to:

- maximum 20 degrees for speeds 30 mph or less,
- maximum 16 degrees for speeds 30 to 40 mph, and
- maximum 12 degrees for speeds 40 mph or higher *(13)*.

The Chowdhury et al. study further concluded that at most curves the posted advisory speeds were not only well below the prevailing traffic speed but also below the posted advisory speed recommended by the existing ball-bank criteria *(13)*. The study further argued that the ball-bank criterion suggests driver discomfort thresholds at very low and unrealistic associated operating speeds and concluded that this is why the profession should not expect compliance from drivers. Note that this study did not appear to distinguish trucks from passenger vehicles.

The disparity between the AASHTO advisory speed setting criteria and operating speeds on curves has recently been recognized and codified into the 2003 federal version of the Manual on Uniform Traffic Control Devices. The Manual on Uniform Traffic Control Devices (2003 Edition) indicates in Section 2C.36 that:

> *"A Curve Speed sign may be used at and beyond the beginning of a curve following a Horizontal Alignment and Advisory Speed sign combination, or when there is a need to remind road users of the recommended speed, or where the recommended speed changes because of a change in curvature (see Section 2C.06). Based on engineering judgment, the Curve Speed sign may be installed on the inside or outside of the curve to enhance its visibility.*
>
> *The advisory speed may be the 85th percentile speed of free-flowing traffic, the speed corresponding to a 16-degree ball-bank indicator reading, or the speed otherwise determined by an engineering study because of unusual circumstances.*
>
> *Support: A 10-degree ball-bank indicator reading, formerly used in determining advisory speeds, is based on research from the 1930s. In modern vehicles, the 85th percentile speed on curves approximates a 16-degree reading. This is the speed at which most drivers' judgment recognizes incipient instability along a ramp or curve (14)."*

The 2006 Texas Manual on Uniform Traffic Control Devices omits the federal language quoted above and does not reference recommended ball-bank readings to be used for advisory speeds on curves *(15)*. The 2003 TMUTCD also does not contain language or guidance on the recommended ball-bank readings to be used to determine advisory speeds for curve warning signs *(15)*.

One study of curve operations in New Zealand also found results similar to recent studies in the United States *(16)*. The study suggested changing New Zealand's advisory speed system to more accurately reflect the actual operating speed. This study also compared the methods of determining lateral accelerations. Researchers studied readings from both the ball-bank indicator and accelerometer and concluded that both devices may be used to set advisory speeds. Researchers also concluded that any data collected by an accelerometer should be smoothed to reduce lateral acceleration peaks, avoiding potential errors in suggesting appropriate advisory speeds.

A study by Voigt et al. examined the speeds of various types of vehicles on freeway-to-freeway connector ramps in Houston, Texas *(1)*. Researchers collected speed data at chosen locations to determine compliance with posted advisory speed limits and average speeds at points along connector ramp curvature. From these measurements, researchers determined that the driving public often exceeds the posted advisory speed limit, sometimes by more than 10 mph. In addition to examining speed characteristics, researchers conducted lateral acceleration studies on four different vehicles: a passenger car, sport-utility vehicle, dump truck, and 18-wheeler tractor-trailer combination with a loaded trailer. The vehicles were driven through the curves at varying speeds, while researchers monitored a manual ball-bank indicator in addition to collecting lateral acceleration data electronically. While there were no seemingly discernable differences in lateral accelerations by type of vehicle for a given speed along a curve, there appeared to be a 5 to 10 mph difference in the operating speed that caused driver discomfort between passenger cars/sport-utility vehicles and larger vehicles.

The findings of the Voigt et al. study indicated that there may be differences between the maximum comfortable speeds that drivers of heavy vehicles and passenger car type vehicles will accept while traversing a freeway-to-freeway curve. The study concluded that designers should take care to provide adequate deceleration and acceleration distances for tractor-trailers and other heavy vehicles, reduce, where possible, the side friction demand on trucks in the curve by developing superelevation more on the tangent, and place curve advisory speed signing with more regard to the deceleration needs of trucks. The authors also recommended modifying the current advisory speed setting criteria to use a 10-degree ball-bank indication level to set a truck advisory speed and a 13-degree ball-bank level for setting passenger car advisory speeds. These lateral acceleration levels are thought to better represent the 85th percentile speed of the two vehicle types during curve traversal.

TRUCK OPERATIONS

Ervin et al. recognized several cases where roadway geometrics or driver misjudgment may increase the potential for freeway connector crashes *(17)*. The following three cases are most important to this project:

1. Side friction factor is excessive given the roll stability limits of many trucks.
2. Truck drivers assume that the ramp advisory speed does not apply to all curves on the ramp (if there is more than one curve).

3. Deceleration lane lengths are deficient for trucks, resulting in excessive speeds at the entrance of sharply curved ramps.

For the first case, the authors' make a case that the margin of safety for trucks on horizontal curves designed to AASHTO guidelines is much less than the margin of safety for passenger cars. Considering that for many horizontal curves (and as specified in AASHTO guidelines), the superelevation is not fully developed until well into the curve, this means that the side friction factors in some parts of the curve, especially the beginning, are typically higher than the side friction factors used in determining the design superelevation. These side friction factors, in some cases, may exceed the static rollover thresholds that exist for many fully loaded, high center-of-gravity tractor-trailers.

The lower stability threshold of a truck-trailer combination results from the height of the center of gravity of the truck's payload relative to the tractor-trailer's track width, along with many other parameters such as suspension, tires, etc. The general relationship, assumed to be valid for curve design, is that the roll stability limit in g's is:

$$g = t_w / (2*h_{c.g.}) \qquad \text{(Eq. 5)}$$

where: g = roll stability limit;
t_w = track width, or distance between tires on opposite ends of the axle; and
$h_{c.g.}$ = height of the center of gravity.

Equation 5 is only valid when the trailer is considered rigid. However, trailers tend not to be rigid and may flex under stressed conditions. Ervin et al. state that the roll stability limit may be reduced by nearly 40 percent when considering actual truck-trailer flexibilities. This reduction becomes critical when considering that a non-rigid trailer produces g's that may quickly approach the rollover threshold at side friction factors very near design limits. Consider a truck, with a very high center-of-gravity trailer, which is exceeding an advisory speed that was selected according to existing guidelines. In this situation, a good possibility exists that a rollover incident will occur simply because of the physics involved with a flexing trailer. In addition, the incident could take place without ever exceeding the comfort level of the truck driver. Some truck drivers realize this phenomenon; some inexperienced truck drivers may not.

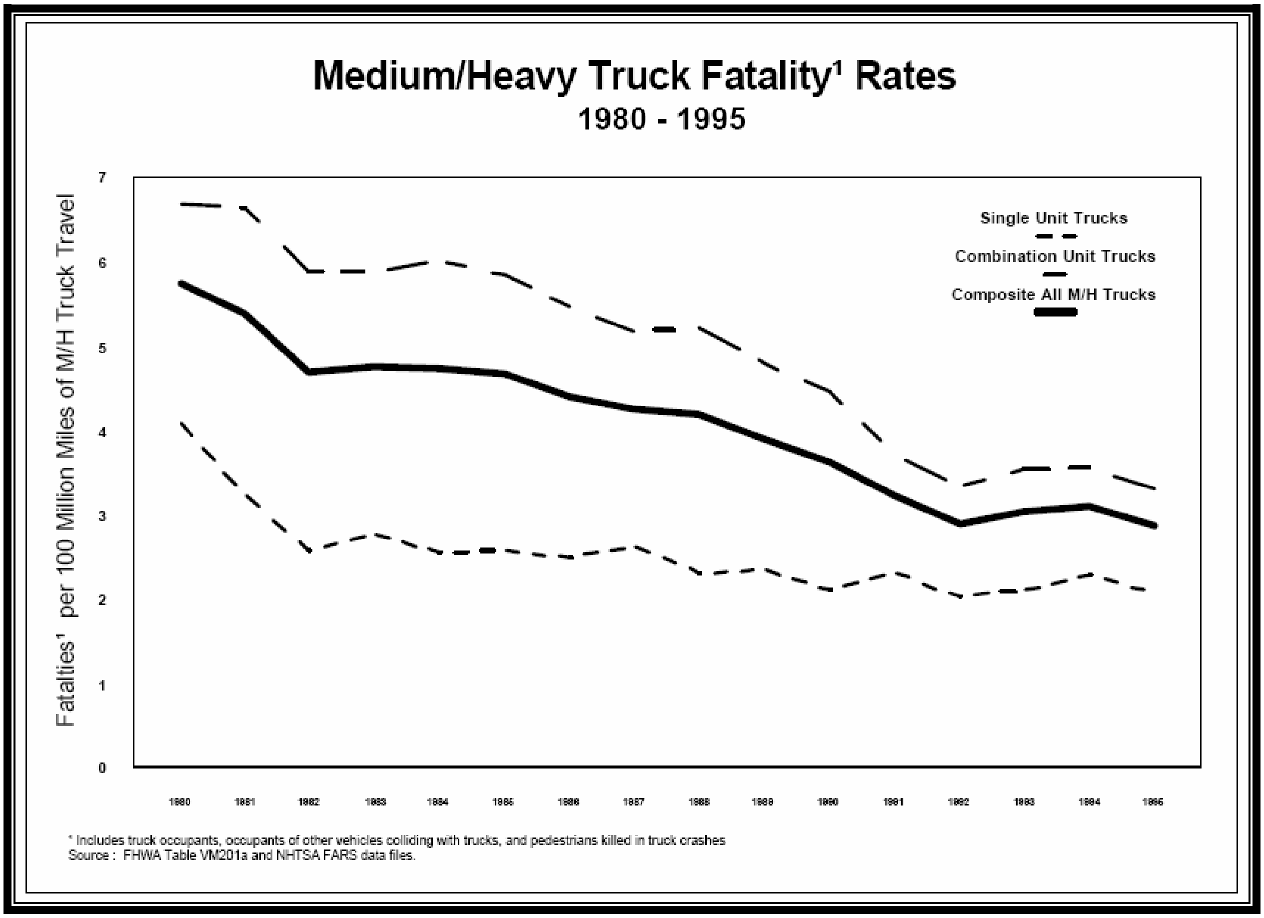
In the second case, Ervin et al. argue that many truck drivers assume that the first advisory speed for a multiple curve ramp is for the first curve, when the limiting curve may be further downstream. It was observed that truck drivers tend to accelerate after leaving the first curve in order to reach the speed needed to merge with high-speed freeway mainlane traffic, only to then encounter a second curve requiring a slower speed. This is of particular concern for connector ramps on a downgrade. This geometry along a connector ramp may not only cause rollover crashes but jack-knife crashes as well. If a truck driver recognizes the upcoming curve and identifies a need to slow down, the onset of heavy braking to reduce speed may cause the cargo to shift and increase the risk of a jack-knife event.

Ervin et al. also concluded that deceleration lanes are not long enough for trucks to reduce speeds and safely negotiate a curve *(17)*. This rationale was based on the fact that the previous design guidelines made the assumption that "average speeds for trucks are generally lower than those of passenger cars." Although the latest AASHTO Green Book did not repeat this assumption, the publication also did not significantly change its recommendations for deceleration lengths. Recent observations could also dispute this assumption as truck speeds appear to be equal to passenger car speeds in most cases.

The *Comprehensive Truck Size and Weight Study* also cited several previous studies that identify concerns with instances of excessive side friction factor demand and limited deceleration lengths *(18)*. The study indicated that trucks with rollover thresholds of 0.30 g can roll over on freeway ramps when traveling as little as 5 mph over the design speed. In similar fashion to studies performed by Ervin et al., this study also recognized that, in many cases, the length of deceleration lanes are not adequate to accommodate the characteristics of safe truck deceleration *(17)*. Vehicles failing to correctly transition from freeway mainlanes that have higher design speeds than the connector ramp curvature may enter with excessive speed. Excessive speed combined with a lack of deceleration length may lead to rollover crashes. The TS&W study also referenced an ITE publication that compared deceleration lane requirements as stated in the AASHTO Green Book (for passenger vehicles) and those requirements that would be required by trucks and found that deceleration lengths would have to increase by more than 50 percent to adequately accommodate the operational characteristics of trucks *(19)*.

SAFETY

The TS&W study indicated that medium to heavy trucks account for 3 percent of vehicles in use on United States roadways and that trucks account for 7 percent of vehicle miles of travel *(18)*. Trucks are involved in only 3 percent of all crashes but account for 8 percent of involvement in fatal crashes. Figure 2 shows that the relative involvement of trucks in fatal crashes has decreased in the last decade *(18)*.



Source: *(18)*
Note: NHTSA FARS is the *National Highway Traffic Safety Administration Fatality Analysis Reporting System*

Figure 2. Medium/Heavy Truck Fatality Rates, 1980-1995.

The following factors contributed to this decline:

- the use of uniform truck driver licensing and tracking of violations under the federal/state Commercial Driver's License Program,
- increased federal and state inspections and audits completed under the Motor Carrier Safety Assistance Program,
- upgrades in training and safety awareness at institutions abiding by guidelines published by the Professional Truck Driver Training Institute,
- awareness of safety management, and
- advances in safety technology in truck designs (seat belts, anti-lock braking systems, under ride guards, etc.) *(18)*.

Although each of the above factors is important, the most critical component in the safe operation of a heavy truck is driver performance. Factors that affect overall driver performance include skill level, experience, awareness, and fatigue. While experienced drivers may have developed the skills necessary to overcome difficult driving conditions or vehicles with less than desirable stability characteristics, inexperienced drivers are more prone to crashes because of these characteristics. One of the most common crash causative factors attributed to the judgment of the driver is traveling at excessive speed *(18)*. Professional truck drivers are typically male and older than the general driving population. However, studies have indicated that younger truck drivers are involved in more crashes than older truck drivers are, a statistic that parallels that of the general driving population *(19)*. Other studies have noted that truck drivers have negative opinions of other drivers, but they do not demonstrate "self-enhancement" that indicates overconfidence *(20)*. As a group, truck drivers do not believe that just because they drive more miles or because they drive trucks, they should become (or feel) overconfident about their abilities. Because they view themselves as driving professionals, more experienced truck drivers use their experience to try to avoid negative driving situations. More recently, the Transportation Research Board's Commercial Truck and Bus Safety Program produced *Synthesis 4 – Individual Differences and the "High-Risk" Commercial Driver*, which provides a very good overview of the factors related to driver risk and confirms earlier works completed on the subject *(21)*.

While the driver is the most critical factor in the safe operation of a truck, the driving environment may also have significant effects on truck operations. Roadway features, traffic congestion, and weather all contribute to the overall operational capabilities of both the driver and vehicle. Roadway features that may affect truck operations include roadway surface type and grade, interchange and intersection geometry, entry and exit ramps, and acceleration and deceleration lanes. Visibility also has a significant impact on truck operation safety. The TS&W study determined that about 35 percent of fatal crashes and 26 percent of nonfatal crashes occur in conditions other than normal daylight. Inclement weather conditions (rain, sleet, snow, ice, fog, and standing water) always present a challenge to the truck driver and may influence the operating characteristics of the truck. Weather and poor visibility both may combine to reduce the available factor of safety for sight distance, decision distance, and time available for evasive maneuvers *(18)*.

Several studies have quoted crash rates for trucks. Janson et al. estimated that 20 to 30 percent of freeway truck crashes occur at or near ramps, despite the fact that interchanges account for less than 5 percent of freeway miles *(22)*. Rollover crashes account for 8 to 12 percent of all truck crashes but account for 60 percent of all truck driver/occupant fatalities *(18)*. These types of crashes are extremely disruptive to the freeway network in the urban environment, especially when hazardous materials are involved. The trucking industry could reduce rollovers by making trailers more roll-stable by using lower deck heights, more axles, and/or stiffer suspensions. However, an immediate help in reducing rollover crashes is for truck drivers to adhere to the posted (or reasonable) advisory speeds through the entire length of a freeway ramp or curve *(18)*. Other studies found that a disproportionate amount of truck rollover crashes occur on freeway ramps (17 percent) *(23)*. A study by Garber et al. found that truck crashes increase on freeway ramps with an increase in ramp curvature and with the differential between the truck speed on the curve approach and the posted advisory speed on the ramp *(24)*.

The study by Janson et al. concluded that no statistical relationship could be found between crashes and roadway geometry (grade, curvature, or curve length) *(22)*. This study concluded that traffic crashes are random events with many causative factors, including driver factors that complicate the identification of specific causes for crashes. This study presents a method to "flag" crash-prone ramps for further investigation and potential improvements, and summarizes the process in three steps of statistical analysis. However, these procedures are highly dependent on crash reporting measures that may not be available in typical crash reporting procedures.

The American Automobile Association (AAA) Foundation for Traffic Safety recently completed a study based upon the Fatality Analysis Reporting System (FARS) data for 35,244 fatal car crashes and 10,732 fatal car-truck crashes for 1995-1998 *(25)*. This analysis supports previous studies *(18, 22, 23, 24)* of fatal car-truck crashes but also shows that unsafe actions by car drivers are more likely to be recorded than unsafe actions by truck drivers, 80 percent for passenger cars compared to 27 percent of heavy vehicles (with at least one unsafe driving act recorded in FARS). Of unsafe actions examined in the AAA study of fatal crashes, 75 percent were linked to car drivers and 25 percent were linked to truck drivers. The majority of the crashes were attributed to just a few unsafe driving actions (independent of whether car- or truck-driver was involved). Five of the 94 listed potential attributing crash factors accounted for about 65 percent of the unsafe driving actions by drivers. The top five factors are:

- failure to stay in the lane or running off of the road (21 percent),
- failure to yield the right-of-way (16 percent),
- driving too fast for conditions or above the speed limit (12 percent),
- failure to obey signs and signals (9 percent), and
- driver inattention (9 percent).

DIFFERENTIAL SPEED LIMITS

The potential safety impact of providing differential advisory speeds to cars and trucks on freeway connector ramps could be similar to those safety impacts seen in use of differential speed limits on general roadway sections. Previous studies *(26, 27, 28, 29)* on the impacts of the use of differential speed limits have generally been inconclusive *(30)*. Several studies have found no significant difference in the actual average speeds or crash experience of roadways with uniform speed limits as opposed to those with differential speed limits. Some of these studies have found that while the crash rates themselves do not change significantly, the types of crashes do change somewhat. For roadways with a slower truck speed limit, rear-end crashes are usually instigated by passenger vehicles. On roadways with uniform speed limits, rear-end crash rates of crashes instigated by trucks are somewhat higher. However, no research has been found to have examined differential advisory speeds, so a direct correlation between differential speed limits and differential advisory speeds cannot be determined from existing research.

EXISTING TRUCK WARNING SYSTEMS

In 1994, McGee and Strickland presented two alternative concepts for truck warning systems *(4)*. The first system was an inroad detection warning system using detectors placed in the roadway to sense truck type, speed, and weight. A controller analyzes captured data and determines if a truck is approaching the rollover threshold. If so, the controller activated a warning device to warn the driver. The second system presented was an in-vehicle warning system. This system relied on the driver to input vehicle parameters (truck and trailer type, load distribution, etc.) into an onboard computer system. At each problematic curve, telemetry on curve geometry is transmitted to the computer, which calculates whether a rollover is possible. A warning (alarm or recorded message) is issued if rollover is possible *(4)*.

Some states, such as Virginia and Maryland, have implemented the in-road detection system. These systems consist of speed detection and vehicle classification using inductive loops embedded in the roadway pavement. The weight of the truck is estimated using commercially available weigh-in-motion equipment. A controller is used to process the speed, classification, and weight inputs and, if warranted, would activate either a static warning sign with flashing beacons or a sign with a supplemental message such as "TRUCKS REDUCE SPEED." Initially, costs for these types of systems were estimated at $100,000 for a one-lane ramp and $160,000 for a two-lane ramp *(4)*.

From 1997 to 1999, the Texas Transportation Institute and the Center for Transportation Research conducted a joint TxDOT-sponsored study on an instrument system that is capable of detecting vehicles that are speeding on ramp approaches. This system was implemented in January 1997 on the IH 610 Southbound to SH 225 Eastbound direct connector ramp in Houston. The system identified trucks by length and height, and if speeding trucks were detected, flashing hazard beacons were activated. The hazard beacons were mounted on standard signs, as well as experimental curve warning signs with advisory speed plates. For trucks identified as violating the preset warning threshold, a speed reduction of 2 mph was observed with the system in operation *(31)*.

EXISTING SIGNING PRACTICES

The TMUTCD lists several signs intended to warn drivers of excessive speed on ramps and exits, including freeway-to-freeway connector ramps *(32)*. The current and previous versions of the TMUTCD do not explicitly address freeway-to-freeway connector signing within its text. However, TMUTCD sections 2C-3 (Placement of Warning Signs), 2C-5 (Curve Sign), 2C-35 (Advisory Speed Plate), 2C-36 (Advisory Exit [or Ramp] Speed Signs) all address signing typically used on freeway-to-freeway connector ramps. The 2003 National MUTCD does not appear to introduce major changes to the suggested curve advisory speed signing practice.

Some TxDOT districts have used alternative, non-standard signing at some freeway connectors where crash experience has indicated the need for additional signing. The IH 610 North Loop Eastbound to US 59 Eastex Freeway Northbound ramp in Houston has graphic signing with a truck advisory speed of 25 mph on an additional overhead sign before the gore point of the exit ramp. The US 59 Eastex Southbound to IH 610 North Loop Westbound connector has a large sign warning drivers to reduce speed on the curve. The TxDOT truck warning systems recently deployed in the greater Houston area consist of the non-standard truck rollover sign with yellow flashers (Figure 3).

Figure 3. Houston Tipping-Truck Active Warning System Signs.

A Freedman et al. study examined alternative signing for freeway exit ramps that had the potential for rollover crashes *(23)*. This study conducted a survey of 38 experienced truck drivers. These drivers selected a sign that used a black silhouette of a truck tipping to one side. The advisory speed was posted on a separate plate (black on yellow) mounted on the sign post and an alternate flasher was located to the right of the sign. Speed data were collected before and after the signs were installed. The results of the study indicated that the flashing sign activated for trucks likely to be exceeding the advisory speed was more effective than a non-flashing speed advisory sign. The study was unable to determine, with statistical significance, if the addition of a truck-specific non-actuated sign by itself had any impact on reducing truck speeds.

CHAPTER 4. STATE OF THE PRACTICE

This chapter summarizes the methodology and findings of two surveys completed to define the current state of the practice with respect to advisory speed signing on freeway-to-freeway connector ramps. The surveys were sent to 25 TxDOT district transportation operations engineers to determine the general practices within Texas. Additional surveys were distributed to all 50 state chief traffic engineers to research the topic nationwide.

These surveys were intended to gather current information from across the country to assess methodologies of addressing the safety of trucks using freeway-to-freeway connector ramps. General topics addressed included countermeasures used to mitigate truck crashes and criteria used to set curve advisory speeds. The survey also inquired about the use of pavement marking treatments used to warn truck drivers of conditions requiring the need for slower curve traversal.

THE SURVEY OF TXDOT DISTRICTS

The survey of TxDOT districts was developed with the intent of determining if districts had problematic freeway-to-freeway connectors (especially for trucks) and how those issues were addressed (what countermeasures were used, etc.). In addition, any information on advisory signing schemes that were being implemented within Texas might be useful for evaluation as part of this research. Appendix A lists an uncompleted copy of the survey as well as a summary of the responses.

The survey was structured in the following manner to:

- inquire about safety problems with trucks at freeway-to-freeway connectors,
- identify any countermeasures employed to address any truck safety issues noted,
- identify specific problematic freeway connector ramps in each district,
- identify existing truck-specific signing implementations,
- inquire about current curve advisory speed setting practices,
- inquire about the use of overhead curve advisory speed signing, and
- inquire about the use of pavement markings used to warn trucks at freeway connectors.

Hardcopy surveys were mailed to all TxDOT district transportation operations engineers in October 2003. Of the 25 districts surveyed, detailed responses were obtained from 17 districts (68 percent), 7 districts (28 percent) responded that they did not have any freeway-to-freeway connector ramps within their jurisdiction, and 1 district (4 percent) did not respond to the survey. Therefore, an overall 96 percent response rate was realized for this survey.

Of the 17 districts responding in detail to the survey, 10 districts indicated experience with problematic truck operations on freeway-to-freeway connector ramps. Those 10 districts included Amarillo, Atlanta, Beaumont, Corpus Christi, Dallas, El Paso, Fort Worth, Houston, Paris, and San Antonio. Seven districts completed the survey but did not indicate any experience with problematic freeway-to-freeway connectors: Abilene, Bryan, Childress, Lubbock, Odessa, Waco, and Wichita Falls.

Seven districts remarked that there were not any freeway-to-freeway connector ramps or problematic connectors within their district and did not complete the remainder of the survey. Those seven districts were Brownwood, Lufkin, Laredo, Pharr, San Angelo, Tyler, and Yoakum. The Austin District did not complete the survey. The results in all statistical comparisons noted below are generally based on 17 responding districts.

The survey initially asked each district if there were any safety problems related to trucks on freeway-to-freeway connector ramps within their jurisdiction. Forty-two percent of the districts had encountered safety issues dealing with trucks at connector ramps. Of the 17 districts responding in detail to the survey, 10 of 17 districts (59 percent) indicated the presence of posted curve advisory speeds applicable for all vehicles in the district. Only 5 of 17 (24 percent) indicated using truck-specific advisory speed warning signs for connector curves. No districts responded that they had used a dual-advisory speed sign, which indicated advisory speeds for passenger vehicles and a separate advisory speed for trucks.

Several districts (5 of 17–29 percent) indicated use of truck-specific warning signs, with or without an advisory speed component. Three of those five districts had supplemented those signs with flashing yellow lights to enhance conspicuity. The Houston District indicated the deployment of 17 systems in their jurisdiction that used a unique active curve warning system that sensed a vehicle's speed and length, resulting in a flashing yellow warning signal for those larger vehicles exceeding the advisory speed on a given curve.

Four districts indicated using pavement markings to warn drivers of all vehicles about advisory speeds on freeway-to-freeway connector curves. The Beaumont District did so specifically for trucks; however, this was actually for a curve on the IH 10 mainlanes near SH 12 in Vidor. The Atlanta District remarked that the IH 30 Westbound to US 59 Southbound connector ramp in Texarkana had been reconstructed in response to truck crash experience.

While 10 districts listed problematic geometric features in the survey, there were 57 total roadway features mentioned by the district transportation operations engineers as concerns. Even though the survey was intended to reveal problematic freeway-to-freeway connector ramps, engineers not only listed directional freeway-to-freeway connectors (40 sites) but entire interchanges (1 location), cloverleaf connector ramps (7 sites), exit ramps (7 sites), and entry ramps (2 sites). These responses may indicate the need for additional guidance at locations other than freeway connector ramps to warn trucks in advance geometrics that may require reduced speeds. The identification of a connector ramp as problematic was strictly a subjective response in the opinion of the responder. Crash data or other safety-related information was not used to quantitatively indicate safety problems.

Nine districts indicated introducing countermeasures in response to truck safety issues at ramps. Countermeasures employed included the use of regular and oversized chevrons, special (non-standard) signing, signing with flashing lights, truck-specific warning signs (tipping-truck type signs), delineators, raised pavement markers, dynamic feedback vehicle speeds while traversing the ramp, and active curve warning systems. While the Dallas District had installed truck-specific warning signs at three locations, the Houston District had signing similar to that presented in Figure 4 at 17 freeway-to-freeway connector ramps.

Figure 4. Houston District Tipping-Truck Sign.

The survey also inquired about the procedures used to set curve advisory warning speeds. Of 19 responses, 12 (63 percent) indicated that advisory speed setting decisions were made at the director of transportation operations engineer level. The maintenance supervisor or staff (21 percent) and traffic engineering section staff (16 percent) were also noted as having advisory speed setting authority. However, only two districts indicated using a formal training program regarding setting advisory speeds on curves.

Of the 17 responding districts, 15 (88 percent) use the ball-bank indicator for setting freeway-to-freeway connector curve speeds, and those 15 districts use the traditional AASHTO guidelines (14 degrees for speeds below 20 mph, 12 degrees for speeds 20 to 35 mph, and 10-degree ball-bank reading for speeds above 35 mph). The Houston District indicated using the 10-degree criteria on all curves while the San Antonio District indicated the use of engineering judgment and actual observation of operating speeds to set advisory speeds on freeway connector curves.

The survey also inquired as to if the respondent had knowledge that the 2001 National MUTCD allowed engineering judgment to be used to set advisory speeds on curves using up to a 16-degree ball-bank reading. Only 2 of 15 responding districts were aware of this rule; however, 8 of the 15 indicated considering using that criteria in the future. In general, crash history or a speed study was noted as the most likely criteria to be used to consider truck-specific warning sign use on connector curves.

Other comments noted by survey participants included the use of "dynamic speed display" signs that show operating approach speed on freeway connector curve approaches (Atlanta District). The Beaumont and Lubbock Districts also remarked that they had considered pavement markings "TRUCKS XX MPH" and tipping-truck signs to be effective but had no quantitative measures of effectiveness for those treatments. At the time of the survey, the Houston District had prepared plans for pavement marking and signing improvements at most direct connectors in the district. These improvements consisted of tipping-truck signs, chevrons, delineators, new "interstate shield" horizontal signing, and rumble strips in advance of the curves. As of the date of this report, many of these improvements have been installed and are operational. No detailed evaluation of their effectiveness has been undertaken.

THE SURVEY OF U.S. STATE DEPARTMENTS OF TRANSPORTATION

The survey of the 50 state Departments of Transportation was developed with the intent of determining if various states had problematic freeway connectors and how those issues were addressed. This survey also asked each state to identify any unique advisory signing schemes that may have been used within their state to address speeds on freeway-to-freeway connectors. Appendix B provides the survey instrument and detailed summary of the responses.

The survey was structured in the following manner to:

- inquire about each state's current curve advisory speed setting practices,
- identify statewide existing truck-specific signing implementations,
- inquire about safety problems with trucks at freeway-to-freeway connectors,
- identify countermeasures employed to address any truck safety issues noted,
- identify problematic freeway connector ramps in each state,
- inquire about the use of overhead curve advisory speed signing, and
- inquire about the use of pavement markings used to warn trucks at freeway connectors.

Each state's chief traffic engineer was invited to participate in an Internet-based survey in October 2003. Twenty-one states provided a detailed response and completed the survey representing a 42 percent response rate. Figure 5 shows those states (shaded) responding to the national survey. Appendix B presents a detailed listing of survey respondents.

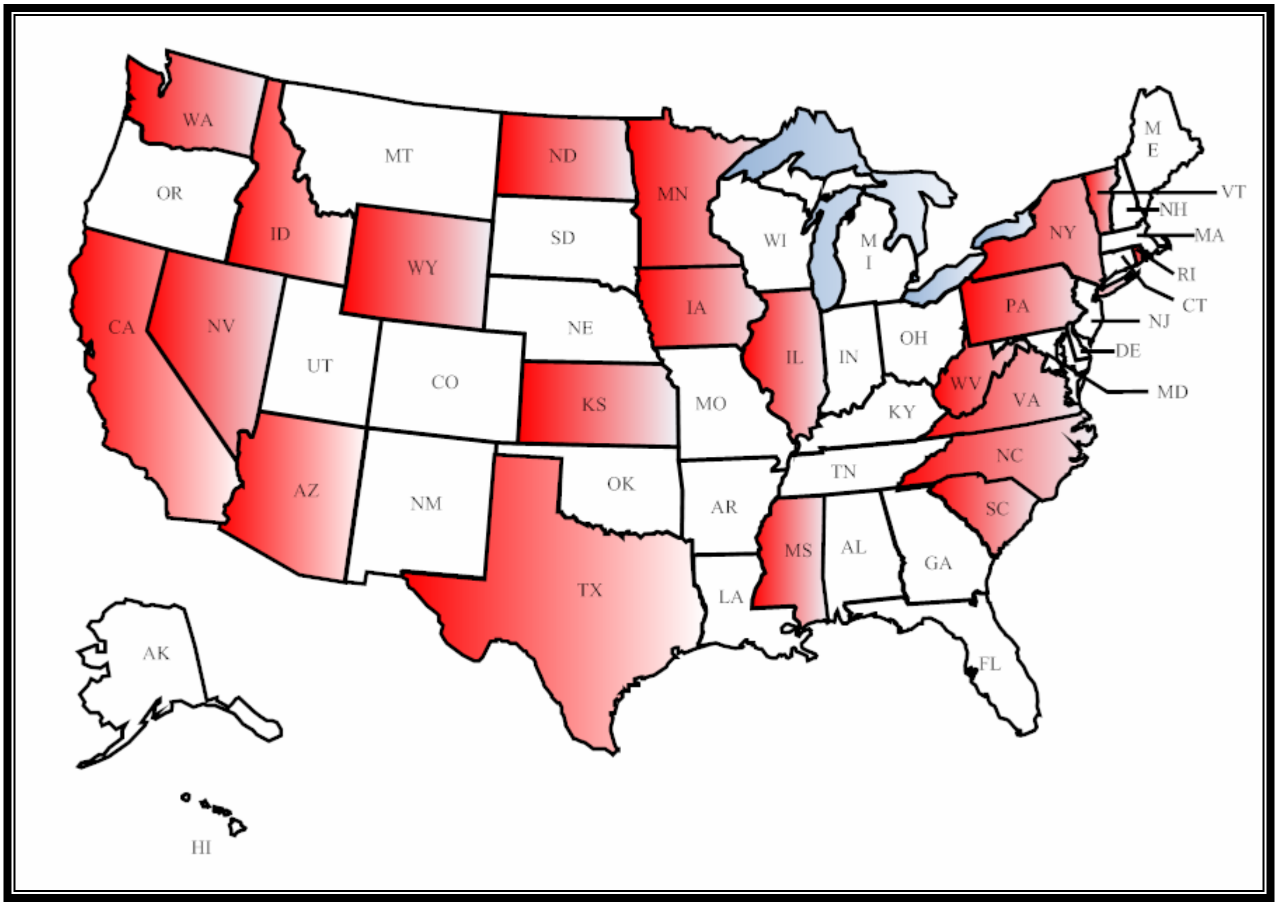


Figure 5. States Responding to the National Survey.

The responses indicate that advisory speed setting for freeway-to-freeway connector ramps is largely a function completed by the states' district or regional offices. Of the responding 21 states, 80 percent set advisory speeds at the district level, with 20 percent setting advisory speeds at the state level. The district traffic engineer is responsible for most decisions in terms of setting the advisory speeds.

While two-thirds of the responding states had experienced problematic freeway-to-freeway connector ramps, only about one-third of the states indicated the development of a non-standard sign (or signs) to warn trucks of lower advisory speeds at freeway connectors. Specific issues noted as problematic were truck rollovers, excessive speed, low speed (<20 mph) ramps, and cloverleaf ramps. Truck rollover experience, noted in more than half of responding states, was the most reported issue on connector ramps.

The states were then queried about their responses to truck-related problems at freeway connectors. Sixteen states (76 percent) used advisory speed signing for all vehicles at connectors, and eight states (38 percent) had employed advisory speed signing tailored for trucks at freeway connectors. Although no state responded using different advisory speeds for trucks and passenger cars at freeway-to-freeway connector ramps, about 60 percent of the states responding had used special warning signs for trucks (tipping-truck signs, etc.), and 36 percent of the responding states indicated use of flashing lights in combination with the truck-specific signing to enhance conspicuity of the signs.

Texas and Virginia indicated the use of active warning systems to warn trucks at freeway-to-freeway connector ramps. According to the survey results, only Texas has deployed pavement markings specifically to warn trucks on the ramps. Nearly 30 percent of states indicated that ramps had been reconstructed to help mitigate truck safety issues. Many states responded that they had used larger-sized signs to enhance visibility (some used diagrammatic signs), flashers, or more numbers of signs at problematic connector ramp locations. Minnesota reported a unique countermeasure in restricting trucks to the outside lane of a two-lane connector ramp to provide increased radii to provide safer conditions for trucks traversing the curve.

Seventeen of 21 states preferred using the ball-bank indicator to set curve advisory speeds. The states using the ball-bank indicator generally followed the AASHTO recommended guidelines (10 degrees for 35 mph and over, 12 degrees for 20-30 mph, and 14 degrees for less than 20 mph). Some states use 10 degrees for all curves, while some indicated the use of 10, 12.5, and 15 degrees as a substitute to AASHTO-guided maximum ball-bank measurements. Five states stated using curve geometric features (degree of curvature, superelevation rate, design side friction factor, etc.) as the basis for setting the advisory speed. Nine states indicated knowledge of the 2003 MUTCD referencing an allowable 16-degree reading on the ball-bank indicator to set advisory speeds, and 12 states would consider using a reading higher than 10 degrees on the instrument to set advisory speed limits.

CHAPTER 5. CANDIDATE STUDY SITES

The results of the TxDOT transportation operations engineers' survey, particularly the listing of problematic freeway connector curves (Question 2, see Appendix A), was used to screen candidate sites for the prototype sign installation. Of those 57 sites, the project monitoring committee asserted that about six implementation sites should be chosen and evaluated for the dual-advisory speed signing effectiveness.

INITIAL DATA COLLECTION

Site visits and data collection were completed at 18 of the 57 freeway-to-freeway connector curves identified as problematic throughout the state. These connectors were chosen upon recommendation of the district transportation operations engineers in the Corpus Christi (6 sites), Dallas (3 sites), El Paso (1 site), Fort Worth (2 sites), Houston (2 sites), and San Antonio (4 sites) Districts. Engineers in the districts selected these sites based on subjective analysis of their problematic operations for trucks. No quantitative crash rate analysis of each of the original 57 candidate sites or these 18 connector ramps was completed due to the complexities in collecting that data. The researchers felt that local experience was more than adequate for selecting the candidate curves below:

- Corpus Christi,
  - IH 37 Northbound to SH 286 Southbound,
  - IH 37 Southbound to SH 181 Northbound,
  - SH 181 Southbound to IH 37 Northbound,
  - SH 286 Northbound to IH 37 Northbound,
  - SH 286 Northbound to IH 37 Southbound,
  - SH 358 Northbound to IH 37 Northbound,
- Dallas,
  - IH 635 Northbound to US 80 Eastbound,
  - US 80 Westbound to IH 635 Northbound,
  - IH 635 Westbound to IH 35E Northbound,
- El Paso,
  - US 54 Westbound to IH 10 Westbound,
- Fort Worth,
  - IH 35W Northbound to IH 820 Westbound (North),
  - US 287 Northbound to IH 35W Northbound (Connector-Entry),
- Houston,
  - IH 610 Eastbound to IH 45 Northbound,
  - US 59 Southbound to IH 610 Eastbound (North),
- San Antonio,
  - IH 35 Northbound to IH 410 Westbound (North),
  - US 281 Southbound to IH 10 Westbound,
  - IH 410 Eastbound to IH 35 Southbound, and
  - IH 410 Southbound to IH 10 Eastbound (Cloverleaf).

TTI staff visited each of these connector curves to assess curve conditions and applicability to the project. During the site visits, conditions of the connector ramps were noted, including presence of skid marks or barrier hits (and location), signing and pavement markings present (and condition), and operational conditions (ball-bank readings and travel speed observations from several runs of each curve). Data collection was completed at each site consisting of classification, speed, and volume counts using automated tube counters for a period of three to five days. With the absence of crash data, researchers were left with the district staff recommendations, total volumes, truck volumes, and the results of their site visits to choose six to eight curves for implementation.

SPEED DATA COLLECTION

TTI researchers sought to obtain volume, speed, and vehicle classification measurements at multiple locations on each connector ramp to measure any operational impacts of the dual-advisory speed signs. Automatic data collection devices were deployed to measure vehicle speeds and classifications at three locations on each study curve:

- upstream of each connector ramp,
- at the point of curvature on each connector, and
- at the midpoint of the curve.

TTI collected the volume, speed, and classification data using TimeMark Delta IIIB portable road tube classifiers. These automatic pneumatic tube classifiers are designed for use on multiple-lane high-volume roadways. For a two-lane connector ramp, the equipment deployment process required installing one set of road tubes across both lanes of the connector ramp spaced exactly 16 feet apart and a second set of road tubes across a single lane of traffic (Figure 6). For the purpose of consistency, researchers separated each of the two sets by 18 inches for each data collection setup. One-lane ramps deployed one set of tubes spaced at 16 feet apart.

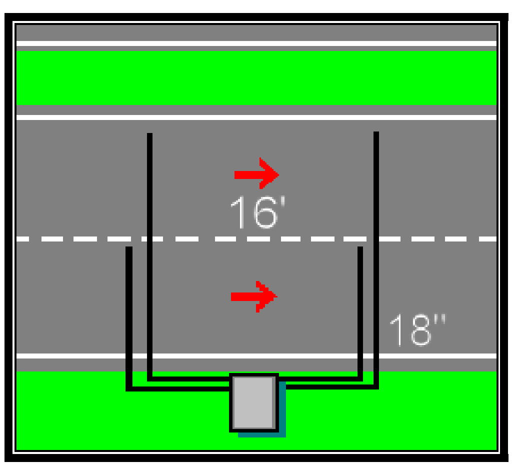


Figure 6. Automatic Traffic Counting Equipment Deployment Layout.

TTI staff programmed the classifier/counters to provide volume, classification, speed, and gap data for each lane of the connector ramps. While most portable traffic data collection equipment is only capable of providing speed and classification data in summarized totals, the TimeMark Delta IIIB units provide a time-stamped "per vehicle" output. This output includes:

- the date/time of day,
- total number of axles,
- spacing between each of the axles,
- an estimated spot speed of the vehicle, and
- the gap between vehicles.

The TimeMark Delta IIIB also assigns a vehicle classification based upon the number of vehicle axles and axle spacing. Table 2 identifies these FHWA classifications used by the TimeMark software.

Table 2. Delta IIIB Counters: Vehicle Classification Table.

Classification Number	Vehicle Description
1	Motorcycle
2	Car (also with 1- or 2-axle trailer)
3	Light roads vehicle (also with 1-, 2-, or 3-axle trailer)
4	2- or 3-axle bus
5	2-axle rigid (heavy goods vehicle) truck
6	3-axle rigid (heavy goods vehicle) truck
7	4- or more axle rigid (heavy goods vehicle) truck
8	Tractor trailer, 3 or 4 axles
9	Tractor trailer, 5 axles
10	Tractor trailer, 6 axles
11	Multi-trailer truck, 5 axles or less
12	Multi-trailer truck, 6 axles
13	Multi-trailer truck, 7 or more axles

TTI collected data for several days at each of the connector ramps. At some locations, especially high-volume locations, research staff encountered difficulty in keeping road tubes properly secured to the roadway surface, typically at the midpoint of the curve. Higher vehicle speeds as well as the ramp curvature caused the road tubes to stretch and slap the pavement causing them to break loose. Although this was the case in early data collection efforts, the research staff was successful in securing the tubes to the pavement using a combination of mechanical fasteners and mastic tape. However, for all phases of data collection (before, early-after, and late-after), researchers collected sufficient data to evaluate speeds at each ramp.

SELECTION OF FINAL STUDY SITES

In general, the candidate sites chosen for dual-advisory speed warning sign implementation tended to be those curves with limiting geometric features (curves that tighten after the initial curvature or have downgrades associated with them) and those with higher truck volumes as a percentage of total volume on the curve. Identification and discussion of the sites used for implementation follows in Figures 7 through 12.

Site #1.

Dallas 1. IH 635 Northbound to US 80 Eastbound, One-Lane Direct Connector Ramp

- Average Daily Volume: 7000-14,000 vehicles per day; Percent Trucks: 9.8 percent;
- Previous Curve Advisory Speed 40 mph;
- Curve Radius, approximately 590 feet;
- Curve Length, approximately 880 feet; and
- Pre-Study Signing Scheme: W13-2, "Exit 40 MPH" at PC of Curve.

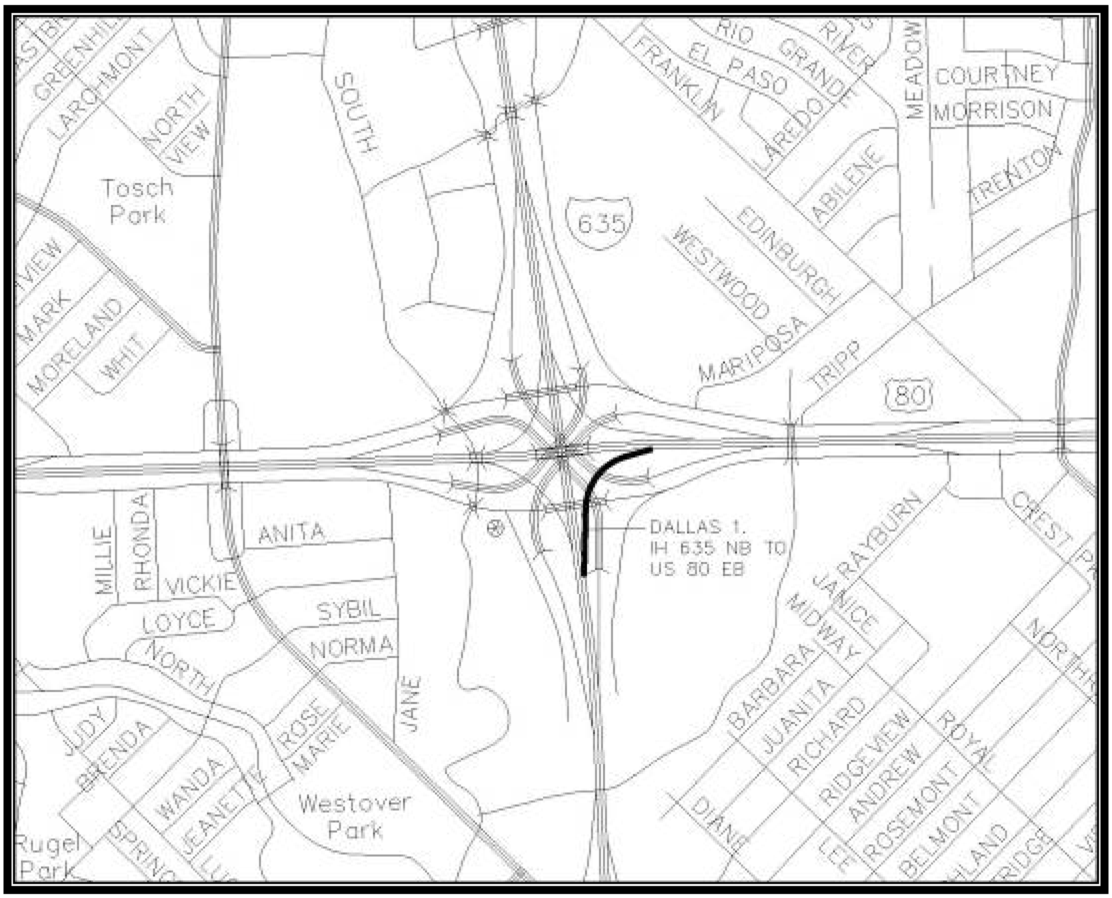


Figure 7. Location of "Dallas 1" Study Site – IH 635 Northbound to US 80 Eastbound, Dallas County.

Site #2.
Dallas 2. US 80 Westbound to IH 635 Northbound, One-Lane Direct Connector Ramp

- Average Daily Volume: 16,000-19,000 vehicles per day; Percent Trucks: 11.9 percent;
- Previous Curve Advisory Speed 40 mph;
- Curve Radius: approximately 540 feet;
- Curve Length: approximately 690 feet; and
- Pre-Study Signing Scheme: W13-2, "Exit 40 MPH" at PC of Curve.

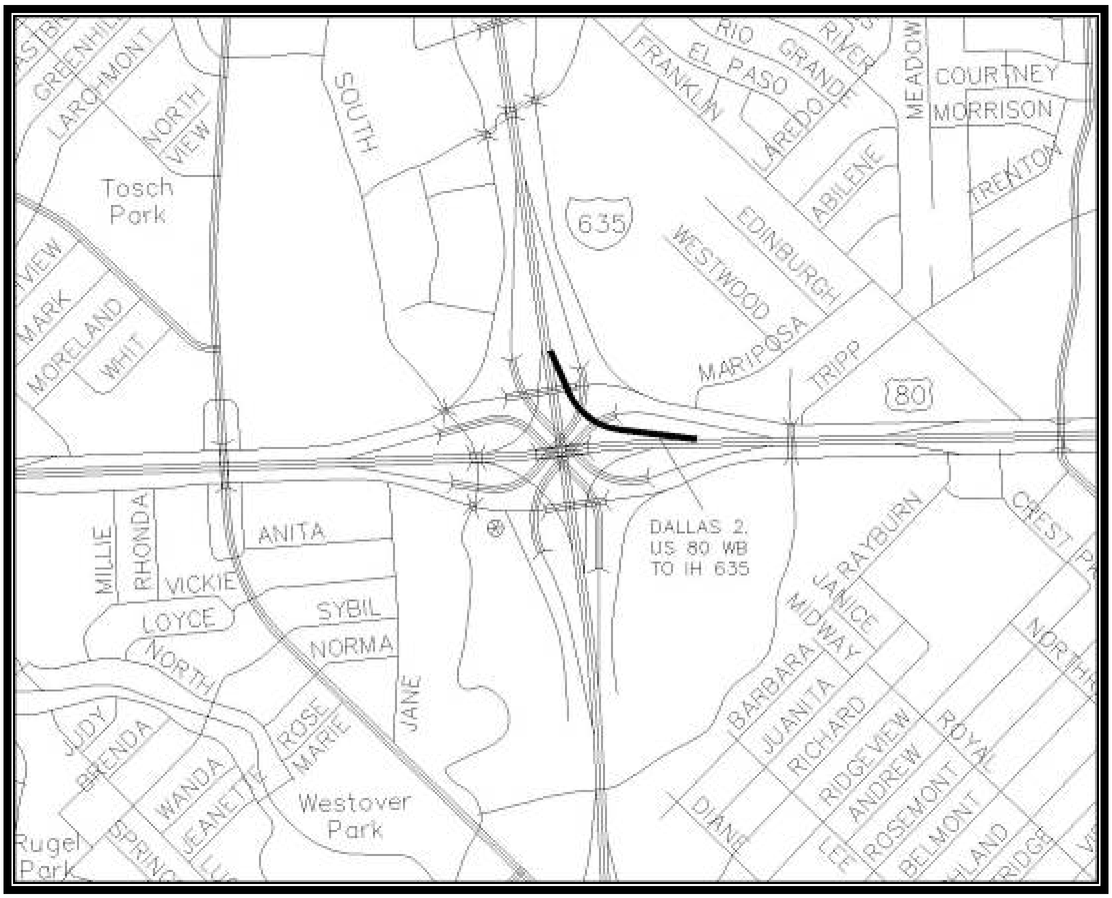


Figure 8. Location of "Dallas 2" Study Site – US 80 Westbound to IH 635 Northbound, Dallas County.

Site #3.

Dallas 3. IH 635 Westbound to IH 35E Northbound, One-Lane Direct Connector Ramp

- Average Daily Volume: 21,000-22,000; Percent Trucks: 11.4 percent;
- Previous Curve Advisory Speed 35 mph;
- Curve Radius: curve 1 – approximately 1920 feet, curve 2 – approximately 510 feet;
- Curve Length: curve 1 – approximately 510 feet, curve 2 – approximately 410 feet; and
- Pre-Study Signing Scheme: W13-2, "Exit 35 MPH" at PC of Curve.

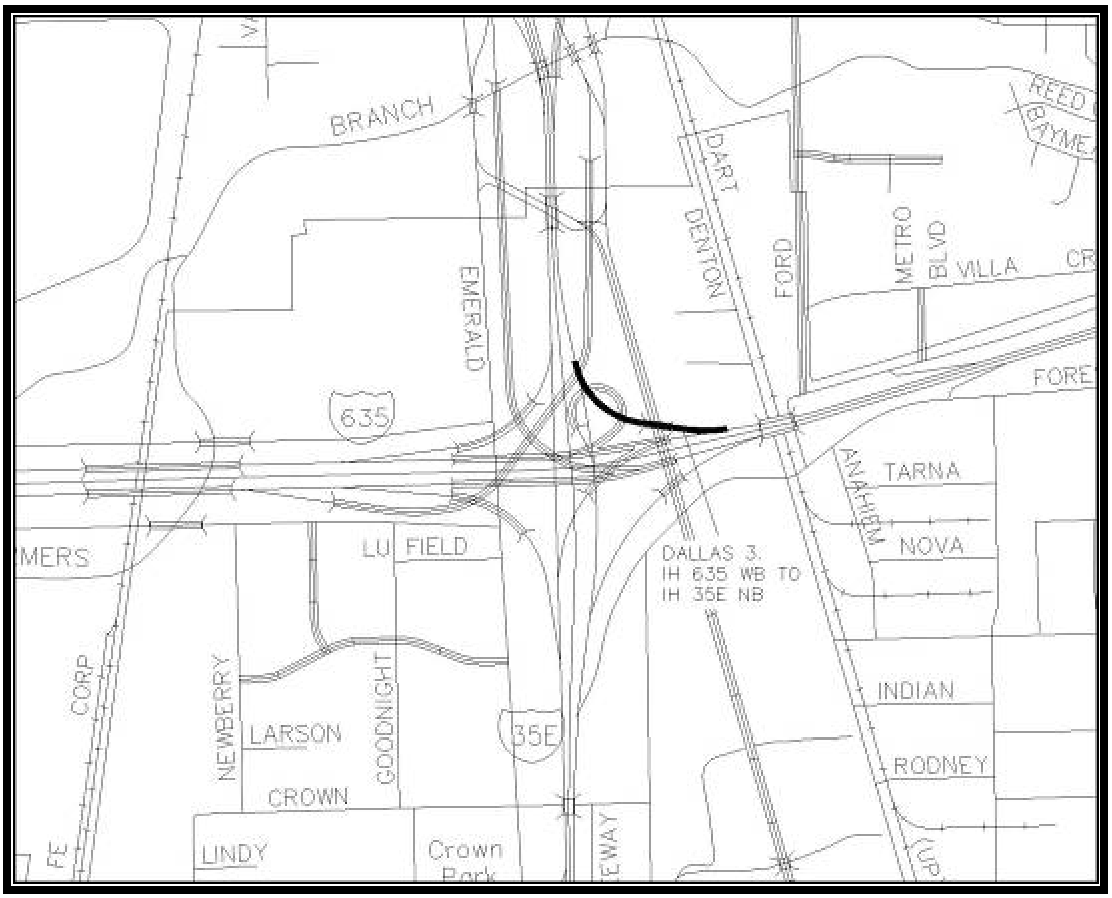


Figure 9. Location of "Dallas 3" Study Site – IH 635 Westbound to IH 35E Northbound, Dallas County

Site #4.

Fort Worth 1. IH 35W Northbound to IH 820 Westbound, One-Lane Direct Connector Ramp

- Average Daily Volume: 10,000-11,500; Trucks: 9.5 percent;
- Previous Curve Advisory Speed: None;
- Curve Radius: approximately 700 feet;
- Curve Length: approximately 610 feet; and
- Pre-Study Signing Scheme: No advisory speed warning signing posted.

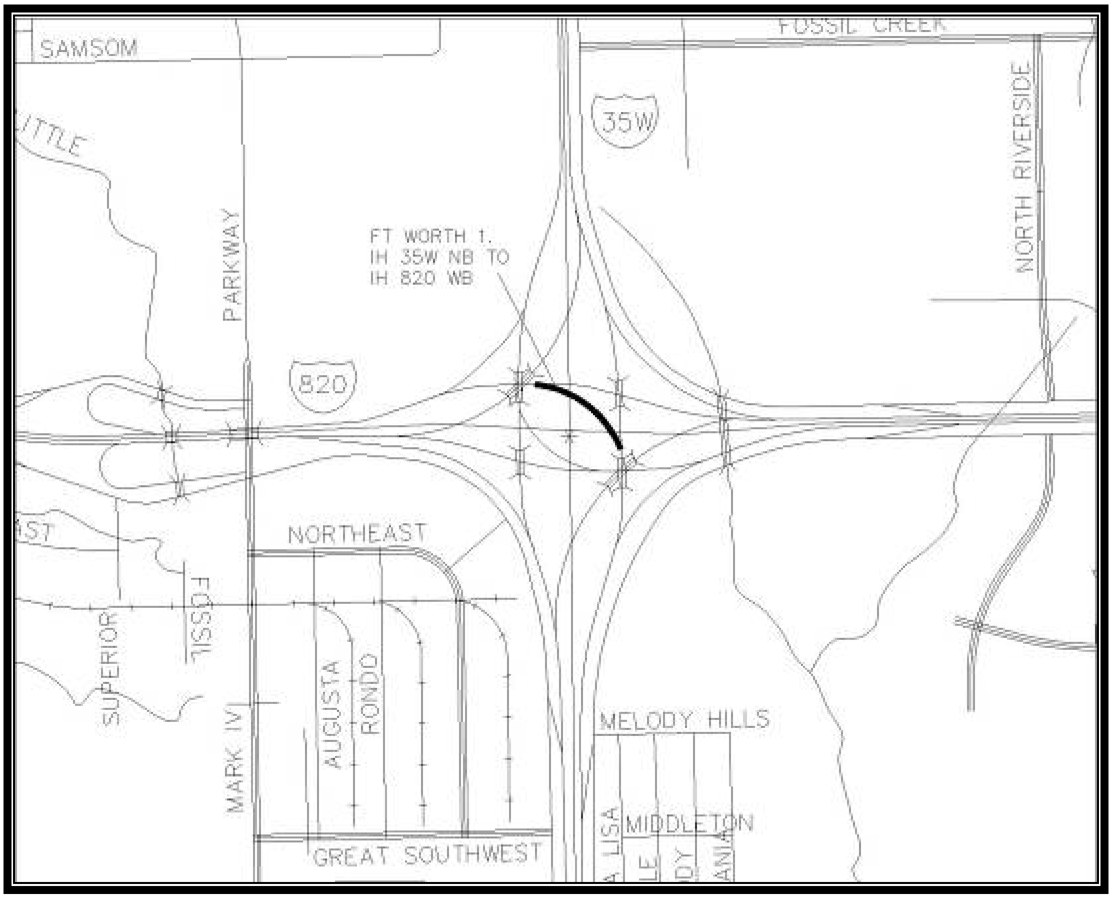


Figure 10. Location of "Fort Worth 1" Study Site – IH 35W Northbound to IH 820 Westbound, Tarrant County.

Site #5.

Houston 1. IH 610 Eastbound to IH 45 Northbound, Two-Lane Direct Connector Ramp

- Average Daily Volume: 38,000; Percent Trucks: 4.6 percent;
- Curve Advisory Speed 35 mph;
- Curve Radius: approximately 470 feet;
- Curve Length: approximately 1020 feet; and
- Pre-Study Signing Scheme: Houston Modified Truck-Tipping Signs (Figure 14), three signs, one approximately 350 feet upstream of PC, one at the PC, and one about 220 feet past the PC with 35 mph advisory plaques.

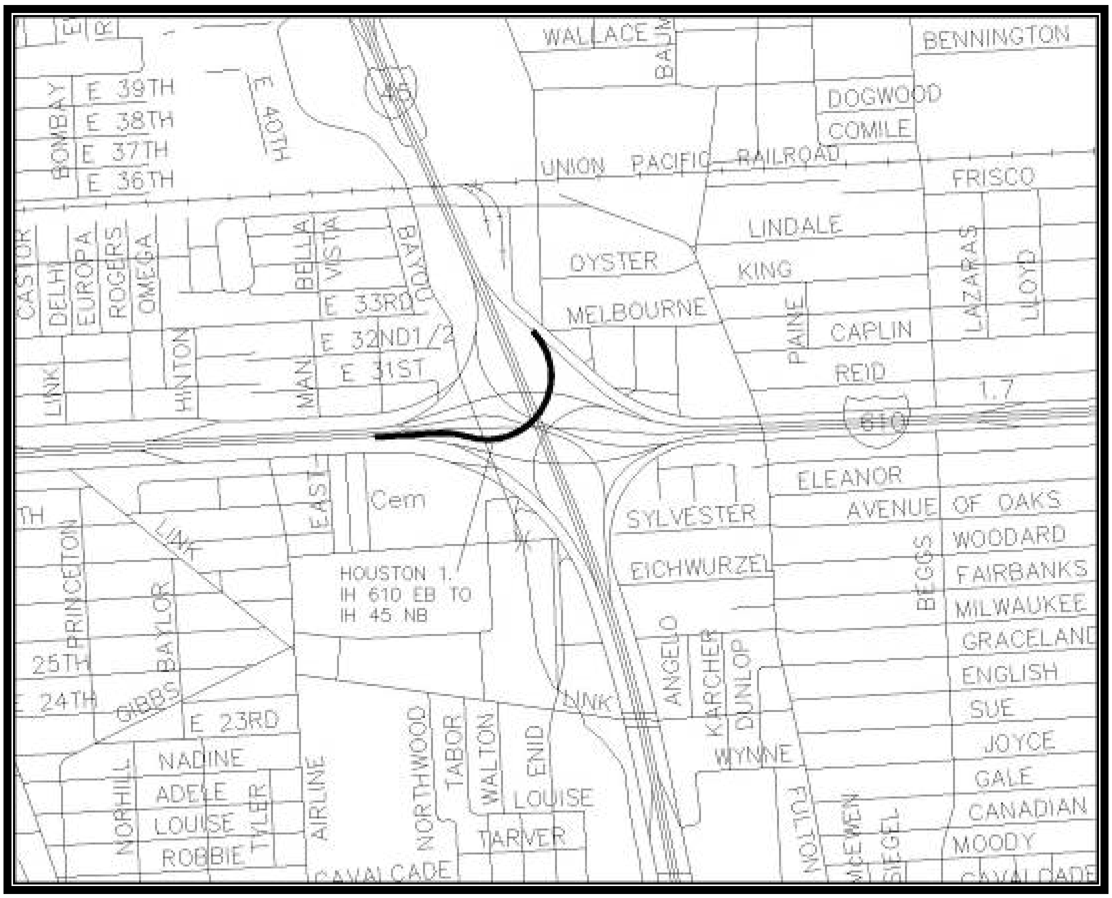


Figure 11. Location of "Houston 1" Study Site – IH 610 Eastbound to IH 45 Northbound, Harris County.

Site #6.

Houston 2. US 59 Southbound to IH 610N Eastbound, Two-Lane Direct Connector Ramp

- Average Daily Volume: 17,000; Percent Trucks: 10.7 percent;
- Curve Advisory Speed 35 mph;
- Curve Radius: approximately 540 feet;
- Curve Length: approximately 500 feet; and
- Pre-Study Signing Scheme: Houston Modified Truck-Tipping Signs (Figure 14), three signs, one approximately 350 feet upstream of PC, one approximately 200 feet from the PC, and one about at the PC; with 35 mph advisory plaques.

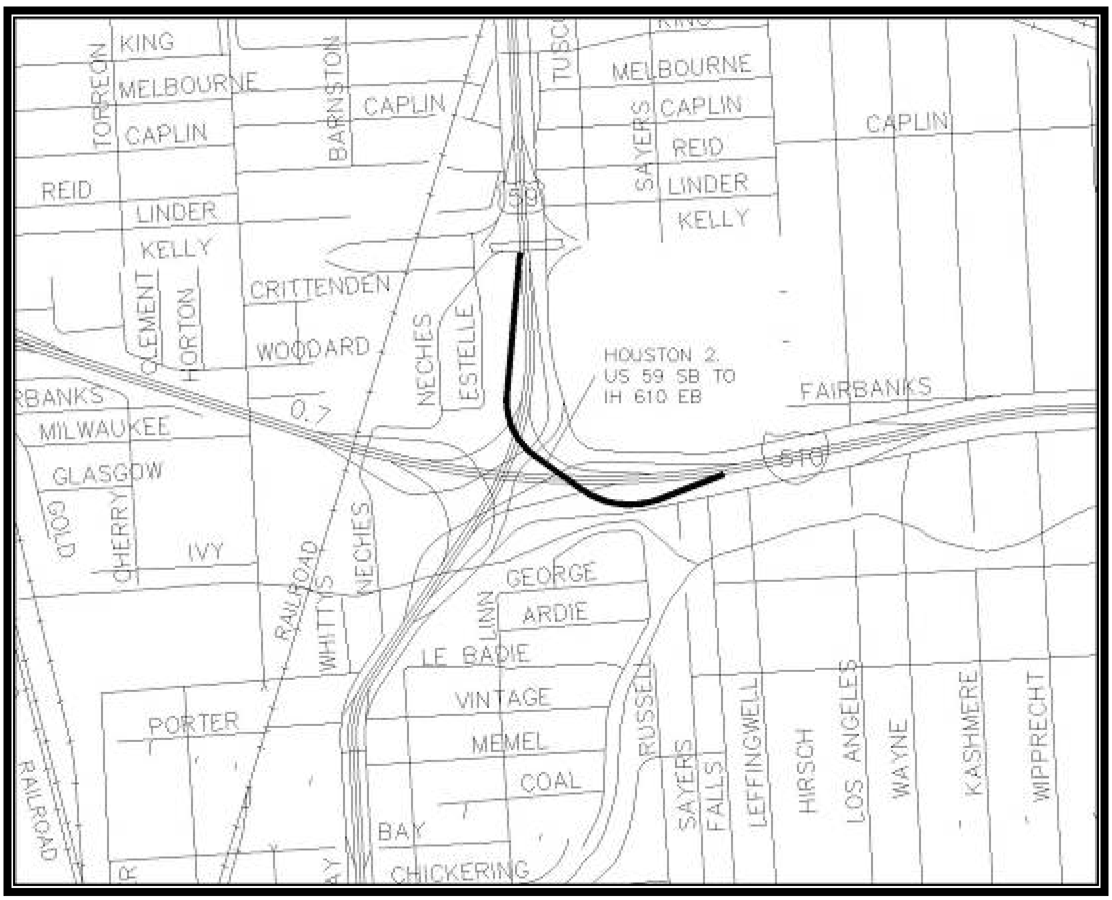


Figure 12. Location of "Houston 2" Study Site – US 59 Southbound to IH 610 Eastbound, Harris County.

The Houston 2 curve was selected as a final study site. The “before” classification, speed, and volume counts using automated tube counters were completed in January 2005. The dual-advisory speed signs were placed on February 26, 2005, and “early-after” data were collected during the first week of March 2005. However, after review of “before” and “early-after” data, anomalies forced a review of the data and curve conditions to see if conditions at the ramp during either data collection period changed. The researchers found that during the “before” data collection period, TxDOT or contractor forces were repairing the guardrail and alternately closing one lane of the two-lane connector ramp at various times of day. Without record of the lane closure and time periods, the researchers were forced to remove the Houston 2 curve from the analysis.

CHAPTER 6. PROTOTYPE SIGN DEVELOPMENT

CANDIDATE SIGN DESIGNS

The dual-advisory speed signing concept was envisioned to combine elements of the standard W13-3 and W1-13 signs and standard advisory speed plaques to convey advisory speed information to both passenger vehicles and trucks on the same sign. Researchers and TxDOT staff indicated that sign layout design candidates should consist of as little text as possible and contain typical texts and graphics. The initial signs consisted of only graphics seen in the W13-3 (Figure 13) and W1-13 (Figure 14) signs in addition to a passenger car graphic taken from the standard W8-5 sign (Figure 15). Researchers also evaluated a non-standard "tipping-truck" sign similar to the W1-13 (Figure 16) that the TxDOT Houston District had previously implemented.

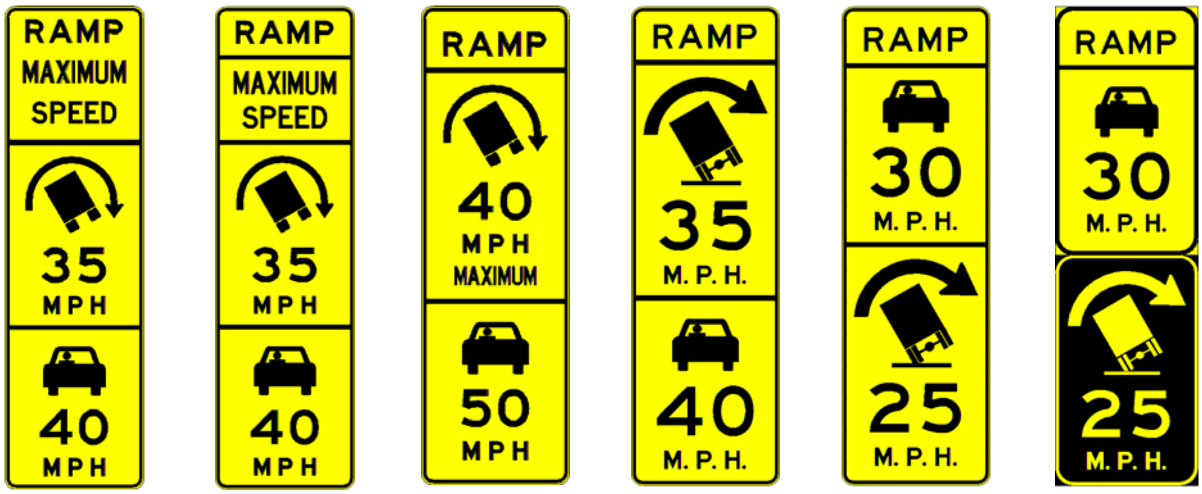
Figure 13. W13-3 – Ramp Advisory Speed Warning Sign.

Figure 14. W1-13 – Standard Tipping-Truck Advisory Speed Warning Sign.

Figure 15. W8-5 – Standard Slippery When Wet Warning Sign.

Figure 16. W1-13 –Truck Advisory Speed Warning Sign (Houston District).

Several combinations of these signs and their individual elements were developed to complete several initial attempts at conveying the dual-advisory speed warning information to both groups of motorists. Figure 17 presents the proposed roadside mount signs, and Figure 18 depicts the preliminary overhead mounted versions.



Test Sign R-A Test Sign R-B Test Sign R-C Test Sign R-D Test Sign R-E Test Sign R-F

Figure 17. Initial Dual-Advisory Speed Concept Signs (Roadside).

Test Sign OH-A Test Sign OH-B

Figure 18. Initial Dual-Advisory Speed Concept Signs (Overhead).

A series of peer reviews, research meetings, and professional critiques were completed for each of the prototype signs that were developed by the researchers. One item of discussion during the peer reviews was the appropriateness of using "MAXIMUM" on a warning sign. A second tenet of the peer review was that the truck graphic as presented in Figure 16 was more conspicuous and had an easy to convey meaning, especially with the roadway as a reference for the "tipping-truck" intention of the sign. The consensus was to test signs R-D, R-E, and R-F in each of the focus group meetings to determine driver reaction and comprehension. The overhead signs were modified to incorporate the most preferred sign of the three roadside signs (R-D, R-E, and R-F) as an attachment to the side of the guide sign; the resulting preferred overhead sign as shown in Figure 19 was developed.

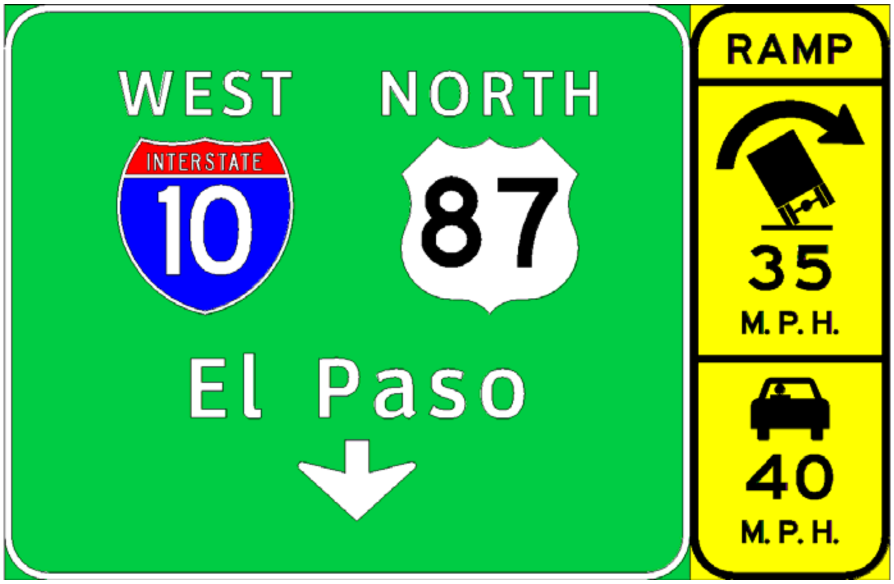


Figure 19. Prototype Overhead Dual-Advisory Speed Warning Sign.

FOCUS GROUP RESULTS

The primary goals of the focus group discussions were to obtain good insight into driver understanding of a dual-advisory speed-signing scheme and ensure that the results of the research were comprehensible to the motoring public. Four focus groups were held in August 2004, two with samples of the general licensed driving population (Houston and San Antonio) and two with groups of professional truck drivers (New Braunfels and Houston). The 51 focus group participants were all licensed drivers in Texas; 25 were in the general population group, and 26 were in the professional truck driver group.

Focus Group Sessions

The questions discussed during focus groups concentrated on two topic areas: warning signs and pavement markings. The majority of each session focused on signing comprehension and discussion. A lesser amount of time was spent on gathering opinions on innovative pavement marking designs that previous research had concluded to have some potential to affect speeds on freeway connectors. Participation was voluntary for all focus group participants and was open to all licensed drivers 18 years of age and older. Groups were given a brief introduction to the study and then asked to identify what they felt were some problems they experience at freeway-to-freeway connector ramps. Participants were asked to think about the signs and pavement markings typically seen on connector ramps, how as drivers they choose which lane to drive in, and at what speed to traverse the ramp. Focus group facilitators then asked participants to sketch signing typically seen on the approach to a freeway connector ramp. This task was performed to determine the level of recall of currently used standard signing schemes individual group members may have. In order to make clear the use of varying advisory signing schemes, participants were shown typical advisory speed signing at connector ramps. The use of W1-2 (Figure 20), W13-2 (Figure 21), and W13-3 (Figure 22) signs were shown to the groups as the most typical signs found at freeway-to-freeway connector ramps in Texas.

Figure 20. W1-2.

Figure 21. W13-2.

Figure 22. W13-3.

The groups were then asked about the use of truck graphics on advisory signs to see what combination of truck graphics and advisory speed signing participants preferred. Three signs currently used on freeways in Texas, the Texas MUTCD *(15)* standard W1-13 (Figure 23), a modified sign with advisory speed (Figure 24), and a modified sign with advisory speed plaque used commonly in the TxDOT Houston District (Figure 25), were shown to the group.

Figure 23. W1-13.

Figure 24. Modified Truck Advisory Speed Warning Sign.

Figure 25. Modified Truck Advisory Speed Warning Sign (Houston).

The focus group participants were then asked to discuss the signs which had been presented (Figures 20 to 25) and to convey their interpretation of the sign, e.g., what they thought when they saw the sign with respect to speed choice. The groups were then given information about how the engineering practice currently sets advisory speeds (based on research from the 1930s and 1940s). Focus group facilitators also provided research details including how current ball-bank values – comfort levels of blindfolded, unbuckled passengers on bench seats – were established. The differences in vehicle factors (suspensions, tires, bucket seating, etc.) from the early vehicles to those common now were mentioned, and a statement was proposed to each group about having different advisory speeds for cars and trucks.

Group participants were then asked if such a sign would change their driving behavior and to sketch their individual idea of what such a sign would look like. After the group had completed sketching their individual dual-advisory speed signs, the timed comprehension sign test was conducted. Four sign types were shown to each group with four different exposure times, for 16 timed comprehension tests. A brief summary and rationale of each test sign is as follows:

- Test Sign #1 (Figure 26) – Modified W13-3 with tipping-truck graphic and associated advisory speed on top, car graphic and associated advisory speed on bottom;
- Test Sign #2 (Figure 27) – Modified W13-3 with car graphic and associated advisory speed on top, tipping-truck graphic and associated advisory speed on bottom;
- Test Sign #3 (Figure 28) – Modified W13-3 with car graphic and associated advisory speed on top, and tipping-truck graphic and associated advisory speed on bottom in reverse (yellow on black) lettering and graphic; and
- Test Sign #4 (Figure 29) – Overhead guide sign with modified W13-3 with tipping-truck graphic and associated advisory speed on top, car graphic and associated advisory speed on bottom placed to the right of the sign.

Participants were asked to identify six characteristics of each sign within the time allotted:

- presence of the word "EXIT" or "RAMP,"
- presence of a truck graphic,
- presence of a car graphic,
- the truck advisory speed,
- the car advisory speed, and
- placement of the truck and car graphics (whether on top or bottom).

Participants were randomly shown four signs for 0.8 seconds, 1.3 seconds, 1.8 seconds, and 2.8 seconds. These intervals had been used with success in several previous sign comprehension studies. After each sign was shown for the required duration, participants noted their observations on an answer sheet. After the comprehension test for all 16 signs was completed, a general discussion ensued on the general layout of the signs and what the group as a whole preferred.

Figure 26. Test Sign #1.

Figure 27. Test Sign #2.

Figure 28. Test Sign #3.

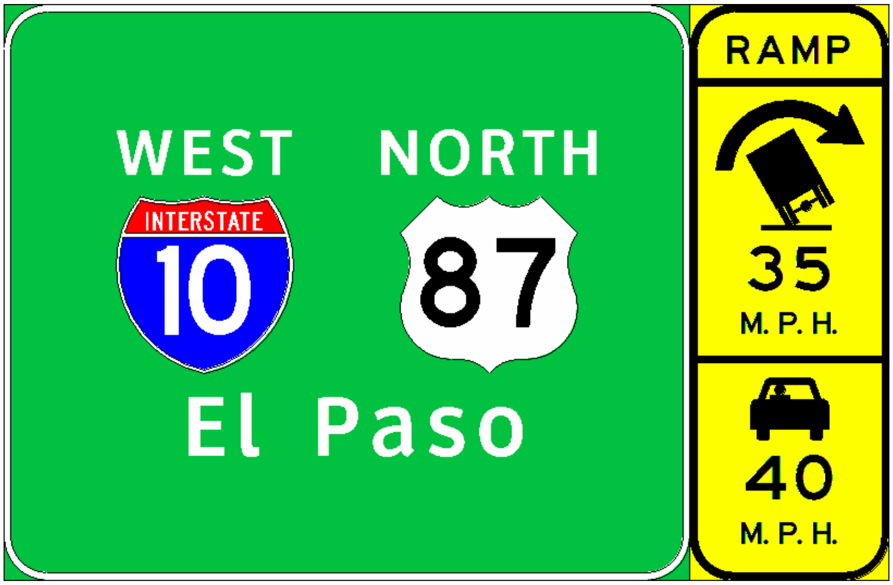


Figure 29. Test Sign #4.

General Population Group Results

The general population groups were recruited in two primary methods:

- using flyers posted in the office buildings where the focus groups were to be held, and
- via phone solicitation using previous focus group participants in other TTI research studies.

The Houston focus group consisted of 12 participants (7 male, 5 female) with ages ranging from 25- to 62-years-old. The San Antonio group consisted of 13 participants (6 male, 7 female) with ages ranging from 18- to 64-years-old. The drivers were generally very experienced drivers, with 20 of 25 having more than 20 years of licensed driving experience. Appendix C summarizes the detailed demographic statistics for the car driver participants.

The focus groups were designed to:

- determine a preference for the truck graphic,
- determine a preference of the dual-advisory sign layout, and
- test sign comprehension of a dual-advisory speed sign.

The participants were very opinionated concerning the issues they see at freeway connector ramps, including not enough signing, signs being too small, and the advisory speeds being unrealistically low. After some discussion about providing different advisory speeds for cars and trucks, participants were asked to each sketch what a dual-advisory speed sign should look like. TTI researchers took some of the more interesting concepts sketched by the group participants and developed these into signs that are presented in Figure 30. The signs sketched by the general population focus groups generally contained more text than graphics, but as expected some sketches did contain truck graphics, curves, and car graphics. Other signs that the general population groups sketched included the text "REDUCED SPEED AHEAD," "EXITSPEED," "REDUCE SPEED TO XX," and "SHARP CURVE."

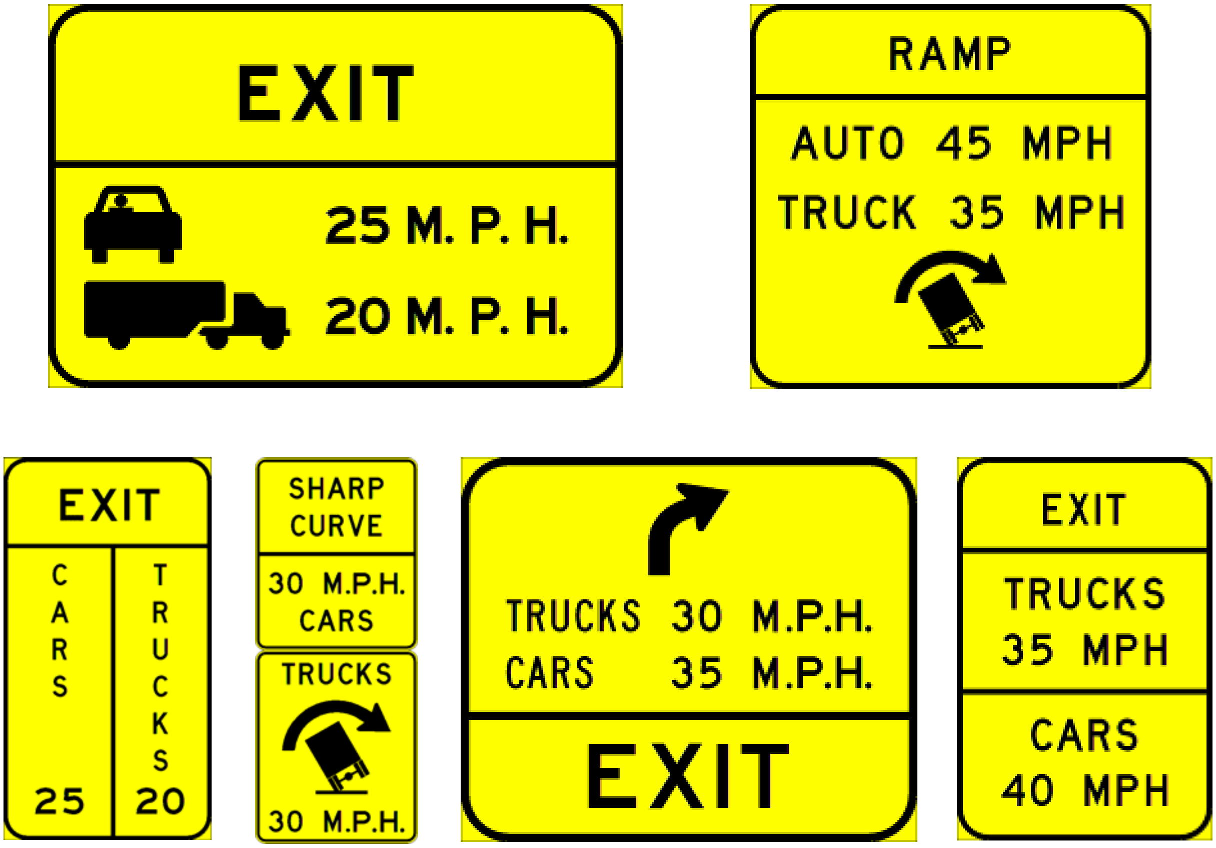


Figure 30. Dual-Advisory Speed Signing Sketched by General Population Focus Groups.

When presented with the question of preference of the three signs shown in Figures 23, 24, and 25, 80 percent of the general population groups preferred the modified truck advisory speed sign shown in Figure 25. Participants thought that the 180-degree curve shown in W1-13 (Figure 23) could relate to a u-turn movement. Some participants remarked that it was not clear if the 35 on Figure 24 was for miles per hour or kilometers per hour since the standard "M.P.H." was not shown. Another comment concerning the preferred sign was the "boldness" of the truck graphic included on the sign.

The timed sign comprehension was used to determine which sign elements drivers could correctly identify in a limited exposure time. The signing elements the focus group members were asked to identify included:

- "RAMP" or "EXIT" wording,
- car and/or truck graphic presence
- location of car and/or truck graphic (top or bottom),
- car advisory speed, and
- truck advisory speed.

The group members were asked to list as many of the elements they recognized and were asked to identify characteristics of those elements they viewed during the allowable exposure time. Some individual participants seemed to focus on the identification of graphical elements, while a lesser percentage focused their comprehension on the text ("RAMP" or "EXIT") and advisory speed. The general population group as a whole was able to identify correctly the sign elements with a 30 to 40 percent success rate.

Of the individual sign elements that participants were asked to identify, the highest rate of comprehension (more than 40 percent) were car and truck graphics. Fewer participants were able to correctly identify the advisory speeds, "RAMP" or "EXIT" designations, or correct location of truck or car graphic (top or bottom of the sign). About 30 to 35 percent of the general population participants correctly identified these sign elements. It did not appear that the exposure rates had much impact on comprehension. Most of the general population participants quickly identified what was important to them (either graphic or speed) on the signs as each was displayed. Interestingly, participants tended to be proficient at correctly identifying one element (either graphic or speed) but not both.

Professional Truck Driver Group Results

The professional truck driver groups were recruited with contacts from the Texas Motor Transportation Association (TMTA), specifically Mr. B.L. Manry of Palletized Trucking in Houston and Mr. Richard Mayuchi of the Wal-Mart Distribution Center in New Braunfels. Each of these organizations hosted the focus group in their training room.

The Houston truck driver focus group consisted of 15 male participants with ages ranging from 40- to 82-years-old (average age 53). The San Antonio group consisted of 11 participants, all male, with ages ranging from 39- to 66-years-old (average age 51). The drivers were generally very experienced drivers, with 25 of 26 having more than 20 years of licensed driving experience. Appendix C summarizes the detailed demographic statistics for the truck driver participants.

The focus group sessions for the professional truck drivers were identical to the general population focus groups. Similar to that of the general population, the focus groups were designed to:

- determine a preference for the truck graphic,
- determine a preference a dual-advisory sign layout, and
- test sign comprehension of a dual-advisory speed sign.

The truck driver participants were very insightful about the issues encountered at freeway connector ramps, including lack of sufficient signing, signs being too small, and geometrics not being "truck friendly." The "not truck friendly" comments generally referenced too short upstream and downstream segments for acceleration and deceleration between connector ramps and the freeway mainlanes, not enough advanced signing in urban conditions, and not enough flashing yellow beacons outfitted warning devices. After some discussion about providing different advisory speeds for cars and trucks, participants were asked to sketch their individual concepts of the ideal dual-advisory speed sign. TTI researchers developed some of the more interesting concepts sketched by the group participants and developed these into signs that are presented in Figure 31.

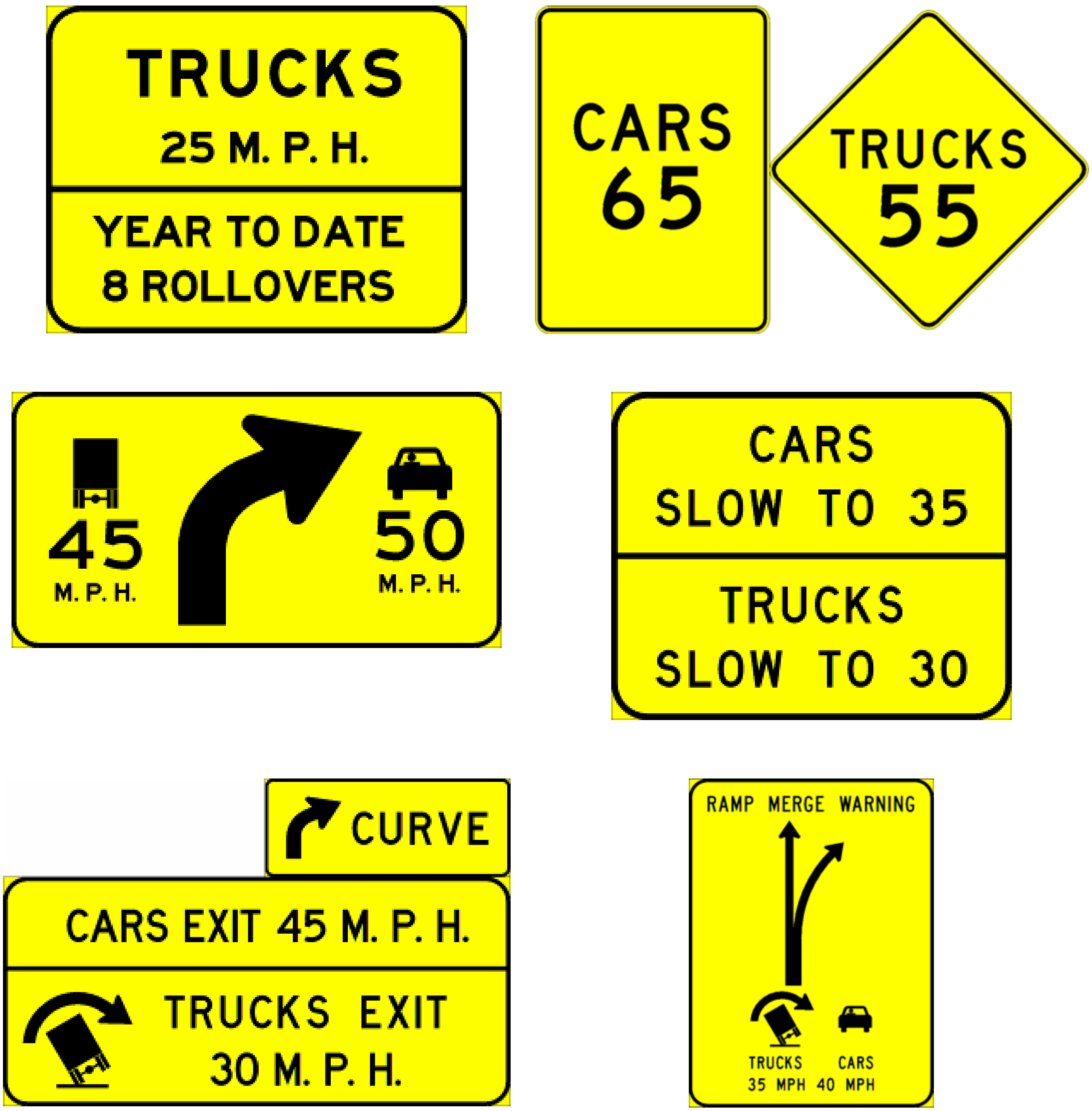


Figure 31. Dual-Advisory Speed Signing Sketched by Truck Driver Focus Groups.

The signs sketched by the truck-driving group were similar to signs sketched by the general population groups in that each generally contained more text than graphics. Similarly, those signs were comprised of graphics that were expected (truck graphics, curves, car graphics, etc.). Other signs that the truck driver groups sketched included the text “RAMP MERGE WARNING,” “CARS EXIT,” “TRUCKS EXIT,” “CURVE,” and “SLOW TO XX.” The truck drivers also conveyed concern that not enough signing was given for changing geometric conditions (e.g., ramp lanes merge ahead) which may cause erratic movements for trucks. Both the New Braunfels and Houston groups of truck drivers remarked that flashing yellow lights intended to warn of upcoming features received more of their attention than signs not equipped with such warning lights.

When presented with the question of preference of the three signs shown in Figures 23, 24, and 25, 50 percent of the general population groups preferred the modified truck advisory speed warning sign (Figure 25), while 46 percent preferred the modified truck advisory speed warning sign (Figure 24). None of the professional truck drivers selected the standard W1-13 sign. Similar to the results of the general population focus groups, the truck driver participants interpreted the 180-degree curve shown on W1-13 as related to a u-turn movement. The “boldness” of the truck graphic on the modified truck advisory speed warning sign (Figure 25) was also a preference among the drivers.

Similar to the general population groups, the sign comprehension test for truck drivers was used to determine which sign elements could be correctly identified in limited exposure time. The group members were asked to list as many of the elements that could be recognized and identified during the allowable exposure time. In general, the truck driving groups performed better on the comprehension analysis than the general population groups. This would be somewhat expected since the truck drivers presumably have much more driving experience and exposure than that of the general population participants.

The truck-driving group as a whole was able to identify correctly the sign elements with an average 40 to 60 percent rate as compared to the 30 to 40 percent success rate of general population participants. Of the individual elements that participants were asked to identify, the highest rate of comprehension were of truck and car graphics; 50 to55 percent correctly identified the truck graphic, and about 50 percent correctly identified the passenger car graphic. Fewer truck driver participants were able to correctly recall the advisory speeds (35 to 40 percent), “RAMP” or “EXIT” designations (40 to 45 percent), or correct location of truck or car graphic (top or bottom) (30 to 40 percent). Similar to the general population groups, exposure times did not appear to have impact on comprehension success rate. Overall, the professional truck drivers were able to identify sign elements at about a 10 percent higher rate than the general population drivers.

FINAL PROTOTYPE SIGN DESIGN

Based on the results of the professional peer review and focus group sessions, a final prototype sign was selected. Test Sign #1 was the preferred sign, with the truck graphic and advisory speed on top and the car graphic and car advisory speed on the bottom. The reverse contrast (yellow on black) was eliminated because of the concerns of both the professional review and focus groups that that treatment meant that trucks should go at the stated advisory speed at night only. Figure 32 shows the detailed measurements for the prototype signing.

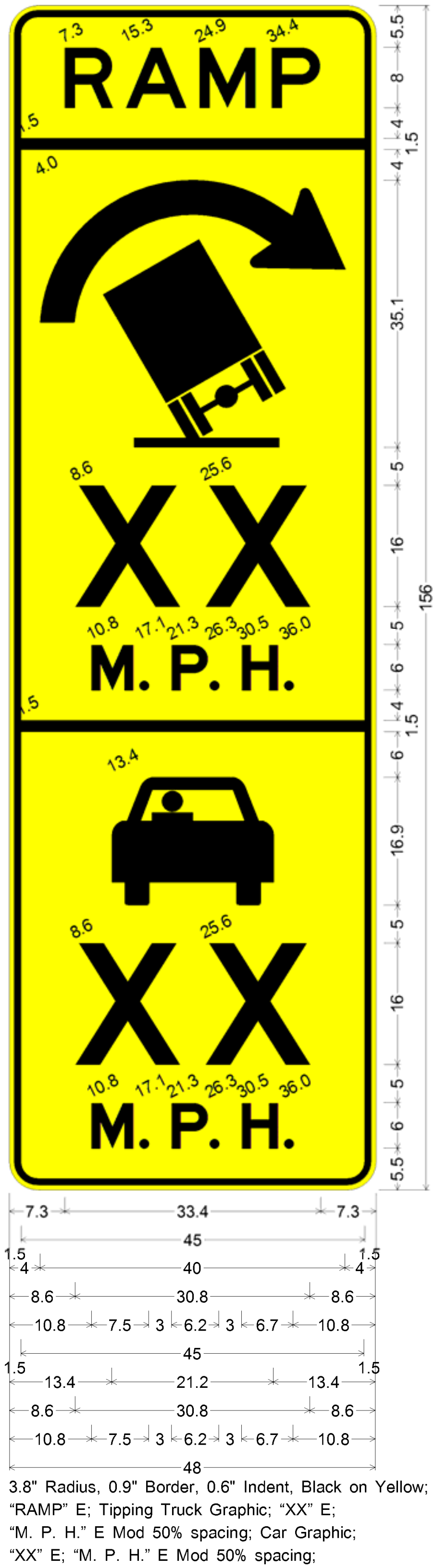


Figure 32. Final Prototype Dual-Advisory Speed Warning Sign Design.

CHAPTER 7. DUAL-SPEED ADVISORY SIGNING IMPLEMENTATION

This chapter describes the ball-bank testing and the procedures used to set the posted advisory speeds for both the passenger vehicles and trucks at each of the six study sites. An important factor in final selection of the study sites were the recommendations of the district transportation operations engineers and the ability of those districts with selected freeway-to-freeway connector ramps to implement the signing in a short time frame. An application for experimental sign evaluation was submitted to and approved by the TxDOT Traffic Operations Division prior to sign implementation in the field.

Mechanical and electronic ball-bank readings were taken at step-wise 5 mph intervals until readings over 14 degrees were obtained at each of the six study sites. The differences between the mechanical and electronic ball-bank readings are a reflection of the operating parameters of each methodology used. The electronic device provides a reading at 250 millisecond intervals and is not subject to the dampening effect of the traditional liquid-filled mechanical ball-bank indicator. Conditions during the run such as irregular pavement (bumps or dips) or driver oversteer can cause increases in the electronic ball-bank readings over those seen in the liquid-filled ball-bank device. Table 3 presents a comparison of these readings for the study ramps. The speed selected for the first ball-bank test run for each curve was generally the speed 5 mph below the existing posted advisory speed unless researchers believed that curve conditions warranted test runs below the existing posted advisory speed.

Table 3. Observed Ball-Bank Indicator Readings.

Site/Speed	30 mph		35 mph		40 mph		45 mph		50 mph		55 mph	
	BB*	EBB	BB	EBB	BB	EBB	BB	EBB	BB	EBB	BB	EBB
Dallas 1					6	6.76	9	9.37	11	11.38	16	16.71
Dallas 2					7	7.72	9	9.48	12	14.15	18	17.17
Dallas 3	5	9.75	7	11.49	11	11.91	14	14.35	18	19.33		
Fort Worth 1					7	8.31	10	11.87	14	14.72		
Houston 1			7	11.23	9	10.66	12	13.78	16	19.31		
Houston 2			8	8.67	10	11.05	15	14.08				

*Note: BB – Ball Bank Indicator; EBB – Electronic Ball Bank Indicator (Accelerometer)

A previous study by Voigt et al. concluded that advisory speeds on freeway-to-freeway connectors for passenger vehicles should be based upon ball-bank readings of 13 to 14 degrees *(1)*. That research also recommended that the advisory speed for trucks be posted using the 10-degree ball-bank reading. Using these guidelines, the dual-advisory speeds used for the implementation sites were determined. Table 4 shows the previous advisory speeds and dual-advisory speed recommendation (as implemented) values.

Table 4. Advisory Speeds Before and After Sign Installation.

Site/Vehicle Classification	Before Installation (All Vehicles)	After Installation (Passenger Vehicle/Heavy Truck)
Dallas 1 – IH 635 Northbound to US 80 Eastbound	40 mph	50 mph/45 mph
Dallas 2 – US 80 Westbound to IH 635 Northbound	40 mph	45 mph/40 mph
Dallas 3 – IH 635 Westbound to IH 35E Northbound	35 mph	40 mph/35 mph
Fort Worth 1 – IH 35W Northbound to IH 820 Westbound	None posted (35 mph)	40 mph/35 mph
Houston 1 – IH 610N Eastbound to IH 45N Northbound	35 mph	45 mph/35 mph
Houston 2*	35 mph	40 mph/35 mph

*later disqualified

In addition to using the ball-bank study results, researchers considered other factors in applying the recommendation for advisory speeds at the study sites. For example, the Dallas 2 curve is on a downgrade and has a "dip" in the road surface about halfway through the curve; concerns existed about an oversteering maneuver that may increase the potential for rollover situation for some high center-of-gravity vehicles. The researchers were uncertain as to the impact of the higher advisory speeds on the rollover potential, so researchers used lower, more conservative values at that location. For the Dallas 1 site, the previous advisory speed (40 mph) was set well below the standard 10-degree thresholds, resulting in higher advisory speeds for both truck and cars on the installed experimental signs. For the other three connector ramps studied, the posted advisory speed limits for trucks were identical to the previous general advisory speed, and advisory speeds for passenger cars were set according to the 14-degree ball-bank reading. The Houston 1 site was the only site where the car and truck posted advisory speed limits differed by more than 5 mph (10 mph in this case). The following pages show photographs (Figures 33 to 42) of each of the test sites after signs were installed.

Figure 33. IH 635 Northbound to US 80 Eastbound (Dallas 1).

Figure 34. US 80 Westbound to IH 635 Northbound (Dallas 2).

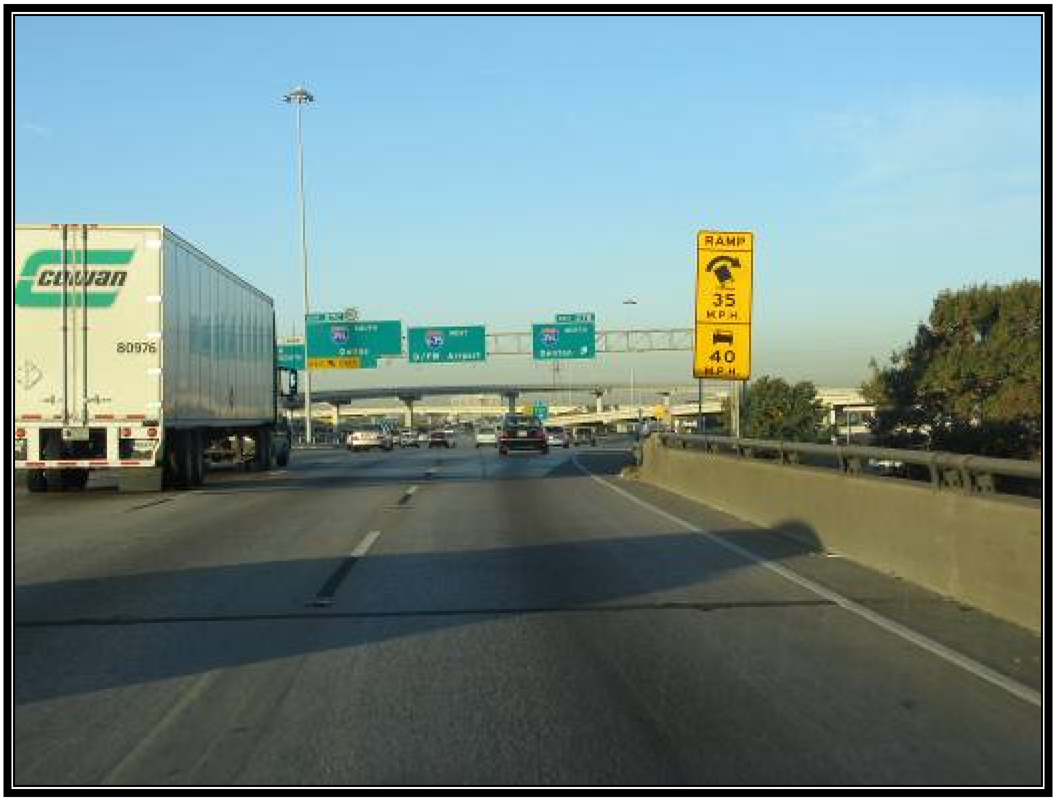


Figure 35. IH 635 Westbound to IH 35E Northbound (Dallas 3 – Upstream).

Figure 36. IH 635 Westbound to IH 35E Northbound (Dallas 3 – at PC).

Figure 37. IH 35W Northbound to IH 820 Westbound (Fort Worth 1 – Upstream).

Figure 38. IH 35W Northbound to IH 820 Westbound (Fort Worth 1 – at PC, Overhead).

Figure 39. IH 610N Eastbound to IH 45 Northbound (Houston 1 – Upstream Overhead).

Figure 40. IH 610N Eastbound to IH 45 Northbound (Houston 1 – at PC).

Figure 41. US 59 Southbound to IH 610 Eastbound (Houston 2 – Upstream Overhead).

Figure 42. US 59 Southbound to IH 610 Eastbound (Houston 2 – at 500 feet upstream of PC).

CHAPTER 8. EFFECTIVENESS OF DUAL-ADVISORY SPEED WARNING SIGNS

INTRODUCTION

In order to determine the operational and safety impacts of the dual-advisory speed sign concept, researchers formulated several data analysis objectives. The first was to complete a comprehensive before-after study of vehicle operational speeds on each of the study freeway-to-freeway connector ramps where the experimental signs had been installed. A second objective was to assess the potential safety benefits of installing the dual-advisory signs by a review of crash records for each of the ramps. This chapter begins with an assessment of the effectiveness of the dual-advisory sign on vehicle operational speeds. This section discusses the data analysis and presents the results from the evaluations by study site. The concluding section presents a naïve before-after crash analysis by study site.

To facilitate a before-after study to determine the impact of the dual-advisory speed warning signs, researchers collected speeds in three study periods:

- before the installation of the dual-advisory speed warning signs,
- early-after (about 1 to 3 months of sign installation), and
- late-after (about 4 to 6 months after installation).

Researchers collected automatic tube data at three locations on each study curve:

- upstream of curve,
- beginning of curve, and
- middle of curve.

VOLUME/SPEED/CLASS DATASET PROCESSING AND QUALITY CONTROL

Prior to the use of any data in analysis, researchers reviewed the data collected via automatic tubes for accuracy at each of the six study sites. Quality control for single lane connector ramps in Dallas and Fort Worth consisted of researchers concentrating on the review of hourly count data and checking for consistency during the AM and PM peak periods to illuminate any incidents or congestion issues.

For the Houston two-lane ramps, quality control procedures included checking not only consistency during the peak periods but also for consistency between the two lanes of traffic. Several times during the data collection, tubes came up on only one lane. In this case, researchers removed all the data for those hours of the data collection.

TTI personnel also reviewed the amount of data collected, setting a requirement of at least 125 heavy vehicle measurements to be included in each study site and curve location. To ensure that "clean" data files were used, researchers renamed the data-reduced text files and denoted them as edited files.

Segmentation of Free Flowing Vehicles

It was necessary to isolate those vehicles that were theoretically under no outside influence in their choice of speed as they approached or traversed the study curves. It was then necessary to define a free-flow condition for vehicles approaching and traversing the connector ramp. The Highway Capacity Manual (HCM) defines free flow speeds as "traffic unaffected by upstream or downstream conditions" *(33)*. Under the assumption that the connector ramp geometry determines the free-flow speed, researchers needed to filter data so that individual speed measurements reflect only those theoretically affected by ramp geometry and unaffected or not influenced by other vehicles, incidents, or congestion. To accomplish this, all data sets were filtered by the length of the headway (or gap) between vehicles. If individual vehicle headway was less than 5 seconds, it was removed from the data set.

ANALYSIS OF FIELD DATA

Using Statistical Analysis Software (SAS), researchers combined vehicles that had been categorized by the TimeMark counter software into the 13 FHWA classification groups. Table 5 summarizes the three categories of vehicles with similar operating characteristics that were created. Researchers completed this in order to facilitate a comparison among vehicle types with similar operating characteristics.

Table 5. Vehicle Groups for Comparison among Types.

Group	FHWA Classification	Description
Passenger Vehicles	1, 2, and 3	Passenger Cars, Light Trucks, Motorcycles
Rigid Vehicles	4, 5, 6, and 7	Larger vehicles between 2 to 4 axles that did not have a detachable trailer for transporting goods
Heavy Vehicles	8, 9, 10, 11, 12, and 13	Various configurations of tractor-trailer combinations

Vehicle speed and classification data were collected, reduced, and analyzed at three locations along each of the connector ramps (upstream of curve, beginning of curve, and middle of curve). Figure 43 shows where these points lie on a typical curve.

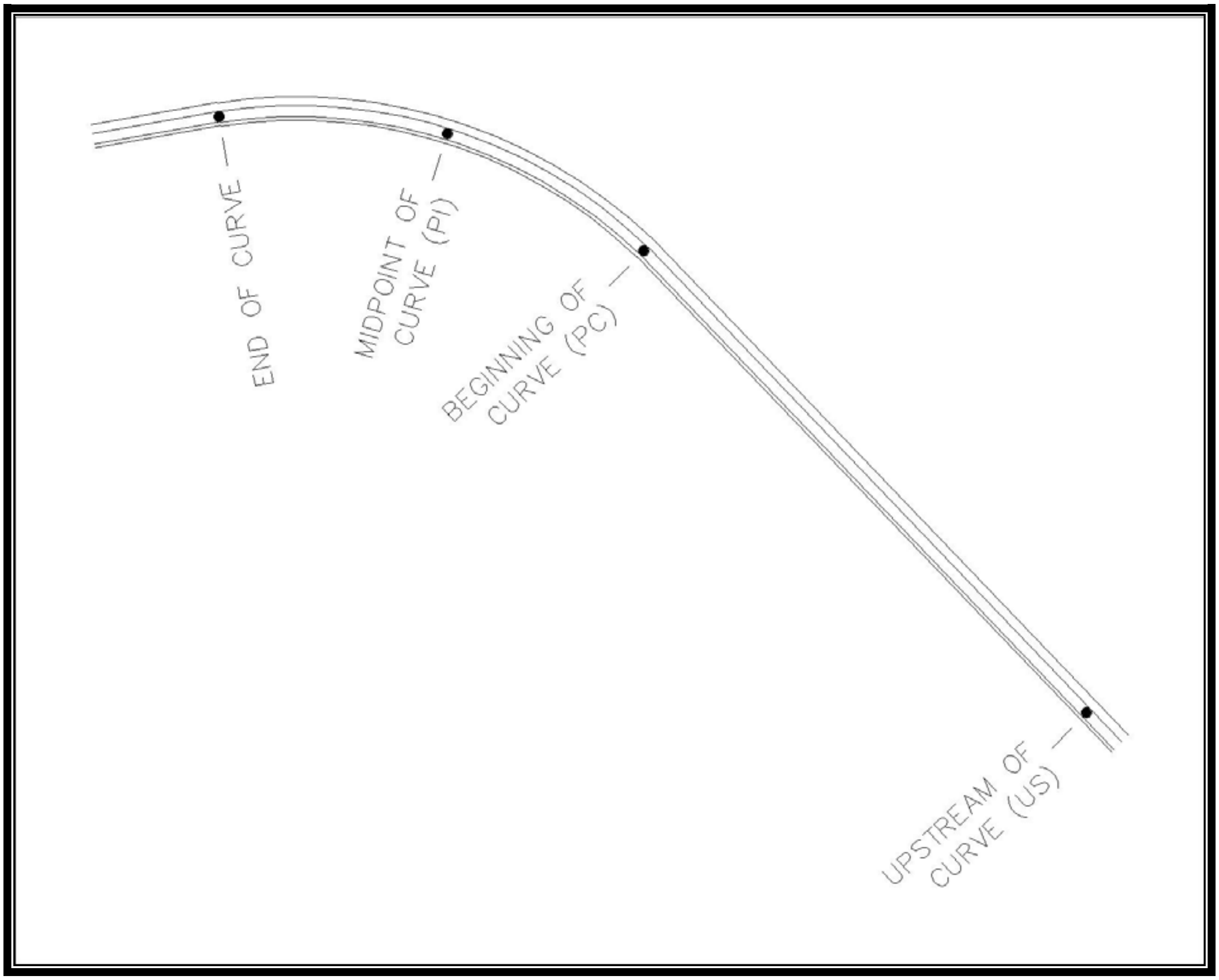


Figure 43. Definition of Curve Points.

Data Analysis Techniques

The primary goal of the research was to quantitatively assess the effects of the installation of the sign with respect to speed reduction on the freeway connector curves. In consideration of the goals of the research, analysts determined that the following evaluations would be appropriate to assess the dual-advisory speed warning sign concept on vehicle operating speeds:

- calculation and analysis of the general statistics for each study curve by curve location (US, PC, and PI), vehicle class (PV, RT, and HT), and study period (before, early-after, and late-after);
- before-after comparison of the 85th percentile speed and mean speed for each study curve by study period, curve location, and vehicle class using the bootstrap comparison method;
- ANOVA for mean speeds at each curve and vehicle type;

- before-after comparison of in-curve speed reductions (US to PI) by study period (before, early-after, and late-after) and vehicle type; and
- before-after comparison of driver compliance of the classification-specific advisory speed.

General Statistical Comparisons

Researchers developed general statistics for each of the study sites by study period (before, early-after, and late-after), curve location (US, PC, and PI), and vehicle type (heavy vehicles, rigid vehicles, and passenger vehicles). General statistics calculated included the mean, standard deviation, standard error, and the 85th percentile speed for each study period at each curve location. From these individual statistics, researchers developed average statistics across study periods and curve locations in an attempt to observe trends and formulate conclusions about the effectiveness of the signs. Appendix D presents individual statistics by study period, curve location, and vehicle type. Appendix E presents a statistical comparison between speeds upstream, at the point of curvature, and at the middle of the curve.

Bootstrapped Before-After Speed Measurement Comparison

TTI researchers used several approaches to quantify the impacts that the dual-advisory speed warning signs had on vehicle operating speeds. Researchers utilized a standard before-after analytical approach for the mean and 85th percentile speeds. Statistical significance testing for changes between the "before," "early-after," and "late-after" study periods was accomplished using the percentile bootstrapped data analysis technique.

Before presenting the results of the analysis, it is important to convey the rationale in using the bootstrapped method for the analysis. If parametric testing (those statistical tests that require assumption of normality) is used on non-normal samples with relatively small sample sizes, findings of statistically significant differences between compared samples could be invalid *(34)*. Assumptions about the population's distribution and parameters are not the only issue at hand with traditional parametric procedures. Sometimes, even if the sample data is from a normal population, it could be inaccurate to test the statistic of interest using commonly available parametric tests. One example of having normal data where parametric testing would not be the best choice is when the statistic of interest is the 85th percentile speed, which is routinely used to set regulatory speed limits or provide judgment about speed distributions. Sometimes, regardless of sample size, analyzing non-normal data or a non-normal statistic, such as the 85th percentile speed, is necessary. In these cases, the data does not satisfy the underlying assumptions of normality or equal variances, and non-traditional, non-parametric statistical procedures should be utilized. One such procedure that can overcome the hostility of analyzing non-normal data parametrically or by any procedure requiring assumptions of distribution and parameters is the bootstrap method.

Bootstrapping is a non-parametric procedure and does not assume the shape of the underlying population's distribution. An important assumption that the bootstrap procedure requires is that the sample data be an accurate representation of the entire population. The bootstrapping method is a simulation method based upon resampling an existing dataset, with replacement, to develop confidence intervals around the mean value of averaged resamples *(35)*. A more detailed explanation of the bootstrapping methodology is as follows.

For example, let x1, x2,... xn be our sample, with mean, μ, and standard deviation, σ. As required by the bootstrap procedure, the existing sample data represents the entire population. In this study, both the mean and 85th percentile speeds were calculated statistics used in the analysis. Using the existing data set, resamples of size B with replacement are used to calculate the desired statistic(s) such as the mean or 85th percentile speed. For the purpose of this project, the data was resampled 300 times, slightly more than the suggested 50-250 resamples, and statistics calculated for each resample. The resamples and calculations provided 300 mean and 85th percentile speed values. The bootstrap procedure requires developing percentiles based on the desired confidence interval. For this project, researchers used a 95 percent confidence interval requiring calculation of the 2.5th and 97.5th percentiles (see Figure 44).

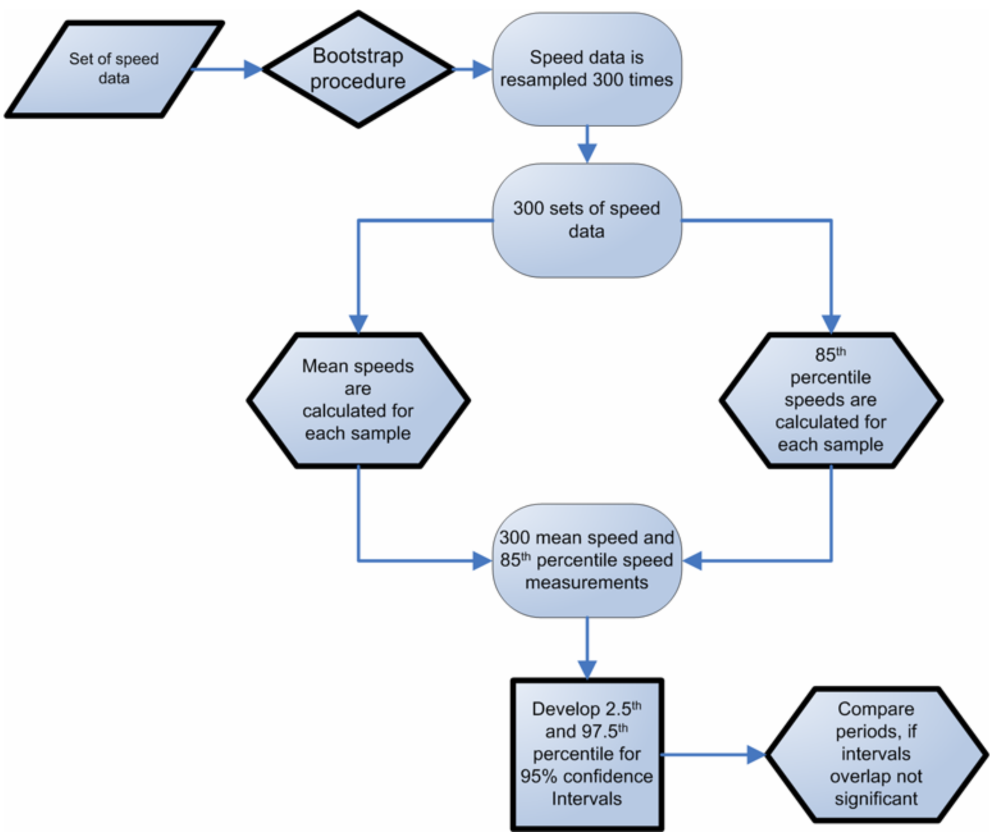


Figure 44. Bootstrapping Procedure.

There are several options for building confidence intervals from bootstrapped data. The four methods for developing bootstrap confidence intervals are the normal approximation method, bias corrected (or BC) method, percentile method, and percentile t method with double bootstrap. Each method has its strengths and weaknesses.

The normal approximation method assumes that the data is normal but no analytic standard error formula exists for this method. One additional problem with this method is that it makes strong parametric assumptions about the distribution of the data that could lead to invalid results. The BC method overcomes the restriction of assuming the sampling distribution is unbiased. One fault of the BC method is that it still requires some parametric assumptions. The percentile t method can correct for parametric assumptions but requires intensive computation time. Another name for the percentile t method is the double bootstrap *(35)*.

The most common of the four methods is the percentile method. This method frees the researcher(s) from the traditional parametric assumptions of both the normal approximation and BC methods. Although this method requires asymmetry about the mean value, this method does not require sampling distributional shape, unlike the others. In addition, when applying the already discussed central limit theorem on the 300 bootstrapped values, researchers can assume that they are approximately normal, and most likely, the data will be asymmetric around the mean. In addition to these positive characteristics, the procedure is relatively easy to use. For example, for confidence level of 95 percentile, alpha equal to 0.05, users of the procedure would calculate the 2.5th and 97.5th values and use them as the lower and upper limits of the confidence interval around the mean of the statistic in question. Two drawbacks of this procedure are that it does not work well with small samples and that there is an underlying assumption that the sampling distribution is an unbiased estimate of the entire population. For this project, the percentile method was used. Data sample sizes were quite large and researchers assumed that the data are a representation of the population.

Users of the bootstrap procedure should compare period confidence intervals to determine statistical significance between samples. If the intervals overlap then the samples are not statistically different. If the intervals do not overlap, then based on the value of alpha the difference in the two samples are considered statically significant at the one-alpha percentile confidence level.

For the purpose of this report, researchers developed confidence intervals around the mean and 85th percentile speeds for each site by study period, curve location, and vehicle type. In general, researchers theorized that the PI location was perhaps the best curve location to formulate conclusions about the effectiveness of the signs, since it is the point on the curve near where the minimum speeds would be observed and maximum centrifugal forces would theoretically be present. Therefore, in the analysis section of this report, only the detailed results for the PI curve locations are presented, with the exception of the Fort Worth site. The Fort Worth site was unique as researchers found a positive effect (reduction in speed) at the PC location. This site did not have a posted advisory speed prior to the implementation of the dual-advisory speed sign.

To determine statistical significance, TTI researchers compared the 95 percent confidence intervals between study periods for each site at the PI. If the confidence intervals did not intersect, then the two compared values could be considered "statistically significantly different."

Analysis of Variance

In addition to a statistical bootstrap approach, a standard ANOVA test was completed using the SAS PROC GLM (generalized linear model) procedure. ANOVA analysis was completed only on mean speed. It would be inappropriate to complete the analysis on the 85th percentile speeds considering the ANOVA's required underlying assumption of normality. The ANOVA procedure also requires that data be random, have a common variance, and have equal population means.

For the purposes of this report, mean speeds fit the underlying data requirement by the definition of the central limit theorem (CLT). The CLT essentially states that with a significant amount of data observation the data naturally conform to the shape of a normal distribution curve. It is common that collected speed data fit the normal distribution, as compared to other types of data (such as crash data), which usually fit to a Poisson or negative binomial distribution.

In addition to the assumption of normality based on the central limit theorem, researchers reviewed several sets of data graphically and observed them as fitting the normal distribution curve. Researchers compared relationships between study period, location on curve, and vehicle class. Researchers also compared combinations of these characteristics.

Researchers completed an ANOVA procedure across locations in the curve (US, PC, and PI), vehicle class, and study period. A basic assumption for using the ANOVA procedure is that the data fits the standard normal distribution. Researchers assumed normality based on the definition of the central limit theorem. Additionally, several data sets were checked to determine if the data fit the symmetrical bell-shaped curve synonymous with the normal distribution.

The common use of traditional parametric procedures such as the student's t-test and ANOVA are based on several major assumptions about the characteristics of the sample data's population. In addition to the assumption of normality, parametric procedures assume samples are independent and random *(35)*. Parametric statistical methods also assume distribution and that sample variances are equal between compared data.

In most cases, data with larger sample sizes meet the requirement of normality based on the central limit theorem; this is especially true when comparing the sample means. The central limit theorem suggests:

> *If random sample of n measurements are repeatedly drawn from a population with a finite mean μ and a standard deviation σ, then when n is large, the relative frequency histogram for the sample means (calculated from the repeated samples) will be approximately normal (bell-shaped) with mean μ and standard deviation $(\sigma/n)^{1/2}$.*

Also, this assumption becomes more precise with increasing number of observations (34).

The Null Hypothesis

The sole reason for using the ANOVA procedure is to statistically determine if the sample means differ from each other. For the purposes of this report, researchers sought to determine whether or not the sample mean speed measurements differ among curve locations sampled, study period, and vehicle class. Using the ANOVA, it is also possible to combine these parameters and determine if the combinations are different. For instance, the question could be asked: *Are the sample means for heavy vehicles from the before period at the PC different from the sample mean for heavy vehicles from the after period at the PI?* If the sample means are identified as statistically different, inferences about the sample population can be drawn *(34)*.

The null hypothesis for this project states that all population means are equal for all conditions. Equation 6 is an example of the null hypothesis. The hypothesis would vary based on the conditions being measured. The example below is for vehicle class.

$$H_o = \mu_{Heavy\,Vehicles} = \mu_{Passenger\,Vehicles} = \mu_{Rigid\,Vehicles} \qquad \text{(Eq. 6)}$$

where μ_n is the population mean for condition "n."

The alternate hypothesis (H_A) is that at least one of the population means differs from the others. The probability of a Type III error (or α) is equal to 0.05 for all tests of significance. Type III sum of squares values were considered for this analysis. Type III values were used instead of Type I because Type I considers variables in sequence. Type III considers each variable in the presence of other independent variables in the model *(36)*. The test statistic used to determine the equality of means is the F statistic. The F test calculates the ratio between sample variance and within sample variance. Sample variance has also been described as the sum of squares value divided by its degrees of freedom. This value has also been called a mean square.

The null hypothesis is rejected based on the calculated F statistic. Significance is based on whether the calculated F statistic is above or below a tabular value based on the degrees of freedom between samples, the degrees of freedom within samples, and the probability, $\alpha = 0.05$. Conveniently, SAS generates a probability value, PR>F. This value directly corresponds to the probability, $\alpha = 0.05$. If the PR>F value is less than $\alpha = 0.05$, then the null hypothesis can be rejected and the change declared significant.

Driver Compliance Monitoring

In addition to the bootstrapped samples and ANOVA analysis, researchers also performed a comparison of driver compliance to the dual-advisory warning speeds. This comparison was performed in order to support other study findings as well as show what level of compliance would be experienced with the use of a higher ball-bank reading to set higher advisory speeds for cars (in other words, to what extent is the new car advisory speed in line with operating speeds). Researchers utilized another SAS program created to calculate driver compliance before, early-after, and late-after to calculate compliance. Researchers, with knowledge of advisory speed limits at each connector ramp, generated compliance percentages by study period and vehicle type.

A final measure examined in the research project was if the users of each of the connector ramps were complying with the advisory speed limits as posted on the experimental signs. The percentage of advisory-speed-compliant drivers was determined for study period, curve location, and vehicle class at each study curve.

Effectiveness of the Dual-Advisory Sign on Safety

Researchers attempted to collect crash data from the cities of Houston, Dallas, Mesquite, and Fort Worth for the sites within those jurisdictions. With the knowledge of the dates of installation for each dual-advisory sign, researchers requested or obtained all available crash records for one year before and up to one year after implementation of the signs. Researchers obtained (or were provided) data for four of the five study sites. The City of Fort Worth was not able to provide crash data within the time constraints of this project. Table 6 presents a summary of crash data successfully collected.

Table 6. Crash Data Collection Summary.

Site	Connector Ramp	Date of Installation	Reports Obtained	Provided By
Dallas 1	IH 635 to US 80 Eastbound	3/29/2005	1	City of Mesquite
Dallas 2	US 80 Westbound to IH 635N	3/30/2005	11	City of Mesquite
Dallas 3	IH 635 Westbound to IH 35E Northbound	10/19/2005	90	City of Dallas
Fort Worth 1	IH 35W to IH 820 Westbound	3/30/2005	-	-
Houston 1	IH 610 Eastbound to IH 45 Northbound	2/26/2005	6	Houston Police

Researchers collected crash data for one year before and one year after the installation of the advisory signs from local police departments with law enforcement jurisdiction at each of the six study sites. Individual crash reports were obtained from the cities of Dallas, Houston, and Mesquite. Researchers reviewed crash narratives and sketches to be certain of the location of the crash and if the crash took place on the connector ramp under study. Seventeen crashes were noted during the two-year study period. Because of the limited number of crashes and short time period studied, researchers used a naïve before-after study to assess the impact of the signs.

Naïve Before-After Crash Analysis

In order to assess the safety impacts of the installation of the dual-advisory speed warning sign, the crash analysis focused on the number of motor vehicle crashes that occurred one year before the installation and compared them to those that took place in the year following the installation. Safety measures of effectiveness (MOEs) consisted of using a naïve before-after approach and a calculated index of effectiveness value *(37)*. Given the small number of crashes and limited time period to be analyzed, this method was the best tool available to provide a statistical comparison with MOEs. Using standard statistical techniques (such as comparative student t-test or ANOVA) are not feasible since crash data is known to fit position or negative binomial distributions and does not fit standard techniques that employ an underlying assumption of normality.

In order to complete the project, several parameters were calculated using the equations below *(37)*:

$$\hat{\lambda} = \sum L(j) \quad \textit{Count of Crashes After} \tag{Eq. 7}$$

$$\hat{\pi} = \sum K(j) \quad \textit{Expected Number of Crashes if Nothing Changed} \tag{Eq. 8}$$

Where the estimates of variance are:

$$VAR\{\hat{\lambda}\} = \sum L(j) \tag{Eq. 9}$$

$$VAR\{\hat{\pi}\} = \sum K(j) \tag{Eq. 10}$$

In addition to these parameters, MOEs include the change in crashes, $\hat{\delta}$, its variance, $VAR\{\hat{\delta}\}$, the index of effectiveness, $\hat{\theta}$, and its variance $VAR\{\hat{\theta}\}$. These MOE expressions are described below:

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{Eq. 11}$$

$$VAR\{\hat{\delta}\} = VAR\{\hat{\pi}\} + VAR\{\hat{\lambda}\} \tag{Eq. 12}$$

$$\hat{\theta} = \frac{\hat{\lambda}/\hat{\pi}}{(1 + VAR\{\hat{\pi}\}/\hat{\pi}^2)} \leftarrow \textit{Adjustment Factor for Less than 500 Observations} \tag{Eq. 13}$$

$$VAR\{\hat{\theta}\} \approx \frac{\theta^2[(VAR\{\hat{\pi}\}/\lambda^2) + (VAR\{\hat{\pi}\}/\hat{\pi}^2)]}{[1 + VAR\{\hat{\pi}\}/\hat{\pi}^2]^2} \leftarrow \textit{Adjustment Factor for Less than 500 Observations} \tag{Eq. 14}$$

The index of effectiveness, $\hat{\theta}$, is the ratio of what safety was with the treatment to what it was without. For example, if the index of effectiveness is 0.83, this value indicates that it is predicted, based on the statistical methodologies used, that installation of the treatment would improve safety by 0.17 or 17 percent. The location after the treatment would likely have 83 percent of the number of crashes that occurred without treatment. If the index of effectiveness is larger than 1.0, the methodology predicts no improvement or increase in the number of crashes with the treatment as opposed to without the treatment. The "naïve" title implies that there are many factors involved in curve safety and that this crash analysis methodology is naïve in its attempt to predict crashes, meaning that factors such as driver type, exposure, and weather are not explicitly considered.

In addition to the before-after study, 95 percent confidence intervals were calculated for the change in the number of crashes. This confidence interval calculation is accomplished by finding the difference in the standard deviations of sample variances for the before and after study periods and multiplying it by a z-value of 1.96 for alpha = 0.05. The method assumed that the standard deviation of variance fits the standard normal distribution. To determine significance, the reader should compare the calculated 95 percent confidence value to the absolute value of the change in crashes. If the 95 percent confidence value is less than the change, it should be considered a significant change.

DALLAS 1 (IH 635 NORTHBOUND TO US 80 EASTBOUND) SITE ANALYSIS

Data observations from this study site were filtered through quality control inspection as presented in the methodology. Vehicles with gaps of less than five seconds were removed from the analysis. Table 7 presents a summary of the number of observations used. Using these observations, researchers completed the speed evaluations for Dallas 1. The previous posted advisory speed for this connector ramp was 40 mph for all vehicles. The new dual-advisory speed limits as posted on the experimental signs were 50 mph for passenger vehicles and 45 mph for trucks. The signs were installed by the TxDOT Dallas District on March 29, 2005.

Table 7. Dallas 1 – Number of Speed Observations Collected.

Vehicle Class	Before	Early-After	Late-After	Upstream (US)	Start (PC)	Middle (PI)
Heavy Vehicles	6036	2142	2553	3802	2776	4153
Passenger Vehicles	16,563	31,385	35,855	29,623	23,410	30,770
Rigid Vehicles	2028	2965	3007	2904	2069	3027

Dallas 1 General Statistics

After the dual-advisory speed sign was installed, the mean heavy truck speed at the PI increased 0.70 mph from 40.31 to 41.01 mph, and the 85th percentile speed increased 0.9 mph from 44.5 to 45.4 mph. The mean speed for passenger vehicles decreased slightly, from 48.41 mph to 47.28 mph, and the 85th percentile speed fell from 53.20 mph to 51.40 mph. Table 8 details the mean and 85th percentile speeds for the US, PC, and PI locations for all three classes of vehicles.

Table 8. Dallas 1 – Mean and 85th Percentile Speed Statistics.

Speed Measurement (mph)*		Before			Early-After			Late-After		
		Count	Mean	85th	Count	Mean	85th	Count	Mean	85th
US	Heavy Vehicles	1848	50.81	56.70	906	49.82	55.40	1048	58.18	62.90
	Passenger Vehicles	5983	57.17	63.30	12,729	56.54	61.20	10,911	61.19	66.50
	Rigid Vehicles	779	53.52	60.80	1179	54.36	59.60	946	59.52	65.50
PC	Heavy Vehicles	2121	43.15	48.70	297	46.45	51.10	358	44.94	49.50
	Passenger Vehicles	5678	51.54	56.70	6686	52.25	56.70	11,046	50.97	55.40
	Rigid Vehicles	702	47.69	54.40	577	50.23	55.40	790	49.50	54.40
PI	Heavy Vehicles	2067	40.31	44.50	939	41.92	47.50	1147	41.01	45.40
	Passenger Vehicles	4902	48.41	53.20	11,970	47.77	52.30	13,898	47.28	51.40
	Rigid Vehicles	547	44.97	50.60	1209	45.87	50.80	1271	44.85	50.30

*For vehicles with headways (gaps) of at least 5 seconds

One interesting finding was that the early-after upstream approach speeds decreased slightly compared to the before conditions, but those upstream speeds were measured as having increased for the late-after results. The researchers hypothesize that the conspicuity of the large sign did have the effect of slowing vehicles on the upstream approach shortly after the signs were installed (observed reductions of 1 to 2 mph). However, it appears that this effect was reduced after the signs had been deployed for a few months. During that same time period, the speed reductions from the PC to PI remained relatively similar (with reductions from 3.5 to 4.4 mph). It appears that motorists were decelerating more between the upstream and PC points after the signs were in place for several months. Upstream speeds were not measured in the adjacent through lanes so no comparison could be made of overall facility speeds increasing or decreasing during the test period.

Dallas 1 Before-After Speed Measurement Bootstrap Method Comparison

Mean and 85th percentile speeds for each connector ramp were compared using the percentile bootstrap statistical technique as outlined in the methodology. This technique was used to establish statistical significance between the “before,” “early-after,” and “late-after” data sets and determine if there were statistically significant differences in the speeds observed before and after the test signing was installed. As presented in Table 9, the outcome of the bootstrap analysis technique for differences in the speed data at the PI curve location yielded:

- statistically significant reductions in passenger vehicle speeds from the before to the after period, and
- statistically significant increases in heavy vehicle speeds from the before to the after period at the PI curve location.

Table 9. Dallas 1 – Changes in Vehicle Speeds, PI, Before to After.

Speed Measurement	Change in Speed (mph) Before to Early-After	Change in Speed (mph) Before to Late-After	Change in Speed (mph) Early-After to Late-After
All Vehicles			
Mean	1.27*	0.71*	-0.56*
85th Percentile	0.00	-0.68*	-0.68*
Passenger Vehicles			
Mean	-0.65*	-1.14*	-0.49*
85th Percentile	-0.99*	-1.65*	-0.66*
Heavy Vehicles			
Mean	1.61*	0.70*	-0.90*
85th Percentile	3.08*	0.89*	-2.19*

* Indicates statistical significance using the bootstrapping method.
A negative value indicates a reduction in speed.

Dallas 1 Analysis of Variance for Speed Characteristics

Researchers performed an analysis of variance for the Dallas 1 site for various data characteristics. The ANOVA output shows that the data was significantly different for study period, curve location, and vehicle class. Combinations of study period, curve location, and vehicle class were also found to be significantly different from each other (Table 10). Statistically, each source of data where PR>F is less than 0.05 suggest that their means are not equal, and the null hypothesis that the means are equal should be rejected. The rejection of the null hypothesis (that the means are equal) supports the findings that speeds changed as a result of the sign treatment.

Table 10. Dallas 1 – ANOVA Analysis Results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Period	2	11,938.25	5969.12	224.89	<.0001
Curve	2	161,064.44	80,532.22	3034.06	<.0001
Vehicle Class	2	21,116.00	10,558.00	397.77	<.0001
Period*Curve	3	8519.36	2839.78	106.99	<.0001
Period*Vehicle Class	4	4845.36	1211.34	45.64	<.0001
Curve*Vehicle Class	4	345.22	86.30	3.25	0.0112
Period*Curve*Vehicle Class	6	1411.49	235.24	8.86	<.0001

*pr > F <0.05 is statistically significant.

Dallas 1 Before-After Advisory Speed Compliance Comparison

Vehicle compliance to the posted advisory speed limit was measured before and after the installation of the dual-advisory sign. Compliance gives some indication of what proportion of the driving population using the subject connector ramp views the advisory speed as appropriate. As can be seen in Figures 45 and 46, compliance at the PC and PI sections of the curve increased progressively from the before to early- and late-after periods. Compliance rates after the signs were installed increased, indicating that the new advisory speeds are much closer to actual operating speeds on the ramp.

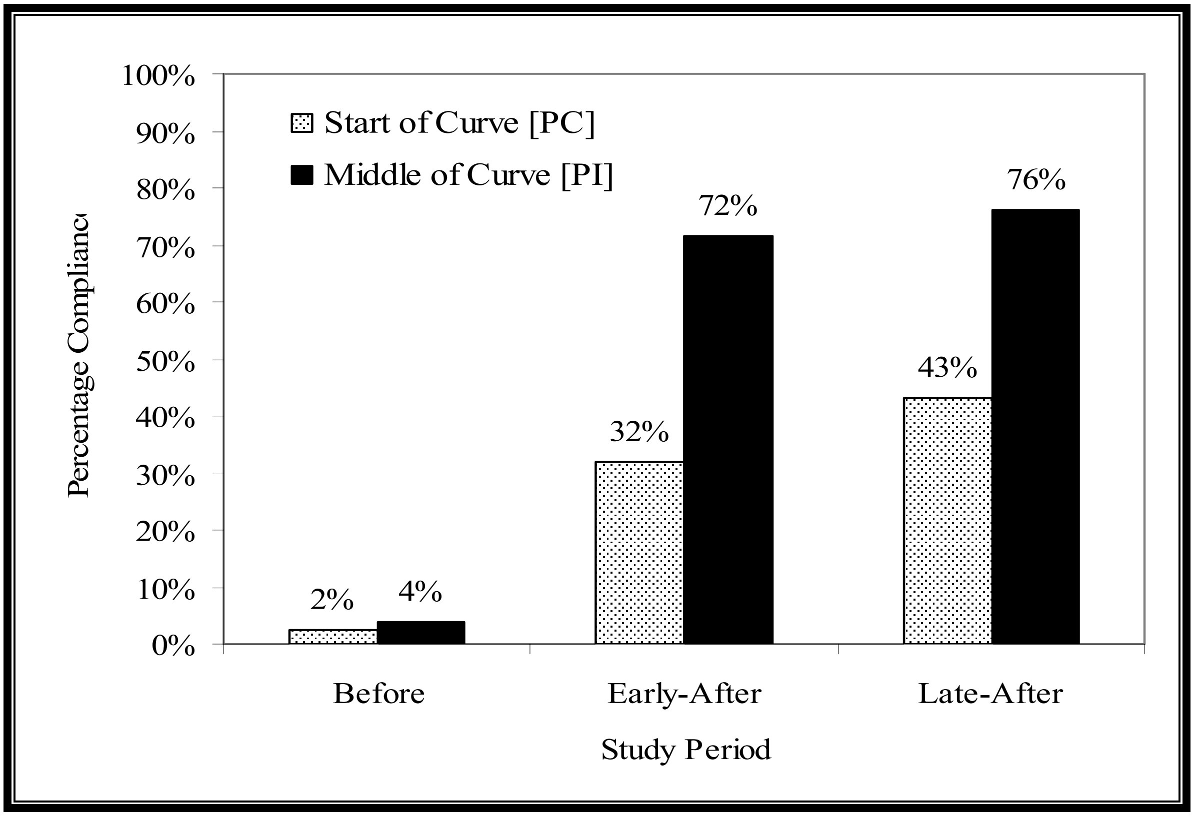


Figure 45. Dallas 1 – Passenger Vehicle Compliance.

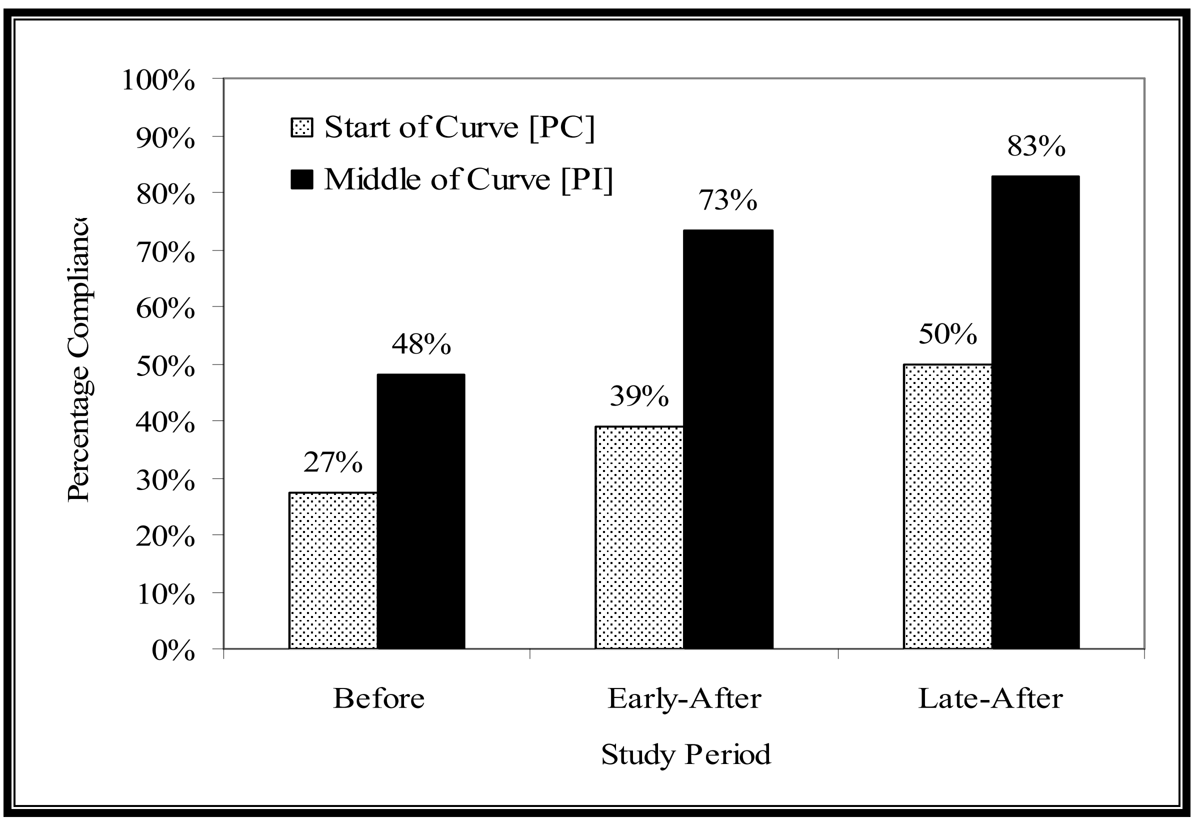


Figure 46. Dallas 1 – Heavy Vehicle Compliance.

Dallas 1 Crash Data Results – Date of Installation: March 30, 2005

The City of Mesquite Police Department provided crash reports for this ramp for the two-year study period beginning March 29, 2004. According to the provided information, it noted only a single crash on this ramp, and it occurred prior to the installation of the signs. Failure to control speed caused this single vehicle crash, which struck the barrier wall.

DALLAS 2 (US 80 WESTBOUND TO IH 635 NORTHBOUND) SITE ANALYSIS

Raw data collection observations were processed through the quality control inspection. Those vehicles in gaps less than five seconds were then removed. Table 11 presents a summary of the number of observations used for each study period and curve location by vehicle type. Using these observations, researchers completed further evaluation of the advisory signs at the Dallas 2 site.

Table 11. Dallas 2 – Number of Speed Observations Collected.

Vehicle Class	Before	Early-After	Late-After	Upstream (US)	Start (PC)	Middle (PI)
Heavy Vehicles	2162	2249	3013	2353	2508	2563
Passenger Vehicles	15,145	17,106	20,407	18,469	16,981	17,208
Rigid Vehicles	1598	1695	1734	1719	1588	1720

Dallas 2 General Statistics

The previous advisory speed at this curve was 40 mph for all vehicles. The new dual-advisory speeds were 45 mph for cars and 40 mph for trucks. The test signs were installed on March 30, 2005. After the dual-advisory speed sign was installed, the mean heavy truck speed at the PI remained practically the same at 40.07 mph before and 40.15 mph after. The 85th percentile truck speed remained the same at 44.30 mph. The mean speed for passenger cars also remained practically the same at 46.55 mph before and 46.66 mph after. The passenger vehicle 85th percentile speed remained the same at 51.1 mph. Table 12 details the mean and 85th percentile speeds for the US, PC, and PI locations for all three classes of vehicles.

Before the installation of the dual-advisory sign, the curve average mean speed for heavy vehicles was 40.07 mph. Mean speeds for heavy vehicles remained steady at 40.13 mph and 40.15 mph at early-after and late-after data collection periods. Mean speeds for passenger vehicles before the installation of the sign were 46.55 mph. Mean speeds for passenger cars increased in both after periods to 50.80 (early) and 51.10 mph (late). Table 12 presents a similar trend for 85th percentile speeds. Vehicle speed also became more uniform as indicated from the decreasing standard deviations through the curve. Researchers observed a similar trend for 85th percentile speeds. Appendix D presents additional general statistical findings for all curve locations by study period.

Table 12. Dallas 2 – Mean and 85th Percentile Speed Statistics.

Speed Measurement (mph)*		Before			Early-After			Late-After		
		Count	Mean	85th	Count	Mean	85th	Count	Mean	85th
US	Heavy Vehicles	422	49.82	55.00	651	48.51	53.50	1280	57.80	62.00
	Passenger Vehicles	3916	56.72	62.50	6008	55.81	61.20	8545	61.36	67.40
	Rigid Vehicles	411	53.25	60.40	547	52.12	58.50	761	59.63	65.10
PC	Heavy Vehicles	839	38.87	43.70	769	39.81	44.50	900	39.59	44.50
	Passenger Vehicles	5482	46.30	51.10	5522	47.30	52.00	5977	47.23	52.00
	Rigid Vehicles	528	43.16	49.00	561	43.52	49.20	499	43.65	49.20
PI	Heavy Vehicles	901	40.07	44.30	829	40.13	44.10	833	40.15	44.30
	Passenger Vehicles	5747	46.55	51.10	5576	46.49	50.80	5885	46.66	51.10
	Rigid Vehicles	659	43.27	48.20	587	43.23	48.50	474	43.82	49.20

*For vehicles with headways (gaps) of at least 5 seconds

Dallas 2 Before-After Speed Measurement Comparison

Mean and 85th percentile speeds for the US, PC, and PI curve locations were compared using the percentile bootstrap statistical technique (see Appendix D). As can be seen in Table 13, the outcome of the technique for the PI location yielded mixed results in the changes in mean and 85th percentile vehicle speeds from the before period to early- and late-after periods. Heavy vehicle speed comparisons show a very small, but statistically significant increase in speed at the PI curve location. However, with such small changes in speed, there was no *practical* difference in speeds at this curve. Statistical significance was measured at the alpha = 0.05 level. Additional curve locations findings can be found in Appendix D.

Table 13. Dallas 2 – Changes in Vehicle Speeds.

	Before to Early-After	Before to Late-After	Early-After to Late-After
All Vehicles			
Mean	0.00	0.26*	0.26*
85th Percentile	-0.11	0.10*	0.21
Passenger Vehicles			
Mean	-0.06	0.11*	0.17
85th Percentile	-0.11	0.01	0.12
Heavy Vehicles			
Mean	0.08	0.08*	0.01
85th Percentile	-0.14	-0.04	0.11*

*Difference is statistically significant.

Dallas 2 Analysis of Variance for Speed Characteristics

Researchers performed an analysis of variance for this site across many of the various data characteristics. The ANOVA output (Table 14) shows that the data was significantly different for study period, curve location, and vehicle class. Combinations of study period, curve location, and vehicle class were also found to be significantly different from each other. Statistically, each source of data where PR>F is less than 0.05 suggest that their means are not equal, and the null hypothesis that the means are equal should be rejected. The rejection of the null hypothesis (that the means are equal) supports the findings that speeds changed as a result of the sign treatment.

Table 14. Dallas 2 – ANOVA Analysis Results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Period	2	23,687.92	11,843.96	471.48	<.0001
Curve	2	301,517.56	150,758.78	6001.40	<.0001
Vehicle Class	2	149,113.26	74,556.63	2967.95	<.0001
Period*Curve	3	22,236.63	7412.21	295.06	<.0001
Period*Vehicle Class	4	2045.38	511.34	20.36	<.0001
Curve*Vehicle Class	4	2186.88	546.72	21.76	<.0001
Period*Curve*Vehicle Class	6	3186.14	531.02	21.14	<.0001

Dallas 2 Before-After Speed Limit Compliance Comparison

Vehicle compliance to the posted advisory speed limit was measured before and after the installation of the dual-advisory sign. As can be seen in Figures 47 and 48, compliance in the PC and PI sections of the curve for passenger vehicles increased from the before to after periods. Heavy vehicle compliance remained close showing very little change. One important note about this curve is that it does involve a downgrade from the beginning to the end of the curve. When setting the advisory speeds, the researchers were more conservative, recommending lower advisory speeds due to the perceived impact of the downgrade on truck operations. More than 60 percent of passenger car drivers and about 50 percent of truck drivers are still exceeding the advisory speeds at this curve.

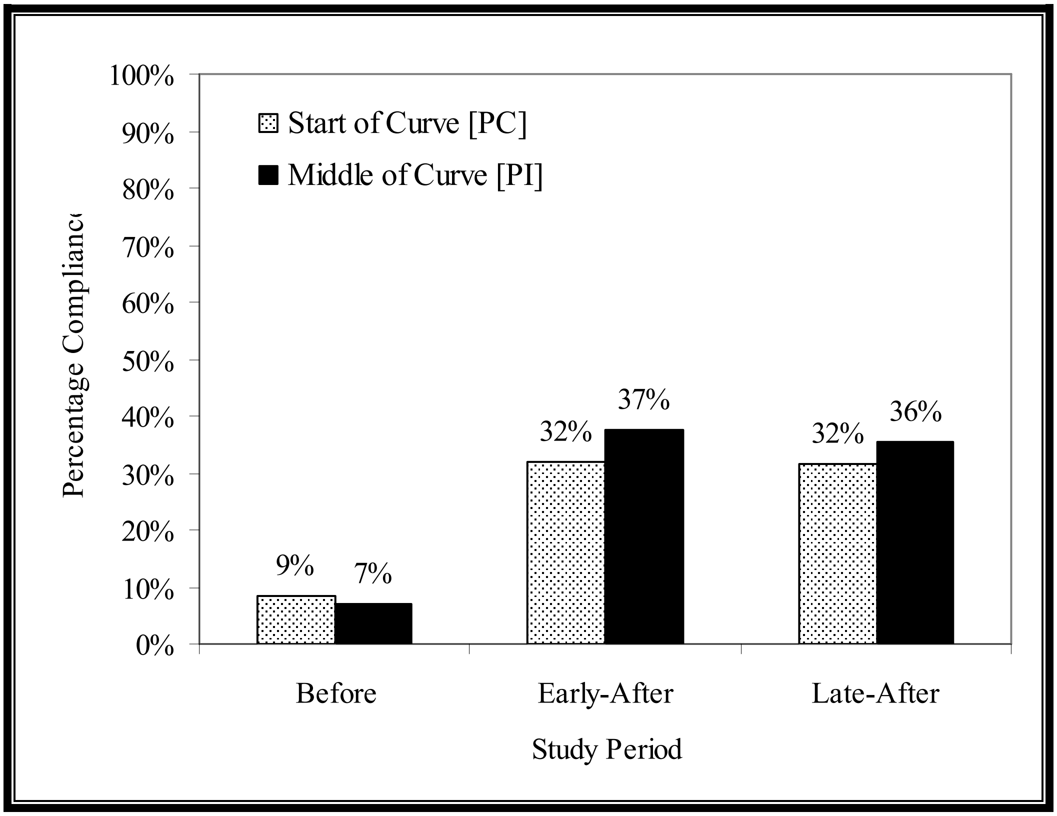


Figure 47. Dallas 2 – Passenger Vehicle Compliance.

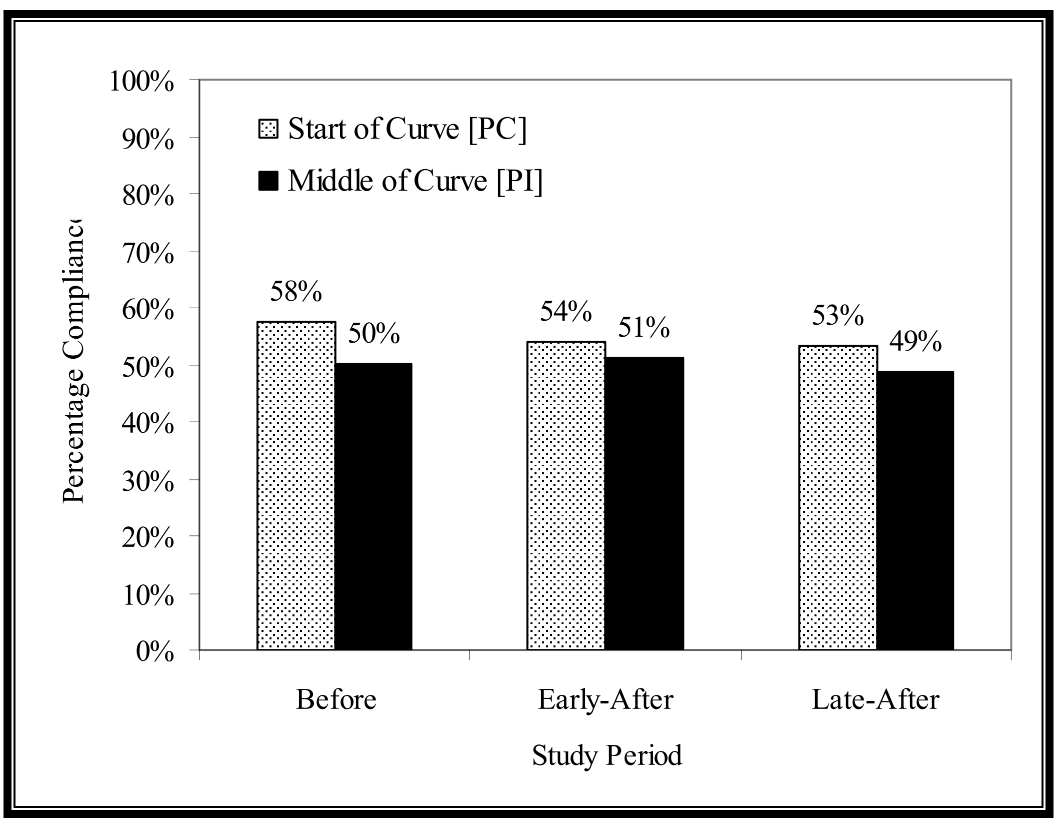


Figure 48. Dallas 2 – Heavy Vehicle Compliance.

Dallas 2 Crash Data Results – Date of Installation: March 30, 2005

The City of Mesquite provided 11 crash reports at or near the study location for the two-year study period from March 30, 2004 to March 30, 2006. Two of the reports were unrelated to the study ramp leaving nine crash reports used for the safety analysis at this connector ramp. Seven of the nine accidents occurred during the one-year period prior to installation of the signs. In four of the seven accidents, speed was a contributing factor. The remaining accidents were rear-end collisions. Only one of the collisions involved a commercial truck.

Researchers observed two crashes during the after period. The first crash involved a commercial truck but was caused by the driver of an emergency vehicle that failed to pass safely. The second involved a single vehicle that hit the guardrail. The officer noted speed and wet pavement as the contributing cause for this crash. Overall, the installation of the sign provided an index of effectiveness value of 2.33. Speed as a contributing factor realized a three-crash reduction and an index of effectiveness value of 2. A higher index of effectiveness value indicates that it is more likely that the treatment improved safety in the after period. Table 15 provides statistical values and MOEs for crashes at this location.

Table 15. Dallas 2 – Naïve Before-After Results.

	Sum K(j) (Before)	Sum L(j) (After)	Change	Theta	STDV{L(j)}	STDV{K(j)}	STDV{K(j)-L(j)}	STDV{Theta}	95% Confidence	Significant Change?
Total Number of Crashes	7.00	2.00	-5.00	0.25	2.65	1.41	2.24	0.07	4.38	Yes
Surface Condition										
Wet	1.00	1.00	0.00	0.50	1.00	1.00	0.00	0.50	0.00	
Dry	6.00	1.00	-5.00	0.14	2.45	1.00	2.24	0.06	4.38	Yes
Light Condition										
Daylight	6.00	2.00	-4.00	0.29	2.45	1.41	2.00	0.09	3.92	Yes
Dark	1.00	0.00	-1.00		1.00	0.00	1.00		1.96	
Contributing Factors										
Speed	4.00	1.00	-3.00	0.20	2.00	1.00	1.73	0.10	3.39	
Other	3.00	2.00	-1.00	0.50	1.73	1.41	1.00	0.23	1.96	
Speed and Other	0.00	0.00	0.00		0.00	0.00	0.00		0.00	
Vehicle Type										
Heavy Truck	1.00	1.00	0.00	0.50	1.00	1.00	0.00	0.50	0.00	

DALLAS 3 (IH 635 WESTBOUND TO IH 35E NORTHBOUND) SITE ANALYSIS

The volume, speed, and classification raw data observations at this freeway connector curve were processed using the methodology outlined at the beginning of this chapter. Table 16 summarizes the number of vehicle observations after the removal of vehicles with gaps less than five seconds. Using these observations, researchers completed the evaluation of the advisory signs at the Dallas 3 study site.

Table 16. Dallas 3 – Number of Speed Observations Collected.

Vehicle Class	Before	Early-After	Late-After	Upstream (US)	Start (PC)	Middle (PI)
Heavy Vehicles	1825	2262	1409	742	1910	2844
Passenger Vehicles	12,311	14,230	9260	8226	12,871	14,704
Rigid Vehicles	1180	1558	1593	697	1958	1676

Dallas 3 General Statistics

The previous advisory speed at this curve was 35 mph for all vehicles. The new dual-advisory speeds were 40 mph for cars and 35 mph for trucks. The test signs were installed on October 19, 2005. After the dual-advisory speed sign was installed, the mean heavy truck speed at the PI reduced (from 39.62 mph before to 38.26 mph after). The 85th percentile truck speed at the PI reduced (from 44.30 mph before to 42.30 mph after). The mean speed for passenger cars at the PI reduced (from 46.62 mph before to 45.52 mph after). The passenger vehicle 85th percentile speed at the PI reduced 1.7 mph (from 51.70 mph before to 50.00 mph after). Table 17 details the mean and 85th percentile speeds for the US, PC, and PI locations for all three classes of vehicles at this curve. Additional general statistical findings for all curve locations by study period can be found in Appendix D.

Table 17. Dallas 3 – Mean and 85th Percentile Speed Statistics.

Speed Measurement (mph)*		Before			Early-After			Late-After		
		Count	Mean	85th	Count	Mean	85th	Count	Mean	85th
US	Heavy Vehicles	280	55.98	64.20	281	56.77	64.20	181	54.65	62.50
	Passenger Vehicles	2608	62.82	69.50	3349	62.05	70.00	2269	62.62	69.00
	Rigid Vehicles	197	58.67	67.40	356	59.64	67.40	144	60.23	65.10
PC	Heavy Vehicles	774	44.77	50.80	770	44.52	50.60	366	50.58	56.70
	Passenger Vehicles	5010	53.24	59.30	4900	52.66	58.20	2961	58.69	65.50
	Rigid Vehicles	487	48.44	55.70	499	48.02	54.40	972	56.14	63.70
PI	Heavy Vehicles	771	39.62	44.30	1211	38.78	43.30	862	38.26	42.30
	Passenger Vehicles	4693	46.62	51.70	5981	46.28	51.10	4030	45.52	50.00
	Rigid Vehicles	496	41.77	47.70	703	42.01	47.70	477	41.55	47.00

*For vehicles with headways (gaps) of at least 5 seconds

Dallas 3 Before-After Speed Measurement Comparison

Mean and 85th percentile speeds for each curve location were compared using the percentile bootstrap statistical technique (see Appendix D). As can be seen in Table 18, the outcome of the technique for curve speed data at the PI yielded statistically significant reductions in mean and 85th percentile passenger vehicle speeds from the before period to early- and late-after periods for the PI location. Statistical significance was measured at the alpha = 0.05 level. Appendix D provides additional curve locations findings.

Table 18. Dallas 3 – Changes in Vehicle Speeds, PI.

	Before to Early-After	Before to Late-After	Early-After to Late-After
All Vehicles			
Mean	-0.57*	-1.32*	-0.75*
85th Percentile	-0.82*	-1.7*	-0.88*
Passenger Vehicles			
Mean	-0.35*	-1.11*	-0.76*
85th Percentile	-0.73*	-1.72*	-0.98*
Heavy Vehicles			
Mean	-0.86*	-1.36*	-0.50
85th Percentile	-0.85	-1.9*	-1.05*

*Difference is statistically significant.

Dallas 3 Analysis of Variance for Speed Characteristics

Researchers performed an analysis of variance for this site across many of the various data characteristics. The ANOVA output (see Table 19) shows that the data was significantly different for all individual characteristics: study period, curve location, and vehicle class. Many combinations of study period, curve location, and vehicle class were also found to be significantly different from each other. Statistically, each source of data where PR>F is less than 0.05 suggests that their means are not equal, and the null hypothesis that the means are equal should be rejected. The rejection of the null hypothesis (that the means are equal) supports the findings that speeds changed as a result of the sign treatment.

Table 19. Dallas 3 – ANOVA Analysis Results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Period	2	6468.85	3234.42	76.73	<.0001
Curve	2	269,104.90	134,552.45	3192.16	<.0001
Vehicle Class	2	94,489.72	47,244.86	1120.85	<.0001
Period*Curve	3	10,532.04	3510.68	83.29	<.0001
Period*Vehicle Class	4	637.71	159.43	3.78	0.0044
Curve*Vehicle Class	4	3854.77	963.69	22.86	<.0001
Period*Curve*Vehicle Class	6	369.61	61.60	1.46	0.187

Dallas 3 Before-After Speed Limit Compliance Comparison

Vehicle compliance to the posted advisory speed limit was measured before and after the installation of the dual-advisory sign. As can be seen in Figures 49 and 50, compliance in the PC section of the curve increased from the before to early- and late-after periods, but percentage compliance remained relatively low. The truck compliance did increase fivefold at the PC, which was encouraging, but was up from only 7 percent to 28 percent. Again, this is somewhat of a blind curve, as the view to the approach to the curve is restricted by the westbound to southbound connector ramp. Similar to the Dallas 3 site, the dual-advisory speed settings were conservative at this ramp as the ball-bank readings were just above the thresholds for a 40 mph truck and 45 mph car advisory speed sign (see Table 4). Lower compliance with the 35 mph truck and 40 mph car advisory speeds would be expected. However, it is interesting that compliance for trucks did increase by a factor of five with the new signs and the same advisory speeds as previously posted, but this increase in compliance is at the PC, not at the PI.

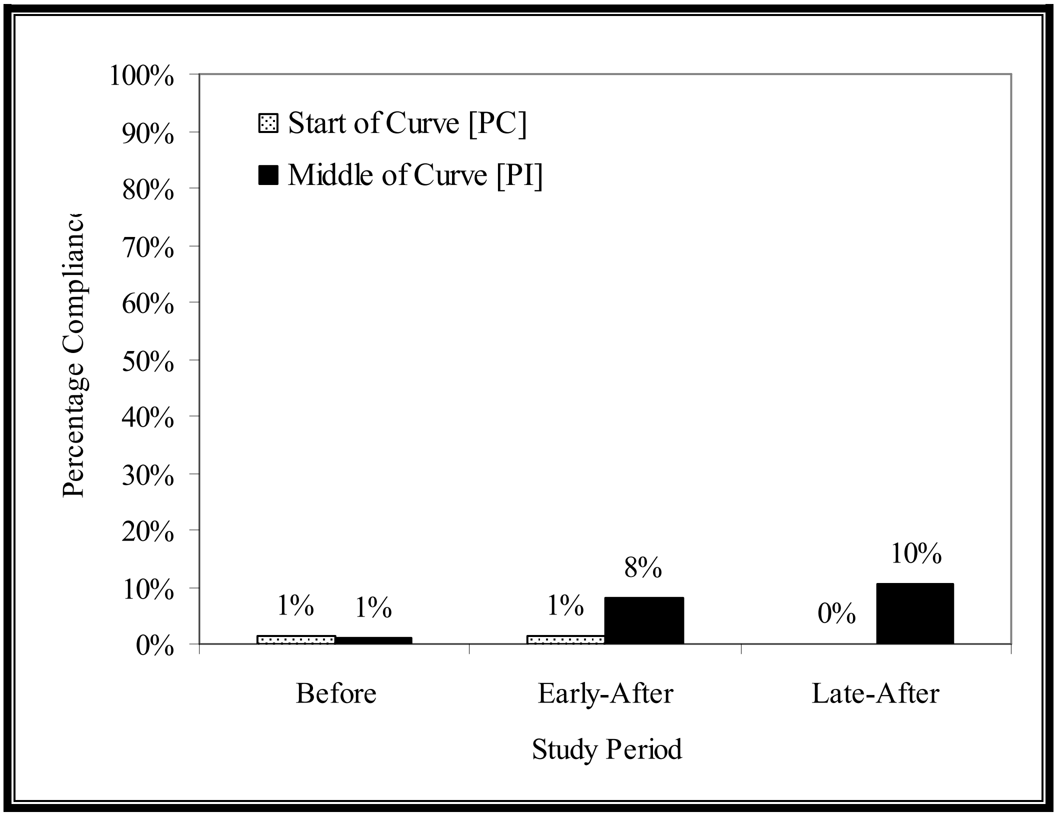


Figure 49. Dallas 3 – Passenger Vehicle Compliance.

Dallas 3 Crash Data Results – Date of Installation: October 19, 2005

The City of Dallas provided more than 90 crash reports for the IH 635 at IH 35E interchange for the two-year study period from October 19, 2004 to October 19, 2006. However, there were no accidents reported at this site during the two-year study period.

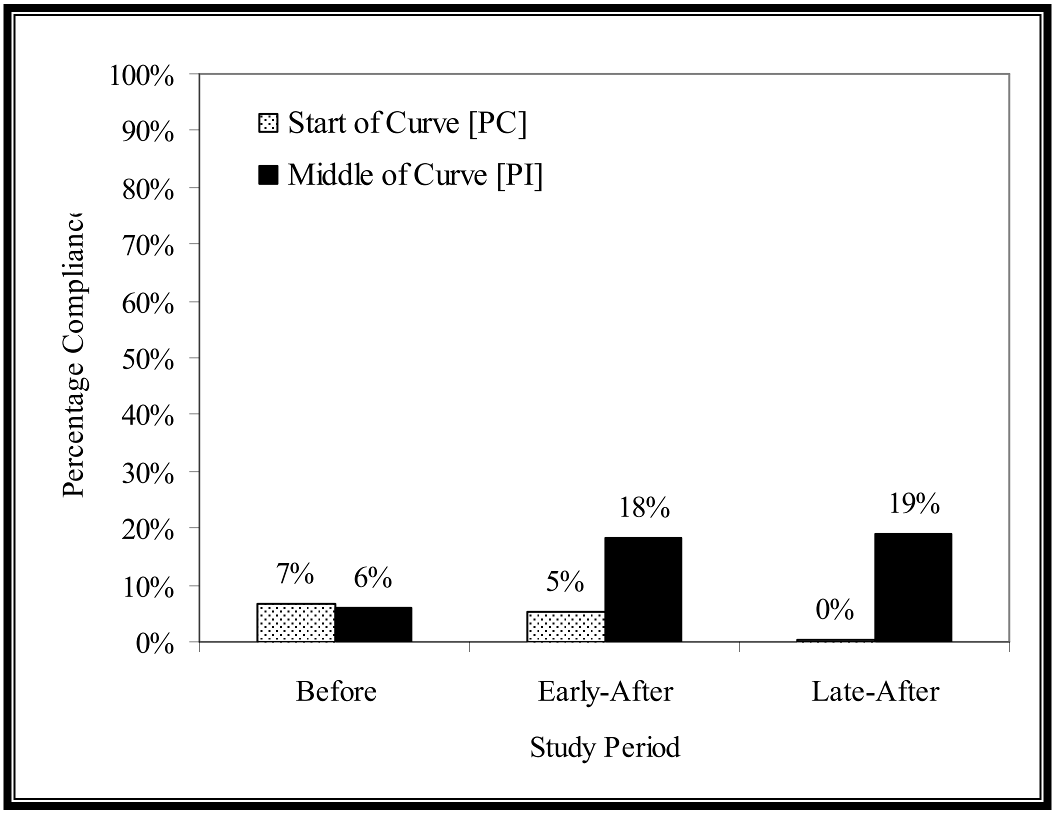


Figure 50. Dallas 3 – Heavy Vehicle Compliance.

FORT WORTH 1 (IH 35W NORTHBOUND TO IH 820 WESTBOUND) SITE ANALYSIS

Raw data collection observations at the Fort Worth curve were processed through the quality control inspection as outlined in the methodology. Once the removal of vehicle observations with gaps less than five seconds was complete, the data set was used for further analysis. Table 20 shows the total number of observations by class, study period, and location on curve. Using these observations, researchers completed further evaluation of the advisory signs at the Fort Worth 1 site.

Table 20. Fort Worth 1 – Number of Speed Observations Collected.

Vehicle Class	Before	Early-After	Late-After	Upstream (US)	Start (PC)	Middle (PI)
Heavy Vehicles	3727	2071	3507	1738	3662	3905
Passenger Vehicles	22,641	21,309	23,509	8733	29,067	29,659
Rigid Vehicles	4178	3715	4809	1481	5685	5536

Fort Worth 1 General Statistics

There was no posted advisory speed at this freeway connector curve before the dual-advisory speed signs were installed. From the ball-bank readings, an advisory speed of 35 mph for all vehicles would have been appropriate if posted. The new dual-advisory speeds were 40 mph for cars and 35 mph for trucks. The test signs were installed on March 29, 2005.

After the dual-advisory speed sign was installed, the mean heavy truck speed at the PI decreased slightly (from 41.02 to 40.17 mph), and the 85th percentile speed reduced slightly (from 45.60 to 45.20 mph). The mean speed for passenger cars actually decreased (from 46.47 mph to 46.11 mph), and the 85th percentile speed remained static at 50.80 mph. Table 21 details the mean and 85th percentile speeds for the US, PC, and PI locations for all three classes of vehicles.

One interesting finding was that the late-after upstream approach speeds for trucks decreased significantly as compared to the before conditions (from 56.74 mph to 51.34 mph). Researchers hypothesize that the conspicuity of the large sign did have the effect of slowing vehicles on the upstream approach after the signs were installed (observed reductions of about 5 mph). A similar reduction is seen at the PC, so that more deceleration to the PI curve speed was occurring upstream of the curve, and not within the curve. This reduction would be hypothesized to lead to a safer truck operation at this curve.

Table 21. Fort Worth 1 – Mean and 85th Percentile Speed Statistics.

Speed Measurement (mph)*		Before			Early-After			Late-After		
		Count	**Mean**	**85th**	**Count**	**Mean**	**85th**	**Count**	**Mean**	**85th**
US	Heavy Vehicles	535	56.74	63.30	559	57.16	63.70	644	51.34	62.50
	Passenger Vehicles	2959	62.83	67.90	3028	62.81	67.90	2746	61.12	67.00
	Rigid Vehicles	477	59.78	66.00	548	59.09	65.50	456	55.88	64.60
PC	Heavy Vehicles	1494	42.02	48.00	868	40.11	46.10	1300	38.98	47.00
	Passenger Vehicles	10,008	45.72	52.00	8999	43.77	50.30	10,060	42.96	51.70
	Rigid Vehicles	1960	44.05	50.30	1387	42.30	49.00	2338	42.50	51.40
PI	Heavy Vehicles	1698	41.02	45.60	644	42.78	48.00	1563	40.17	45.20
	Passenger Vehicles	9674	46.47	50.80	9282	46.90	51.70	10,703	46.11	50.80
	Rigid Vehicles	1741	43.56	48.50	1780	44.02	49.50	2015	42.63	48.20

*For vehicles with headways (gaps) of at least 5 seconds

Fort Worth 1 Before-After Speed Measurement Comparison

Mean and 85th percentile speeds for each curve location were compared using the percentile bootstrap statistical technique (see Appendix D). As can be seen in Table 22, the outcome of the technique for the PI speed data yielded mixed results for the PI section of the curve. Although this was the case with the PI location, the PC location (see Table 23) realized mean and 85th percentile reductions in both after periods. Statistical significance was measured at the alpha = 0.05 level. Appendix D presents additional curve location findings.

Table 22. Fort Worth 1 – Changes in Vehicle Speeds, PI.

Speed Measurement	Before to Early-After	Before to Late-After	Early-After to Late-After
All Vehicles			
Mean	0.86*	-0.41*	-1.27*
85th Percentile	1.13*	0.06*	-1.07*
Passenger Vehicles			
Mean	0.43*	-0.36*	-0.79*
85th Percentile	0.93*	0.05	-0.88*
Heavy Vehicles			
Mean	1.75*	-0.84*	-2.6*
85th Percentile	2.3*	-0.38	-2.68*

*Difference is statistically significant.

Table 23. Fort Worth 1 – Changes in Vehicle Speeds, PC.

Speed Measurement	Before to Early-After	Before to Late-After	Early-After to Late-After
All Vehicles			
Mean	-1.75*	-2.56*	-0.8*
85th Percentile	-1.81*	-0.24	1.57*
Passenger Vehicles			
Mean	-1.94*	-2.75*	-0.81*
85th Percentile	-1.95*	-0.31	1.64*
Heavy Vehicles			
Mean	-1.9*	-3.02*	-1.13*
85th Percentile	-1.92*	-1.14*	0.78

Fort Worth 1 Analysis of Variance for Speed Characteristics

Researchers performed an analysis of variance for this site across many of the various data characteristics. Many combinations of study period, curve location, and vehicle class were also found to be significantly different from each other. Statistically, each source of data where PR>F is less than 0.05 suggests that their means are not equal and the null hypothesis that the means are equal should be rejected. The rejection of the null hypothesis (that the means are equal) supports the findings that speeds changed as a result of the sign treatment. Table 24 presents the results of the ANOVA analysis.

Table 24. Fort Worth 1 – ANOVA Analysis Results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Period	2	2070.10	1035.05	24.38	<.0001
Curve	2	524,213.52	262,106.76	6172.68	<.0001
Vehicle Class	2	57,065.24	28,532.62	671.95	<.0001
Period*Curve	3	4692.40	1564.13	36.84	<.0001
Period*Vehicle Class	4	829.32	207.33	4.88	0.0006
Curve*Vehicle Class	4	3538.18	884.55	20.83	<.0001
Period*Curve*Vehicle Class	6	750.75	125.12	2.95	0.0071

Fort Worth 1 Before-After Speed Limit Compliance Comparison

Vehicle compliance to the posted advisory speed limit was measured before and after the installation of the dual-advisory sign. As can be seen in Figures 51 and 52, compliance in the PC section of the curve increased progressively from the before to early- and late-after periods. As compared to other sites, compliance at the PC at this location increased much more than compliance at the PI. This is probably a factor resulting from the case that no advisory speed was provided at this site prior to the dual-advisory speed warning sign installation. This is a hidden curve on a downgrade, so drivers were probably reacting to the upstream signing by slowing somewhat and then adjusting their speed in the curve after the curve enters the visual field.

Fort Worth 1 Crash Data Results – Date of Installation: March 29, 2005

No statistical analysis was completed for the Fort Worth connector ramp because crash data for this ramp was not available

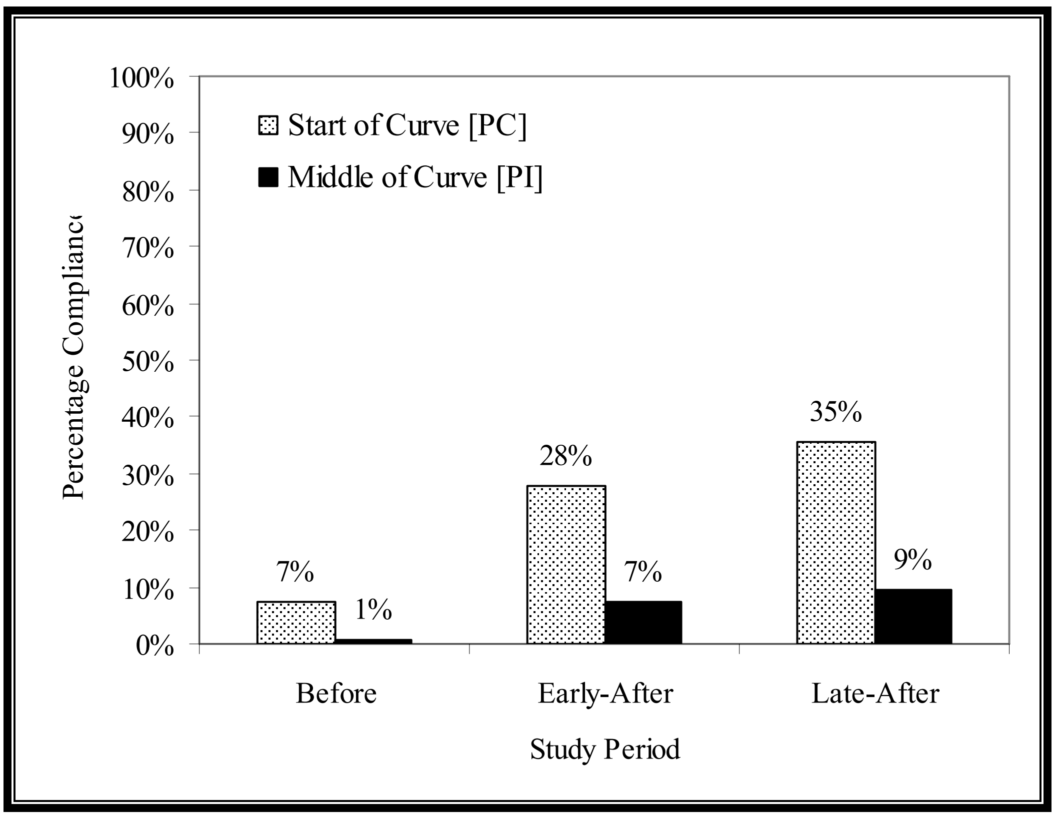


Figure 51. Fort Worth 1 – Passenger Vehicle Compliance.

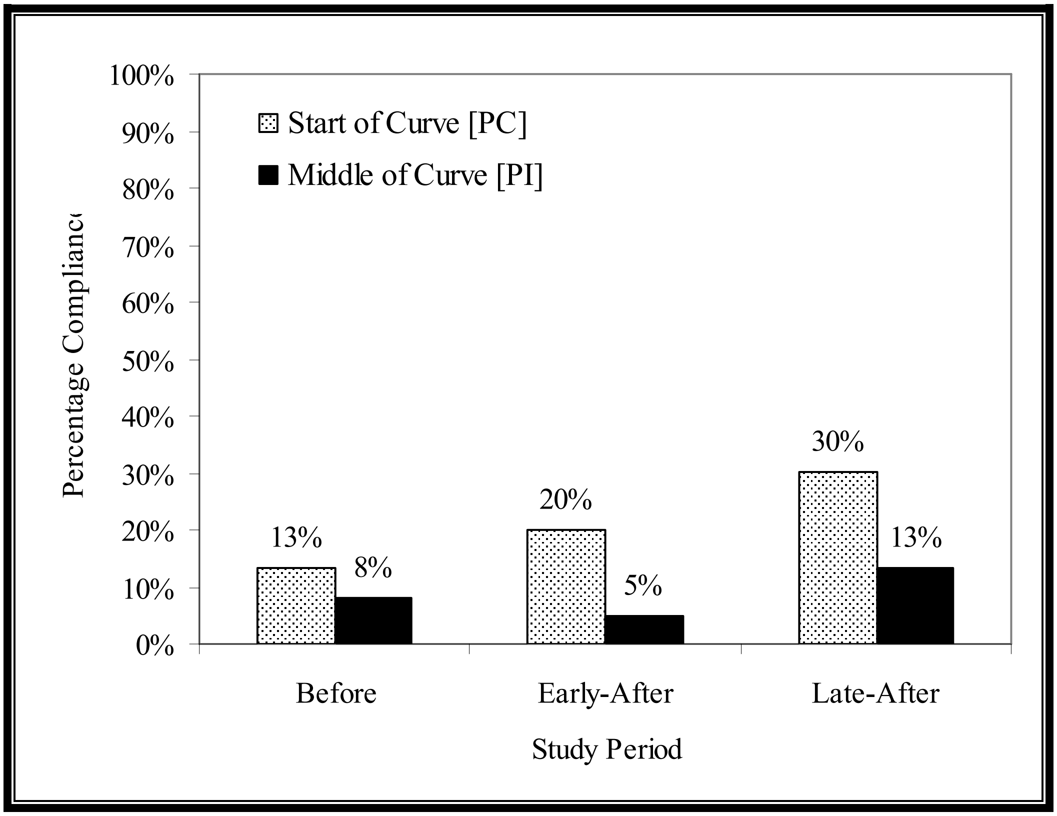


Figure 52. Fort Worth 1 – Heavy Vehicle Compliance.

HOUSTON 1 (IH 610 EASTBOUND TO IH 45 NORTHBOUND) SITE ANALYSIS

Per-vehicle volume, speed, and classification data collection observations were reduced using the quality control inspection process outlined in the methodology. The study data set was finalized after the removal of vehicles with gaps less than five seconds. Table 25 shows the number of observations by vehicle class, study period, and curve location. Using these observations, researchers completed the evaluation of the advisory signs.

Table 25. Houston 1 – Number of Speed Observations Collected.

Vehicle Type	Before	Early-After	Late-After	Upstream (US)	Start (PC)	Middle (PI)
Heavy Vehicles	1948	3479	3410	1496	3287	4054
Passenger Vehicles	36,887	66,578	49,443	23,933	60,175	68,800
Rigid Vehicles	2659	5146	7276	1831	8040	5210

Houston 1 General Statistics

The previous advisory speed at this curve was 35 mph for all vehicles. The new dual-advisory speeds were 45 mph for cars and 35 mph for trucks. The test signs were installed on February 26, 2005.

After the dual-advisory speed sign was installed, the mean heavy truck speed at the PI decreased from 37.56 to 36.11 mph, and the 85th percentile speed decreased from 41.85 to 40.74 mph. The mean speed for passenger cars actually decreased slightly from 43.07 mph to 41.93 mph, and the 85th percentile speed fell from 47.70 mph to 47.00 mph. Table 26 details the mean and 85th percentile speeds for the US, PC, and PI locations for all three classes of vehicles. The Houston 1 site showed that the signs seem to have a positive impact of reducing speeds upstream (in advance of overhead signing), as well as at the PI of the curve.

Table 26. Houston 1 – Mean and 85th Percentile Speed Statistics.

Speed Measurement (mph)*		Before			Early-After			Late-After		
		Count	Mean	85th	Count	Mean	85th	Count	Mean	85th
US	Heavy Vehicles	425	55.72	62.50	517	56.27	64.50	554	52.75	59.80
	Passenger Vehicles	8206	63.06	69.00	8314	62.92	69.20	7413	60.31	66.50
	Rigid Vehicles	522	59.14	66.20	747	59.83	66.80	562	56.42	63.40
PC	Heavy Vehicles	1003	48.00	54.40	783	49.51	56.00	1501	48.30	55.20
	Passenger Vehicles	17,922	51.23	58.40	21,357	54.07	59.60	20,896	55.71	63.40
	Rigid Vehicles	1424	49.72	56.90	1611	53.74	60.30	5005	56.53	65.00
PI	Heavy Vehicles	520	37.56	41.85	2179	36.88	41.40	1355	36.11	40.70
	Passenger Vehicles	10,759	43.07	47.70	36,907	42.67	47.60	21,134	41.93	47.00
	Rigid Vehicles	713	40.34	45.80	2788	40.13	45.30	1709	39.95	45.70

*For vehicles with headways (gaps) of at least 5 seconds

Houston 1 Before-After Speed Measurement Comparison

The mean and 85th percentile speeds for each curve location were compared using the percentile bootstrap statistical technique (see Appendix D). As can be seen in Table 27, the outcome of the technique for PI speed data yielded statistically significant reductions in mean and 85th percentile speeds for each vehicle class from the before period to early- and late-after periods. Statistical significance was measured at the alpha = 0.05 level. Appendix D presents additional curve location findings.

Table 27. Houston 1 – Changes in Bootstrapped Mean and 85th Percentile Speeds.

Speed Measurement	Before to Early-After	Before to Late-After	Early-After to Late-After
All Vehicles			
Mean	-0.47*	-1.21*	-0.74*
85th Percentile	-0.36*	-0.88*	-0.52*
Passenger Vehicles			
Mean	-0.4*	-1.15*	-0.75*
85th Percentile	-0.26*	-0.8*	-0.54*
Heavy Vehicles			
Mean	-0.67*	-1.45*	-0.79*
85th Percentile	-0.47	-1.23	-0.75

Houston 1 Analysis of Variance for Speed Characteristics

Researchers performed an analysis of variance for this site across many of the various data characteristics. As displayed in Table 28, the ANOVA output shows that the data was significantly different for curve location and vehicle class. The outcome of this analysis supports previous evaluation findings.

Table 28. Houston 1 – ANOVA Analysis Results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Period	2	702.31	351.15	8.45	0.0002
Curve	2	456,370.52	228,185.26	5491.34	<.0001
Vehicle Class	2	71,034.98	35,517.49	854.74	<.0001
Period*Curve	3	18,125.31	6041.77	145.40	<.0001
Period*Vehicle Class	4	2849.49	712.37	17.14	<.0001
Curve*Vehicle Class	4	7282.31	1820.58	43.81	<.0001
Period*Curve*Vehicle Class	6	2257.38	376.23	9.05	<.0001

Houston 1 Before-After Speed Limit Compliance Comparison

Vehicle compliance to the posted advisory speed limit was measured before and after the installation of the dual-advisory sign. As can be seen in Figures 53 and 54, compliance in the PC section of the curve remained flat from the before to early- and late-after periods and percentage compliance remained relatively low. However, for passenger vehicles the compliance rate went from 4 percent for the previous advisory speed of 35 mph to 74 percent for the 45 mph advisory speed. Truck compliance did increase at the PC with the new signs, which was encouraging, and was up from 25 percent to 37 percent. It is interesting that compliance for trucks did increase with the new signs and with the same advisory speeds as previously posted, and this increase in compliance is at the PI.

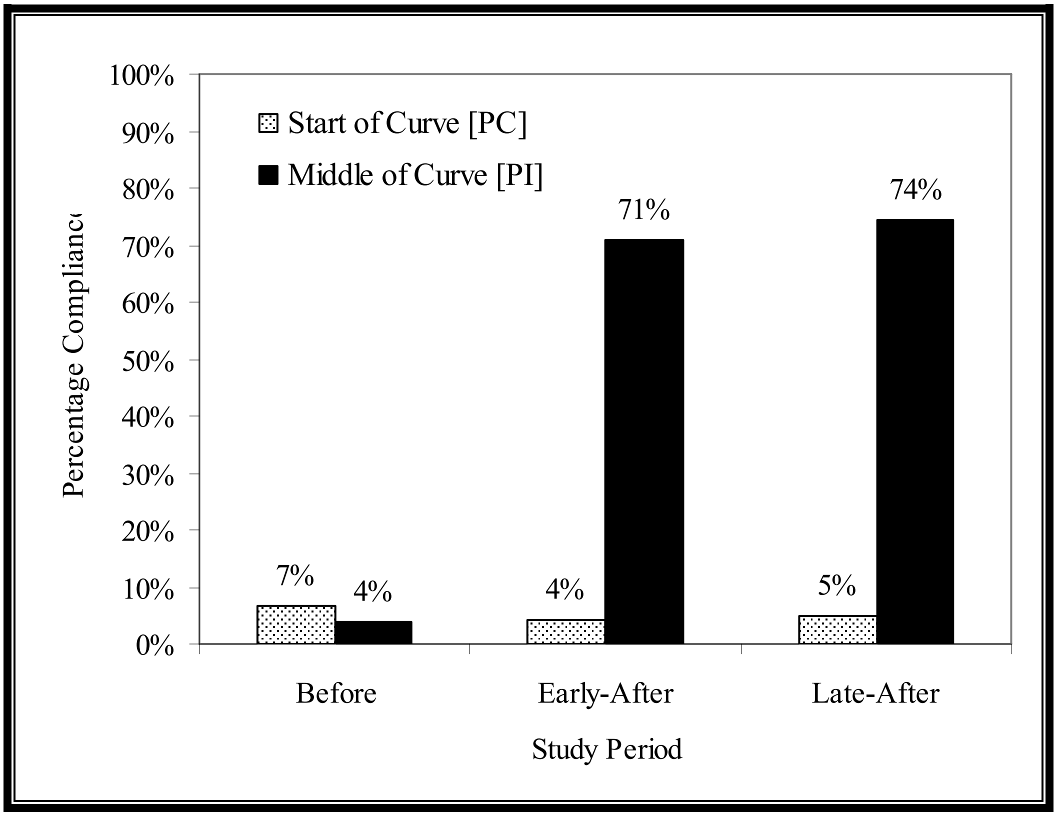


Figure 53. Houston 1 – Passenger Vehicle Compliance.

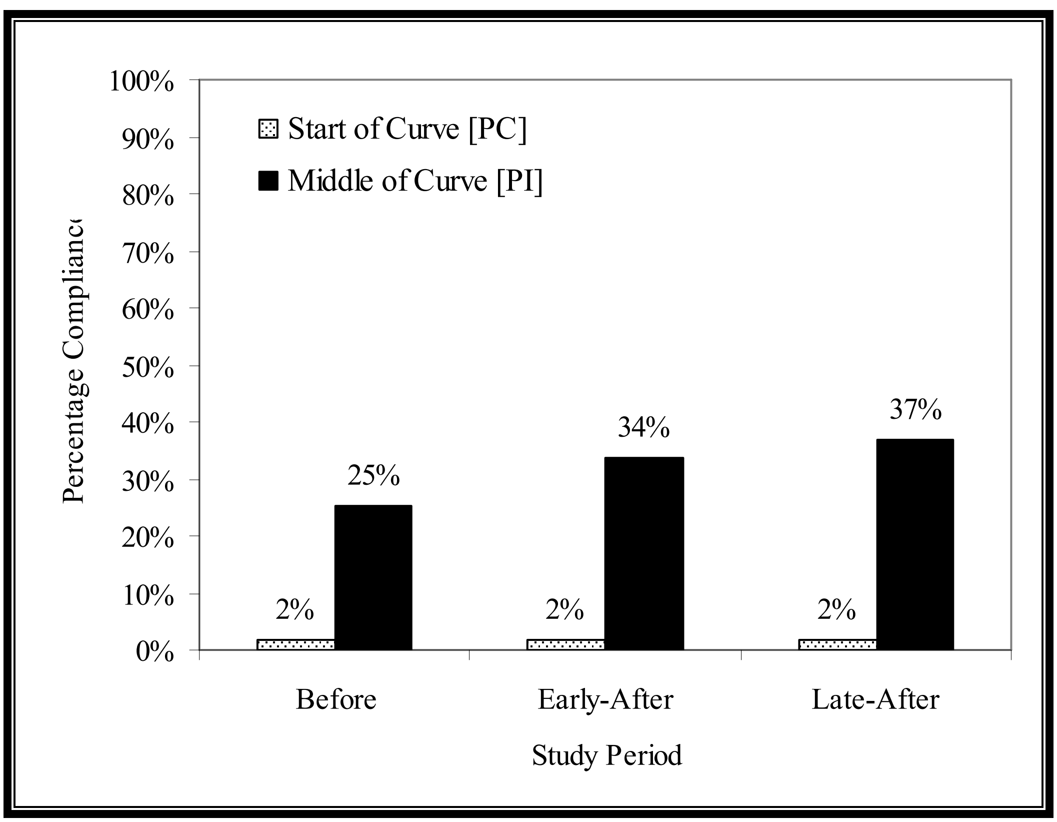


Figure 54. Houston 1 – Heavy Vehicle Compliance.

Houston 1 Crash Data Results – Date of Installation: February 26, 2005

Crash records were provided for six incidents that occurred on the ramp during the two-year study period (February 26, 2004 to February 26, 2006). Two single-vehicle crashes occurred prior to the installation of the experimental signs. The first crash occurred at night and involved a driver unfamiliar with the interchange; the driver's vehicle crashed into the connector ramp barrier wall on the wet pavement. The condition of the pavement was not a factor in a second crash. The responding officers for both crashes indicated that speed was a contributing factor in both instances.

During the one-year after period, a total of four crashes were observed on the ramp. Three of the crashes involved a single vehicle that crashed into the barrier wall along the connector. The first crash was caused by the driver of the vehicle falling asleep while driving. A second crash included the driver failing to control speed, resulting in the vehicle leaving the roadway and striking trees in the median. In the third, an unlicensed teenager crashed a vehicle into the guardrail; it was noted that speed was not a factor in this crash. The remaining crash involved a vehicle being struck by a commercial truck that failed to drive in a single lane. Because the truck driver failed to stop and give information, it is unclear if the lane change was intentional.

The total number of crashes at this location increased. However, the connector ramp realized a reduction in the number of speed-related incidents and yielded an index of effectiveness value of 1.0. Table 29 provides statistical values and MOEs for crashes at this location.

Table 29. Houston 1 – Naïve Before-After Results.

	Sum K(j) (Before)	Sum L(j) (After)	Change	Theta	STDV{L(j)}	STDV{K(j)}	STDV{K(j)-L(j)}	STDV{Theta}	95% Confidence	Significant
Total Number of Crashes	2.00	4.00	-2.00	1.33	1.41	2.00	1.41	0.67	2.77	
Surface Condition										
Wet	1.00	0.00	1.00		1.00	0.00	1.00		1.96	
Dry	1.00	4.00	-3.00	2.00	1.00	2.00	1.73	1.58	3.39	
Light Condition										
Daylight	1.00	1.00	0.00	0.50	1.00	1.00	0.00	0.50	0.00	
Dark	1.00	3.00	-2.00	1.50	1.00	1.73	1.41	1.22	2.77	
Contributing Factors										
Speed	2.00	1.00	1.00	0.33	1.41	1.00	1.00	0.24	1.96	
Other	0.00	3.00	-3.00		0.00	1.73	1.73		3.39	
Speed and Other	0.00	0.00	0.00		0.00	0.00	0.00		0.00	
Vehicle Type										
Heavy Truck	0.00	1.00	-1.00		0.00	1.00	1.00		1.96	

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

This research project completed an evaluation of dual-advisory speed warning signs on freeway-to-freeway connector ramps at five locations in Texas. The project was divided into six basic tasks:

1. literature review,
2. survey of TxDOT transportation operations engineers,
3. survey of state chief transportation engineers,
4. development of prototype signing concepts,
5. focus groups, and
6. sign implementation and analysis of effectiveness.

There have been previous studies that have examined the relationship between truck crashes and freeway connector ramp geometry. However, this project recognizes the disparity in the relationship between vehicle operations and current advisory speed signing practices and provides a mechanism for traffic engineers to provide enhanced advisory speed information to trucks and passenger vehicles at problematic freeway connectors. Given the strong evidence that there is a significant differential between speeds that cars and heavy trucks can negotiate freeway connector curvature comfortably and safely, this research study was tasked by TxDOT to investigate current signing practices and examine whether a dual-advisory speed signing scheme can safely address this differential and improve safety on Texas freeways.

STUDY METHODOLOGY

A comprehensive literature search was conducted to identify publications on existing methods and practices on differential advisory speed signing for trucks and passenger vehicles on freeway-to-freeway connectors. While a robust base of research exists on the issues of truck safety and curve safety, no literature to date has examined the use of a dual-advisory speed limit concept that provides different advisory speed limits for cars and trucks.

Two surveys were completed to determine if any dual-advisory speed concepts were currently being used as well as to investigate the current state of the practice with respect to mitigating safety issues at freeway connectors. Transportation operations engineers for each of the 25 TxDOT districts and the chief traffic engineer of each state were contacted to determine if either had implemented differential speed advisory signing or were in the process of considering differential signing on connector ramps.

From the review of existing Texas and national practice, several candidate dual-speed advisory speed signing concepts were developed. Sign development incorporated known existing signing practices (whether standard or non-standard) and relied upon the Texas Manual on Uniform Traffic Control Devices as a guide in sign development. This task focused on development of both graphics and text that was perceived to most efficiently give drivers meaningful warning information. These candidate signs were reviewed by traffic engineering professionals (members of TxDOT staff, TTI researchers, and others) to determine the signs' suitability and application to MUTCD principles.

The prototype dual-advisory warning speed signs developed were then evaluated by focus groups and individual interviews with an audience consisting of the driving public. Two of the focus groups included a subset of the general driving population, while the other two consisted of professional truck drivers. This task provided good insight into driver understanding of a dual-advisory speed signing scheme and served to ensure that the goal of the research was comprehensible to the motoring public. The results of the focus group studies were used as guidance in selecting the design of experimental signs that were deployed in the field.

Six implementation sites were then chosen based upon initial recommendations of TxDOT staff of problematic freeway-to-freeway connector ramps throughout the state. The next step included determining the appropriate advisory speeds for passenger vehicles and trucks as well as working with the department for construction and deployment of the signs at each location. "Before" data collection was completed at three points along each ramp to assess traffic volume, vehicle classification, and vehicle speeds with the then-existing signing configurations. After the installation of the experimental sign treatments, "after" data were collected to assess the impact of the signing technique used. Crash data were then requested for each of the sites from local police departments in Mesquite, Houston, Dallas, and Fort Worth. The measures of effectiveness used to determine if the new signs were of benefit were speed reduction and crash rate analyses. One of the six sites (Houston 2) was subsequently disqualified after identification of irregularities in the data caused by maintenance activities during data collection. Crash data was unavailable for the Fort Worth site.

Several data analysis objectives were developed with the primary goal to quantitatively assess the effects of the installation of the sign with respect to speed reduction on the freeway connector ramps. Speeds were measured at the US, PC, and PI locations on each connector ramp, and the researchers reviewed speed data for heavy vehicles, passenger vehicles, and rigid vehicles. Again, those vehicles with less than a five-second gap were eliminated from the analysis so that only vehicles believed to be "free-flowing" were included. In consideration of these factors and the goals of the research, analysts determined that the following evaluations would be appropriate to assess the dual-advisory speed warning sign concept on vehicle operating speeds:

- calculation and analysis of the general statistics for each study curve by curve location (US, PC, and PI), vehicle class, and study period (before, early-after, and late-after);
- before-after comparison of the 85^{th} percentile speed and mean speed for each study curve by curve location (US, PC, and PI), vehicle class, and study period (before, early-after, and late-after);
- ANOVA for mean speeds at each curve and vehicle type; and
- before-after comparison of driver compliance of the classification-specific advisory speed.

In order to assess the safety impacts of the installation of the dual-advisory speed warning signs, the crash analysis focused on the number of motor vehicle crashes that occurred one year before the installation and compared them to those that took place in the following year. Safety measures of effectiveness consisted of using a naïve before-after approach and a calculated index of effectiveness value *(37)*. Given the small number of crashes and limited time period during which crash experience were to be monitored, this method was the best tool available to provide a statistical comparison with MOEs.

In addition to the before-after study, 95 percent confidence intervals were calculated for the change in the number of crashes. These confidence intervals are found by calculating the difference in the standard deviations of sample variances for the before and after study periods and multiplying it by a z-value of 1.96 for alpha = 0.05. In completing this, the method assumed that the standard deviation of variance fits the standard normal distribution. To determine significance, the reader should compare the calculated 95 percent confidence value to the absolute value of the change in crashes. If the 95 percent confidence value is less than the change, it should be considered a significant change.

EFFECTS OF THE DUAL-ADVISORY SPEED WARNING SIGN

Based on the results of the analysis of average and 85th percentile speeds at the midpoint of each study curve, the dual-advisory warning signs generally had a positive impact on reducing speeds at the PC of the curve and/or having an accompanying reduction in speed-related crashes at the study sites. Table 30 presents a summary of the measures of effectiveness used to quantify the overall effectiveness of the experimental dual-advisory speed signs deployed at six freeway-to-freeway connector ramps.

Table 30. Effects of Dual-Advisory Warning Sign Concept.

Study Site	Vehicle Type/Advisory Speed	Speed Change Before-After Middle of Curve		Percent PI Compliance		Speed-Related Crash Experience
		Average Speed*	85th Percentile Speed	Before	After	
Dallas 1	Car – 50 mph Truck – 45 mph	– +	– +	4 48	76 83	Reduced (1 Before – 0 After)
Dallas 2	Car – 45 mph Truck – 40 mph	+ +	nc nc	7 50	36 49	Reduced (4 Before – 1 After)
Dallas 3	Car – 40 mph Truck – 35 mph	– –	– –	1 6	10 19	No Change (0 Before – 0 After)
Fort Worth 1	Car – 40 mph Truck – 35 mph	– –	nc –	8 1	13 9	N/A
Houston 1	Car – 45 mph Truck – 35 mph	– –	– –	4 25	74 37	Reduced (2 Before – 1 After)

*Note: "–" indicates decrease in speed; "+" indicates an increase in speed; "nc" indicates no change in speed

From the summary of results, it could be inferred that the dual-advisory speed signs had a positive impact on operations and safety at the study sites. Three of the sites (Dallas 3, Fort Worth 1, and Houston 1) had reductions in average car and truck speeds along the connector ramp, increased compliance to the posted advisory speed, and reductions in speed-related crashes (Houston 1). The Dallas 1 and Dallas 2 curves both experienced a reduction in crashes during the year after the signs were installed; however, the data collected at both of these sites indicated either small increases or no changes in average or 85th percentile speeds. It appears that there was no negative impact on safety when using a 13-degree ball-bank reading to set passenger car advisory speeds.

The researchers were somewhat conservative in the approach in setting the advisory speeds on the experimental signs at the study sites. For example, at the Dallas 3 site, ball-bank readings of 11 degrees at 40 mph and 14 degrees at 45 mph were obtained in the field, but the 10-degree truck and 13-degree car recommendations were used for guidance in selecting the posted advisory speed. This particular site had one of the two lowest compliance rates before and after, implying that the advisory speeds were still set below the point where a vast majority of drivers are comfortable traversing the curve. Perhaps a more realistic advisory speed at this ramp would have been 35 mph for trucks and 45 mph for cars. A similar case existed at the Fort Worth 1 site, where test speeds were set somewhat lower due to two factors: 1) there was no previous advisory speed posted, and 2) the connector ramp includes a "blind curve" on a downgrade. However, the study results still indicated a reduction in average and 85th percentile speeds and an associated increase in compliance. Although these were noted to occur at lesser amounts than at other study sites, the deployment of the dual signs did achieve the intended results.

Looking specifically at three sites in which the posted advisory speed limits for trucks on the experimental sign was the same as the previous general advisory sign, the rate of compliance either changed little (Dallas 2) or increased modestly (from 25 percent to 37 percent at Houston 1). This infers that truck drivers are heeding the additional speed warning specifically intended for the heavy vehicles. If this higher compliance is by drivers of vehicles with higher centers of gravity, then the signs have completed the concept of conveying the warning message to vehicles that may be more likely to roll over on connector ramps. A positive finding is that the dual-advisory speed limit signs accomplished this goal with no perceived negative impact on safety while reducing speed-related crashes at three sites with a history of such crashes prior to installation of the experimental signs.

Recommended Future Implementation of the Dual-Advisory Warning Signs

Based upon a review of operational data and crash experience at six field study sites, it appears that the use of the dual-advisory speed limit sign is a viable concept and provides enhanced warning to trucks on freeway-to-freeway connectors. While providing additional warning to drivers of trucks, the signs appear not to sacrifice the ability to inform drivers of passenger cars of an appropriate advisory speed on the ramps as well. The use of a ball-bank indicator of 10 degrees to set advisory speeds for trucks and of 14 degrees for passenger vehicles appears to be appropriate. In the absence of dual-advisory signs, it is recommended to use either engineering judgment as allowed in the federal MUTCD or to continue to use a 10-degree ball-bank reading to set curve advisory speeds for 35 mph and higher speeds.

This research also indicated that engineers might set advisory speeds up to 5 mph higher than indicated at ball-bank readings of 10 degrees without much adverse impact expected. For example, an engineer setting advisory speeds at a ramp that has a ball-bank reading of 11 degrees at 40 mph and 14 degrees at 45 mph might use engineering judgment to set the speed at 40 mph, instead of 35 mph, knowing that this will be a much more realistic advisory speed. The researchers would recommend that such a sign deployment as indicated in this example be monitored for crash experience.

The dual-advisory signs should be considered on freeway-to-freeway connector ramps where there has been a demonstrated truck crash experience over time and where the engineer feels that truck-specific warning is warranted.

Recommendations for Future Research

This project concentrated on the design, deployment, and evaluation of experimental signs for providing dual-advisory speed limit information to drivers of passenger cars and trucks on freeway-to-freeway connector ramps. Throughout this research project, the researchers were able to identify additional areas of interest that were out of the scope and time frame of this effort.

- Surveys indicated that similar issues that exist for truck operations on freeway connector ramps also occur along normal roadway horizontal curves and on some entrance and exit ramps. Consideration should be given to evaluating the use of the dual-advisory speed warning signs as developed in this project and using the ball-bank guidelines presented in this project on these other curve types as well.
- In the study focus groups, the professional truck drivers indicated that they were more prone to heeding the warning of a particular sign if it has supplemental flashing yellow beacons. Further research is necessary to investigate if the use of flashing beacons used to supplement the dual-advisory signs has any additional impact on truck speeds and safety.

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APPENDIX A. TEXAS DEPARTMENT OF TRANSPORTATION SURVEY RESULTS

SURVEY RESULTS FOR THE STATE OF THE PRACTICE FOR ADVISORY SPEED SETTING ON FREEWAY-TO-FREEWAY CONNECTOR CURVES

TEXAS DEPARTMENT OF TRANSPORTATION TRANSPORTATION OPERATIONS ENGINEERS

Texas Department of Transportation, Research Project 0-4813

Survey Questionnaire

<u>Freeway-to-Freeway Connector Ramps:</u>
<u>Current Signing and Pavement Marking Practices</u>

The survey that you have been asked to complete is part of a Federal Highway Administration/Texas Department of Transportation research project to document the current practice of signing and pavement markings for freeway-to-freeway connector ramps, or for connector ramps that link higher-speed facilities.

A particular focus of this research is on advisory speed signing and/or striping for heavy trucks (or other vehicles with high-centers-of-gravity) on freeway-to-freeway connectors**.** We are also interested in documenting experience with differential speed limits and advisory speeds for trucks and cars on freeway connector ramps.

The intended recipient of this survey is a traffic engineer in your district that has districtwide knowledge of the existing installation of advisory signing or pavement markings for trucks on freeway-to-freeway connector ramps.

Please return your completed questionnaire, along with any supporting documents as soon as possible to:

Mr. Tony Voigt, P.E.
Research and Implementation - Houston
Texas Transportation Institute
701 N. Post Oak, Suite 430
Houston, Texas 77024

If you have any questions, please contact Mr. Voigt by telephone at 713-686-2971, by fax at 713-686-5396, or by email at a-voigt@tamu.edu.

Thank you for your assistance!

Agency Experience

1. Has your agency encountered safety problems related to trucks (and/or other vehicles with high centers-of-gravity) on freeway-to-freeway interchange ramps?

☐ YES ☐ NO

If YES, what types of countermeasures have you used for such problems? (Check all that apply):

A. Advisory speed limits for all vehicles on particular ramps ☐

B. Advisory speed limits for trucks on particular ramps ☐

C. Differential advisory speed limits for cars and trucks on particular ramps ☐

D. Regulatory speed limits for all vehicles on particular ramps ☐

E. Regulatory speed limits for trucks on particular ramps ☐

F. Special warning signs for trucks (truck rollover/tipping sign) ☐

G. Special warning signs for trucks with permanent flashers ☐

H. Special warning signs for trucks with flashers activated when a high-speed truck is detected ☐

I. Special pavement marking warnings for all vehicles ☐

J. Special pavement marking warnings for trucks ☐

K. Reconstruction of ramp to change horizontal curve radius or superelevation ☐

L. Others (please specify below):

2. With respect to truck crash history, please list any existing problematic freeway-to-freeway connector locations below (use the back of this page to list more than 10 locations):

	City	Fwy (Dir) From	Fwy (Dir) To	Posted Advisory Speed	Ramp Type (directional, cloverleaf)
Ex.	*Any town*	*IH 90 (EB)*	*IH 5 (NB)*	*35 mph*	*Directional*
#1					
#2					
#3					
#4					
#5					
#6					
#7					
#8					
#9					
#10					

3. Of the freeway-to-freeway connectors listed in question #2, have any traffic control treatments (signing, pavement markings, barriers, truck barriers, chevrons, delineators, etc.) been used to correct truck operational problems?

☐ YES ☐ NO

If YES, please list location (by #) and modifications made. Please also indicate if any "before-after" study had quantified the benefits of the modifications made (use back of sheet for more space).

4. Have any of the ramps listed in question #2 been re-designed or geometrically modified to address a higher truck crash frequency (by increasing curve radius, superelevation, etc.)?

☐ YES ☐ NO

If YES, please list location (by #) and modifications made.

5. Has any signing been installed on any of these freeway-to-freeway connector ramps that specifically address truck warning speeds?

☐ YES ☐ NO

If YES, please list location (by #) and modifications made.

6. Has any signing been installed on any freeway-to-freeway connectors that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles?

☐ YES ☐ NO

If YES, please list location (by #) and modifications made.

Agency Criteria for Making Advisory Speed Decisions

7. At what staff level are advisory speed setting decisions made?

8. Does your agency have a training program that addresses setting advisory speeds on curves?

☐ YES ☐ NO

9. Does your agency use the ball-bank indicator as the measuring device to set freeway-to-freeway curve advisory speeds?

☐ YES ☐ NO

If NO, what device, and how is it used to set advisory speeds?

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10. Does your agency use the traditional ball-bank readings (14^o for speeds below 20 mph, 12^o for speeds 20 to 35 mph, and 10^o for speeds above 35 mph) to set the freeway-to-freeway connector curve advisory speed?

☐ YES ☐ NO

If NO, what readings do you use?

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11. Are you aware that proposed revisions (part 2) to the 2001 MUTCD will allow engineering judgment to set advisory speeds on curves using up to a 16^o reading on the ball-bank indicator?

☐ YES ☐ NO

12. If empirically justified, would you use a ball-bank indicator reading higher than 10^o to set advisory speeds on curves?

☐ YES ☐ NO

13. What criteria are used to install signing for freeway-to-freeway connectors that addresses advisory speeds for trucks (safety record, speed studies, etc.)?

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14. If any signing has been installed on any freeway-to-freeway connector that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles, what criteria were used to set the different advisory speeds?

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General Questions

15. Has your agency developed any non-standard signs or sign panels for advisory speed limits on freeway-to-freeway connectors?

☐ YES ☐ NO

16. Does your agency use overhead signing for advisory speed limits on freeway-to-freeway connectors?

☐ YES ☐ NO

17. Has your agency encountered any other specific safety problems related to the operation of (or interaction between) heavy trucks and cars that have not been mentioned previously in your responses to this questionnaire?

☐ YES ☐ NO

If YES, what is the nature of these problems?

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18. Has your agency used any pavement markings or marker treatments intended to warn?

☐ YES ☐ NO

If YES, what is the nature of these problems?

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19. Do you have any additional thoughts or comments on signing and pavement markings for heavy trucks on freeway-to-freeway connectors?

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20. Would you like to receive a summary of results from our survey?

☐ YES ☐ NO

Thank you for your time and cooperation in filling out this survey. Please provide the name of the person completing this questionnaire or someone else who may be contacted to obtain any needed follow-up information:

Name:	
Title:	
Agency:	
Street Address/P.O. Box:	
City, State, and Zip Code:	
Telephone:	
Fax:	
E-Mail:	

SURVEY RESULTS

1. Has your agency encountered safety problems related to trucks (and/or other vehicles with high centers-of-gravity) on freeway-to-freeway interchange ramps?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	10	42%	59%
No	7	29%	41%
No Response	7	29%	
Total Responses	24		

If YES, what types of countermeasures have you used for such problems? (Check all that apply):

1A. Advisory speed limits for all vehicles on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	10	42%	59%
No	7	29%	41%
No Response	7	29%	
Total Responses	24		

1B. Advisory speed limits for trucks on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	4	17%	24%
No	13	54%	76%
No Response	7	29%	
Total Responses	24		

1C. Differential advisory speed limits for cars and trucks on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	17	71%	100%
No Response	7	29%	
Total Responses	24		

1D. <u>Regulatory speed limits</u> for all vehicles on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	17	71%	100%
No Response	7	29%	
Total Responses	24		

1E. <u>Regulatory speed limits for trucks</u> on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	17	71%	100%
No Response	7	29%	
Total Responses	24		

1F. <u>Special warning signs for trucks</u> (truck rollover/tipping signs).

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	5	21%	29%
No	12	50%	71%
No Response	7	29%	
Total Responses	24		

1G. <u>Special warning signs for trucks with permanent flashers</u>.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	3	13%	18%
No	14	58%	82%
No Response	7	29%	
Total Responses	24		

1H. <u>Special warning signs for trucks with flashers activated when a high-speed truck is detected</u>.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	1	4%	6%
No	16	67%	94%
No Response	7	29%	
Total Responses	24		

1I. Special pavement marking warnings for all vehicles.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	4	17%	24%
No	13	54%	76%
No Response	7	29%	
Total Responses	24		

1J. Special pavement marking warnings for trucks.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	1	4%	6%
No	16	67%	94%
No Response	7	29%	
Total Responses	24		

1K. Reconstruction of ramp to change horizontal curve radius or superelevation.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	1	4%	6%
No	16	67%	94%
No Response	7	29%	
Total Responses	24		

1L. Others (please specify)

Beaumont District. Our location involves the mainlanes of IH 10 westbound at SH 12 in Vidor (Orange Co) between mile marker 861 and 862. Westbound has a 3-degree right curve at the SH 12 overpass. The location had various truck accidents in the past. This location has had numerous warning features installed for trucks. The other locations listed in Question 2 have not had the problems or the public concern that our IH 10 mainlane site has had. We have not had freeway-to-freeway connector problem with trucks as much as the mainlane curve problem mentioned.

Fort Worth District. We removed the southbound IH 35 to southbound SH 287 ramp. It was known for truck rollovers. Traffic is now routed to the IH 30 exit. We had signed for "No Trucks" on this ramp prior to its removal.

San Antonio District. Used linear delineators (6 inch), Type E Yellow along the IH 35 southbound to IH 10 westbound connector ramp.

2. With respect to truck crash history, please list any existing problematic freeway-to-freeway connector locations below (use the back of this page to list more than 10 locations):

Curve #	District	City	Freeway From	Freeway To	Advisory Speed	Ramp Type
1	AMA	Amarillo	IH 40 WB	IH 27 SB	35	Directional
2	ATL	Texarkana	IH 30 WB	US 59 SB	30	Cloverleaf
3	BMT	Port Arthur	SH 73 WB	US 69 NB	35	Directional
4	BMT	Port Arthur	SH 73 EB	US 69 NB	20	Cloverleaf
5	BMT	Orange	IH 10 WB	SH 87	15	Buttonhook Exit Ramp
6	BMT	Vidor	IH 10 WB	Mainlanes	45	Mainlanes
7	CRP	Corpus Christi	US 77 SB	IH 37 SB	45	Directional
8	CRP	Corpus Christi	US 77 SB	IH 37 NB	45	Directional
9	CRP	Corpus Christi	IH 37 SB	SH 358 EB	45	Directional
10	CRP	Corpus Christi	IH 37 NB	SH 358 EB	45	Directional
11	CRP	Corpus Christi	SH 358 WB	IH 37 NB	45	Directional
12	CRP	Corpus Christi	IH 37 SB	SH 286 SB	45	Directional
13	CRP	Corpus Christi	IH 37 NB	SH 286 SB	45	Directional
14	CRP	Corpus Christi	SH 386 NB	IH 37 SB	40	Directional
15	CRP	Corpus Christi	SH 386 SB	IH 37 NB	40	Directional
16	CRP	Corpus Christi	IH 37 SB	US 181 NB	35	Directional
17	DAL	Dallas	IH 45 NB	IH 20 EB	45	Directional
18	DAL	Dallas	US 80 WB	IH 635 NB	*	Directional
19	DAL	Dallas	US 80 WB	IH 635 SB	30	Directional
20	DAL	Dallas	IH 30 EB	Loop 12	20	Cloverleaf
21	DAL	Dallas	Loop 12	IH 30 WB	20	Cloverleaf
22	DAL	Dallas	IH 635 NB	IH 635 WB	*	Interchange
23	DAL	Dallas	Spur 366 WB	IH 356 SB	*	Cloverleaf
24	ELP	El Paso	US 54 NB	IH 10 WB	35	Directional
25	ELP	El Paso	Loop 375 NB	IH 10 WB	*	Cloverleaf
26	PAR	Sherman	Spur 503 WB	US 75 SB	45	Directional
27	FTW	Fort Worth	IH 35W SB	IH 820 EB (North)	*	Directional

Table continued on next page.

2. With respect to truck crash history, please list any existing problematic freeway-to-freeway connector locations below (use the back of this page to list more than 10 locations) (continued):

Curve #	District	City	Freeway From	Freeway To	Advisory Speed	Ramp Type
28	FTW	Fort Worth	IH 35W NB	IH 820 WB (North)	*	Directional
29	FTW	Fort Worth	IH 35W SB	Spur 280	*	Exit Ramp
30	FTW	Fort Worth	US 287 NB	IH 35W NB	*	Entrance Ramp/Connection
31	FTW	Fort Worth	IH 820 EB	US 287 NB	*	Entrance Ramp/Connection
32	FTW	Arlington	IH 30 EB	SH 360 NB	*	Exit Ramp
33	FTW	Arlington	IH 30 WB	SH 360 SB	*	Exit Ramp
34	FTW	Fort Worth-West	IH 820 SB	IH 30 WB	*	Exit Ramp
35	FTW	Fort Worth-West	IH 30 EB	IH 820 SB	*	Exit Ramp
36	FTW	Fort Worth	SH 360 NB	SH 183 EB	*	Exit Ramp Directional
37	SAT	San Antonio	IH 35 SB	IH 10 WB	25	Directional
38	SAT	San Antonio	IH 35 NB	US 281 NB	24	Directional
39	SAT	San Antonio	IH 410 EB	IH 35 SB	25	Directional
40	SAT	San Antonio	IH 35 NB	IH 410 WB	25	Directional
41	HOU	Houston	IH 10 WB	IH 610 NB	40	Directional
42	HOU	Houston	IH 10 WB	IH 610 SB	40	Directional
43	HOU	Houston	IH 610 EB (North)	IH 45 NB	35	Directional
44	HOU	Houston	IH 610 WB (North)	IH 45 SB	40	Directional
45	HOU	Houston	IH 45 NB	IH 610 WB (North)	40	Directional
46	HOU	Houston	IH 45 NB	IH 610 EB (North)	40	Directional
47	HOU	Houston	IH 45 SB	IH 610 WB (North)	45	Directional
48	HOU	Houston	IH 45 SB	IH 610 EB (North)	40	Directional
49	HOU	Houston	IH 610 EB (North)	US 59 NB	25	Directional
50	HOU	Houston	US 59 NB	IH 610 WB (North)	30	Directional
51	HOU	Houston	US 59 SB	IH 610 EB (North)	35	Directional
52	HOU	Houston	SH 225 WB	IH 610 NB (East)	40	Directional
53	HOU	Houston	IH 610 EB (South)	SH 288 NB	40	Directional
54	HOU	Houston	SH 288 NB	IH 610 WB (South)	40	Directional
55	HOU	Houston	SH 288 NB	IH 610 EB (South)	40	Directional
56	HOU	Houston	US 290 WB	IH 610 NB (West)	40	Directional
57	HOU	Houston	IH 45 SB	IH 10 WB	40	Directional

3. Of the freeway-to-freeway connectors listed in question #2, have any traffic control treatments (signing, pavement markings, barriers, truck barriers, chevrons, delineators, etc.) been used to correct truck operational problems?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	9	38%	75%
No	3	12%	25%
No Response	12	50%	
Total Responses	24		

3A. If YES, please list location (by #) and modifications made. Please also indicate if any "before-after" study had quantified the benefits of the modifications made (use back of sheet for more space).

Table 2 Curve Number	Modifications Noted
1	Installed chevrons and special signing
2	Installed oversize chevrons
4	Installed signing, pavement markings
5	Installed signing, chevrons, pavement markings
6	Installed large warning signs with tipping-truck graphic and flashing lights, pavement marking with "Trucks 45 MPH," large chevrons, and metal orange flags
7-16	Yes, modifications made (not specified), results not quantified
17-23	Yes, modifications made (not specified), results not quantified
26	Added tipping truck on curve sign. No studies but trucks stopped losing their loads on curve.
27-36	Do not have specific information
37-40	Installed delineators, chevrons, and raised pavement markers on curves #37,#39, and #40; installed dynamic feedback sign for speed advisory on #37; installed chevrons on curve #38
41-57	All locations have flashing lights with tipping-truck signs (ground mounted) except for curve #49, which has overhead tipping-truck signs and roadside signs with flashing lights; no before/after studies

4. Have any of the ramps listed in question #2 been re-designed or geometrically modified to address a higher truck crash frequency (by increasing curve radius, superelevation, etc.)?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	2	8%	18%
No	9	38%	82%
No Response	13	54%	
Total Responses	24		

4A. If YES to question #4, please list location (by #) and modifications made.

Table 2 Curve Number	Modifications Noted
2	Currently on schedule for directional interchange
7-16	We have modified some ramps but not specifically for trucks.
25	New interchange is under construction

5. Has any <u>signing</u> been installed on any of these freeway-to-freeway connector ramps that specifically address truck warning speeds?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	3	13%	25%
No	9	37%	75%
No Response	12	50%	
Total Responses	24		

5A. If YES, please list location (by #) and modifications made.

Table 2 Curve Number	Modifications Noted
18	Unspecified
20	Unspecified
21	Unspecified
47-57	All locations have flasher with tipping-truck signs (ground mounted) except curve #49, which has overhead tipping-truck signs and roadside signs with flashers.

6. Has any signing been installed on any freeway-to-freeway connectors that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	13	54%	100%
No Response	11	46%	
Total Responses	24		

7. At what staff level is advisory speed setting decisions made?

Response	Number of Responses	Percent of Total
Director of Trans. Operations	12	63%
Traffic Engineering Section	2	11%
Engr. Tech. Supervisor	1	5%
Maintenance Supervisor	3	16%
Engineering Tech.	1	5%
Total Responses*	19	

*8 districts did not respond; some districts indicated more than one level of decision making

8. Does your agency have a training program that addresses setting advisory speeds on curves?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	2	8%	12%
No	15	63%	88%
No Response	7	29%	
Total Responses	24		

9. Does your agency use the ball-bank indicator as the measuring device to set freeway-to-freeway curve advisory speeds?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	15	63%	88%
No	2*	8%	12%
No Response	7	29%	
Total Responses	24		

*Note: The Beaumont District indicated use of ball-bank and electronic inclinometer; San Antonio responded that they use engineering judgment and/or speed observations.

10. Does your agency use the traditional ball-bank readings (14^o for speeds below 20 mph, 12^o for speeds 20 to 35 mph, and 10^o for speeds above 35 mph) to set the freeway-to-freeway connector curve advisory speed?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	15	63%	88%
No	2*	8%	12%
No Response	7	29%	
Total Responses	24		

*Note: The Houston District uses 10 degrees on all curves; the San Antonio District uses engineering judgment and/or speed observations.

11. Are you aware that proposed revisions (part 2) to the 2001 MUTCD will allow engineering judgment to set advisory speeds on curves using up to a 16° reading on the ball-bank indicator?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	2	8%	12%
No	15	63%	88%
No Response	7	29%	
Total Responses	24		

12. If empirically justified, would you use a ball-bank indicator reading higher than 10° to set advisory speeds on curves?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	8	33%	57%
No	6	25%	43%
No Response	10	42%	
Total Responses	24		

13. What criteria are used to install signing for freeway-to-freeway connectors that addresses advisory speeds for trucks (safety record, speed studies, etc.)?

Response	Number of Responses*	Percent of Total	Percent of Responding
No Specific Criteria	1	5%	13%
Crash History	5	25%	63%
Speed Study	2	10%	25%
No Response	12	60%	
Total Responses	20		

*15 districts did not respond; some districts indicated more than one level of criteria

14. If any signing has been installed on any freeway-to-freeway connector that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles, what criteria were used to set the different advisory speeds?

No responses to this question – no districts have used differing speeds for trucks versus cars.

15. Has your agency developed any non-standard signs or sign panels for advisory speed limits on freeway-to-freeway connectors?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	3	13%	19%
No	13	54%	81%
No Response	8	33%	
Total Responses	24		

APPENDIX B. UNITED STATES STATE DEPARTMENTS OF TRANSPORTATION SURVEY RESULTS

SURVEY RESULTS FOR THE STATE OF THE PRACTICE FOR ADVISORY SPEED SETTING ON FREEWAY-TO-FREEWAY CONNECTOR CURVES

UNITED STATES STATE DEPARTMENTS OF TRANSPORTATION

Texas Department of Transportation, Research Project 0-4813

Survey Questionnaire

Freeway-to-Freeway Connector Ramps:
Current Signing and Pavement Marking Practices

The survey that you have been asked to complete is part of a Federal Highway Administration/Texas Department of Transportation research project to document the current practice of signing and pavement markings for freeway-to-freeway connector ramps, or for connector ramps that link higher-speed facilities.

A particular focus of this research is on advisory speed signing and/or striping for heavy trucks (or other vehicles with high-centers-of-gravity) on freeway-to-freeway connectors. We are also interested in documenting experience with differential speed limits and advisory speeds for trucks and cars on freeway connector ramps.

The intended recipient of this survey is a traffic engineer in your state that has statewide knowledge of the existing installation of advisory signing or pavement markings for trucks on freeway-to-freeway connector ramps.

Please take a few minutes to complete the web-based questionnaire by December 31, 2003.

1. At what staff level are freeway-to-freeway connector advisory speed-setting decisions made?

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2. Has your agency developed any <u>non-standard</u> signs or sign panels for advisory speed limits on freeway-to-freeway connectors?

☐ YES ☐ NO

3. Does your agency use <u>overhead</u> signing for advisory speed limits on freeway-to-freeway connectors?

☐ YES ☐ NO

4. Has your agency encountered any safety problems related to the operation of <u>heavy trucks</u> on freeway connectors?

☐ YES ☐ NO

If YES, what is the nature of these problems?

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5. If your agency has experienced safety problems related to trucks on freeway-to-freeway interchange ramps, what types of countermeasures have you used for such problems? (Check all that apply):

A. Advisory speed limits for all vehicles on particular ramps ☐

B. Advisory speed limits for trucks on particular ramps ☐

C. Differential advisory speed limits for cars and trucks on particular ramps ☐

D. Regulatory speed limits for all vehicles on particular ramps ☐

E. Regulatory speed limits for trucks on particular ramps ☐

F. Special warning signs for trucks (truck rollover/tipping sign) ☐

G. Special warning signs for trucks with permanent flashers ☐

H. Special warning signs for trucks with flashers activated when a high-speed truck is detected ☐

I. Special pavement marking warnings for all vehicles ☐

J. Special pavement marking warnings for trucks ☐

K. Reconstruction of ramp to change horizontal curve radius or superelevation ☐

L. Others (please specify below):

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6. Has your state installed any warning signs on freeway-to-freeway connector ramps that specifically address truck warning speeds?

☐ YES ☐ NO

If YES, please list some example locations.

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7. If your answer to question #6 was YES, what criteria are used to install signing for freeway-to-freeway connectors that addresses advisory speeds for trucks (safety record, speed studies, etc.)?

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8. Has your state installed any signing on any freeway-to-freeway connectors that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles?

☐ YES ☐ NO

If YES, please list location and describe the signing scheme.

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9. If your answer to question #7 was YES, please describe what criteria were used to set the different advisory speeds for trucks and cars?

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General Curve Advisory Speed-Setting Questions

10. What method does your agency use to set freeway-to-freeway curve advisory speeds (ball-bank, operating speeds, etc.)?

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11. If your agency uses the ball-bank indicator, what readings are used and how do they vary with speed (for example: 14 for <= 20 mph)?

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12. Are you aware that the 2003 MUTCD (Section 2C.36) allows engineering judgment to set advisory speeds on curves using up to a 16^{o} reading on the ball-bank indicator?

☐ YES ☐ NO

13. Will your state consider using a ball-bank indicator reading higher than 10^{o} to set advisory speeds on higher-speed connector curves?

☐ YES ☐ NO

Pavement Marking Questions

14. Has your agency used any pavement markings or marker treatments intended to warn trucks or other heavy vehicles about making appropriate speed decisions at freeway-to-freeway connectors?

☐ YES ☐ NO

If YES, what is the nature of these problems and how were pavement markings or markers used?

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15. Do you have any additional thoughts or comments on signing and pavement markings for heavy trucks on freeway-to-freeway connectors?

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Thank you for your time and cooperation in filling out this survey. A summary of results from our survey will be sent to the person listed as the main contact for the survey. Please provide the name of the person completing this questionnaire or someone else who may be contacted to obtain any needed follow-up information:

Name:
Title:
Agency:
Street Address/P.O. Box:
City, State, and Zip Code:
Telephone:
Fax:
E-Mail:

For any questions or comments on this survey, please contact Mr. Garry Ford, P.E., by telephone at 210-979-9411, by fax at 210-979-9694, or by email at g-ford@tamu.edu.

Thank you for your assistance!

SURVEY RESULTS

1. At what staff level are freeway-to-freeway connector advisory speed-setting decisions made ?

Response	Number of Responses	Percent of Total	Percent of Responding
District/Region Level	16	73%	80%
State Level	4	18%	20%
No Response	2	9%	
Total Responses	22		

2. Has your agency developed any non-standard signs or sign panels for advisory speed limits on freeway-to-freeway connectors (Non-standard refers to signing not in the Standard Highway Signs Manual)?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	8	36%	36%
No	14	64%	64%
No Response	0	0%	
Total Responses	22		

3. Does your agency use overhead signing for advisory speed limits on freeway-to-freeway connectors?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	9	41%	43%
No	12	54%	57%
No Response	1	5%	
Total Responses	22		

4A. Has your agency encountered any safety problems related to the operation of heavy trucks on freeway connectors?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	14	64%	64%
No	8	36%	36%
No Response	0	0%	
Total Responses	22		

4B. If YES to question 4A, what is the nature of these problems?

Response	Number of Responses	Percent of Total
Truck Overturns/Tipping/Excessive Speed	10	52%
Only on Low Speed Ramps (<20 mph)	2	11%
Cloverleaf Ramps	3	16%
Run-off-the-road Crashes	1	5%
Geometrics (reverse curve)	2	11%
Downgrade	1	5%
Total Responses	19	

(each state could have multiple responses)

5. If your agency has experienced safety problems related to trucks freeway-to-freeway interchange ramps, what types of countermeasures have you used for such problems?

5A. <u>Advisory speed limits for all vehicles</u> on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	16	73%	73%
No	6	27%	27%
No Response	0	0%	
Total Responses	22		

5B. <u>Advisory speed limits for trucks</u> on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	8	36%	36%
No	14	64%	64%
No Response	0	0%	
Total Responses	22		

5C. <u>Differential advisory speed limits</u> for cars and trucks on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	22	100%	100%
No Response	0	0%	
Total Responses	22		

5D. <u>Regulatory speed limits</u> for all vehicles on particular ramps.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	22	100%	100%
No Response	0	0%	
Total Responses	22		

5E. <u>Regulatory speed limits for trucks</u> on particular ramps

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	22	100%	100%
No Response	0	0%	
Total Responses	22		

5F. <u>Special warning signs for trucks</u> (truck rollover/tipping signs)

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	13	59%	59%
No	9	41%	41%
No Response	0	0%	
Total Responses	22		

5G. <u>Special warning signs for trucks with permanent flashers</u>.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	8	36%	36%
No	14	64%	64%
No Response	0	0%	
Total Responses	22		

5H. <u>Special warning signs for trucks with flashers activated when a high-speed truck is detected</u>.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	2	9%	9%
No	20	91%	91%
No Response	0	0%	
Total Responses	22		

5I. Special pavement marking warnings for all vehicles.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	1	5%	5%
No	21	95%	95%
No Response	0	0%	
Total Responses	22		

5J. Special pavement marking warnings for trucks.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	1	5%	5%
No	21	95%	95%
No Response	0	0%	
Total Responses	22		

5K. Reconstruction of ramp to change horizontal curve radius or superelevation.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	6	27%	27%
No	16	73%	73%
No Response	0	0%	
Total Responses	22		

5L. Others (please specify)

- Regulatory sign "TRUCKS USE RIGHT LANE" on a 2-lane ramp (Minnesota)
- Installation of larger (60 inch x 60 inch) graphic truck rollover/tipping signs
- Installation of larger (24 inch x 30 inch) advisory speed signs
- Installation of "Safe-T-Spins" on warning signs
- Use of W1-13 sign (truck rollover sign)
- Move advance warning signs back upstream before downgrade
- Add chevrons (ASTM TY IX) for curve delineation
- Installation of large diagrammatic signing
- Installation of warning signs that light up with fiber optic lights

6A. Has your state installed any warning signs on freeway-to-freeway connector ramps that specifically address truck warning speeds?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	10	45%	45%
No	12	55%	55%
No Response	0	0%	
Total Responses	22		

6B. If answering YES to question 6A, please list some example locations.

IH 20 EB at SC RT 277; IH 20 WB at IH 26 EB; IH 126 at Greystone Blvd.; IH 95 NB at IH 26 WB (South Carolina)

IH 85 at IH 77 in Charlotte, North Carolina. (Truck rollover signs with permanent flashers); IH 26/IH 240 at US 19-23 (Truck rollover signs with speed advisories); Note: We are in the process of installing continuous flashers on these signs due to continued problems (North Carolina)

TRUCKS-CURVE TIGHTENS-MAX SPEED XX MPH (Iowa)

IH 64 Eastbound at IH 77 (Bigley Avenue Interchange) in Charleston, West Virginia; IH 64 at IH 77 split in Charleston; IH 64 at IH 77 split in Beckley (West Virginia)

San Antonio, Beaumont (Texas)

Use of W4-22 (CA Code) – Tipping-truck symbol with advisory speed limit, used on ramps or branch connectors (California).

We use truck rollover/tipping sings on some off ramps that have tight horizontal curves (Nevada).

Truck rollover sign W1-13 (Vermont)

7. If your answer to question 6A was YES, what criteria are used to install signing for freeway-to-freeway connectors that addresses advisory speeds for trucks (safety record, speed studies, etc.)?

Response	Number of Responses	Percent of Total
Crash History	8	80%
Ramp Geometrics	1	10%
Spot Speed Study	1	10%
Total Responses	10	

8A. Has your state installed any signing on any freeway-to-freeway connectors that has different advisory speeds for trucks as opposed to the posted advisory speed for other vehicles.

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	0	0%	0%
No	20	91%	100%
No Response	2	9%	
Total Responses	22		

8B. If YES, please list location and describe the signing scheme.

(Iowa) IH 380 SB ramp to IH 80 WB. The sign described in the answer to question 6B is installed at the beginning of the ramp, and a standard RAMP advisory speed is installed further down the ramp for other vehicles.

9. If your answer to question 8A was YES, please describe what criteria were used to set the different advisory speeds for trucks and cars?

(Iowa) Crash History

10. What method does your agency use to set freeway-to-freeway curve advisory speeds (ball-bank, operating speeds, etc.)?

Response	**Number of Responses**	**Percent of Total**
Ball-bank Indicator	17	61%
Electronic Ball-bank Indicator	1	4%
Based on Curve Geometric Features (e+f, D)	5	17%
Speed Study	1	4%
Sight Distance	1	4%
Design Speed	2	7%
No Response	1	4%
Total Responses	28	

(Each State could have multiple responses)

11. If your agency uses the ball-bank indicator, what readings are used, and how do they vary with speed (for example: 14 for <= 20 mph)?

- 10 degrees is used for all speeds.
- 14 – Below 20 mph; 12 – 20 to 30 mph; 10 – 35mph and above
- 10 degrees for above 30 mph (advisory at 35); 12 degrees for 30 and under
- 10 degrees (for speeds 35 mph and higher); 12.5 degrees (for speeds 25 mph and 30 mph); 15 degrees (for speeds 20 mph and below)

- We have a spreadsheet program that the electronic ball-bank readings are downloaded into, and it calculates the safe speed for a particular curve.
- NY State MUTCD recommends a maximum deflection of 10 degrees. However, this may be somewhat conservative at lower speeds. The AASHTO manual, *A Policy on Geometric Design of Highways and Streets*, allows 14 degrees at speeds equal to or less than 20 mph and 12 degrees for speeds of 25 and 30 mph.

12. Are you aware that the 2003 MUTCD (Section 2C.36) allows engineering judgment to set advisory speeds on curves using up to a 16^{o} reading on the ball-bank indicator?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	9	41%	41%
No	13	59%	59%
No Response	0	0%	
Total Responses	22		

13. Will your state consider using a ball-bank indicator reading higher than 10^{o} to set advisory speeds on higher-speed connector curves?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	12	55%	55%
No	10	45%	45%
No Response	0	0%	
Total Responses	22		

14A. Has your agency used any pavement markings or marker treatments intended to warn trucks or other heavy vehicles about making appropriate speed decisions at freeway-to-freeway connectors?

Response	Number of Responses	Percent of Total	Percent of Responding
Yes	3	14%	14%
No	18	81%	86%
No Response	1	5%	
Total Responses	22		

14B. If YES, what is the nature of these problems and how were pavement markings or markers used?

- The Wisconsin DOT has used transverse rumble strips to call attention to advisory signs.
- We have used chevron warning signs in some of the ramp curves
- Trucks going too fast on a reverse curve. Markers used on pavement are “TRUCK SPEED 45 MPH.”

15. Do you have any additional thoughts or comments on signing and pavement markings for heavy trucks on freeway-to-freeway connectors?

Colorado, Pennsylvania, and a few other states have had success in using automated warning systems to reduce the number of truck rollovers. Their systems weigh each truck in motion, measure the height of a truck's load, calculates an appropriate advisory speed, and then displays the speed on a Dynamic Message Sign. The North Carolina DOT has considered installing similar type systems, but as of today, no systems like this have been installed.

There is a pooled fund study for traffic control devices that is looking at using markings for speed reduction. The results of this study should be out later this year.

New York is experimenting with speed reduction markings at a freeway ramp from NY 690 to IH 90 near Syracuse. This is being done as one of four test sites for a FHWA Pooled Fund Traffic Control Study. Other sites will be in Texas and Mississippi. Although the markings are meant for all vehicles, it is hoped that they will have a positive impact on trucks as well.

APPENDIX C. FOCUS GROUP DEMOGRAPHICS AND SUMMARY RESULTS

Table C1. Focus Group Demographics.

	Houston General	San Antonio General	Houston Trucks	San Antonio Trucks	Total
Number of Participants	12	13	15	11	51
Sex					
Male	7	6	15	11	39
Female	5	7	0	0	12
Total	12	13	15	11	51
Age					
Average	47	44	53	51	49
Minimum	25	18	40	39	18
Maximum	62	64	82	66	82
Education					
High School / GED	4	5	8	6	23
Some College	2	7	5	2	16
College Graduate	4	1	1	2	8
Masters Degree	2	0	0	1	3
Ph.D. Degree	0	0	0	0	0
No Response	0	0	1	0	1
Total	12	13	15	11	51

Table C2. Focus Group Licensing/Experience.

	Houston General	San Antonio General	Houston Trucks	San Antonio Trucks	Total
Number of Participants	12	13	15	11	51
Driving Experience – Time					
<5 years	0	2	0	0	2
5-9 years	0	0	0	0	0
10-19 years	1	2	1	0	4
>20 years	11	9	14	11	45
Total	12	13	15	11	51
Driving Experience – Cars/Light Trucks					
Cars/Light Trucks, etc.	12	13	15	11	51
No Response	0	0	0	0	0
Commercial Drivers License (CDL)					
Have Texas CDL?	1	0	15	9	25
No	11	13	0	2	26
No Response	0	0	0	0	0
Total	12	13	15	11	51
Commercial Drivers License Class					
Class A	0	1	15	8	24
Class B	0	0	0	0	0
Class C	1	0	0	0	1
No Response	11	12	0	3	26
Total	12	13	15	11	51
Driving Experience – Heavy Trucks					
18 Wheelers/Heavy Trucks	0	0	15	9	24
No Response	12	13	0	2	27
Total	12	13	15	11	51
Truck Driving Experience – Time					
<5 years	0	0	0	1	1
5-9 years	0	0	0	0	0
10-19 years	0	1	4	2	7
>20 years	0	0	11	6	17
No Response	12	12	0	2	26
Total	12	13	15	11	51

APPENDIX D. DETAILED STATISTICAL ANALYSIS OUTPUT

BOOTSTRAP STATISTICAL ANALYSIS
SPEED CHANGE ANALYSIS

Table D-1. Bootstrap Confidence Intervals: Dallas 1 – IH 635 NB to US 80 EB.

Speed Measurement (mph)			*Before*			*Early-After*			*Late-After*		
			Lower	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*
Upstream, US	**All**	Mean	55.31	55.48	55.64	55.86	55.96	56.04	60.72	60.83	60.92
		85th Percentile	62.00	62.31	62.50	60.80	60.98	61.20	66.00	66.10	66.50
	Pass.	Mean	56.98	57.16	57.33	56.44	56.54	56.63	61.08	61.18	61.29
		85th Percentile	63.30	63.33	63.70	61.20	61.21	61.60	66.50	66.50	66.50
	Heavy	Mean	50.51	50.81	51.08	49.50	49.82	50.18	57.91	58.18	58.45
		85th Percentile	56.70	56.83	57.10	55.00	55.37	55.70	62.50	62.93	63.30
Start of Curve, PC	**All**	Mean	48.99	49.13	49.28	51.74	51.86	51.96	50.62	50.70	50.78
		85th Percentile	55.40	55.63	55.70	56.40	56.44	56.70	55.00	55.32	55.40
	Pass.	Mean	51.39	51.53	51.67	52.12	52.24	52.36	50.89	50.97	51.05
		85th Percentile	56.40	56.75	57.10	56.40	56.66	56.70	55.40	55.42	55.70
	Heavy	Mean	42.90	43.13	43.34	45.96	46.46	46.99	44.52	44.94	45.39
		85th Percentile	48.50	48.80	49.20	50.60	51.11	51.70	49.00	49.48	50.00
Middle of Curve, PI	**All**	Mean	45.81	45.94	46.07	47.13	47.21	47.29	46.58	46.65	46.72
		85th Percentile	51.70	51.96	52.00	51.70	51.96	52.00	51.10	51.28	51.40
	Pass.	Mean	48.27	48.42	48.54	47.69	47.77	47.84	47.21	47.28	47.35
		85th Percentile	52.90	53.17	53.50	52.00	52.18	52.30	51.40	51.52	51.70
	Heavy	Mean	40.15	40.31	40.48	41.58	41.92	42.24	40.76	41.02	41.24
		85th Percentile	44.30	44.47	44.80	47.00	47.55	48.00	44.90	45.36	45.60

Gaps: >5 seconds
Number of Bootstraps: 300
Before – 40 mph
Early-After – 50 mph (cars) / 45 mph (trucks)
Late-After – 50 mph (cars) / 45 mph (trucks)

Table D-2. Bootstrap Confidence Intervals: Dallas 2 – US 80 WB to IH 635 NB.

Speed Measurement (mph)			*Before*			*Early-After*			*Late-After*		
			Lower	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*
Upstream, US	**All**	Mean	55.62	55.80	55.97	54.74	54.88	55.02	60.71	60.80	60.91
		85th Percentile	61.60	61.85	62.00	60.40	60.75	60.80	66.50	66.52	67.00
	Pass.	Mean	56.54	56.72	56.89	55.68	55.82	55.95	61.24	61.36	61.48
		85th Percentile	62.00	62.45	62.90	60.80	61.17	61.20	67.00	67.21	67.40
	Heavy	Mean	49.32	49.84	50.37	48.12	48.53	48.96	57.54	57.80	58.05
		85th Percentile	54.80	55.16	55.70	53.20	53.63	54.40	61.60	62.10	62.50
Start of Curve, PC	**All**	Mean	45.01	45.14	45.28	46.02	46.15	46.30	45.94	46.05	46.17
		85th Percentile	50.30	50.50	50.60	51.40	51.46	51.70	51.10	51.38	51.40
	Pass.	Mean	46.18	46.29	46.41	47.17	47.31	47.43	47.11	47.22	47.32
		85th Percentile	50.80	50.98	51.10	52.00	52.06	52.30	51.70	51.93	52.30
	Heavy	Mean	38.61	38.89	39.18	39.51	39.83	40.11	39.28	39.59	39.86
		85th Percentile	43.10	43.59	43.90	43.90	44.42	44.90	43.70	44.46	44.90
Middle of Curve, PI	**All**	Mean	45.34	45.45	45.57	45.35	45.46	45.57	45.60	45.71	45.82
		85th Percentile	50.30	50.51	50.60	50.30	50.40	50.60	50.60	50.61	50.80
	Pass.	Mean	46.44	46.55	46.67	46.36	46.49	46.61	46.54	46.66	46.77
		85th Percentile	50.80	51.05	51.10	50.80	50.94	51.10	50.80	51.06	51.10
	Heavy	Mean	39.83	40.07	40.33	39.87	40.15	40.42	39.90	40.16	40.42
		85th Percentile	43.90	44.29	44.80	43.90	44.15	44.50	43.70	44.26	44.80

Gaps: >5 seconds
Number of Bootstraps: 300
Before – 40 mph
Early-After – 45 mph (cars) / 40 mph (trucks)
Late-After – 45 mph (cars) / 40 mph (trucks)

Table D-3. Bootstrap Confidence Intervals: Dallas 3 – IH 635 WB to IH 35 NB.

Speed Measurement (mph)			*Before*			*Early-After*			*Late-After*		
			Lower	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*
Upstream, US	**All**	Mean	61.61	61.94	62.22	61.13	61.46	61.75	61.63	61.94	62.19
		85th Percentile	69.00	69.26	69.50	69.00	69.49	70.00	68.40	68.51	69.00
	Pass.	Mean	62.52	62.82	63.11	61.71	62.05	62.38	62.36	62.63	62.92
		85th Percentile	69.50	69.73	70.00	69.50	70.02	70.50	68.40	69.07	69.50
	Heavy	Mean	54.47	55.97	57.35	55.43	56.75	57.82	52.72	54.69	56.41
		85th Percentile	63.30	64.31	65.10	63.30	64.04	65.10	61.20	62.32	63.30
Start of Curve, PC	**All**	Mean	51.66	51.82	51.98	51.13	51.27	51.44	57.23	57.43	57.64
		85th Percentile	58.50	58.57	58.90	57.40	57.54	57.80	64.20	64.66	65.10
	Pass.	Mean	53.09	53.25	53.41	52.51	52.66	52.81	58.48	58.70	58.93
		85th Percentile	59.30	59.35	59.60	58.20	58.24	58.50	65.10	65.40	66.00
	Heavy	Mean	44.33	44.76	45.17	44.07	44.54	44.96	49.92	50.55	51.33
		85th Percentile	50.30	50.80	51.40	50.00	50.60	51.40	56.10	56.67	57.80
Middle of Curve, PI	**All**	Mean	45.17	45.31	45.47	44.62	44.74	44.85	43.85	44.00	44.15
		85th Percentile	50.80	51.05	51.10	50.00	50.23	50.30	49.20	49.35	49.50
	Pass.	Mean	46.47	46.63	46.79	46.16	46.28	46.40	45.36	45.52	45.67
		85th Percentile	51.40	51.71	52.00	50.80	50.97	51.10	49.80	49.99	50.30
	Heavy	Mean	39.30	39.62	39.93	38.52	38.77	39.05	37.98	38.26	38.54
		85th Percentile	43.70	44.19	44.90	42.90	43.34	43.70	41.90	42.29	42.50

Gaps: >5 seconds
Number of Bootstraps: 300
Before – 35 mph
Early-After – 40 mph (cars) / 35 mph (trucks)
Late-After – 40 mph (cars) / 35 mph (trucks)

Table D-4. Bootstrap Confidence Intervals: Fort Worth 1 – IH 35W NB to IH 820 WB.

Speed Measurement (mph)			*Before*			*Early-After*			*Late-After*		
			Lower	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*
Upstream, US	**All**	Mean	61.42	61.65	61.86	61.36	61.55	61.74	58.54	58.87	59.17
		85th Percentile	67.40	67.46	67.90	67.00	67.35	67.40	66.00	66.34	66.50
	Pass.	Mean	62.61	62.84	63.04	62.59	62.81	62.99	60.82	61.12	61.41
		85th Percentile	67.90	68.14	68.40	67.90	68.04	68.40	67.00	67.11	67.40
	Heavy	Mean	56.02	56.77	57.52	56.46	57.17	57.80	50.17	51.37	52.45
		85th Percentile	62.90	63.31	63.70	62.90	63.73	64.60	62.00	62.41	62.90
Start of Curve, PC	**All**	Mean	44.95	45.06	45.16	43.18	43.30	43.42	42.37	42.50	42.64
		85th Percentile	51.40	51.66	51.70	49.80	49.85	50.00	51.10	51.42	51.70
	Pass.	Mean	45.57	45.72	45.85	43.62	43.78	43.91	42.80	42.97	43.14
		85th Percentile	52.00	52.13	52.30	50.00	50.18	50.30	51.70	51.82	52.00
	Heavy	Mean	41.68	42.01	42.33	39.68	40.12	40.53	38.58	38.99	39.39
		85th Percentile	47.70	48.05	48.50	45.60	46.13	46.70	46.30	46.91	47.60
Middle of Curve, PI	**All**	Mean	45.30	45.38	45.46	46.15	46.24	46.33	44.88	44.97	45.07
		85th Percentile	50.00	50.25	50.30	51.10	51.38	51.40	50.30	50.31	50.60
	Pass.	Mean	46.38	46.47	46.55	46.82	46.90	47.00	46.03	46.11	46.21
		85th Percentile	50.80	50.81	51.10	51.70	51.73	52.00	50.80	50.86	51.10
	Heavy	Mean	40.83	41.02	41.24	42.37	42.77	43.16	39.93	40.17	40.41
		85th Percentile	45.20	45.55	45.80	47.30	47.85	48.50	44.80	45.17	45.60

Gaps: >5 seconds
Number of Bootstraps: 300
Before – None posted (35 mph)
Early-After – 40 mph (cars) / 35 mph (trucks)
Late-After – 40 mph (cars) / 35 mph (trucks)

Table D-5. Bootstrap Confidence Intervals: Houston 1 – IH 610 EB to IH 45 NB.

Speed Measurement (mph)			*Before*			*Early-After*			*Late-After*		
			Lower	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*	*Lower*	*Mean*	*Upper*
Upstream, US	**All**	Mean	62.37	62.50	62.64	62.19	62.32	62.45	59.42	59.56	59.71
Upstream, US	**All**	85th Percentile	68.60	68.74	69.00	69.00	69.04	69.20	65.60	65.99	66.20
Upstream, US	**Pass.**	Mean	62.94	63.06	63.19	62.80	62.92	63.05	60.15	60.31	60.46
Upstream, US	**Pass.**	85th Percentile	69.00	69.10	69.20	69.20	69.32	69.60	66.20	66.42	66.50
Upstream, US	**Heavy**	Mean	55.13	55.74	56.36	55.60	56.30	56.99	52.13	52.79	53.38
Upstream, US	**Heavy**	85th Percentile	62.00	62.60	63.40	63.60	64.36	65.30	59.30	59.80	60.30
Start of Curve, PC	**All**	Mean	50.86	50.97	51.08	53.82	53.90	53.97	55.35	55.45	55.54
Start of Curve, PC	**All**	85^{th} Percentile	58.20	58.24	58.40	59.30	59.46	59.60	63.40	63.42	63.60
Start of Curve, PC	**Pass.**	Mean	51.11	51.23	51.35	54.00	54.07	54.15	55.61	55.71	55.80
Start of Curve, PC	**Pass.**	85^{th} Percentile	58.40	58.46	58.60	59.30	59.52	59.60	63.10	63.37	63.40
Start of Curve, PC	**Heavy**	Mean	47.65	48.01	48.37	49.04	49.49	49.93	47.96	48.30	48.63
Start of Curve, PC	**Heavy**	85^{th} Percentile	53.70	54.37	54.90	55.40	55.94	56.60	54.80	55.32	55.80
Middle of Curve, PI	**All**	Mean	42.58	42.67	42.78	42.15	42.20	42.25	41.39	41.46	41.53
Middle of Curve, PI	**All**	85^{th} Percentile	47.40	47.60	47.70	47.10	47.24	47.30	46.70	46.73	46.80
Middle of Curve, PI	**Pass.**	Mean	42.98	43.07	43.17	42.62	42.67	42.72	41.86	41.93	42.00
Middle of Curve, PI	**Pass.**	85^{th} Percentile	47.70	47.80	48.10	47.40	47.54	47.60	46.80	47.00	47.10
Middle of Curve, PI	**Heavy**	Mean	37.16	37.56	37.99	36.69	36.89	37.06	35.83	36.10	36.35
Middle of Curve, PI	**Heavy**	85^{th} Percentile	41.10	41.87	42.80	41.00	41.40	41.70	40.20	40.64	41.10

Gaps: >5 seconds
Number of Bootstraps: 300
Before – 35 mph
Early-After – 45 mph (cars) / 35 mph (trucks)
Late-After – 45 mph (cars) / 35 mph (trucks)

Table D-6. Measured Speed Differentials: Dallas 1 - IH 635 NB to US 80 EB.

Speed Measurement (mph)		**Speed Differential**						**Reductions in Differential Speeds US to PC**					
		Before		*Early-After*		*Late-After*		*Before – Early-After*		*Before – Late-After*		*Early-After – Late-After*	
		Mean	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*
US to PC	***Heavy Vehicles***	-7.66	-8.00	-3.37	-4.30	-13.23	-13.40	-4.29	-3.70	5.57	5.40	9.86	9.10
	Passenger Vehicles	-5.63	-6.60	-4.30	-4.50	-10.21	-11.10	-1.33	-2.10	4.58	4.50	5.92	6.60
	Rigid Vehicles	-5.83	-6.40	-4.13	-4.20	-10.03	-11.10	-1.70	-2.20	4.19	4.70	5.90	6.90
US to PI	***Heavy Vehicles***	-10.50	-12.20	-7.90	-7.90	-17.17	-17.50	-2.60	-4.30	6.67	5.30	9.27	9.60
	Passenger Vehicles	-8.76	-10.10	-8.78	-8.90	-13.90	-15.10	0.02	-1.20	5.15	5.00	5.13	6.20
	Rigid Vehicles	-8.55	-10.20	-8.48	-8.80	-14.67	-15.20	-0.07	-1.40	6.12	5.00	6.19	6.40
PC to PI	***Heavy Vehicles***	-2.84	-4.20	-4.52	-3.60	-3.93	-4.10	1.68	-0.60	1.09	-0.10	-0.59	0.50
	Passenger Vehicles	-3.12	-3.50	-4.48	-4.40	-3.69	-4.00	1.36	0.90	0.57	0.50	-0.79	-0.40
	Rigid Vehicles	-2.72	-3.80	-4.35	-4.60	-4.65	-4.10	1.63	0.80	1.93	0.30	0.30	-0.50

Gaps: >5 seconds
Before - 40 mph
Early-After – 50 mph (cars) / 45 mph (trucks)
Late-After – 50 mph (cars) / 45 mph (trucks)

Table D-7. Measured Speed Differentials: Dallas 2 – US 80 WB to IH 635 NB.

Speed Measurement (mph)		**Speed Differential**						**Reductions in Differential Speeds US to PC**					
		Before		*Early-After*		*Late-After*		*Before – Early-After*		*Before – Late-After*		*Early-After – Late-After*	
		Mean	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*
US to PC	***Heavy Vehicles***	-10.94	-11.30	-8.70	-9.00	-18.21	-17.50	-2.24	-2.30	7.26	6.20	9.51	8.50
	Passenger Vehicles	-10.42	-11.40	-8.51	-9.20	-14.13	-15.40	-1.91	-2.20	3.71	4.00	5.62	6.20
	Rigid Vehicles	-10.09	-11.40	-8.60	-9.30	-15.98	-15.90	-1.50	-2.10	5.89	4.50	7.39	6.60
US to PI	***Heavy Vehicles***	-9.74	-10.70	-8.38	-9.40	-17.65	-17.70	-1.36	-1.30	7.91	7.00	9.27	8.30
	Passenger Vehicles	-10.16	-11.40	-9.32	-10.40	-14.69	-16.30	-0.84	-1.00	4.53	4.90	5.37	5.90
	Rigid Vehicles	-9.98	-12.20	-8.89	-10.00	-15.81	-15.90	-1.09	-2.20	5.83	3.70	6.92	5.90
PC to PI	***Heavy Vehicles***	1.20	0.60	0.32	-0.40	0.55	-0.20	0.88	1.00	0.65	0.80	-0.23	-0.20
	Passenger Vehicles	0.26	0.00	-0.81	-1.20	-0.56	-0.90	1.07	1.20	0.82	0.90	-0.25	-0.30
	Rigid Vehicles	0.11	-0.80	-0.29	-0.70	0.17	0.00	0.41	-0.10	-0.06	-0.80	-0.47	-0.70

Gaps: >5 seconds
Before – 40 mph
Early-After – 45 mph (cars) / 40 mph (trucks)
Late-After – 45 mph (cars) / 40 mph (trucks)

Table D-8. Measured Speed Differentials: Dallas 3 – IH 635 WB to IH 35E NB.

Speed Measurement (mph)		**Speed Differential**						**Reductions in Differential Speeds US to PC**					
		Before		*Early-After*		*Late-After*		*Before – Early-After*		*Before – Late-After*		*Early-After – Late-After*	
		Mean	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*
US to PC	***Heavy Vehicles***	-11.22	-13.40	-12.25	-13.60	-4.07	-5.80	1.03	0.20	-7.14	-7.60	-8.18	-7.80
	Passenger Vehicles	-9.58	-10.20	-9.38	-11.80	-3.93	-3.50	-0.19	1.60	-5.65	-6.70	-5.45	-8.30
	Rigid Vehicles	-10.23	-11.70	-11.62	-13.00	-4.09	-1.40	1.39	1.30	-6.14	-10.30	-7.53	-11.60
US to PI	***Heavy Vehicles***	-16.36	-19.90	-17.99	-20.90	-16.40	-20.20	1.63	1.00	0.04	0.30	-1.59	-0.70
	Passenger Vehicles	-16.19	-17.80	-15.77	-18.90	-17.10	-19.00	-0.42	1.10	0.91	1.20	1.33	0.10
	Rigid Vehicles	-16.91	-19.70	-17.63	-19.70	-18.68	-18.10	0.72	0.00	1.78	-1.60	1.05	-1.60
PC to PI	***Heavy Vehicles***	-5.14	-6.50	-5.74	-7.30	-12.32	-14.40	0.59	0.80	7.18	7.90	6.59	7.10
	Passenger Vehicles	-6.62	-7.60	-6.39	-7.10	-13.17	-15.50	-0.23	-0.50	6.55	7.90	6.78	8.40
	Rigid Vehicles	-6.67	-8.00	-6.00	-6.70	-14.59	-16.70	-0.67	-1.30	7.92	8.70	8.58	10.00

Gaps: >5 seconds
Before – 35 mph
Early-After – 40 mph (cars) / 35 mph (trucks)
Late-After – 40 mph (cars) / 35 mph (trucks)

Table D-9. Measured Speed Differentials: Forth Worth 1 - IH 35W NB to IH 820 WB.

Speed Measurement (mph)		**Speed Differential**						**Reductions in Differential Speeds US to PC**					
		Before		*Early-After*		*Late-After*		*Before – Early-After*		*Before – Late-After*		*Early-After – Late-After*	
		Mean	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*
US to PC	***Heavy Vehicles***	-14.72	-15.30	-17.06	-17.60	-12.35	-15.50	2.34	2.30	-2.37	0.20	-4.70	-2.10
	Passenger Vehicles	-17.11	-15.90	-19.04	-17.60	-18.16	-15.30	1.92	1.70	1.05	-0.60	-0.88	-2.30
	Rigid Vehicles	-15.73	-15.70	-16.79	-16.50	-13.37	-13.20	1.06	0.80	-2.36	-2.50	-3.42	-3.30
US to PI	***Heavy Vehicles***	-15.72	-17.70	-14.38	-15.70	-11.17	-17.30	-1.34	-2.00	-4.55	-0.40	-3.21	1.60
	Passenger Vehicles	-16.36	-17.10	-15.91	-16.20	-15.01	-16.20	-0.45	-0.90	-1.35	-0.90	-0.90	0.00
	Rigid Vehicles	-16.22	-17.50	-15.07	-16.00	-13.25	-16.40	-1.15	-1.50	-2.97	-1.10	-1.82	0.40
PC to PI	***Heavy Vehicles***	-1.00	-2.40	2.68	1.90	1.18	-1.80	-3.68	-4.30	-2.18	-0.60	1.50	3.70
	Passenger Vehicles	0.76	-1.20	3.13	1.40	3.15	-0.90	-2.38	-2.60	-2.40	-0.30	-0.02	2.30
	Rigid Vehicles	-0.49	-1.80	1.72	0.50	0.12	-3.20	-2.21	-2.30	-0.61	1.40	1.60	3.70

Gaps: >5 seconds
Before – None posted (35 mph)
Early-After – 40 mph (cars) / 35 mph (trucks)
Late-After – 40 mph (cars) / 35 mph (trucks)

Table D-10. Measured Speed Differentials: Houston 1 – IH 610 EB to IH 45 NB.

Speed Measurement (mph)		Speed Differential						Reductions in Differential Speeds US to PC					
		Before		*Early-After*		*Late-After*		*Before – Early-After*		*Before – Late-After*		*Early-After – Late-After*	
		Mean	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*	*Mean*	*85th*
US to PC	***Heavy Vehicles***	-7.72	-8.10	-6.75	-8.50	-4.45	-4.60	-0.97	0.40	-3.27	-3.50	-2.30	-3.90
	Passenger Vehicles	-11.83	-10.60	-8.85	-9.60	-4.60	-3.10	-2.98	-1.00	-7.23	-7.50	-4.25	-6.50
	Rigid Vehicles	-9.42	-9.30	-6.08	-6.50	0.11	1.60	-3.34	-2.80	-9.53	-10.90	-6.19	-8.10
US to PI	***Heavy Vehicles***	-18.17	-20.65	-19.38	-23.10	-16.64	-19.10	1.22	2.45	-1.53	-1.55	-2.74	-4.00
	Passenger Vehicles	-19.99	-21.30	-20.25	-21.60	-18.39	-19.50	0.26	0.30	-1.60	-1.80	-1.86	-2.10
	Rigid Vehicles	-18.81	-20.40	-19.69	-21.50	-16.47	-17.70	0.89	1.10	-2.34	-2.70	-3.23	-3.80
PC to PI	***Heavy Vehicles***	-10.45	-12.55	-12.63	-14.60	-12.19	-14.50	2.18	2.05	1.74	1.95	-0.44	-0.10
	Passenger Vehicles	-8.15	-10.70	-11.40	-12.00	-13.78	-16.40	3.24	1.30	5.63	5.70	2.38	4.40
	Rigid Vehicles	-9.38	-11.10	-13.61	-15.00	-16.57	-19.30	4.23	3.90	7.19	8.20	2.96	4.30

Gaps: >5 seconds
Before – 35 mph
Early-After – 45 mph (cars) / 35 mph (trucks)
Late-After – 45 mph (cars) / 35 mph (trucks)

APPENDIX E. STATISTICAL SUMMARY

SPEED DIFFERENTIALS:
UPSTREAM VS. POINT OF CURVATURE VS. MIDPOINT OF CURVE

Table E-1. Dallas 1 Changes in Speed – US.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	0.48*	5.34*	4.87*
85th Percentile	-1.33*	3.8*	5.12*
Passenger Vehicles			
Mean	-0.62*	4.03*	4.65*
85th Percentile	-2.12*	3.17*	5.29*
Heavy Vehicles			
Mean	-0.99*	7.37*	8.36*
85th Percentile	-1.46*	6.1*	7.56*

Table E-2. Dallas 1 Changes in Speed – PC.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	2.73*	1.57*	-1.16*
85th Percentile	0.81*	-0.31	-1.12*
Passenger Vehicles			
Mean	0.71*	-0.56*	-1.27*
85th Percentile	-0.09	-1.33*	-1.24*
Heavy Vehicles			
Mean	3.33*	1.81*	-1.52*
85th Percentile	2.32*	0.68*	-1.64*

Table E-3. Dallas 1 Changes in Speed – PI.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	1.27*	0.71*	-0.56*
85th Percentile	0	-0.68*	-0.68*
Passenger Vehicles			
Mean	-0.65*	-1.14*	-0.49*
85th Percentile	-0.99*	-1.65*	-0.66*
Heavy Vehicles			
Mean	1.61*	0.7*	-0.9*
85th Percentile	3.08*	0.89*	-2.19*

* indicates statistically significant difference.

Table E-4. Dallas 2 Changes in Speed – US.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.92*	5.01*	5.92*
85th Percentile	-1.1*	4.66*	5.77*
Passenger Vehicles			
Mean	-0.9*	4.64*	5.54*
85th Percentile	-1.28*	4.76*	6.04*
Heavy Vehicles			
Mean	-1.31*	7.97*	9.28*
85th Percentile	-1.53*	6.94*	8.47*

Table E-5. Dallas 2 Changes in Speed – PC.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	1.01*	0.91*	-0.1
85th Percentile	0.96*	0.88*	-0.08
Passenger Vehicles			
Mean	1.02*	0.93*	-0.09
85th Percentile	1.08*	0.94*	-0.14
Heavy Vehicles			
Mean	0.93*	0.69*	-0.24
85th Percentile	0.83	0.87*	0.04

Table E-6. Dallas 2 Changes in Speed – PI.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	0	0.26*	0.26*
85th Percentile	-0.11	0.1*	0.21
Passenger Vehicles			
Mean	-0.06	0.11*	0.17
85th Percentile	-0.11	0.01	0.12
Heavy Vehicles			
Mean	0.08	0.08*	0.01
85th Percentile	-0.14	-0.04	0.11*

* indicates statistically significant difference.

Table E-7. Dallas 3 Changes in Speed – US.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.48	0	0.48
85th Percentile	0.24	-0.75	-0.98
Passenger Vehicles			
Mean	-0.77*	-0.19	0.58
85th Percentile	0.29	-0.66	-0.96
Heavy Vehicles			
Mean	0.78	-1.28	-2.05
85th Percentile	-0.27	-1.99	-1.72

Table E-8. Dallas 3 Changes in Speed – PC.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.55*	5.61*	6.16*
85th Percentile	-1.03*	6.09*	7.12*
Passenger Vehicles			
Mean	-0.59*	5.45*	6.04*
85th Percentile	-1.11*	6.06*	7.16*
Heavy Vehicles			
Mean	-0.23	5.79*	6.02*
85th Percentile	-0.19	5.87*	6.07*

Table E-9. Dallas 3 Changes in Speed – PI.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.57*	-1.32*	-0.75*
85th Percentile	-0.82*	-1.7*	-0.88*
Passenger Vehicles			
Mean	-0.35*	-1.11*	-0.76*
85th Percentile	-0.73*	-1.72*	-0.98*
Heavy Vehicles			
Mean	-0.86*	-1.36*	-0.5
85th Percentile	-0.85	-1.9*	-1.05*

* indicates statistically significant difference.

Table E-10. Fort Worth 1 Changes in Speed – US.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.1	-2.78*	-2.68*
85th Percentile	-0.12	-1.12*	-1.01*
Passenger Vehicles			
Mean	-0.03	-1.72*	-1.69*
85th Percentile	-0.11	-1.03*	-0.92*
Heavy Vehicles			
Mean	0.4	-5.4*	-5.8*
85th Percentile	0.42	-0.9	-1.32

Table E-11. Fort Worth 1 Changes in Speed – PC.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-1.75*	-2.56*	-0.8*
85th Percentile	-1.81*	-0.24	1.57*
Passenger Vehicles			
Mean	-1.94*	-2.75*	-0.81*
85th Percentile	-1.95*	-0.31	1.64*
Heavy Vehicles			
Mean	-1.9*	-3.02*	-1.13*
85th Percentile	-1.92*	-1.14*	0.78

Table E-12. Fort Worth 1 Changes in Speed – PI.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	0.86*	-0.41*	-1.27*
85th Percentile	1.13*	0.06*	-1.07*
Passenger Vehicles			
Mean	0.43*	-0.36*	-0.79*
85th Percentile	0.93*	0.05	-0.88*
Heavy Vehicles			
Mean	1.75*	-0.84*	-2.6*
85th Percentile	2.3*	-0.38	-2.68*

* indicates statistically significant difference.

Table E-13. Houston 1 Changes in Speed – US.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.18	-2.94*	-2.76*
85th Percentile	0.3	-2.75*	-3.05*
Passenger Vehicles			
Mean	-0.14	-2.75*	-2.6*
85th Percentile	0.22	-2.68*	-2.9*
Heavy Vehicles			
Mean	0.57	-2.95*	-3.52*
85th Percentile	1.76*	-2.8*	-4.56*

Table E-14. Houston 1 Changes in Speed – PC.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	2.93*	4.48*	1.55*
85th Percentile	1.22*	5.18*	3.96*
Passenger Vehicles			
Mean	2.85*	4.48*	1.63*
85th Percentile	1.06*	4.91*	3.85*
Heavy Vehicles			
Mean	1.48*	0.29*	-1.19*
85th Percentile	1.57*	0.95*	-0.62

Table E-15. Houston 1 Changes in Speed – PI.

Speed Measurements	*Before to Early-After*	*Before to Late-After*	*Early-After to Late-After*
All Vehicles			
Mean	-0.47*	-1.21*	-0.74*
85th Percentile	-0.36*	-0.88*	-0.52*
Passenger Vehicles			
Mean	-0.4*	-1.15*	-0.75*
85th Percentile	-0.26*	-0.8*	-0.54*
Heavy Vehicles			
Mean	-0.67*	-1.45*	-0.79*
85th Percentile	-0.47	-1.23	-0.75

* indicates statistically significant difference.