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16. Abstract

This research project examined the speed characteristics of passenger cars and vehicles with high centers of gravity on freeway connectors to determine any discernable differences between the two vehicles types. Data to determine compliance with posted advisory speed limits and average speeds at points along connector ramps were collected on freeway connectors in Houston. Four different vehicles were driven through the curves at varying speeds while monitoring a manual ball-bank indicator as well as collecting lateral acceleration data electronically.

The project determined that the general public often exceeds the posted advisory speed limits, often by more than 10 mph. While there are no seemingly discernable differences in lateral accelerations by different types of vehicles for a given speed along a curve, there may be a 5 to 10 mph difference in the driver's comfortable speed between vehicle types.

The findings of this project indicate that there may be differences between the maximum comfortable speeds that drivers of heavy vehicles and passenger car type vehicles will accept for a freeway-to-freeway curve. The following conclusions confirmed by this project are applicable to freeway-to-freeway connectors and should be considered in their design, and especially in their re-design: to provide adequate deceleration and acceleration distances for tractor-trailers and other heavy vehicles, to reduce the side friction demand on trucks in the curve by developing superelevation more on the tangent, to place curve advisory speed signing with more regard to the deceleration needs of trucks.

The results of this project indicate that modifying the current advisory speed setting criteria to use a 10-degree level to set a truck advisory speed and a 13-degree level for setting a more realistic passenger car advisory speed may be appropriate to more closely represent the 85th percentile speed of each vehicle on a curve.

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EVALUATION OF VEHICLE SPEEDS ON FREEWAY-TO-FREEWAY CONNECTOR RAMPS IN HOUSTON

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the views or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (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 this project was Anthony Voigt, P.E. #84845.

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1.0 INTRODUCTION

Interchanges on freeways have proven to be particularly dangerous for large trucks, especially those traveling at high speeds on freeway-to-freeway connector ramps. Numerous studies have documented that crashes, particularly truck crashes, tend to cluster at freeway interchange ramps, especially off-ramps and connectors. Many of these truck crashes are a result of single-vehicle crashes where the interaction of truck performance, driver expectations, driver performance, and roadway geometry interact.

The development of this research project was based largely on experience in the Houston urban area where truck rollover crashes have occurred on several freeway-to-freeway connector ramps in the past decade. Truck rollovers are typically high impact and high visibility incidents that can snarl traffic during any time of the day. These incidents tend to require several hours for cleanup, often result in injuries or fatalities, and can result in high traffic delays within the freeway interchanges. While several previous studies have examined the relationship between truck crashes and ramp geometry, this study focused on examining the relationship between vehicle operations and current advisory speed signing practices and whether there should be a distinction between passenger cars and trucks with respect to advisory speed signing on freeway-to-freeway connectors.

The primary goal of this research project was to examine the speed characteristics of passenger cars and vehicles with high centers of gravity on freeway connectors and determine if there were any discernable differences in the speed characteristics between the two vehicle types. Included in the category of vehicles with high centers of gravity are 18-wheel tractor-trailers, single-unit trucks, vans, and sport-utility vehicles (SUVs). The research narrowed its focus to seven freeway-to-freeway connector ramps in the Houston urban area; each generally located on the northern and eastern sections of Interstate Highway (IH) 610 at United States Highway (US) 290, IH 45 North, US 59 Eastex, and State Highway (SH) 225 interchanges.

The Houston area, like other major urban areas across the state, has experienced significant growth in the number of trucks on its urban highways. Being at the center of the IH 45 and IH 10 crossroads, and with the Port of Houston and a large warehousing industry in the city, Houston's freeways accommodate thousands of trucks with varying configurations and cargo on a daily basis. The ever-increasing number of trucks on these freeways has an impact on traffic operations by reducing capacity and increasing the potential for vehicle conflicts. As a regional shipping and trucking center, Houston also attracts truck drivers that may not be as experienced or familiar with the local freeway system and its interchanges. These unfamiliar drivers must rely on the posted advisory speeds and advance curve warning signing to select appropriate speeds while negotiating freeway connector ramps.

Recent data collected in the Houston area on freeway-to-freeway connector ramps indicated that all types of vehicles are exceeding the posted limits by varying amounts, from 5 miles per hour (mph) to over 15 mph. These higher speeds may result in uncomfortable lateral accelerations for many drivers and passengers, but may not necessarily result in a loss of control. While speeds in excess of the posted advisory speeds may be acceptable to driver comfort and vehicle physics a majority of the time, there are situations where inexperienced or inattentive drivers of large truck-trailer combinations with high centers of gravity can exceed the speeds and rollover may occur. This situation can be especially dangerous for less experienced truck drivers, who may not have a full appreciation for the physics of the trailer they are pulling. This lack of experience can be compounded during inclement weather or in high-volume traffic, where vehicle headways may be less than desirable. In addition, because of the current method of horizontal curve design in the United States, many freeway-to-freeway connector curves may have reduced margins of safety, particularly for high center of gravity vehicles, such as tractor-trailers hauling loads of different configurations.

This project focused on an examination of the comfort levels for drivers of various types of vehicles: passenger cars, sport-utility vehicles, heavy-duty dump trucks and 18-wheelers. Each of these vehicles was driven through seven freeway-to-freeway connectors at speeds ranging from 30 mph to 55 mph, depending on the particular freeway connector curve. Researchers recorded ball-bank indicator readings (taken manually) and electronic lateral acceleration readings during each drive through the curve. These measurements were used to determine if the comfort levels experienced by drivers of the different vehicle types were similar and how they corresponded to the existing advisory speed setting criteria. If the levels of comfort were similar for drivers of all vehicle types, then the current procedures of setting speed advisory levels for all vehicles would be appropriate for all curves, without modification. However, if the comfort levels of the drivers for different vehicle types were found to be different, then the possibility of a dual advisory speed would be recommended for further investigation.

OVERVIEW AND BACKGROUND

The national authoritative reference for the geometric design of horizontal curves is the American Association of State Highway and Transportation Officials (AASHTO) *A Policy on the Geometric Design of Highways and Streets*, more commonly known as the “Green Book” (1). The objective of the horizontal curve design policy is to select a curve radius and superelevation rate so that the unbalanced lateral acceleration remains within comfortable limits. These limits were based on research conducted in the 1930s and 1940s using primarily passenger cars. These early studies established that the maximum unbalanced lateral acceleration ranged from a maximum of 0.17 *g* at 20 mph to 0.10 *g* at 70 mph, based on driver and passenger comfort levels in passenger cars.

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 all classes of motor vehicles from the 1940s to the early 2000s. The assumptions made in developing the side friction factors used in design were mainly contrived from the comfort levels of drivers (and passengers) of passenger cars. The design procedure was assumed to leave a significant factor of safety between the level of comfort and that of skidding or rollover. The driver that traverses a curve at a speed higher than used for design will experience a level of lateral acceleration that may make him uncomfortable but not necessarily create a safety problem (a crash may not occur). However, one concern with the phenomenon of drivers traversing curves at higher speeds is that truck drivers may not realize that the margin of safety between those lateral accelerations that exceed their comfort levels and those that may lead to skidding or rollover caused by a trailer loading condition has been reduced.

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 the physics of passenger cars.

These guidelines do not explicitly address the physics of heavy vehicles and especially the physics of trailers pulled by trucks. There is an especially interesting relationship between design speed and the margin of safety for trucks traversing curves. For example, for 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. The margin between design and truck rollover speeds increases as design speeds increase. For example, for four curves designed to AASHTO standards with superelevation of 0.04, rollover speeds would be 27 mph for a 20 mph curve and 40 mph for a 30 mph curve, but the truck would 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 the most dangerous situations created for trucks given current design criteria are on the low design speed curves, typical of many freeway connector ramps. The low-speed ramp scenario (common with cloverleaf interchanges) has been wisely phased out in the Houston area over several decades at major freeway-to-freeway interchanges, so none of the curves examined in this project are of this type.

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

$$e + f = \frac{v^2}{15R}$$

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. 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 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 trucks is different than that of passenger cars.

The AASHTO curve design criteria do not specifically consider vehicle rollover thresholds. Typical passenger cars will skid before they rollover, with the rollover thresholds for cars at 1.2 g or higher. However, tractor-trailers can have fairly low rollover thresholds (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.

STUDY GOALS AND METHODOLOGY

This project examines the following issues:

- Given the changes in roadway and vehicle performance over the last 50 to 60 years, is there a discernable change in the lateral acceleration that drivers will accept on a freeway-to-freeway connector ramp? If so:
- Is there a difference between the lateral acceleration or comfort level that drivers of different types of vehicles will accept for a given curve? If so:
- If differences in lateral acceleration or comfort level exist, is there enough evidence to support either a revision in current advisory speed setting criteria or introduction of a dual advisory speed signing criteria for cars and trucks?

The methodology of the project is summarized as follows:

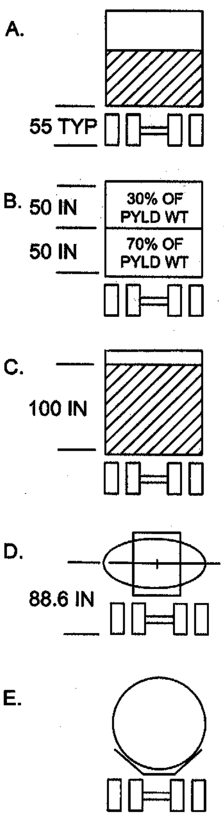
1. Identify at least 30 freeway-to-freeway connectors in the Houston area that are perceived to experience truck rollovers and other crash rates at a higher than average proportion.
2. Select 7 to 10 freeway-to-freeway connectors for further study and survey curve conditions.
3. Conduct speed/classification/volume studies for each ramp on upstream approach, at point of curvature, and at midpoint of curve.
4. Acquire ball-bank indicator and electronic lateral accelerometer and prepare mechanism for use in various vehicles.
5. Conduct travel studies through selected curves while varying speeds at 5 mph increments until drivers exceed comfort levels for four types of vehicles: passenger cars, sport-utility vehicles, dump trucks and tractor-trailer combinations.
6. Conduct analysis of ball-bank readings and accelerometer readings – examine data for differences between vehicles.
7. Conduct analysis of speeds before, at the beginning, and at the midpoint of the curve to determine speed reductions experienced by drivers.
8. Present summary and implementation recommendations.
9. Identify areas for further study.

2.0 LITERATURE REVIEW

As compared to lighter, more maneuverable passenger cars, light trucks, sport-utility vehicles, heavy trucks, and truck-trailer combinations have many potential limitations on their ability to traverse horizontal curves, especially on freeway-to-freeway connectors. These limitations range from size and weight characteristics to mechanical performance parameters. Crash experience in the Houston area indicates that many truck rollover incidents may be caused by excessive speed when entering or during traversal of a horizontal curve. There may be many reasons that truck drivers exceed the posted advisory speed on a freeway-to-freeway connector, but among the most prominent reasons may be inadequate deceleration distance, the need to hold speed for merging into freeway mainlanes, or a lack of understanding of the geometric limitations of many freeway connectors.

The basis for geometric design in this country is the American Association of State Highway and Transportation Officials' *A Policy on the Geometric Design of Highways and Streets* (the "Green Book") (2). The AASHTO Green Book leans heavily towards providing design guidance based on passenger car operations, not heavy trucks. As a result, many ramps may not adequately accommodate the varying operational parameters of trucks.

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 operational 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 for design include the design speed, superelevation rate, and side friction factor. As a truck travels through a curve, the truck speed, combined with the ramp curvature and superelevation level creates a lateral acceleration (3). For each truck and loading circumstance, there is a maximum lateral acceleration threshold that, if exceeded, will cause the truck to roll over (3). The University of Michigan Transportation Research Institute (UMTRI) developed rollover threshold values for various trucks and loading conditions using various static and dynamic testing (4, 5). These thresholds are presented in Figure 1.



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

ROLLOVER THRESHOLD VALUES FOR VARIOUS EXAMPLE TRUCK VEHICLES
FROM REFERENCE 4

FIGURE 1 — Texas Transportation Institute — PROJECT 0-4318 — SCALE: NTS — DATE: 11/1/02 — EXHIBIT 1

Figure 1. Rollover Thresholds for Various Heavy Vehicles.

Side friction factors recommended for design were 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. Harwood et al. also noted that the margins between design and rollover speeds increase as design speeds increase (6). For example, for four curves with superelevation of 0.04, rollover speeds would be 27 mph for a 20 mph curve and 40 mph for a 30 mph curve, but the truck would skid at 54 mph on a 40 mph curve and 67 mph on a 50 mph curve. These factors seem to indicate that the most dangerous situations created for trucks given current design criteria are on the low-design speed curves, typical of many freeway connector ramps.

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 (see Figure 2). A study by Fitzpatrick et al. (7) presented a survey indicating that 88 percent of states, cities, or counties that responded use the ball-bank indicator to set safe speeds on curves. The ball-bank indicator measures relative lateral acceleration that drivers and passengers sense on 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 (8). The need for a consensus method to determine safe speeds on curves lead the Bureau of Public Roads (in 1935) 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 runs with test vehicles during the 1930s, it was 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 (9).

Figure 2. Ball-Bank Indicator.

Because the mid-1930s testing indicated that the maximum side friction that a driver would accept before discomfort was about 0.14 or 0.15, the 10-degree limit was deemed a close fit to the side friction at discomfort for higher speeds (8). 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 came the 12-degree reading for curves of 30 mph and 14 degrees for curves of 20 mph or less. These recommendations were promulgated throughout many texts over the next several decades and found themselves into a set of AASHTO policies in the late 1930s and early 1940s. These recommendations may be found in various handbooks and guidelines, including the Institute of Transportation Engineer's (ITE) *Transportation and Traffic Engineering Handbooks*, *Traffic Control Devices Handbook*, and the 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.

The ball-bank test runs are typically made with a driver and an observer. After checks of calibration to ensure that the ball is on zero when the vehicle is in a horizontal position, the vehicle is driven on the subject curve at a constant speed, parallel to the center of the curve (8). The criterion for setting the advisory speed on the curve is the speed where a ball-bank indicator reads 10 degrees or less for 35 mph or greater. The decision to provide an advisory speed plate is made when the safe operating speed as determined by the ball-bank indicator is less than the prevailing speed on the roadway. The value shown on the plate usually corresponds to the lowest speed (to the nearest 5 mph) obtained during trial runs that create a reading of 10 degrees or more on the ball-bank indicator (9, 23).

The physics that explain the mathematical relationships involved in depicting motion around a horizontal curve can be described using several equations (1, 10). Given that a vehicle is moving at a constant speed v on a curve or constant radius R, the acceleration is directed towards 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 the equation:

$$a_{per} = \frac{v^2}{R} \tag{1}$$

where:

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

A vehicle generates this measure of lateral acceleration as it traverses a curve of constant radius counterbalanced by the vehicle weight and roadway superelevation and side friction development between the tires and pavement surface. The AASHTO Green Book uses the point mass model to determine the minimum radius of curve given a superelevation rate so that the lateral acceleration is kept at a desirable maximum level based on driver and passenger comfort.

When combined with the second law of physics, the point mass model used to represent vehicle motion on a horizontal curve is:

$$e + f = \frac{v^2}{15R} \tag{2}$$

where:

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

Equation 2 may be thought of as a supply-demand equation. The left side of equation 2 represents the amount of lateral acceleration supplied, while the right side is the demanded lateral acceleration.

The ball-bank indicator has long been used by agencies to measure the point of discomfort for drivers and passengers on curves. The 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. The ball-bank reading (α) is indicative of the combined effect of body roll angle (θ), centrifugal force angle (φ), and superelevation angle (ρ) (1, 10) and is related by the following equation:

$$\alpha = \theta - \varphi + \rho \tag{3}$$

Moyer and Berry recommended overlooking the body roll term of this equation as long as the observers understood its impact (9). 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 the calculation of safe speeds on curves, as it was found statistically insignificant (10). Carlson and Mason concluded that the ball-bank indicators can be correlated directly with driver comfort and lateral acceleration values used in curve design; however, they did not examine further the validity of the AASHTO-recommended values of lateral acceleration.

The following indicates the current AASHTO guidelines for setting advisory speeds on curves:

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 (2).

Again, these criteria are based on tests conducted in the 1930s and were intended to represent the 85- to 90-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 (11). These guidelines resulted from the Moyer and Berry study of vehicles in the 1940s (9). It has been argued over the past few decades 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 (11).

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 that would be recommended by the ball-bank test (11). They further argued that the ball-bank criteria resulted in very low and unrealistic speeds and concluded that this is why the profession should not expect compliance from drivers. This study did not appear to distinguish trucks from passenger cars.

One study of curve operations in New Zealand also found results similar to recent studies in the United States (12). The study suggested changing New Zealand's advisory speed system to more accurately reflect the actual operating speed. This study also compared the method of determining lateral accelerations either by ball-bank readings or accelerometer and concluded that both devices may be used. However, the data collected by the accelerometer needed to be smoothed to reduce lateral acceleration peaks.

TRUCK OPERATIONS

Ervin, MacAdam, and Barnes recognized several cases where roadway geometrics or driver misjudgment may increase the potential for freeway connector crashes (13). The following three are most important to this study:

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

For Case 1, Ervin, MacAdam, and Barnes make a case that the margin of safety for trucks on horizontal curves designed by AASHTO guidelines is much less than the margin of safety for passenger cars. Considering that for many curves (and as specified in AASHTO guidelines) superelevation is not fully developed until well into the curve means that the side friction factors are typically higher than the side friction factors used in determining the design superelevation. These side friction factors, in many 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-trailers track width, along with many other parameters such as suspension, tires, etc. The general relationship, assumed to be valid for curve design, was that the roll stability limit in g's is:

$$g = \text{Track Width} / (2 * \text{Height of Center of Gravity})$$

where g = roll stability limit; and Track Width is distance between tires on opposite ends of the axle.

This equation is valid when the trailer is considered rigid. However, trailers tend not to be rigid frames and may flex under stressed conditions. Ervin, MacAdam, and Barnes state that the roll stability limit may be reduced by nearly 40 percent in actual truck conditions. This reduction becomes critical when you consider that the g's produced by a non-rigid trailer may quickly approach the rollover threshold at side friction factors very near design limits. Obviously, if a particular truck, with a very high-center-of-gravity trailer, is exceeding the advisory speed selected according to existing guidelines, a good possibility exists that a rollover incident will occur because of the physics of the trailer even though the comfort level of the truck driver has not been exceeded.

For Case 2, Ervin, MacAdam, and Barnes 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 has yet to be traversed. These advisory speeds are located on many freeway-to-freeway ramps in the Houston area (IH 610 Eastbound to US 59 Northbound, US 59 Northbound to IH 610 Westbound for example). Truck drivers will then begin to accelerate to prepare to merge into mainlane traffic, only to find a second curve requiring a slower speed or a curve on a downgrade – which may be unexpected by drivers. This situation can also cause not only rollover crashes, but jackknife crashes as well. If the truck drivers recognize the upcoming curve and judge a need to slow down, they may begin heavy braking to reduce speed, which might cause load shift and a resulting jackknife situation. This condition may especially be aggravated by freeway-to-freeway connectors where the second curve is on a downgrade.

Ervin, MacAdam, and Barnes also argued that for Case 3, deceleration lanes were not long enough to achieve enough speed reduction. 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." The Green Book did not repeat this assumption but did not change significantly its recommendations for deceleration lengths. Recent observations could also dispute this assumption, with truck speeds equal to passenger car speeds in most cases.

The *Comprehensive Truck Size and Weight (TS&W) Study* also cited several previous studies that identified these problems (Cases 1 and 3) as a concern (14). The study indicated that trucks with rollover coefficients of 0.30 *g* can roll over on freeway ramps when traveling as little as 5 mph over the design speed. In many cases, the length of deceleration lanes is not adequate to accommodate the characteristics of truck deceleration. This lack of deceleration length, combined with the fact that many freeway ramp design speeds are significantly lower than those on the freeway mainlanes, may lead to rollover crashes caused by excessive speed on low-design speed ramps. The TS&W study referenced an ITE publication that compared deceleration lane requirements as stated in the Green Book (for passenger cars) 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 (15).

SAFETY

The Texas Department of Transportation (TxDOT) has enhanced its priority on freeway connector ramp safety in recent years as the impact of rollover crashes on freeway connectors has become more evident in the public vision. This increased importance of finding causative factors for connector crashes has led to this research. Previous researchers have recognized that several variables contribute to crash risk: 1) vehicle (including trailers and other equipment); 2) driver performance; and 3) the environment (weather, roadway, etc.) (14). While driver errors are typically blamed for causing crashes, vehicle and equipment failures also play a role. However, in many cases it is difficult to determine if vehicle equipment failure was a causative factor in crashes. The environment in which a vehicle operates can impact safety greatly by magnifying driver errors and preventing recovery in time to avoid or reduce the severity of a crash.

Trucks are especially prone to crashes that may have equipment and vehicle causative factors as the driver is generally independent of the trailer. A rollover incident may occur even though the truck driver does not exceed his or her comfort level on a given curve. The physical characteristics of the truck-trailer combination that have a great amount of influence on truck safety include number of trailers in combination, trailer length, center of gravity, and mechanical systems (brakes, engine characteristics). The braking ability of a heavy vehicle allows the truck to maintain control when decelerating and retain stability during maneuvers. The ability to negotiate turns (and guard against rollovers) and maneuver in traffic, as well as maneuver when confronted with a potential crash situation, is another driver/vehicle interaction worth examining (14).

The TS&W Study indicated that medium to heavy trucks account for 3 percent of vehicles in use on United States roadways and account for 7 percent of vehicle miles of travel (14). However, trucks are involved in 3 percent of all crashes, and the relative involvement of trucks involved in fatal crashes has decreased in the last decade. This decline has been attributed to several factors:

- 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.) (14).

The most critical component in the safe operation of a heavy truck is the performance of the driver. Factors that affect 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 inferior stability characteristics, inexperienced drivers are more prone to crashes because of these characteristics. However, one of the most common crash causative factors attributed to the judgment of the driver is traveling at excessive speed (14). 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 – a situation that parallels the general driving population (15). Other studies have noted that truck drivers have negative opinions of other drivers, but they do not demonstrate 'self-enhancement' that indicates overconfidence (16). As a group, truck drivers do not believe that just because they drive more miles or because they drive a truck, 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.

While the driver is the most critical factor in the safe operation of a truck, the driving environment may have significant effects on truck operations. Roadway geometry, traffic congestion, and weather all contribute to the overall operational capabilities of both the driver and vehicle. Roadway geometric 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 shows 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, 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 (14).

Several studies have quoted crash rates for trucks. Janson et al. (17) 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. Rollover crashes account for 8 to 12 percent of all truck crashes but account for 60 percent of all truck driver/occupant fatalities (14). 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, a more 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 (14). Other studies found that a disproportionate amount of truck rollover crashes occur on freeway ramps (17 percent) (18). A study by Garber et al. found that truck crashes increase on freeway ramps with an increase in ramp curvature and with the amount of difference between truck speed on the curve approach and the posted advisory speed on the ramp (19).

The study by Janson et al. concluded that no statistical relationship could be found between crashes and roadway geometry (grade, curvature, or length) (17). This study concluded that traffic crashes are random events with many causative factors, including driver factors that complicate determination of specific causes for crashes. This study was intended to present a method to "flag" crash-prone ramps for further investigation and potential improvements, and summarize the process in three steps of statistical analysis. However, these procedures are highly dependent on crash reporting measures that may not be explicitly available in the Texas 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 (20). This analysis supports previous studies of car-truck crashes, which also show that unsafe actions by car drivers are more likely to be recorded than unsafe actions by truck drivers. About 80 percent of car drivers had at least one unsafe driving act recorded compared to 27 percent of truck drivers. Each driver could have up to four unsafe driving acts recorded, and of these unsafe actions examined, 75 percent were linked to car drivers and 25 percent were linked to truck drivers. The majority of the crashes were related to just a few unsafe driving actions. Just five of the 94 potential factors accounted for about 65 percent of the unsafe driving actions by car drivers. The top five factors are:

- failure to keep 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).

EXISTING TRUCK WARNING SYSTEMS

In 1994, McGee and Strickland presented two alternative concepts for truck warning systems (3). The first system is an inroad detection warning system using detectors placed in the roadway to sense truck type, speed, and weight. A controller would take input data and determine if the truck was approaching the rollover threshold. If so, the controller activated a warning device to warn the driver. The second system is an in-vehicle warning system. This system relies on the driver to input vehicle parameters (truck and trailer type, load distribution) 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 (3).

Several sites have implemented the in-road detection system (Virginia and Maryland for example). These systems consist of speed detection and vehicle classification using induction loops embedded in the pavement. The weight of the truck is found using commercially available weigh-in-motion (WIM) equipment. A controller is used to process the inputs and 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 (3).

From 1997 to 1999, the Texas Transportation Institute (at Texas A&M University) and the Center for Transportation Research (at the University of Texas) conducted a joint investigation of an instrument system that detected high-center-of-gravity vehicles that were speeding on ramp approaches. This system was implemented in January 1997 on the IH 610 Southbound to SH 225 Eastbound direct connector ramp. The speeding trucks activated flashing hazard beacons 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 (21). In the Houston, Texas, area, the Houston District of TxDOT has recently implemented non-WIM systems at more than 20 problem freeway-to-freeway connector ramps using in-pavement loop detectors or video image detection systems (VIVDS) detection.

EXISTING SIGNING PRACTICES

The Texas Manual of Uniform Traffic Control Devices (TxMUTCD) lists several signs intended to warn drivers of excessive speed on ramps and exits, including freeway connector ramps (22). The 1980 TxMUTCD does not explicitly address freeway-to-freeway connector signing within its text. However, TxMUTCD 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 at freeway-to-freeway connector curves. The 2000 National MUTCD does not appear to introduce major changes to the suggested curve advisory speed signing practice.

TxDOT has 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 has graphic signing with a truck advisory speed of 25 mph on an additional 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.

The Freedman et al. study examined alternative signing for freeway exit ramps that had potential for rollover crashes (18). 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. An alternate flasher was located to the right of the sign. Speed data was 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.

3.0 METHODOLOGY

This section presents the study methodology and summarizes the criteria used to select the study curves; collect speed, volume, and vehicle classification data; and collect ball-bank and lateral accelerometer readings.

SELECTION OF STUDY CURVES

The identification and selection of the freeway-to-freeway connectors selected for further study began by meeting with the Texas Department of Transportation (TxDOT) Houston District staff and identifying historically accident-prone connector ramps. The initial list included over 30 freeway-to-freeway connector curves in the Houston, Texas, region. Table 1 shows these potential sites, and Figure 3 shows their locations with respect to the Houston freeway system. Curve sites selected for the study are shown in italics in Table 1.

From these 30 potential sites, seven were selected for further study based on several criteria:

- historic accident frequency and severity,
- ability to implement and collect automatic volume/speed/classification data,
- ability to collect ball-bank readings with minimal interference from traffic during off-peak hours, and
- proximity to other study connectors.

These criteria were selected based on the practical limitations placed on data collection during actual field conditions. The historic accident data were taken from the Texas Department of Public Safety's (DPS) and TxDOT's Master Accident Database. These data gave a relative measure of the accident history of a majority of the candidate curves.

Table 1. Preliminary Site Selection List.

Overall Candidate Curve Number	Facility "From" and Direction	Facility "To" and Direction	Left or Right Side Exit	Ramp Lanes	Mainlane Speed Limit	Posted Ramp Advisory Speed	Posted Advisory Speed for Trucks?	Comments
1	IH 10 East EB	IH 610 East Loop SB	R	2	55	35	none	35: Exit sign, advanced curve sign with 40 mph curve adv plate; 3-sign roll w/ flash for trucks
2	IH 10 East WB	IH 610 East Loop SB	R	1	55	35	none	35: Exit sign, advanced curve sign with 40 mph curve adv plate; 3-sign roll w/ flash for trucks
3	IH 10 East WB	IH 610 East Loop NB	R	2	55	35	none	35: Exit sign, advanced curve sign with 40 mph curve adv plate; 3-sign roll w/ flash for trucks
4	IH 10 Katy EB	IH 610 West Loop NB	R	1	55	40	none	Signs: Exit: 40 mph, no curve signs
5	IH 10 Katy EB	IH 610 West Loop SB	R	2	55	40	none	Signs: Exit: 40 mph, no curve signs
6	IH 45 Gulf NB	US 59 Southwest SB	L	2	55	40	none	Exit: 40 mph, curve warning sign + 40 mph plate on left
7	IH 45 Gulf NB	IH 610 South Loop EB	R	2	55	none	none	New install of 3-sign truck rollover flashers
8	IH 45 Gulf SB	IH 610 South Loop EB	R	3	55	none	none	No signing/marking speed guidance
9	IH 45 Gulf NB	IH 610 South Loop WB	L	2	55	none	none	No signing/marking speed guidance
10	***IH 45 North SB***	***IH 610 North Loop WB***	***R***	***2***	***55***	***none***	***none***	***3-sign truck roll signs on 2nd curve***
11	IH 45 North NB	IH 610 North Loop WB	R	2	55	none	none	3-sign truck roll signs on 2nd curve
12	IH 45 North SB	IH 10 Katy WB	R	1	55	40	none	Exit: 40 mph - compound curve (curve-tangent-curve combination)
13	***IH 610 East Loop SB***	***SH 225 LaPorte EB***	***R***	***2***	***55***	***35***	***none***	***Exit 35 mph - curve sign with 35 mph plate, 3-sign rollover flash installed***
14	***IH 610 North Loop WB***	***IH 45 North SB***	***L***	***2***	***55***	***40***	***none***	***Ramp: 40 mph - no curve signs, sharp curve-tangent-curve combination***

Table 1. Preliminary Site Selection List (continued).

Overall Candidate Curve Number	Facility "From" Direction	Facility "To" Direction	Left or Right Side Exit	Ramp Lanes	Mainlane Speed Limit	Posted Ramp Advisory Speed	Posted Advisory Speed for Trucks?	Comments
15	***IH 610 North Loop EB***	***US 59 Eastex NB***	***R***	***2***	***55***	***none***	***25***	***Ramp advisory speed for trucks only. Overhead 25 mph sign with graphic, 25 mph roll at 1st PC of 1st curve, 35 mph roll on 2nd curve***
16	***IH 610 North Loop EB***	***IH 45 North NB***	***L***	***2***	***55***	***35***	***none***	***Large (6'x6' maybe) curve warning sign (35 mph) at PC; Exit: 35 mph ahead of PC***
17	IH 610 North Loop WB	US 59 Eastex NB	R	2	55	35	none	Exit: 35 mph, 3-sign truck roll flash installed, advanced curve sign on right (no plate) and large text sign (reduced speed on curves ahead)
18	IH 610 South Loop EB	SH 288 South NB	R	2	55	40	none	Curve-tangent-curve; signs include Exit: 40 and curve with adv. plate on 2nd curve on right side; includes 3-sign truck roll flashers
19	IH 610 South Loop WB	SH 288 South NB	R	1	55	40	none	Signs include Exit: 40 and curve warning with 40 mph advisory plate
20	IH 610 South Loop WB	IH 45 Gulf SB	R	2	55	35	none	Signs include Exit: 35 - no curve warning signs
21	IH 610 South Loop EB	IH 45 Gulf SB	R	1	55	40	none	Signs include Exit: 40 - no curve warning signs
22	IH 610 West Loop NB	US 59 Southwest SB	R	1	55	40	none	Curve warning sign (with 40 mph) plate past PC
23	IH 610 West Loop SB	US 59 Southwest NB	R	2	55	40	none	
24	SH 225 LaPorte WB	IH 610 East Loop NB	R	1	55	none	none	3-sign truck roll signs, no advisory speed
25	SH 288 South NB	IH 610 South Loop WB	L	1	55	40	none	Ramp: 40 mph sign on right side (NB to EB at PC), 3-sign truck roll signs installed, 40 mph curve warning sign (obscured by roll sign)
26	SH 288 South NB	IH 610 South Loop EB	L	1	55	40	none	Ramp: 40 mph sign on right side at PC, 3-sign truck roll signs installed
27	***US 290 NW Fwy EB***	***IH 610 North Loop EB***	***R***	***2***	***55***	***40***	*none*	***Curve warning sign with 40 mph plate past PC***

Table 1. Preliminary Site Selection List (continued).

Overall Candidate Curve Number	Facility "From" Direction	Facility "To" Direction	Left or Right Side Exit	Ramp Lanes	Mainlane Speed Limit	Posted Ramp Advisory Speed	Posted Advisory Speed for Trucks?	Comments
28	US 59 Eastex SB	IH 610 North Loop EB	R	2	55	none	none	3-sign truck roll signs, curve warning sign (no advisory speed) at PC of 2nd curve
29	***US 59 Eastex NB***	***IH 610 North Loop WB***	***R***	***2***	***55***	***30***	***none***	***Exit: 35 mph, no curve signs***
30	US 59 Eastex SB	IH 45 Gulf SB	R	1	55	40	none	Curve warning sign (with 40 mph) plate at PC
31	US 59 Southwest SB	SP 529 (near Beasley)	-	-	-	-	-	Not investigated, too far removed from primary study area
32	US 59 Southwest NB	IH 45 Gulf NB	L	2/1	55	35	none	Curve warning sign with 35 mph plate at curve PC
33	US 59 Southwest NB	IH 610 West Loop NB	R	2	55	?	?	Ramp closed at time in field (6/3/02)

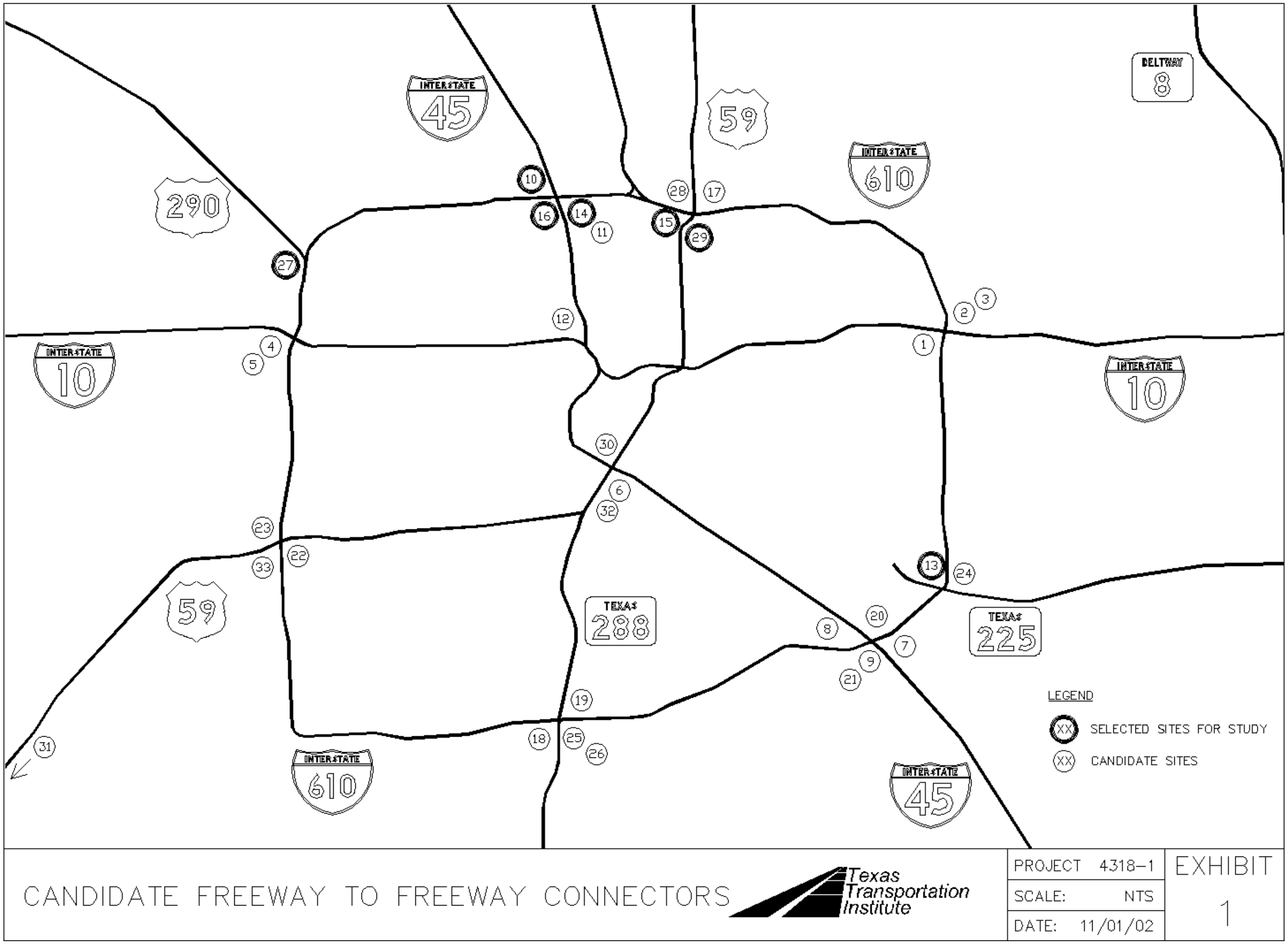


Figure 3. Candidate Freeway-to-Freeway Connectors.

The practical ability to safely place automated volume/speed/classification tube counters was also an important criterion used. All candidate connectors have high-speed approaches (55+ mph), and some had narrow or no shoulders for TTI personnel to implement data collection equipment. Researchers eliminated a few curves where data collection was extremely difficult due to traffic conditions.

Some candidate connectors experience high levels of congestion for a majority of the day and thus slower travel speeds with less propensity for a rollover incident. These connectors were eliminated because of the difficulty to complete ball-bank studies without influence from other traffic.

The proximity to other study connector ramps was the final factor involved in selecting connector ramps. Researchers considered the time and cost associated with travel where possible to reduce time in transit between sites for efficient data collection.

REVIEW OF CRASH RECORDS

A review of TxDOT/DPS crash records was completed to confirm a history of crashes on specific freeway-to-freeway connector ramps. TxDOT provided the latest three years of crash data for selected interchanges with the IH 610 Loop Freeway. Data were provided for 1997, 1998, and 1999 in summarized totals as well as a more detailed listing of coded individual crash records. The quality of the coded information depends upon the degree of accuracy of DPS data entry clerks who input the field crash reports into the computer system. For this analysis, the critical information is the designation of the "Part of Road No. 1 Involved" which can be used to identify that the crash occurred on a freeway-to-freeway connection.

The available crash records as provided by TxDOT were reviewed to identify the number of crashes that occurred on connector ramps and what proportion of these crashes involved a truck. Table 2 summarizes the information. Without reviewing the individual crash reports as filled out by the investigating officer, it is difficult to draw concrete solutions concerning similar factors with regards to crashes on freeway connectors. However, the review of the TxDOT/DPS summarized records indicates that about one in four crashes occurring within freeway interchanges occur on the direct connector ramps. Additionally, about half of those crashes on the connectors involve a truck.

Table 2. Crashes at Selected Houston Urban Interchanges (1997-1999).

Freeway Interchange	Number of Crashes		
	Total	Connectors Only	Involved Truck on Connector
IH 610 NL @ US 290	288	28 (10%)	16 (54%)
IH 610 NL @ IH 45N	653	192 (29%)	110 (57%)
IH 610 NL @ US 59N	265	63 (24%)	37 (59%)
IH 610 SL @ IH 45S	466	97 (27%)	44 (45%)
IH 610 EL @ IH 10E	146	63 (43%)	36 (57%)
IH 610 SL @ SH 288	203	57 (28%)	25 (44%)
IH 610 WL @ US 59S	1,179	248 (21%)	97 (39%)
IH 610 WL @ IH 10W	329	70 (21%)	44 (63%)
Average:		23%	50%

Notes: Excludes crashes on frontage roads and transit facilities.
Source: TxDOT/DPS crash records.

SPEED/CLASS/VOLUME DATA COLLECTION AND ANALYSIS

The actual speeds of the various classes of vehicles were measured by installing portable road tube classifiers on selected connector ramps as identified in Table 1. This effort served to measure the speeds of the vehicles traversing the connector ramp at critical locations within the curve. These speeds were measured on the mainlane approaching the ramp, at the point of curve, and again at the midpoint of the curve. If a connector curve had two curves separated by a tangent section, data collection was completed at the beginning of the second curve and at the midpoint of the second curve. Each of the traffic classifiers remained at the study sites for a minimum of three days. Because of the high speed and high volume of traffic using each of the connector ramps, this equipment was deployed during time periods when traffic volumes were expected to be lighter. Some locations were equipped during a midday weekday period, while others were completed on a Saturday morning. The data collected for this portion of the research study provided insight into driver behavior while traversing the connector ramps as well as a measure of compliance with the posted advisory speed limit.

BALL-BANK AND ACCELEROMETER DATA COLLECTION AND REDUCTION

The majority of data collection activities consisted of driving four different types of vehicles at various approach speeds through each of the seven study connector ramps. Data collection resulted in the completion of 99 individual drive-through studies which would require a detailed analysis. Data were collected using a traditional manual ball-bank indicator as well as a digital lateral accelerometer. A mounting apparatus (Figure 4) was developed such that both devices could be used in conjunction with each other during the field data collection. Although the digital unit is self-leveling, the mounting device was designed such that the manual indicator could be in different types of vehicles. It was stabilized to the windshield by three suction cup mounts and supported and leveled by a mounting bracket with two additional adjustable legs.

The RDS7-BB digital unit is manufactured by Rieker Electronics, Inc., and allows data to be output into a portable computer for detailed analyses. It has a total range of 50º (± 25º) and will output data into a file every 0.25 seconds. Product specifications and summarized operating instructions for the digital ball-bank indicator used for this study may be found in the appendix.

This project completed a multitude of drive-throughs using the four vehicle types. It used two types of passenger vehicles. A 1998 Pontiac Grand Prix (see Figure 5) completed a total of 28 individual studies on the seven field sites.

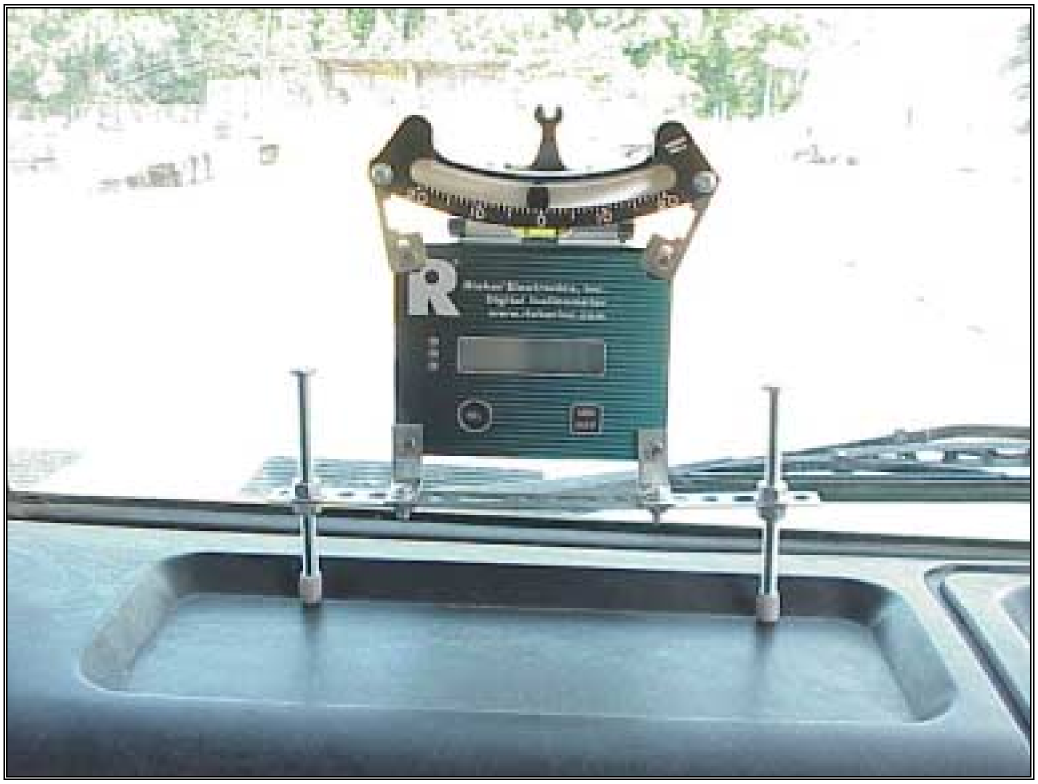


Figure 4. Data Collection Apparatus.

Figure 5. Passenger Car Test Vehicle (1998 Pontiac Grand Prix).

Twenty-seven studies were completed using a 2002 Chevrolet Blazer that represented the sport-utility component of passenger vehicles (see Figure 6).

Figure 6. Sport-Utility Test Vehicle (2000 Chevrolet Blazer).

TxDOT provided use of a rigid type of heavy truck. The dump truck (Figure 7) was driven by a TxDOT professional driver and was loaded with crushed gravel. The fourth vehicle type used was a loaded semi-tractor combination that was loaded with pallets (Figure 8). Palletized Trucking Company of Houston donated the use of the vehicle, all fuel, and any vehicle operating costs. Research project funds paid an hourly wage to secure the services of the professional truck driver assigned by the company to operate the vehicle during the studies. This partnership between TxDOT and the private sector was important in successfully completing this research project. As the cargo on the trailer consisted of only pallets, again provided by the private sector, the test vehicle was not as heavy as would have been desirable. However, it was not possible to obtain a test tractor-trailer combination vehicle for use in the studies; therefore the worst condition of a loaded vehicle traversing the freeway connector could not be evaluated. However, considering that many trailers may be empty or not fully loaded, the average or more typical operating conditions on the freeways was indeed studied.

Figure 7. Dump Truck Test Vehicle (Chevrolet/Volvo).

Figure 8. Tractor-Trailer Test Vehicle (Peterbilt).

4.0 ANALYSIS AND RESULTS

This section presents the results of the data collection and analysis and provides a discussion of the results. Included in this section are the results of the speed and classification study as well as the ball-bank/accelerometer runs.

FIELD-MEASURED SPEEDS ON CONNECTOR RAMPS

In order to better assess the actual speeds of vehicles on the connector ramps, Texas Transportation Institute (TTI) staff developed a plan to measure the speeds at multiple locations along each of the seven study sites. The objective of these field studies was to determine vehicle speeds upstream of the connector ramps, at the point of curvature on the connector, and at the midpoint of the curve. In instances of the connector ramp consisting of two curves, the data were collected for both curves along the ramp. The data were collected using TimeMark Delta IIIB portable road tube classifiers. These classifiers are designed for use on multiple-lane high-volume roadways.

For this effort, the classifier/counters were programmed to provide classification, speed, and gap data on each of the two lanes of the connector ramps. Counter placement was completed using TTI personnel with flagmen posted as needed for safe operations. The equipment deployment process required installing one set of road tubes across both lanes of the connector ramp spaced exactly 16 feet apart; a second set of road tubes was also installed across a single lane of traffic (Figure 9). Each of the two sets was also separated by 18 inches.

Data were collected for several days (a minimum of 72 hours) at each of the connector ramps. Some difficulties were encountered at some locations in keeping the road tubes properly secured to the roadway surface. This difficulty was due to the high speeds of vehicles as well as the curvature of the ramps on which the studies were being completed. However, sufficient data were collected to evaluate the existing speeds on five of the seven ramps on which the classifiers were installed.

Figure 9. Field Installation of Road Tubes for Classification Studies.

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 "per vehicle" output. This output includes the date/time of day, total number of axles, the spacing between each of the axles, an estimated spot speed of the vehicle, and the gap between vehicles. In addition, based upon the number of axles and spacing, a vehicle classification is also assigned. Table 3 identifies these Federal Highway Administration (FHWA) classifications.

To facilitate a comparison among vehicle types, the vehicles were combined into groups of vehicles with similar operating characteristics. FHWA classifications 1-3 were combined into the "passenger vehicle" category. "Rigid vehicles" were defined as large vehicles between 2 to 4 axles that do not have a detachable trailer for transporting goods (FHWA classifications 4-7). Vehicles of FHWA classifications 8-13 were combined into a "heavy truck" category consisting of various configurations of tractor-trailer combinations.

Table 3. 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

Prior to the completion of any analyses, the data at each classification stations for each of the seven study sites were reviewed for accuracy. Of the 27 total count stations, the data collected at three stations were determined to not be usable for this research study. The data collection at two of the stations produced no usable data because of difficulty in keeping the road tubes properly secured to the roadway within the curve of the connector ramp. A third count station produced data of approach speeds that appeared to be significantly lower than the actual observed speeds. Another possible concern with the data is that the speeds of vehicles following in close proximity to each other would be different than those traveling isolated from other vehicles. The average and 85^{th} percentile speeds of all vehicles were compared to data consisting of only those vehicles separated by a gap greater than 4 seconds. The differences in the average for each of these data sets were not significant; therefore, other vehicles using the connector do not significantly impact the driver's speed along the ramps.

The first set of comparisons involved a determination concerning drivers and whether or not they were reducing their vehicular speed while traversing the connector ramp. Comparisons were made of each of the vehicle's upstream approach speed on the freeway with the speed of the vehicles measured at the point of curvature of the connector ramp. An additional comparison was made to determine the speed reduction from the start of the curve to the midpoint of the curve; this comparison was hypothesized to be the most likely area of highest speed reduction as motorists tend to accelerate immediately beyond the midpoint of the curve. Three of the connector ramps have a second curve; comparison to the start of that curve to its midpoint was also completed. Table 4 presents these comparisons using the average speed of all types of vehicles combined. Comparisons for the other vehicle types for the average and 85th percentile speed are provided in the appendix.

Table 4. Calculated Change in Speeds as Motorists Traverse Connector Ramps.

Connector Ramp	Average Speed Reduction (mph)	
	From Upstream of Start of Curve to Center of Curve 1	From Center of Curve 1 to Center of Curve 2
I-45 North SB to I-610 N. Loop WB	-3.3	-7.6
I-610 N. Loop EB to US 59 Eastex NB	-8.5	+3.8
I-610 E. Loop SB to SH 225 EB	-2.2	n/a
US 290 EB to I-610 N. Loop EB	-2.6	n/a
US 59 Eastex NB to I-610 N. Loop WB	-10.8	+1.2

Note: These are for all vehicle types; more detailed data may be found in the appendix.

At each of the five ramps studied above, all classes of vehicles reduced their speeds while passing through the midpoint or most critical section of the curve. This speed reduction differs for each of the curves based upon the degree of the curve and the drivers' perception of the need to reduce their speed. In two of the three sites containing a second curve, the vehicles actually increased their speeds while progressing through the curve. The most likely factor to cause the vehicle acceleration is the down slope of the connector ramp within the section with the second curve. A number of crashes have historically occurred near the second curve of these connector ramps. Many drivers, especially of large trucks, may not be aware of the second curve and may actually traverse it faster than intended or try to brake, not realizing that a jackknife condition may result.

The second analysis consisted of determining the compliance of vehicles using the connector ramp with the advisory speed as posted on the curves. This comparison was made for six of the connector ramps. In addition to comparing the average, 50th percentile, and 85th percentile speeds, the percentage of vehicles exceeding the posted advisory speed limit was also reported. A review of the data determined that there was a difference between the speeds of the three classes of vehicles (passenger vehicles, rigid vehicles, heavy trucks) such that each should be reported separately. Table 5 reports the speeds for each of the six curves. It proved to be very difficult to evaluate the degree of compliance due to the lack of posted advisory speed limits on some of the study connector ramps. However, based upon the minimal compliance observed, the lack of signage may have a limited impact upon slowing traffic on the connectors. The drivers may be more impacted by a visual perception of the need to reduce their speeds as opposed to any static signing.

BALL-BANK AND ELECTRONIC ACCELEROMETER ANALYSIS

The collection of ball-bank and electronic accelerometer readings examined what differences, if any, exist among the lateral accelerations between different vehicle types. Each of the vehicles used in the study was in generally good condition with good tires. The passenger car, sport-utility vehicle, and semi-tractor trailer combination each operated with good ride ability and smooth acceleration and operation. The dump truck suspension was very stiff, resulting in a much rougher ride than the other three vehicles. This rough ride was seen in the accelerometer data, characterized by wider ranges of readings. Figures 10 through 13 show the range of digital accelerometer readings gathered on straight sections of freeway for each vehicle. Note the large spread of readings for the dump truck, indicating the relatively rough ride caused by a "stiffer" suspension.

This study used only one driver for each of the vehicle types (each vehicle type had a different driver). Each of the drivers could be considered experienced with the type of vehicle driven. The characteristics of the drivers were as follows:

- Passenger Car – male, mid-30s, 15+ years of driving experience;

Table 5. Measured Speeds on Connector Ramps.

Connector Ramp	Posted Advisory Speed Limit (mph)	Type of Vehicle	Measured Vehicle Speeds (mph)				% Exceeding Posted Advisory Limit
			Average	50%'tile	70%'tile	85%'tile	
IH 45 North SB to IH 610 North Loop WB (First Curve)	None	Pass Veh	51.0	51.0	54.0	56.9	N/A
		Rigid Veh	51.6	51.3	54.4	57.7	N/A
		Hvy Trks	47.3	47.3	50.0	52.6	N/A
		All	51.0	51.0	54.0	56.9	N/A
IH 45 North SB to IH 610 North Loop WB (Second Curve)	None	Pass Veh	46.4	46.4	48.8	51.2	N/A
		Rigid Veh	46.3	46.2	48.8	51.2	N/A
		Hvy Trks	43.0	43.3	45.6	47.6	N/A
		All	46.3	46.4	48.7	51.0	N/A
IH 610 North Loop EB to IH 45 North NB	35 mph	Pass Veh	40.2	40.7	43.3	45.8	82%
		Rigid Veh	38.9	39.1	41.9	45.0	71%
		Hvy Trks	34.6	35.6	38.1	40.4	51%
		All	40.0	40.6	43.2	45.7	81%
IH 610 North Loop EB to US 59 North NB (First Curve)	25 mph (trucks only)	Pass Veh	43.2	43.3	45.7	48.1	N/A
		Rigid Veh	43.1	42.7	45.3	48.1	N/A
		Hvy Trks	39.7	39.6	42.3	45.1	99%
		All	43.1	43.2	45.6	48.1	N/A
IH 610 North Loop EB to US 59 North NB (Second Curve)	35 mph (trucks only)	Pass Veh	49.6	49.1	51.9	54.8	N/A
		Rigid Veh	49.3	48.8	51.9	55.4	N/A
		Hvy Trks	45.7	45.0	47.9	50.8	97%
		All	49.4	49.0	51.7	54.8	N/A
IH 610 East Loop SB to SH 225 EB	35 mph	Pass Veh	49.5	49.5	52.1	54.9	99%
		Rigid Veh	48.7	48.7	51.5	54.4	98%
		Hvy Trks	45.4	45.4	48.2	50.8	97%
		All	48.9	49.0	51.7	54.5	98%
US 290 EB to IH 610 North Loop EB	None	Pass Veh	47.9	48.1	50.3	52.4	N/A
		Rigid Veh	46.6	46.4	48.8	51.2	N/A
		Hvy Trks	43.7	43.7	46.0	48.1	N/A
		All	47.7	47.7	50.0	52.3	N/A
US 59 North NB to IH 610 North Loop WB (First Curve)	30 mph	Pass Veh	38.6	39.1	41.5	43.8	94%
		Rigid Veh	38.8	38.3	40.8	43.4	94%
		Hvy Trks	35.5	35.1	37.9	40.0	87%
		All	38.5	39.0	41.2	43.7	93%
US 59 North NB to IH 610 North Loop WB (Second Curve)	30 mph	Pass Veh	41.4	41.4	43.3	45.4	99%
		Rigid Veh	40.4	39.3	41.7	44.3	97%
		Hvy Trks	36.6	36.5	38.6	40.6	94%
		All	41.2	41.1	43.2	45.3	99%

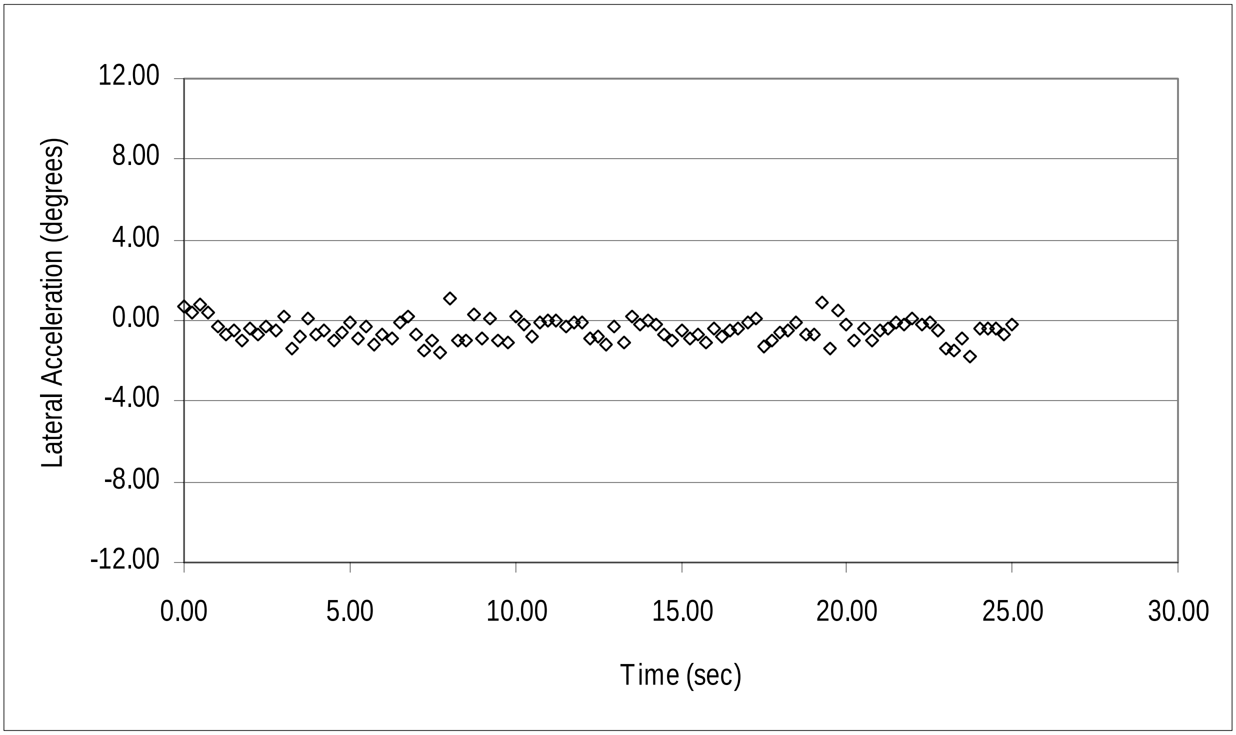


Figure 10. Lateral Accelerations versus Time: Passenger Car on Straight Roadway.

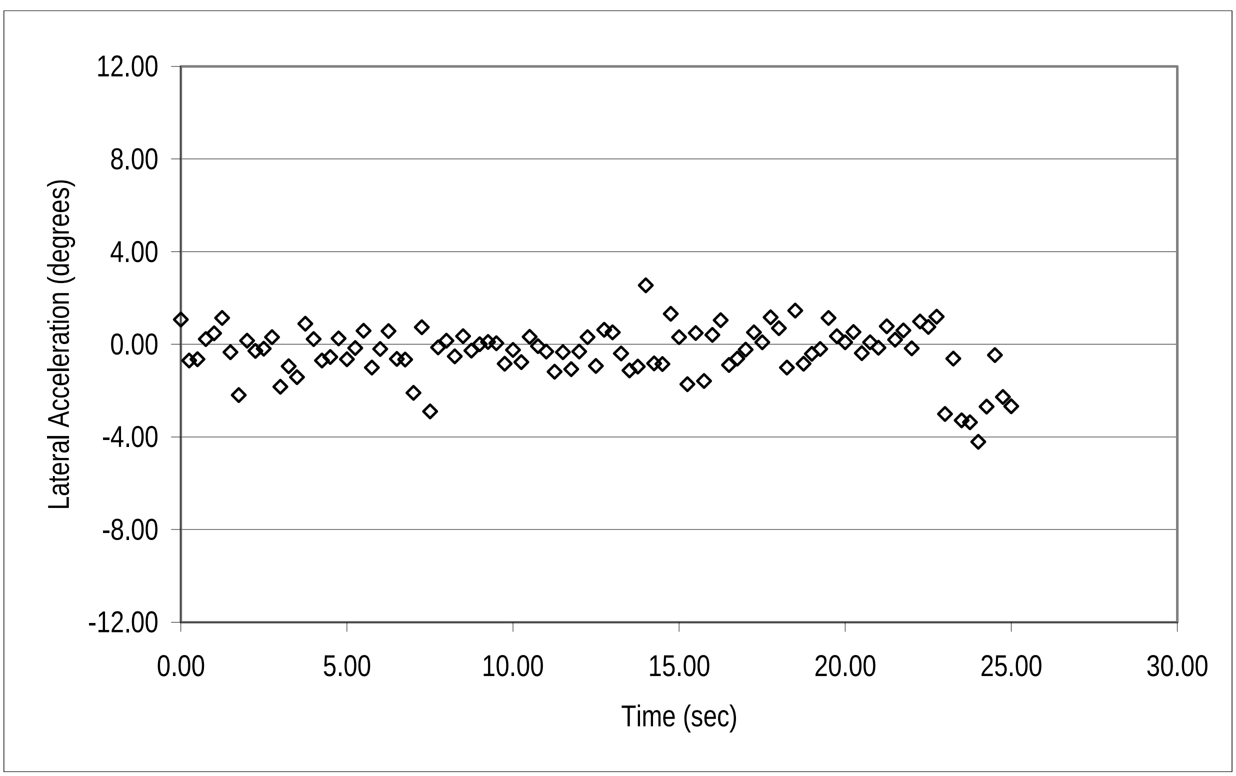


Figure 11. Lateral Accelerations versus Time: Sport-Utility Vehicle on Straight Roadway.

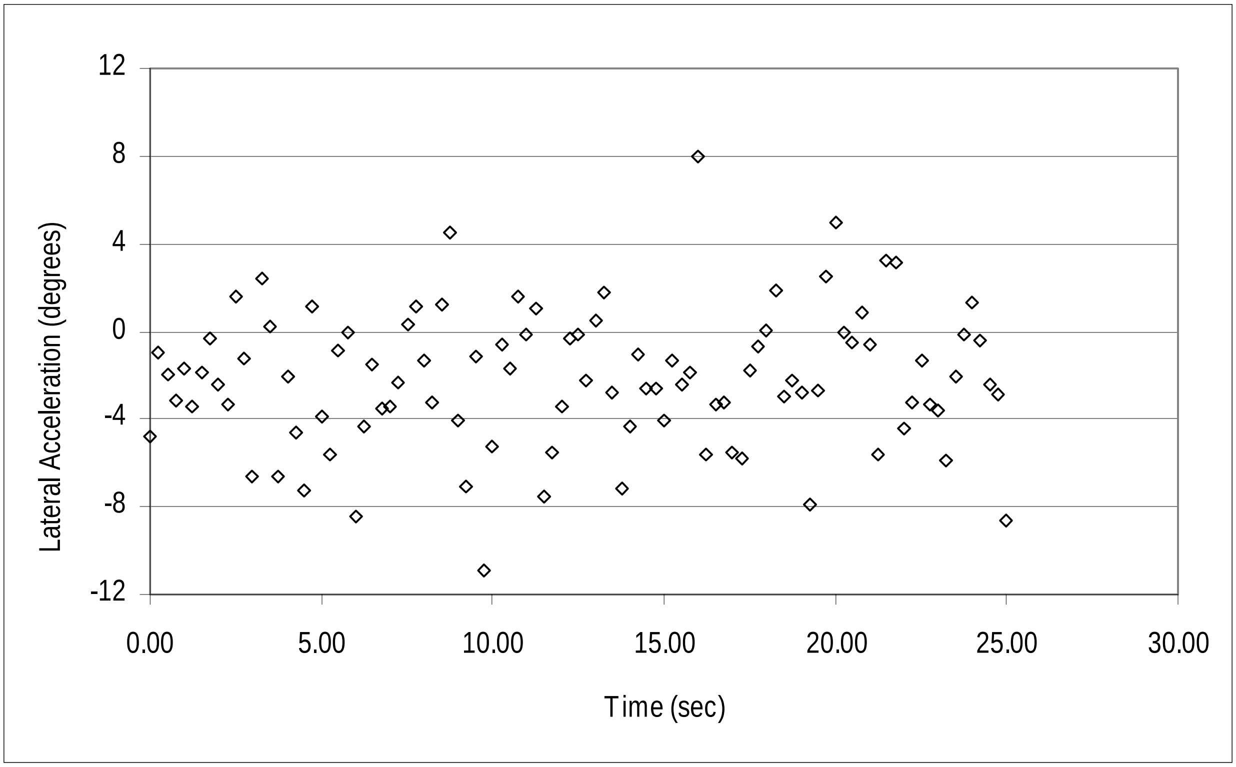


Figure 12. Lateral Accelerations versus Time: Dump Truck on Straight Roadway.

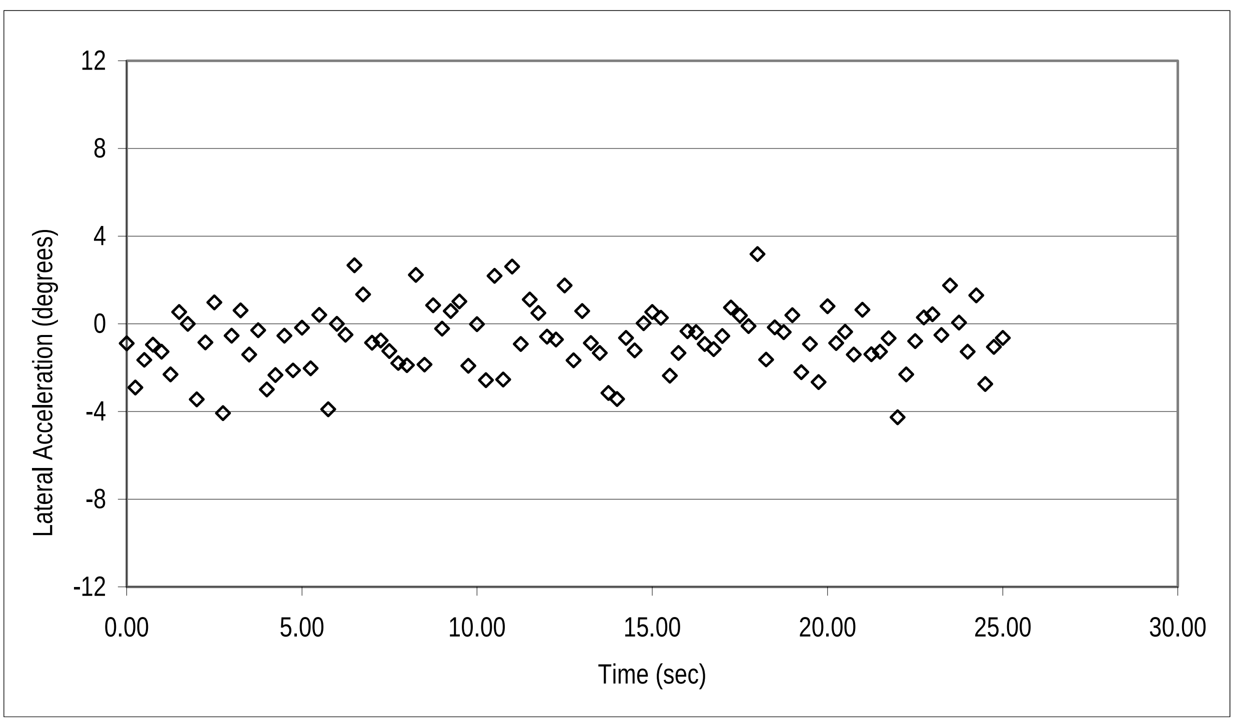


Figure 13. Lateral Accelerations versus Time: Tractor-Trailer on Straight Roadway.

- Sport-Utility Vehicle – male, early 30s, 15+ years of driving experience;
- Heavy-Duty Dump Truck – male, late 40s, 20+ years of driving experience with heavy-duty trucks and equipment;
- Semi-Tractor Trailer Combination – male, 50+ years old, 30+ years driving experience with tractor-trailers.

While it may be difficult to make statistically significant findings from such a limited sample of drivers and vehicles, the intent of this project was to determine if there are perceived relationships that exist between the lateral accelerations for various vehicle types and whether the existing method to determine curve advisory speeds are appropriate for the vehicle population as a whole. If the findings of this project indicate that changes in advisory speed signing may be appropriate for differing vehicle types, then future studies should confirm the results of this project and make firm recommendations on advisory speed signing guidelines by using larger sample sizes and more drivers per vehicle.

As shown in Table 5, for the curves where advisory speeds were indicated in the field, the passenger car and sport-utility vehicle group exceeded the advisory speed 82 to 99 percent of the time. Heavy vehicles, including the tractor-trailer group exceeded the advisory speed 51 to 99 percent of the time. The tractor-trailer group's average speed was closer to the advisory speed than any other vehicle group, usually exceeding the posted advisory speed from 0 to 10 mph. The average passenger car/sport-utility group exceeded the advisory speed from 5 to 15 mph.

BALL-BANK AND LATERAL ACCELEROMETER RESULTS

The ball-bank/accelerometer apparatus was placed in the centermost position on the dashboard, held in place by three suction cups and two rubber-covered legs (see Figure 4). The accelerometer reported data directly to text files using HyperTerminal on a laptop computer. Data collection was undertaken using the procedures outlined in the "Methodology" section of this report. Once the data collection was complete for a data collection run for a given vehicle and speed on a particular curve, the data collector appended the accelerometer reading text file with the ball-bank indicator reading and any pertinent comments about the run.

During the field data collection, the observer started collecting the accelerometer readings as close to the beginning of the curve as possible. The observer then stopped recording the accelerometer data at some point past the end of the curve when it was possible to safely save the data file. When reviewing the raw accelerometer data, it became apparent that some amount of data cleaning procedure would be needed to remove the excess readings after the vehicle exited the curve.

Data from each run that was made, regardless of vehicle, was cleaned in the following manner:

1. Create graph of accelerometer reading versus time in curve.
2. Given the length of the curve and number of 250 millisecond accelerometer reading intervals, truncate the data collected after the accelerations exceeded the approximate curve length *and* after the accelerations returned to center near zero, which denoted that the vehicle had completed negotiating the curve.
3. If a connector had two curves separated by a short tangent section, the accelerometer readings taken while traversing the tangent section were deleted.

Figure 14 shows an example.

The convention for the sign of the lateral acceleration was negative for curves to the left and positive for curves to the right. This curve was for the case of a passenger car, traveling on the US 290 eastbound to IH 610 eastbound connector ramp at 50 mph. This data set would be cleaned to exclude all observations beyond 20 seconds, which corresponds to the vehicle completely exiting the curve. The consistently straight data between 20 and 27 seconds shows the accelerations experienced on a straight section of freeway. The period from 27 seconds to 35 seconds during the run captured a series of lane changes to exit the freeway. Figure 14 was typical of the data collected on each curve.

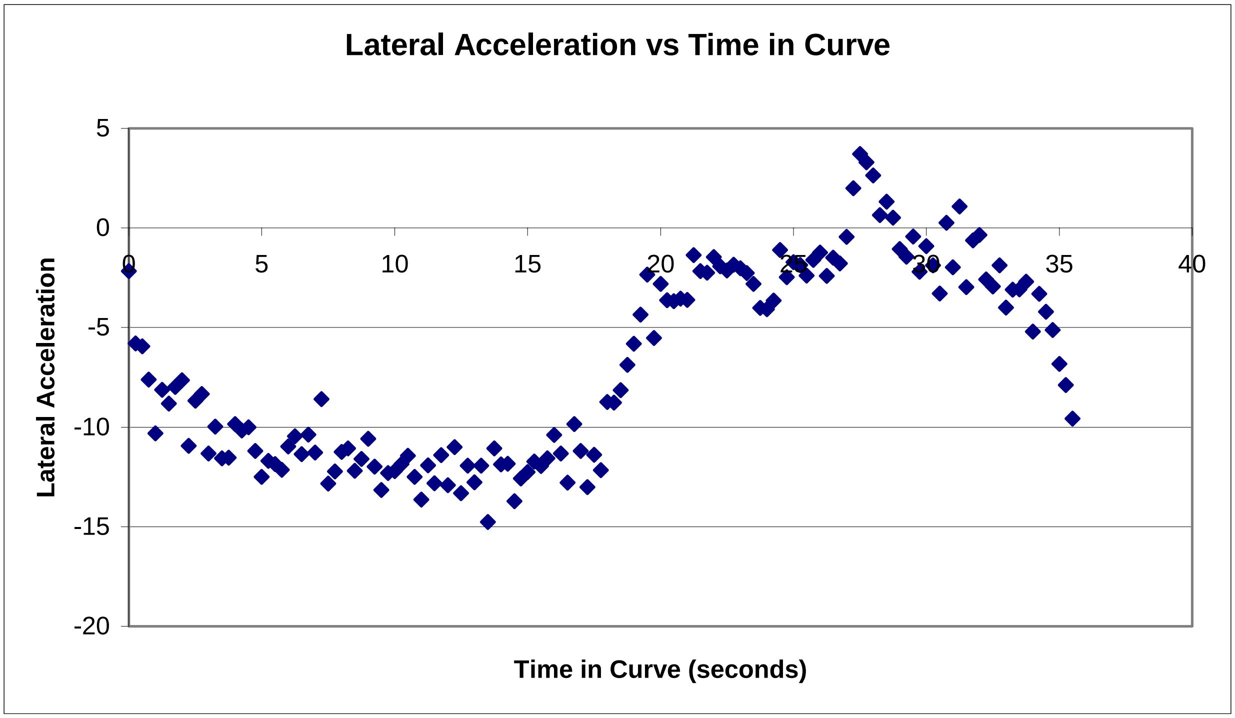


Figure 14. Graphical Representation of Raw Dataset from Accelerometer Readings for Typical Curve (Passenger Car, 50 mph, US 290 EB to IH 610 EB).

Figure 15 presents the graphical representation of the "clean" data set ready for further analysis. The remaining readings were then included in any further analyses.

The analysis effort then focused on determining if the lateral accelerations experienced for drivers of four different vehicle types were approximately the same for a given speed and connector ramp.

Researchers examined several mathematical models to determine if they could be used to represent each data collection run for a regression analysis. However, there was too much variability in the data relationships to make statistical comparisons. A regression analysis was deemed inappropriate given the amount of variability between and among curves and vehicles. However, there were relationships, especially in the maximum manual ball-bank indicator and accelerometer readings, which were used for meaningful analysis.

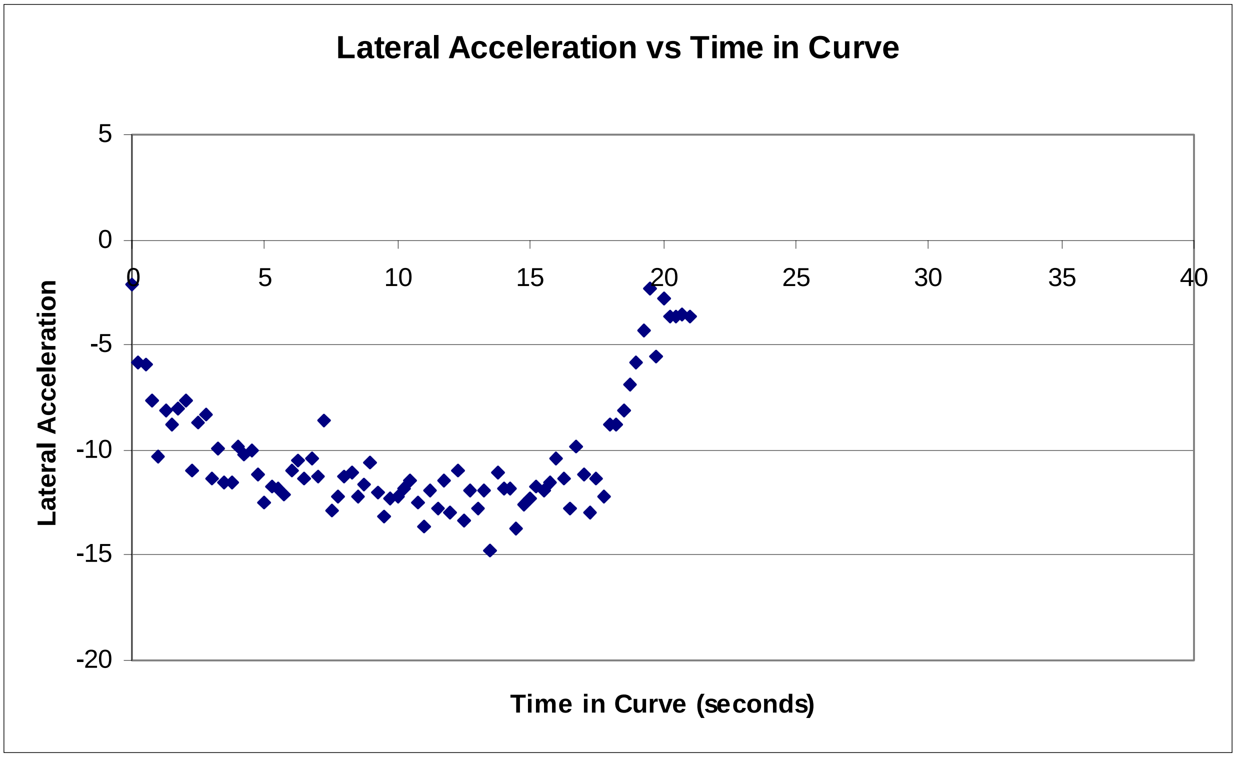


Figure 15. Graphical Representation of Cleaned Dataset from Accelerometer Readings for Typical Curve (Passenger Car, 50 mph, US 290 EB to IH 610 EB).

The first method of analysis was to sort the clean data for each connector, vehicle, and speed run. The data was sorted from minimum to maximum without regard for when in the curve the lateral acceleration was experienced. Figure 16 presents a graphical representation of the sorted data (the same data shown in Figures 14 and 15).

As the analysis continued, the general shape of the curve with two opposite tails on each end of the curve connected by a relatively linear relationship became apparent. The tails are thought to represent suspension noise and steering path corrections during the negotiation of the connector ramp. The region of data between the tails gives an indication of the range of lateral accelerations that might be felt by a driver while traveling normally through a curve, excluding those accelerations caused by suspension noise (potholes, driver path corrections, merging movements, etc.).

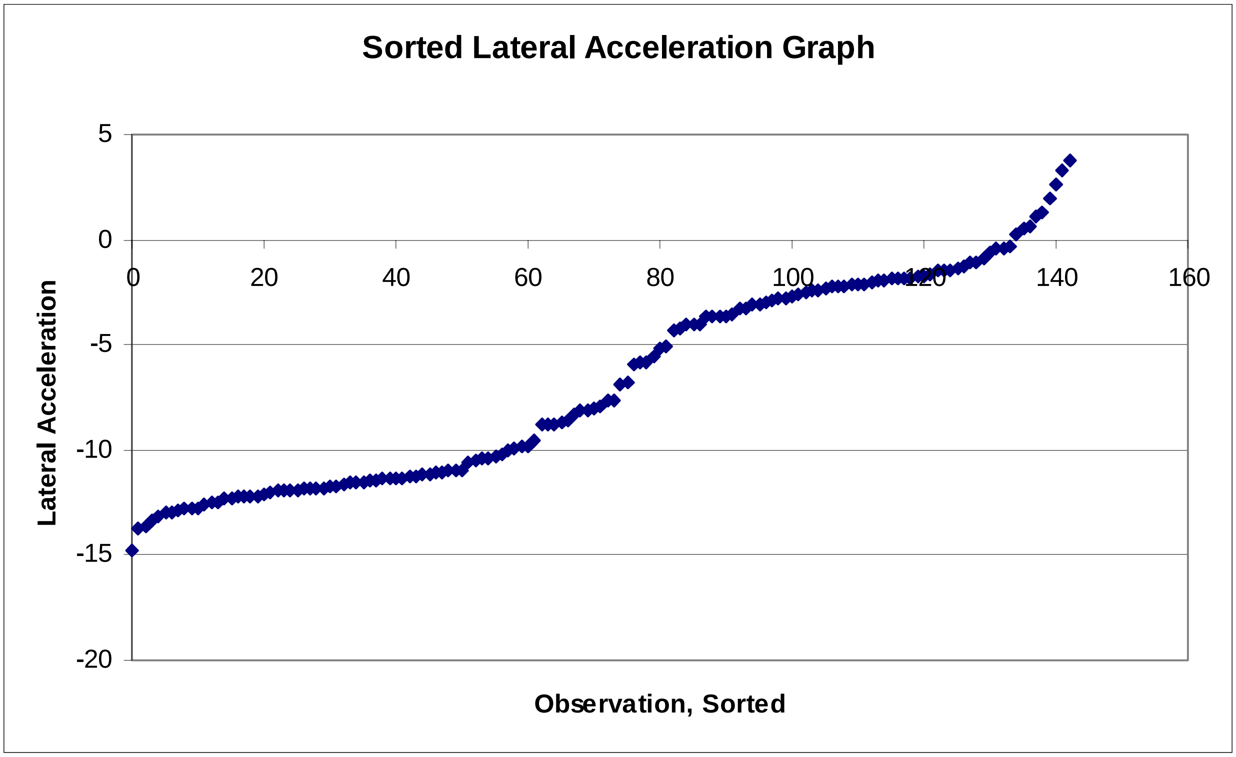


Figure 16. Graphical Representation of Cleaned Dataset from Accelerometer Readings, Sorted from Minimum to Maximum for Typical Curve (Passenger Car, 50 mph, US 290 EB to IH 610 EB).

A measure that quickly became apparent is that there seemed to be a relationship between the amount of time spent above 0.10 *g* lateral acceleration and the comfort level of a driver to attempt the curve at a 5 mph higher increment. While the maximum lateral accelerations experienced by drivers of each type of vehicle were similar for a given curve and speed, the time in the curve above 0.10 *g* lateral acceleration before a driver was uncomfortable differed by vehicle. The 10 degree threshold was chosen for analysis because it corresponds with the current advisory speed criteria to set the advisory speed at the speed experiencing 0.10 *g* lateral acceleration on the ball-bank reading.

Table 6 presents the average maximum ball-bank reading, maximum accelerometer reading, and average percent of time in curve exceeding 10 degrees on the accelerometer (or above 0.10 *g* lateral acceleration). These averages represent those readings taken on the maximum comfortable speed. Note that the 85th percentile speed corresponds very well to the maximum "comfortable" speed of the test drivers. From this result, researchers inferred that the

Table 6. Maximum "Comfortable" Curve Speed and Time in Curve above 0.10 *g* Lateral Acceleration.

	85th Percentile Speed in Middle of Curve (mph)	Maximum Comfortable Speed on Curve of Test Vehicle (mph)	Maximum Ball-Bank Reading (degrees)	Maximum Accelerometer Reading (degrees)	Percent of Time in Curve of 0.10 *g* (%)
US 290 EB to IH 610 EB					
Passenger Car	52	50	13	14.8	65
Sport Utility	52	50	14	15.4	73
Dump Truck	51	50	14	21.1	47
18-Wheeler	48	45	10	13.7	7
US 59 NB to IH 610 WB					
Passenger Car	44	45	14	16.1	51
Sport Utility	44	45	16	16.8	47
Dump Truck	43	45	14	18.8	36
18-Wheeler	40	40	13	16.0	29
IH 610 WB to IH 45 SB					
Passenger Car	n/a	50	17	19.7	78
Sport Utility	n/a	50	17	18.3	74
Dump Truck	n/a	45	13	23.2	32
18-Wheeler	n/a	40	9	13.4	3
IH 610 EB to US 59 NB					
Passenger Car	48	50	17	18.3	51
Sport Utility	48	50	16	17.4	52
Dump Truck	48	45	14	18.4	32
18-Wheeler	45	40	11	14.8	9
IH 610 EB to IH 45 NB					
Passenger Car	46	50	17	19.3	58
Sport Utility	46	50	16	17.0	72
Dump Truck	45	45	12	20.3	33
18-Wheeler	40	40	9	13.4	3
IH 45 SB to IH 610 WB					
Passenger Car	57	55	13	15.8	33
Sport Utility	57	55	14	14.8	32
Dump Truck	57	50	13	19.3	25
18-Wheeler	53	45	10	14.1	4
IH 610 SB to SH 225					
Passenger Car	55	50	15	15.9	62
Sport Utility	55	50	16	17.2	63
Dump Truck	54	45	13	18.2	33
18-Wheeler	51	50	15	17.3	46

maximum ball-bank reading for passenger cars of 13 to 14 degrees would represent a lateral acceleration threshold more realistic of today's driver comfort levels. The threshold for the tractor-trailer was decidedly lower than that of passenger cars. The 85th percentile speed also corresponded well to the maximum comfortable speed of the test vehicle, which may be used to infer that the ball-bank reading of around 10 is an acceptable measure to set realistic advisory speeds for large trucks. These results would seem to confirm the expectation that car drivers' comfort levels have changed from the assumptions used in current advisory speed setting practice. It also infers that there may be a need to develop a two-tiered system for setting advisory speeds on curves for both cars and heavy trucks.

Figure 17 presents a typical graph of speed versus maximum ball-bank indicator reading for the four vehicle types on a freeway-to-freeway connector. This particular graph is for the US 290 eastbound to IH 610 eastbound connector ramp. The figure indicates that the average maximum ball-bank readings for the different vehicles were not significantly different for a given speed, usually only differing within a 2 to 3 degree range. However, note that the dump truck and tractor-trailer did not attempt speeds as high as the passenger car and sport-utility vehicle. The drivers of the dump truck and tractor-trailer did not feel comfortable matching the maximum comfortable speeds of the drivers of the passenger car and sport-utility vehicle. This figure was typical of the other six study sites.

Figure 17. Speed versus Maximum Ball-Bank Reading for Various Vehicle Types (US 290 EB Ramp to IH 610 EB Mainlanes).

Table 7 presents the summary results showing the average maximum ball-bank indicator reading for each vehicle type, regardless of curve site, against the average maximum accelerometer reading on the maximum "comfortable" speed run for each vehicle.

Table 7. Average Readings from Curve Runs: Maximum "Comfortable" Speed.

Vehicle	Average Maximum Ball-Bank Reading	Average Maximum 0.25 sec Accelerometer Reading on "Comfortable" Speed Run	Average Percent of Time in Curve Greater than 0.10 *g*
Passenger Car	15	17.1	57
Sport Utility	16	16.7	59
Dump Truck	13	19.9	34
18-Wheeler	11	14.7	14

In general, the drivers of the passenger car and sport-utility vehicle would accept much more time in curve above 0.10 *g* lateral acceleration and higher maximum ball-bank readings than the dump-truck driver and especially the 18-wheeler driver. This finding is consistent with other research and is an expected outcome of this project. Table 7 also indicates that drivers are experiencing absolute maximum lateral accelerations above the maximum indicated by the ball-bank indicator. For the seven test curves, drivers of passenger cars and sport-utility vehicles experienced a maximum lateral acceleration of 5 to 10 percent greater than the indicated maximum average ball-bank reading. This reading indicates that the suspensions of these types of vehicles may have advanced to the point where they allow very good handling along the curve if the driver is able to hold a steady path along the curve alignment. The difference between the maximum accelerometer reading and maximum ball-bank reading for the dump truck and tractor-trailer was on the magnitude of 30 to 50 percent, indicating that even if the driver is able to hold the path through the curve consistently, the suspension of these types of vehicles will induce accelerations that exceed those indicated by the ball-bank indicator. This finding further supports the suggestion of a dual advisory speed scheme.

5.0 FINDINGS AND RECOMMENDATIONS

This section presents a summary of the project findings and makes recommendations for design, implementation, and further study.

STUDY FINDINGS

Researchers used the results of this project to make some generalized statements about the current practice of speed advisory setting and existing traffic operations on freeway-to-freeway connectors:

- The non-truck-driving motoring public (drivers in passenger cars, light trucks, and sport-utility vehicles) generally exceeds the posted advisory speed limit on freeway-to-freeway connectors, often by more than 10 mph.
- There is no seemingly discernable difference in the lateral accelerations experienced by drivers (often within 2-3 degrees) in different types of vehicles for a given speed over the course of a freeway-to-freeway connector curve.
- There may be differences in the lateral accelerations experienced briefly by larger vehicles with stiffer suspensions (dump trucks, etc.) in freeway-to-freeway connectors for a given speed.
- There appears to be a 5 to 10 mph higher difference between a driver's maximum comfortable curve speed between passenger cars/sport-utility vehicles and larger vehicles on most freeway-to-freeway connectors.

Since the lateral accelerations experienced by different vehicles are essentially the same for a given curve through the speed ranges tested in this project, but the maximum comfortable speeds differ greatly (5 to 10 mph), it can be concluded that drivers of larger vehicles may be more aware of the dangers and consequences of excessive speed on freeway-to-freeway connectors. Interviews with truck drivers confirmed this finding. The truck drivers responded that their peers are more aware of the pitfalls of excessive speeds, especially on curves with a combination of horizontal and vertical grades, typical of curves at freeway interchanges. Truck driver training programs have included more intensive education about the physics of tractor-trailers for at least the past decade. However, less experienced truck drivers may need more guidance, especially on unfamiliar facilities, than advisory speed warning signing and systems can provide.

There appeared to be a relationship between the amount of time spent above 0.10 g lateral acceleration and the comfort level of a driver to attempt the curve at a 5 mph higher increment. Even though the maximum lateral accelerations experienced by drivers of each type of vehicle were similar for a given curve and speed, the time in the curve above 0.10 g lateral acceleration before a driver was uncomfortable differed by vehicle. The 10 degree threshold was chosen for comparison because it corresponds with the current advisory speed criteria.

It was observed that the 85^{th} percentile speed on a particular curve typically corresponds very well to the maximum "comfortable" speed of the test drivers. From this result, researchers inferred that the observed maximum ball-bank reading for passenger cars of 13 to 14 degrees would represent a lateral acceleration threshold more realistic of today's driver comfort levels. It was also found that the threshold for the tractor-trailer was decidedly lower than that of passenger cars. The 85^{th} percentile speed observed for each curve also generally corresponded well to the maximum comfortable speed of the tractor-trailer test vehicle. This observation may be used to infer that the ball-bank reading of around 10 is an acceptable measure to set realistic advisory speeds for large trucks. These results seem to confirm the expectation that the comfort threshold for car drivers has changed from the assumptions used in current advisory speed setting practice. It also infers that there may be a need to develop a two-tiered system for setting advisory speeds on curves for both cars and heavy trucks.

From a comparison of the curve running speed versus the maximum ball-bank indicator reading for the four vehicle types on a freeway-to-freeway connector, it was observed that the average maximum ball-bank readings for the different vehicles were not significantly different for a given speed, usually only differing within a 2 to 3 degree range. This difference indicates that the lateral accelerations experienced by drivers of different vehicle types are similar. However, the dump-truck and tractor-trailer drivers did not attempt speeds as high as the passenger car and sport-utility vehicle. The drivers of the dump truck and tractor-trailer did not feel comfortable matching the maximum comfortable speeds of the drivers of the passenger car and sport-utility vehicle. This response was questioned of the dump-truck and tractor-trailer drivers, who responded that they know, because of experience, that a higher speed might have negative consequences.

In general, the drivers of the passenger car and sport-utility vehicle would accept much more time in curve above 0.10 g lateral acceleration and experience higher maximum ball-bank readings than the dump-truck driver and especially the 18-wheeler driver. This finding is consistent with other research and is an expected outcome of this project. The findings also indicate that drivers are experiencing absolute maximum lateral accelerations above the maximum indicated by the ball-bank indicator. Drivers of passenger cars and sport-utility vehicles experienced a maximum lateral acceleration of 5 to 10 percent greater than the indicated maximum average ball-bank reading. This difference indicates that the suspensions of these types of vehicles may have advanced to the point where they allow very good handling along the curve if the driver is able to hold a steady path along the curve alignment. The difference between the maximum accelerometer reading and maximum ball-bank reading for the dump truck and tractor-trailer were on the magnitude of 30 to 50 percent, indicating that even if the driver is able to hold the path through the curve consistently, the suspension of these types of vehicles will induce accelerations that exceed those indicated by the ball-bank indicator.

RECOMMENDATIONS

While previous studies of ramp geometry, speed, and safety have been more statistically based, this project was more anecdotal in nature, and any conclusions or recommendations must be tempered by the fact that there was a limited number of test drivers and vehicles used for the project. Researchers used the findings of the project, however, to discuss their significance with respect to current advisory speed setting practices for freeway-to-freeway direct connector ramps.

The findings exhibited here indicate that there may be differences in the maximum comfortable speeds that drivers of heavy vehicles and passenger-car type vehicles will accept for a freeway-to-freeway curve. While there are numerous variables that may govern these differences, the measure of lateral acceleration tends to make comparisons for various ramps possible, since this measure "normalizes" the geometric design factors such as superelevation, radius, and side friction factors.

The following conclusions confirmed by this project are applicable to freeway-to-freeway connectors and should be considered in their design, and especially in their re-design:

- Provide adequate deceleration and acceleration distances for tractor-trailers and other heavy vehicles. This recommendation infers that designers should not use the minimum lengths as specified by the AASHTO guidelines, but should consider lengthening these areas by 30 to 50 percent to accommodate a greater variety of large vehicle characteristics. This distance lengthening would assist the truck driver in exiting and entering the mainlane traffic stream at speeds greatly different from other vehicles in the traffic stream.
- Where possible, reduce the side friction demand. Consider developing superelevation more on the tangent, allowing the trailer of a tractor-trailer combination to adjust the distribution of its load before entering the curve. Consider the negative effect of placing restrictive, low-speed horizontal curves on downgrades.
- Limit the use of sharp, short curves near the gore points of freeway-to-freeway connector ramps, especially where the point of curvature for the ramp curve is close to the ramp diverge point. This situation presents itself as a short reverse curve and can cause load instability from the rocking motion resulting from traversing the reverse curve.

It is advised to place curve advisory speed signing with more regard to the deceleration needs of trucks. It was noted that on many of the study curves, the curve warning signs were placed too close, or even past the point of curvature than recommended in the TxMUTCD. Guidelines presented in the 2000 MUTCD may be used to determine sign placement, considering both approach speed and curve speed. It was also noted that many of the truck rollover warning systems occluded the regular curve warning signs near the point of curvature, virtually negating the effect of providing an advisory speed whatsoever. It is also recommended to use the new W13-5 sign (2000 MUTCD) to supplement the W13-2 (EXIT + speed advisory sign) and W13-3 (RAMP + speed advisory sign). The W13-5 provides the term "CURVE" instead of "RAMP" or

"EXIT" with an advisory speed. This sign could be used further upstream of where the traditional W1-2 Curve Warning Sign with advisory speed plaque is typically placed. Where two connectors are sharing the same approach and may have differing advisory speeds, more signing may be required to warn trucks of a required speed reduction, and this additional signing should be placed more in advance than would be required of passenger car operations because of the deceleration characteristics of larger vehicles.

As the results of this project indicate, in addition to the proper selection and placement of traditional signing for connector curves to accommodate trucks, non-standard or differential signing should be considered where a demonstrated history of truck crashes merits giving trucks more advisory information than what would be considered "normal" or "standard." One such procedure would be to use a ball-bank indicator test (in a passenger car or light truck) to determine at what speed the 10-degree level would be achieved. This 10-degree level would be used to set a truck advisory speed. The test would also determine the speed at which the 13-degree level would be achieved and used for setting a more realistic passenger car speed that would approximately represent the 85th percentile speed on the curve. Again, this procedure is based on limited field-testing of vehicles and on correlating these limited results to many thousands of speed readings at each study curve, so there may be some basis to implementing a dual system in the field at yet-to-be-determined test sites.

RECOMMENDATIONS FOR FUTHER RESEARCH

While this research project provided some insight into the behavior of vehicles with high centers of gravity, it also produced several additional questions that could not be answered within the scope of this project. TxDOT should consider adding these topics to the research program in the near future to continue to address this issue.

1. While using a dual ball-bank reading test may provide for differential advisory speeds for a given curve, the method to convey this information to car and truck drivers is yet to be determined. Further research would be necessary to test various signing concepts to focus groups of drivers representing both passenger car drivers, as well as truck drivers.

2. One of the more interesting items evaluated in the project was the amount of time that drivers were willing to accept exceeding 0.10 *g* lateral acceleration. While the results were similar for the two passenger vehicles, the amount of time for the dump truck was 40 percent less and that for the tractor-trailer was 75 percent less. This phenomenon should be evaluated with a larger sample of drivers and vehicle types to better determine comfort levels of drivers in modern vehicles.
3. In addition to evaluation of driver behavior with respect to speed on freeway-to-freeway connectors, a similar study should be completed on rural roadways.
4. As the research results determined that drivers of all vehicle types generally do not adhere to the posted advisory speed limits on connector ramps, new techniques for increasing this compliance should be researched.
5. Since the drivers of large vehicles safely traverse the curves at slower speeds than passenger cars, research is needed to study the impacts of having different advisory speeds for trucks and cars on connector ramps.

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APPENDIX

RIEKER DIGITAL BALL-BANKING INDICATOR DATA

RIEKER®
ELECTRONICS INC

RDI Series: RDS7-BB

Digital Ball Banking Indicator

Model RDS7-BB includes several new features - making it the most versatile ball banking system offered for determining safe curve speed.

Features

- ±25° Input Range
- Auto Leveling (no need for a level mounting surface)
- Velcro Mounting for Quick Installation and Easy Removal
- Angle Display in Degrees, Percent Grade, or Inch per Foot Rise
- 0.1° or 0.01° Display Resolution
- Relative Zero
- Min/Max Reading (freezes the highest Left and Right corner readings)
- Customizable Trip Angles
- ±10° Audible Alarm
- RS232 Serial Output (directly to your laptop!)

Description

Power Supply

The RDS7-BB is powered by a standard 12 Volt cigarette lighter style cable connection. First, insert the power supply cable, which is included with the RDI unit, into the unit's serial port. Then connect the other end into the cigarette lighter socket of the vehicle. Optional cables are available if the vehicle does not have a standard cigarette lighter socket.

Mounting

The RDS7-BB can be mounted on any surface that is within 10 degrees of level. To determine if the surface is within the appropriate level, power up the unit and place it on the desired location. If the unit displays less than 10 degrees then the chosen location is fine. Once the mounting location has been determined, wipe the surface clean with a cleanser such as Windex and then apply one of the supplied strips of Velcro. Apply the remaining strip of Velcro to the bottom of the unit. The RDS7-BB is ready to attach to the vehicle's surface. With the vehicle on a relatively level surface, power up the unit and look at the digital display to determine if the unit is reading 0 degrees or level. If the selected mounting location is level the unit is ready to begin ball bank operation.

Auto Leveling

If the unit is not level, but within ±10 degrees, press and release the REL button. The display will read "REL ON" for one second then revert to normal with the unit reading zero. If after pressing the REL button and the display reads "OVER RANGE" the unit is not within ±10 degrees from level. The operator must re-position the unit then repeat auto leveling.

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voice: 610-534-9000 | fax: 610-534-4670 | email: info@riekerinc.com | web: www.riekerinc.com

- When the unit is in REL mode you will see the (*) symbol displayed indicating that the relative zero (REL) function is active. Please remember that the unit should be auto leveled using the REL button while the vehicle is on a flat surface. Auto leveling with the REL button must be performed whenever the unit has been powered off.

Operation
Once the RDS7-BB unit has been auto leveled, the operator is ready to go to work. Before driving the stretch of road with the curve that will be evaluated, press the MIN/MAX button slowly three (3) times: The *first* press will display "LEFT" for one second, then freeze the (-) side reading. The *second* press will display "RIGHT" for one second, then freeze the (+) side reading. The *third* press of the MIN/MAX button will display "RESET", then immediately go back to normal function.

When in the act of determining safe curve speed, the MINIMUM reading corresponds to left hand turns and the MAXIMUM corresponds to right hand turns. The RDS7-BB unit comes factory set to sound an alarm at ±10 degrees, allowing the operator to safely drive through the corner - eyes on the road, not the unit. If the system determines the vehicle has exceeded ±10 degrees, it will sound an alarm, which indicates to the operator to press the MIN/MAX button to display the highest value achieved - providing the necessary information to determine the safe speed for that curve.

RS232 Output
If a laptop computer will be used in conjunction with the RDS7-BB, the appropriate Rieker power cord will be needed to provide RS232 output. This modified power cord splits to provide a serial port connector as well as the cigarette lighter adaptor. To install: First, insert the cable's single-end serial connector into the RDS7-BB's serial port then attach the computer serial port connector to the laptop's serial port. Finally, insert the cigarette lighter adaptor end into the cigarette lighter socket of the vehicle - the unit and computer can now be switched on.

When power is supplied to the unit data will begin to flow to the laptop. A single column of numbers will appear on the screen with a (+) or (-) sign to distinguish between a left or right turn. Pressing the MIN/MAX button will stop the flow of data from the RDS7-BB. We recommend you press the MIN/MAX two (2) times in order to display the "MAX" reading, specifically so that the unit is not outputting data to the computer. When driving and ready to start recording data press the MIN/MAX button one more time to reset the unit and it will resume sending data. Once you have completed the course that you want to record press the MIN/MAX button again to stop the flow of data.

Over Range
The RDS7-BB has a total range of 50 degrees (±25°). When this range is exceeded the display will read "OVER RANGE". While this will probably not occur during normal use it can occur when mounting the unit or when using the REL button for auto leveling. If you are mounting the unit on a surface that is out of level by more than ±10 degrees the display will read "OVER RANGE". If this occurs, simply re-position the unit to within ±10 degrees of level.

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SPEED DATA

Measured Vehicle Speeds on Connector Ramps

CONNECTOR	Posted Advisory	Type of	Speed (mph) on Approach to Ramp					Speed (mph) At Point of Curve - First Curve				
RAMP	Speed (mph)	Vehicle	Samples	Average	50%'tile	70%'tile	85%'tile	Samples	Average	50%'tile	70%'tile	85%'tile
IH 45 N. SB TO	none	Pass Veh	61,902	44.3	44.1	48.8	53.4	37,951	54.2	54.4	57.5	60.5
IH 610 WB		Rigid Veh	1,857	51.9	48.7	54.4	66.8	4,823	55.0	54.9	58.4	61.8
		Hvy Trks	1,771	42.8	42.8	48.1	52.1	809	50.2	50.5	53.2	56.4
		ALL	65,530	44.5	44.2	49.0	53.6	43,583	54.2	54.4	57.5	60.8
IH 610 EB TO	35	Pass Veh	61,941	56.2	57.0	60.3	63.4					
IH 45 NB		Rigid Veh	2,417	54.7	55.8	59.1	62.3					
		Hvy Trks	1,157	50.6	54.1	57.0	59.3					
		ALL	65,515	56.1	57.0	60.0	63.1					
IH 610 EB TO	25 for trucks only	Pass Veh	24,864	54.2	52.8	56.6	62.3	19,460	51.8	51.9	54.8	57.3
US 59 NB	no speed	Rigid Veh	1,860	57.5	57.9	63.1	67.1	1,304	51.2	51.2	54.5	57.5
	for other veh	Hvy Trks	1,024	50.1	49.6	52.6	55.6	841	48.0	48.3	51.7	54.1
		ALL	27,748	54.2	52.8	56.9	62.5	21,605	51.6	51.7	54.5	57.3
IH 610 SB TO	35	Pass Veh	22,007	63.1	62.3	67.1	71.9	14,051	51.5	51.5	54.4	57.0
SH 225 EB		Rigid Veh	7,029	65.8	65.6	69.9	74.1	1,664	50.9	50.5	54.0	57.5
		Hvy Trks	3,216	60.0	60.0	63.6	67.1	1,270	47.2	47.4	50.2	52.6
		ALL	32,252	63.4	62.8	67.4	71.9	16,985	51.1	51.2	54.0	56.9
IH 610 WB TO	40	Pass Veh	26,602	55.0	58.8	63.1	66.8	41,646	47.5	48.1	50.8	53.7
IH 45 N. SB		Rigid Veh	1,669	55.9	58.6	62.3	65.6	3,413	47.4	47.7	51.0	54.0
		Hvy Trks	585	48.7	54.9	58.4	61.3	1,202	41.2	42.9	46.2	49.1
		ALL	28,856	54.9	58.8	63.1	66.5	46,261	47.3	47.9	50.8	53.6
US 290 EB TO	40	Pass Veh	56,733	58.8	59.1	62.5	66.2	10,149	50.5	50.7	53.2	55.8
IH 610 EB		Rigid Veh	6,853	58.6	59.1	62.5	66.2	760	49.8	49.5	52.3	54.9
		Hvy Trks	1,935	55.2	56.0	59.1	61.8	435	47.8	47.4	50.0	52.4
		ALL	65,521	58.7	58.8	62.5	65.9	11,344	50.3	50.5	53.0	55.6
US 59 NB TO	30	Pass Veh	31,525	53.9	53.7	56.4	59.3	27,219	49.5	49.6	52.3	54.8
IH A10610 WB		Rigid Veh	1,556	51.7	51.5	54.5	57.5	2,105	47.8	47.9	51.0	54.1
		Hvy Trks	957	49.2	49.3	52.1	54.5	893	44.0	44.2	47.0	49.5
		ALL	34,038	53.7	53.6	56.4	59.1	30,217	49.3	49.5	52.1	54.5

Note: Sample numbers may vary due to tubes up at different times.

Measured Vehicle Speeds on Connector Ramps

CONNECTOR	Posted Advisory	Type of	Speed (mph) Middle of First Curve					Speed (mph) At Point of Curve - Second Curve					Speed (mph) Middle of Second Curve				
RAMP	Speed (mph)	Vehicle	Samples	Average	50%'tile	70%'tile	85%'tile	Samples	Average	50%'tile	70%'tile	85%'tile	Samples	Average	50%'tile	70%'tile	85%'tile
IH 45 N. SB TO	none	Pass Veh	55,047	51.0	51.0	54.0	56.9	29,573	53.9	54.0	57.0	60.3	29,555	46.4	46.4	48.8	51.2
IH 610 WB		Rigid Veh	9,031	51.6	51.3	54.4	57.7	7,091	54.2	54.1	57.3	60.5	1,109	46.3	46.2	48.8	51.2
		Hvy Trks	1,437	47.3	47.3	50.0	52.6	501	50.3	50.2	53.6	56.6	363	43.0	43.3	45.6	47.6
		ALL	65,515	51.0	51.0	54.0	56.9	37,165	54.0	54.0	57.0	60.3	31,027	46.3	46.4	48.7	51.0
IH 610 EB TO	35	Pass Veh	56,029	40.2	40.7	43.3	45.8										
IH 45 NB		Rigid Veh	2,421	38.9	39.1	41.9	45.0										
		Hvy Trks	1,723	34.6	35.6	38.1	40.4										
		ALL	60,173	40.0	40.6	43.2	45.7										
IH 610 EB TO	25 for trucks only	Pass Veh	57,488	43.2	43.3	45.7	48.1	29,064	45.8	45.8	48.3	50.8	55,842	49.6	49.1	51.9	54.8
US 59 NB	no speed	Rigid Veh	3,483	43.1	42.7	45.3	48.1	2,219	45.0	45.0	47.9	50.5	10,316	49.3	48.8	51.9	55.4
	for other veh	Hvy Trks	2,225	39.7	39.6	42.3	45.1	949	41.3	41.5	44.1	46.7	2,706	45.7	45.0	47.9	50.8
		ALL	63,196	43.1	43.2	45.6	48.1	32,232	45.6	45.7	48.2	50.8	68,864	49.4	49.0	51.7	54.8
IH 610 SB TO	35	Pass Veh	46,940	49.5	49.5	52.1	54.9										
SH 225 EB		Rigid Veh	10,466	48.7	48.7	51.5	54.4										
		Hvy Trks	6,451	45.4	45.4	48.2	50.8										
		ALL	63,857	48.9	49.0	51.7	54.5										
IH 610 WB TO	40	Pass Veh															
IH 45 N. SB		Rigid Veh															
		Hvy Trks															
		ALL															
US 290 EB TO	40	Pass Veh	59,240	47.9	48.1	50.3	52.4										
IH 610 EB		Rigid Veh	3,915	46.6	46.4	48.8	51.2										
		Hvy Trks	2,363	43.7	43.7	46.0	48.1										
		ALL	65,518	47.7	47.7	50.0	52.3										
US 59 NB TO	30	Pass Veh	11,083	38.6	39.1	41.5	43.8	25,521	40.2	40.0	42.4	44.7	38,436	41.4	41.4	43.3	45.4
IH A10610 WB		Rigid Veh	1,277	38.8	38.3	40.8	43.4	2,325	39.6	38.9	41.8	44.6	3,266	40.4	39.3	41.7	44.3
		Hvy Trks	329	35.5	35.1	37.9	40.0	811	34.1	33.7	36.1	38.6	1,190	36.6	36.5	38.6	40.6
		ALL	12,689	38.5	39.0	41.2	43.7	28,657	40.0	39.9	42.3	44.7	42,892	41.2	41.1	43.2	45.3

Note: Sample numbers may vary due to tubes up at different times.

BALL-BANK/DIGITAL BALL-BANK RESULTS

Connector:

US 290 EB to IH 610 EB

Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
	30 mph Test Runs			35 mph Test Runs			40 mph Test Runs		
manual ball bank reading:	0	0	0	0	0	0	-8	-7	-7
average of ball bank readings:			0.00			0.00			-7.33
number of 250ms speed observations	0	0	0	0	0	0	100	100	100
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			-7.3
maximum 250ms reiker reading			0.0			0.0			-9.2

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	-7.5	-7	-7.5
average of ball bank readings:			0.00			0.00			-7.33
number of 250ms speed observations	0	0	0	0	0	0	96	96	96
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			-7.3
maximum 250ms reiker reading			0.0			0.0			-8.7

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-5	-4	-5	-9	-9.5	-8
average of ball bank readings:			0.00			-4.67			-8.83
number of 250ms speed observations	0	0	0	119	120	119	115	113	115
number of 250ms periods over 10 degrees	0	0	0	1	1	1	13	9	4
number of observations over 10 degrees	0	0	0	1	1	1	13	9	4
percent of time over 10 degrees	0%	0%	0%	1%	1%	1%	11%	8%	3%
average number of 250ms periods over 10 deg			0.00			1.00			8.67
average time (sec) in curve over 10 deg			0.00			0.25			2.17
average max ball bank reading			0.0			-4.7			-8.8
maximum 250ms reiker reading			0.0			-13.3			-15.4

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-6	-5	-5	-8	-7.5	-7.5
average of ball bank readings:			0.00			-5.33			-7.67
number of 250ms speed observations	0	0	0	118	117	120	104	104	104
number of 250ms periods over 10 degrees	0	0	0	0	0	0	2	0	0
number of observations over 10 degrees	0	0	0	0	0	0	2	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	2%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.67
average time (sec) in curve over 10 deg			0.00			0.00			0.17
average max ball bank reading			0.0			-5.3			-7.7
maximum 250ms reiker reading			0.0			-7.6			-10.7

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve			Middle of First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
US 290 EB TO IH 610 EB	Pass Veh	56733	58.8	66.2	10149	50.5	55.8	59240	47.9	52.4
	Rigid Veh	6853	58.6	66.2	760	49.8	54.9	3915	46.6	51.2
	Hvy Trks	1935	55.2	61.8	435	47.8	52.4	2363	43.7	48.1
	ALL	65521	58.7	65.9	11344	50.3	55.6	65518	47.7	52.3

Legend: Runs not made at this speed (grey); Runs corresponding to 85th percentile speed (yellow)

Connector:
US 290 EB to IH 610 EB

	45 mph Test Runs			50 mph Test Runs			55 mph Test Runs		
Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	-8	-7	-7
average of ball bank readings:			0.00			0.00			-7.33
number of 250ms speed observations	0	0	0	0	0	0	100	100	100
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			-7.3
maximum 250ms reiker reading			0.0			0.0			-9.2

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	-7.5	-7	-7.5
average of ball bank readings:			0.00			0.00			-7.33
number of 250ms speed observations	0	0	0	0	0	0	96	96	96
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			-7.3
maximum 250ms reiker reading			0.0			0.0			-8.7

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-5	-4	-5	-9	-9.5	-8
average of ball bank readings:			0.00			-4.67			-8.83
number of 250ms speed observations	0	0	0	119	120	119	115	113	115
number of 250ms periods over 10 degrees	0	0	0	1	1	1	13	9	4
number of observations over 10 degrees	0	0	0	1	1	1	13	9	4
percent of time over 10 degrees	0%	0%	0%	1%	1%	1%	11%	8%	3%
average number of 250ms periods over 10 deg			0.00			1.00			8.67
average time (sec) in curve over 10 deg			0.00			0.25			2.17
average max ball bank reading			0.0			-4.7			-8.8
maximum 250ms reiker reading			0.0			-13.3			-15.4

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-6	-5	-5	-8	-7.5	-7.5
average of ball bank readings:			0.00			-5.33			-7.67
number of 250ms speed observations	0	0	0	118	117	120	104	104	104
number of 250ms periods over 10 degrees	0	0	0	0	0	0	2	0	0
number of observations over 10 degrees	0	0	0	0	0	0	2	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	2%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.67
average time (sec) in curve over 10 deg			0.00			0.00			0.17
average max ball bank reading			0.0			-5.3			-7.7
maximum 250ms reiker reading			0.0			-7.6			-10.7

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile
US 290 EB TO IH 610 EB	Pass Veh	56733	58.805	66.2	10149	50.47	55.8
	Rigid Veh	6853	58.619	66.2	760	49.77	54.9
	Hvy Trks	1935	55.205	61.8	435	47.79	52.4
	ALL	65521	58.679	65.9	11344	50.32	55.6

Legend:
- Runs not made at this speed
- Runs corresponding to 85th percentile speed

Connector:
US 59 NB to IH 610 WB

	30 mph Test Runs			35 mph Test Runs			40 mph Test Runs		
Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-12	-12	-11	-13	-15	-14
average of ball bank readings:			0.00			-11.67			-14.00
number of 250ms speed observations	0	0	0	105	106	105	98	98	98
number of 250ms periods over 10 degrees	0	0	0	22	26	19	28	31	23
number of observations over 10 degrees	0	0	0	22	26	19	28	31	23
percent of time over 10 degrees	0%	0%	0%	21%	25%	18%	29%	32%	23%
average number of 250ms periods over 10 deg			0.00			22.33			27.33
average time (sec) in curve over 10 deg			0.00			5.58			6.83
average max ball bank reading			0.0			-11.7			-14.0
maximum 250ms reiker reading			0.0			-14.3			-16.1

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	-7	-7	-7	-11	-12	-10	-17	-15	-16
average of ball bank readings:			-7.00			-11.00			-16.00
number of 250ms speed observations	116	116	116	104	103	104	95	94	93
number of 250ms periods over 10 degrees	0	0	0	13	16	6	37	39	38
number of observations over 10 degrees	0	0	0	13	16	6	37	39	38
percent of time over 10 degrees	0%	0%	0%	13%	16%	6%	39%	41%	41%
average number of 250ms periods over 10 deg			0.00			11.67			38.00
average time (sec) in curve over 10 deg			0.00			2.92			9.50
average max ball bank reading			-7.0			-11.0			-16.0
maximum 250ms reiker reading			-8.1			-12.1			-16.8

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-10	-12	-11	-12	-14	-15
average of ball bank readings:			0.00			-11.00			-13.67
number of 250ms speed observations	0	0	0	123	123	123	113	113	113
number of 250ms periods over 10 degrees	0	0	0	9	14	15	17	30	29
number of observations over 10 degrees	0	0	0	9	14	15	17	30	29
percent of time over 10 degrees	0%	0%	0%	7%	11%	12%	15%	27%	26%
average number of 250ms periods over 10 deg			0.00			12.67			25.33
average time (sec) in curve over 10 deg			0.00			3.17			6.33
average max ball bank reading			0.0			-11.0			-13.7
maximum 250ms reiker reading			0.0			-15.4			-18.8

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	-8	-9	-6.5	-13	-12	-12	-13	-13	0
average of ball bank readings:			-7.83			-12.33			-13.00
number of 250ms speed observations	120	120	120	112	112	106	106	106	0
number of 250ms periods over 10 degrees	1	2	0	25	13	23	32	30	0
number of observations over 10 degrees	1	2	0	25	13	23	32	30	0
percent of time over 10 degrees	1%	2%	0%	22%	12%	22%	30%	28%	0%
average number of 250ms periods over 10 deg			1.00			20.33			20.67
average time (sec) in curve over 10 deg			0.25			5.08			5.17
average max ball bank reading			-7.8			-12.3			-13.0
maximum 250ms reiker reading			-11.5			-13.9			-16.0

Measured Vehicle Speeds on Connector Ramps

	Type of	Approach to Ramp			Prior to First Curve			Middle of First Curve		
CONNECTOR RAMP	Vehicle	Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
US 59 NB TO IH 610 WB	Pass Veh	31525	53.9	59.3	27219	49.5	54.8	11083	38.6	43.8
	Rigid Veh	1556	51.7	57.5	2105	47.8	54.1	1277	38.8	43.4
	Hvy Trks	957	49.2	54.5	893	44.0	49.5	329	35.5	40.0
	ALL	34038	53.7	59.1	30217	49.3	54.5	12689	38.5	43.7

Legend: Runs not made at this speed
Runs corresponding to 85th percentile speed

Connector:
US 59 NB to IH 610 WB

	45 mph Test Runs			50 mph Test Runs			55 mph Test Runs		
Passenger Car	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-18	-20	-20	-20	-20	-20	0	0	0
average of ball bank readings:			-19.33			-20.00			0.00
number of 250ms speed observations	88	88	88	78	78	78	0	0	0
number of 250ms periods over 10 degrees	46	46	44	41	42	43	0	0	0
number of observations over 10 degrees	46	46	44	41	42	43	0	0	0
percent of time over 10 degrees	52%	52%	50%	53%	54%	55%	0%	0%	0%
average number of 250ms periods over 10 deg			45.33			42.00			0.00
average time (sec) in curve over 10 deg			11.33			10.50			0.00
average max ball bank reading			-19.3			-20.0			0.0
maximum 250ms reiker reading			-22.4			-24.1			0.0

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-20	-19	-18	0	0	0	0	0	0
average of ball bank readings:			-19.00			0.00			0.00
number of 250ms speed observations	90	90	90	0	0	0	0	0	0
number of 250ms periods over 10 degrees	42	43	41	0	0	0	0	0	0
number of observations over 10 degrees	42	43	41	0	0	0	0	0	0
percent of time over 10 degrees	47%	48%	46%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			42.00			0.00			0.00
average time (sec) in curve over 10 deg			10.50			0.00			0.00
average max ball bank reading			-19.0			0.0			0.0
maximum 250ms reiker reading			-20.1			0.0			0.0

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-17	-18	-19	0	0	0	0	0	0
average of ball bank readings:			-18.00			0.00			0.00
number of 250ms speed observations	104	104	104	0	0	0	0	0	0
number of 250ms periods over 10 degrees	29	42	43	0	0	0	0	0	0
number of observations over 10 degrees	29	42	43	0	0	0	0	0	0
percent of time over 10 degrees	28%	40%	41%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			38.00			0.00			0.00
average time (sec) in curve over 10 deg			9.50			0.00			0.00
average max ball bank reading			-18.0			0.0			0.0
maximum 250ms reiker reading			-23.2			0.0			0.0

18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	0	0	0	0	0	0	0	0	0
average of ball bank readings:			0.00			0.00			0.00
number of 250ms speed observations	0	0	0	0	0	0	0	0	0
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			0.0
maximum 250ms reiker reading			0.0			0.0			0.0

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve			Middle of Second Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile
US 59 NB TO IH 610 WB	Pass Veh	25521	40.2	44.7	38436	41.4	45.4
	Rigid Veh	2325	39.6	44.6	3266	40.4	44.3
	Hvy Trks	811	34.1	38.6	1190	36.6	40.6
	ALL	28657	40.0	44.7	42892	41.2	45.3

Legend:
- Runs not made at this speed
- Runs corresponding to 85th percentile speed

Connector:
IH 610 WB to IH 45 SB

Passenger Car	30 mph Test Runs 30-1	30-2	30-3	35 mph Test Runs 35-1	35-2	35-3	40 mph Test Runs 40-1	40-2	40-3
manual ball bank reading:	0	0	0	-7	-7	-7	-10	-9	-8.5
average of ball bank readings:			0.00			-7.00			-9.17
number of 250ms speed observations	0	0	0	122	122	122	108	108	108
number of 250ms periods over 10 degrees	0	0	0	0	0	0	2	1	0
number of observations over 10 degrees	0	0	0	0	0	0	2	1	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	2%	1%	0%
average number of 250ms periods over 10 deg			0.00			0.00			1.00
average time (sec) in curve over 10 deg			0.00			0.00			0.25
average max ball bank reading			0.0			-7.0			-9.2
maximum 250ms reiker reading			0.0			-8.5			-11.1

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-8	-8	-8	-12	-11	-11
average of ball bank readings:			0.00			-8.00			-11.33
number of 250ms speed observations	0	0	0	131	131	131	105	109	109
number of 250ms periods over 10 degrees	0	0	0	0	0	0	28	7	5
number of observations over 10 degrees	0	0	0	0	0	0	28	7	5
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	27%	6%	5%
average number of 250ms periods over 10 deg			0.00			0.00			13.33
average time (sec) in curve over 10 deg			0.00			0.00			3.33
average max ball bank reading			0.0			-8.0			-11.3
maximum 250ms reiker reading			0.0			-9.7			-12.1

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-7	-7	-7	-10	-10	-10
average of ball bank readings:			0.00			-7.00			-10.00
number of 250ms speed observations	0	0	0	123	123	123	112	112	112
number of 250ms periods over 10 degrees	0	0	0	5	6	3	15	20	11
number of observations over 10 degrees	0	0	0	5	6	3	15	20	11
percent of time over 10 degrees	0%	0%	0%	4%	5%	2%	13%	18%	10%
average number of 250ms periods over 10 deg			0.00			4.67			15.33
average time (sec) in curve over 10 deg			0.00			1.17			3.83
average max ball bank reading			0.0			-7.0			-10.0
maximum 250ms reiker reading			0.0			-16.3			-20.6

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	-5	-5	-5	-7	-7	-7	-8	-9	-9
average of ball bank readings:			-5.00			-7.00			-8.67
number of 250ms speed observations	147	147	145	113	114	114	109	109	109
number of 250ms periods over 10 degrees	0	0	0	0	0	3	2	4	4
number of observations over 10 degrees	0	0	0	0	0	3	2	4	4
percent of time over 10 degrees	0%	0%	0%	0%	0%	3%	2%	4%	4%
average number of 250ms periods over 10 deg			0.00			1.00			3.33
average time (sec) in curve over 10 deg			0.00			0.25			0.83
average max ball bank reading			-5.0			-7.0			-8.7
maximum 250ms reiker reading			-8.3			-10.6			-13.4

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve			Middle of First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610 WB TO IH 45 N. SB	Pass Veh	26602	55.0	66.8	41646	47.5	53.7	0	0.0	0.0
	Rigid Veh	1669	55.9	65.6	3413	47.4	54.0	0	0.0	0.0
	Hvy Trks	585	48.7	61.3	1202	41.2	49.1	0	0.0	0.0
	ALL	28856	54.9	66.5	46261	47.3	53.6	0	0.0	0.0

Legend:
- Runs not made at this speed (grey)
- Runs corresponding to 85th percentile speed (yellow)

Connector:
IH 610 WB to IH 45 SB

	45 mph Test Runs			50 mph Test Runs			55 mph Test Runs		
Passenger Car	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-12	-12	-18	-17	-17	0	0	0
average of ball bank readings:			-12.33			-17.33			0.00
number of 250ms speed observations	99	99	99	84	84	84	0	0	0
number of 250ms periods over 10 degrees	48	59	53	68	66	62	0	0	0
number of observations over 10 degrees	48	59	53	68	66	62	0	0	0
percent of time over 10 degrees	48%	60%	54%	81%	79%	74%	0%	0%	0%
average number of 250ms periods over 10 deg			53.33			65.33			0.00
average time (sec) in curve over 10 deg			13.33			16.33			0.00
average max ball bank reading			-12.3			-17.3			0.0
maximum 250ms reiker reading			-15.6			-19.7			0.0

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-14	-15	-17	-17	-18	0	0	0
average of ball bank readings:			-14.00			-17.33			0.00
number of 250ms speed observations	104	104	104	99	99	99	0	0	0
number of 250ms periods over 10 degrees	61	52	61	74	72	73	0	0	0
number of observations over 10 degrees	61	52	61	74	72	73	0	0	0
percent of time over 10 degrees	59%	50%	59%	75%	73%	74%	0%	0%	0%
average number of 250ms periods over 10 deg			58.00			73.00			0.00
average time (sec) in curve over 10 deg			14.50			18.25			0.00
average max ball bank reading			-14.0			-17.3			0.0
maximum 250ms reiker reading			-15.3			-18.3			0.0

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-13	-13	0	0	0	0	0	0
average of ball bank readings:			-13.00			0.00			0.00
number of 250ms speed observations	105	105	105	0	0	0	0	0	0
number of 250ms periods over 10 degrees	36	34	30	0	0	0	0	0	0
number of observations over 10 degrees	36	34	30	0	0	0	0	0	0
percent of time over 10 degrees	34%	32%	29%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			33.33			0.00			0.00
average time (sec) in curve over 10 deg			8.33			0.00			0.00
average max ball bank reading			-13.0			0.0			0.0
maximum 250ms reiker reading			-23.2			0.0			0.0

18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	0	0	0	0	0	0	0	0	0
average of ball bank readings:			0.00			0.00			0.00
number of 250ms speed observations	0	0	0	0	0	0	0	0	0
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			0.0
maximum 250ms reiker reading			0.0			0.0			0.0

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve			Middle of Second Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610 WB TO IH 45 SB	Pass Veh	0	0	0	0	0	0
	Rigid Veh	0	0	0	0	0	0
	Hvy Trks	0	0	0	0	0	0
	ALL	0	0	0	0	0	0

Legend:
- Runs not made at this speed
- Runs corresponding to 85th percentile speed

Connector:
IH 610 EB TO US 59 NB

Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
	30 mph Test Runs			35 mph Test Runs			40 mph Test Runs		
manual ball bank reading:	-6	-6	-5	-7	-7	-8	-9	-10	-11
average of ball bank readings:			-5.67			-7.33			-10.00
number of 250ms speed observations	137	134	137	132	134	135	123	121	119
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	9	27
Number of observations over 10 degrees	0	0	0	0	0	0	0	9	27
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	7%	23%
average number of 250ms periods over 10 deg			0.00			0.00			12.00
average time (sec) in curve over 10 deg			0.00			0.00			3.00
average max ball bank reading			-5.7			-7.3			-10.0
maximum 250ms reiker reading			-8.1			-8.5			-12.1

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-6	-7	-7	-14	-13	-10
average of ball bank readings:			0.00			-6.67			-12.33
number of 250ms speed observations	0	0	0	125	125	125	115	115	114
number of 250ms periods over 10 degrees	0	0	0	0	0	0	26	26	3
Number of observations over 10 degrees	0	0	0	0	0	0	26	26	3
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	23%	23%	3%
average number of 250ms periods over 10 deg			0.00			0.00			18.33
average time (sec) in curve over 10 deg			0.00			0.00			4.58
average max ball bank reading			0.0			-6.7			-12.3
maximum 250ms reiker reading			0.0			-7.6			-14.8

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-7.5	-7	-7.5	-11	-10	-11
average of ball bank readings:			0.00			-7.33			-10.67
number of 250ms speed observations	0	0	0	130	130	130	114	114	114
number of 250ms periods over 10 degrees	0	0	0	2	2	4	11	8	14
Number of observations over 10 degrees	0	0	0	2	2	4	11	8	14
percent of time over 10 degrees	0%	0%	0%	2%	2%	3%	10%	7%	12%
average number of 250ms periods over 10 deg			0.00			2.67			11.00
average time (sec) in curve over 10 deg			0.00			0.67			2.75
average max ball bank reading			0.0			-7.3			-10.7
maximum 250ms reiker reading			0.0			-11.8			-13.9

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	-5	-6	-5	-8	-7	-8	-11	-10	-13
average of ball bank readings:			-5.33			-7.67			-11.33
number of 250ms speed observations	135	135	138	114	108	113	111	111	108
number of 250ms periods over 10 degrees	0	0	0	1	0	1	16	5	18
Number of observations over 10 degrees	0	0	0	1	0	1	16	5	18
percent of time over 10 degrees	0%	0%	0%	1%	0%	1%	14%	5%	17%
average number of 250ms periods over 10 deg			0.00			0.67			13.00
average time (sec) in curve over 10 deg			0.00			0.17			3.25
average max ball bank reading			-5.3			-7.7			-11.3
maximum 250ms reiker reading			-7.2			-10.4			-14.8

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve			Middle of First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
I-610 EB TO US 59 NB	Pass Veh	24864	54.2	62.3	19460	51.8	57.3	57488	43.2	48.1
	Rigid Veh	1860	57.5	67.1	1304	51.2	57.5	3483	43.1	48.1
	Hvy Trks	1024	50.1	55.6	841	48.0	54.1	2225	39.7	45.1
	ALL	27748	54.2	62.5	21605	51.6	57.3	63196	43.1	48.1

Legend:
Runs not made at this speed
Runs corresponding to 85th percentile speed

Connector:
IH 610 EB TO US 59 NB

	45 mph Test Runs			50 mph Test Runs			55 mph Test Runs		
Passenger Car	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-12	-12	-13	-18	-16	-16	0	0	0
average of ball bank readings:			-12.33			-16.67			0.00
number of 250ms speed observations	104	100	103	95	99	99	0	0	0
number of 250ms periods over 10 degrees	28	32	41	48	48	54	0	0	0
number of observations over 10 degrees	28	32	41	48	48	54	0	0	0
percent of time over 10 degrees	27%	32%	40%	51%	48%	55%	0%	0%	0%
average number of 250ms periods over 10 deg			33.67			50.00			0.00
average time (sec) in curve over 10 deg			8.42			12.50			0.00
average max ball bank reading			-12.3			-16.7			0.0
maximum 250ms reiker reading			-14.0			-18.3			0.0

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-13	-13	-16	-16	-17	0	0	0
average of ball bank readings:			-13.00			-16.33			0.00
number of 250ms speed observations	106	105	106	100	100	99	0	0	0
number of 250ms periods over 10 degrees	45	37	44	51	52	52	0	0	0
number of observations over 10 degrees	45	37	44	51	52	52	0	0	0
percent of time over 10 degrees	42%	35%	42%	51%	52%	53%	0%	0%	0%
average number of 250ms periods over 10 deg			42.00			51.67			0.00
average time (sec) in curve over 10 deg			10.50			12.92			0.00
average max ball bank reading			-13.0			-16.3			0.0
maximum 250ms reiker reading			-13.6			-17.4			0.0

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-14.5	-15	0	0	0	0	0	0
average of ball bank readings:			-14.17			0.00			0.00
number of 250ms speed observations	119	119	119	0	0	0	0	0	0
number of 250ms periods over 10 degrees	39	37	39	0	0	0	0	0	0
number of observations over 10 degrees	39	37	39	0	0	0	0	0	0
percent of time over 10 degrees	33%	31%	33%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			38.33			0.00			0.00
average time (sec) in curve over 10 deg			9.58			0.00			0.00
average max ball bank reading			-14.2			0.0			0.0
maximum 250ms reiker reading			-18.4			0.0			0.0

18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	0	0	0	0	0	0	0	0	0
average of ball bank readings:			0.00			0.00			0.00
number of 250ms speed observations	0	0	0	0	0	0	0	0	0
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			0.0
maximum 250ms reiker reading			0.0			0.0			0.0

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve			Middle of Second Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610 EB TO US 59 NB	Pass Veh	29064	45.8	50.8	55842	49.6	54.8
	Rigid Veh	2219	45.0	50.5	10316	49.3	55.4
	Hvy Trks	949	41.3	46.7	2706	45.7	50.8
	ALL	32232	45.6	50.8	68864	49.4	54.8

Legend:
- Runs not made at this speed
- Runs corresponding to 85th percentile speed

Connector:
IH 610 EB TO IH 45 NB

Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
	30 mph Test Runs			35 mph Test Runs			40 mph Test Runs		
manual ball bank reading:	0	0	0	-7	-7	-7	-10	-10	-10
average of ball bank readings:			0.00			-7.00			-10.00
number of 250ms speed observations	0	0	0	129	129	129	108	111	114
number of 250ms periods over 10 degrees	0	0	0	1	2	0	8	5	6
number of observations over 10 degrees	0	0	0	1	2	0	8	5	6
percent of time over 10 degrees	0%	0%	0%	1%	2%	0%	7%	5%	5%
average number of 250ms periods over 10 deg			0.00			1.00			6.33
average time (sec) in curve over 10 deg			0.00			0.25			1.58
average max ball bank reading			0.0			-7.0			-10.0
maximum 250ms reiker reading			0.0			-11.2			-12.0

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-7	-8	-8	-10	-10	-10
average of ball bank readings:			0.00			-7.67			-10.00
number of 250ms speed observations	0	0	0	130	130	130	118	118	118
number of 250ms periods over 10 degrees	0	0	0	6	0	0	3	2	2
number of observations over 10 degrees	0	0	0	6	0	0	3	2	2
percent of time over 10 degrees	0%	0%	0%	5%	0%	0%	3%	2%	2%
average number of 250ms periods over 10 deg			0.00			2.00			2.33
average time (sec) in curve over 10 deg			0.00			0.50			0.58
average max ball bank reading			0.0			-7.7			-10.0
maximum 250ms reiker reading			0.0			-13.5			-11.3

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-5	-6	-6	-10	-8	-9
average of ball bank readings:			0.00			-5.67			-9.00
number of 250ms speed observations	0	0	0	135	135	124	127	127	127
number of 250ms periods over 10 degrees	0	0	0	5	11	4	21	15	16
number of observations over 10 degrees	0	0	0	5	11	4	21	15	16
percent of time over 10 degrees	0%	0%	0%	4%	8%	3%	17%	12%	13%
average number of 250ms periods over 10 deg			0.00			6.67			17.33
average time (sec) in curve over 10 deg			0.00			1.67			4.33
average max ball bank reading			0.0			-5.7			-9.0
maximum 250ms reiker reading			0.0			-15.2			-16.3

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	-5	-5	-5	-7	-8	-8	-8	-9	-9
average of ball bank readings:			-5.00			-7.67			-8.67
number of 250ms speed observations	125	125	123	114	119	119	110	110	110
number of 250ms periods over 10 degrees	0	0	0	0	0	3	2	4	4
number of observations over 10 degrees	0	0	0	0	0	3	2	4	4
percent of time over 10 degrees	0%	0%	0%	0%	0%	3%	2%	4%	4%
average number of 250ms periods over 10 deg			0.00			1.00			3.33
average time (sec) in curve over 10 deg			0.00			0.25			0.83
average max ball bank reading			-5.0			-7.7			-8.7
maximum 250ms reiker reading			-8.3			-10.6			-13.4

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve			Middle of First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610EB TO IH 45 NB	Pass Veh	61941	56.2	63.4	0	0.0	0.0	56029	40.2	45.8
	Rigid Veh	2417	54.7	62.3	0	0.0	0.0	2421	38.9	45.0
	Hvy Trks	1157	50.6	59.3	0	0.0	0.0	1723	34.6	40.4
	ALL	65515	56.1	63.1	0	0.0	0.0	60173	40.0	45.7

Legend:
- Runs not made at this speed (grey)
- Runs corresponding to 85th percentile speed (yellow)

Connector:
IH 610 EB TO IH 45 NB

Passenger Car	45 mph Test Runs 45-1	45-2	45-3	50 mph Test Runs 50-1	50-2	50-3	55 mph Test Runs 55-1	55-2	55-3
manual ball bank reading:	-13	-12	-13	-17	-16	-18	0	0	0
average of ball bank readings:			-12.67			-17.00			0.00
number of 250ms speed observations	105	105	105	93	99	0	0	0	0
number of 250ms periods over 10 degrees	34	24	35	55	56	0	0	0	0
number of observations over 10 degrees	34	24	35	55	56	0	0	0	0
percent of time over 10 degrees	32%	23%	33%	59%	57%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			31.00			37.00			0.00
average time (sec) in curve over 10 deg			7.75			9.25			0.00
average max ball bank reading			-12.7			-17.0			0.0
maximum 250ms reiker reading			-16.0			-19.3			0.0

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-13	-12	-16	-16	0	0	0	0
average of ball bank readings:			-12.67			-16.00			0.00
number of 250ms speed observations	102	105	105	95	95	0	0	0	0
number of 250ms periods over 10 degrees	47	43	43	65	72	0	0	0	0
number of observations over 10 degrees	47	43	43	65	72	0	0	0	0
percent of time over 10 degrees	46%	41%	41%	68%	76%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			44.33			45.67			0.00
average time (sec) in curve over 10 deg			11.08			11.42			0.00
average max ball bank reading			-12.7			-16.0			0.0
maximum 250ms reiker reading			-15.2			-17.0			0.0

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-12	-12	-12	0	0	0	0	0	0
average of ball bank readings:			-12.00			0.00			0.00
number of 250ms speed observations	112	119	121	0	0	0	0	0	0
number of 250ms periods over 10 degrees	38	40	40	0	0	0	0	0	0
number of observations over 10 degrees	38	40	40	0	0	0	0	0	0
percent of time over 10 degrees	34%	34%	33%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			39.33			0.00			0.00
average time (sec) in curve over 10 deg			9.83			0.00			0.00
average max ball bank reading			-12.0			0.0			0.0
maximum 250ms reiker reading			-20.3			0.0			0.0

18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	0	0	0	0	0	0	0	0	0
average of ball bank readings:			0.00			0.00			0.00
number of 250ms speed observations	0	0	0	0	0	0	0	0	0
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			0.0
maximum 250ms reiker reading			0.0			0.0			0.0

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve Samples	Average	85%'tile	Middle of Second Curve Samples	Average	85%'tile
IH 610 EB TO IH 45 NB	Pass Veh	0	0	0	0	0	0
	Rigid Veh	0	0	0	0	0	0
	Hvy Trks	0	0	0	0	0	0
	ALL	0	0	0	0	0	0

Legend:
Runs not made at this speed
Runs corresponding to 85th percentile speed

Connector:
IH 45 SB to IH 610 WB

Passenger Car	30 mph Test Runs 30-1	30-2	30-3	35 mph Test Runs 35-1	35-2	35-3	40 mph Test Runs 40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	6	5	6
average of ball bank readings:			0.00			0.00			5.67
number of 250ms speed observations	0	0	0	0	0	0	115	115	109
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			5.7
maximum 250ms reiker reading			0.0			0.0			7.4

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	6	6	7
average of ball bank readings:			0.00			0.00			6.33
number of 250ms speed observations	0	0	0	0	0	0	130	130	130
number of 250ms periods over 10 degrees	0	0	0	0	0	0	0	0	0
number of observations over 10 degrees	0	0	0	0	0	0	0	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.00
average time (sec) in curve over 10 deg			0.00			0.00			0.00
average max ball bank reading			0.0			0.0			6.3
maximum 250ms reiker reading			0.0			0.0			6.5

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	0	0	0	8	6	7
average of ball bank readings:			0.00			0.00			7.00
number of 250ms speed observations	0	0	0	0	0	0	131	119	114
number of 250ms periods over 10 degrees	0	0	0	0	0	0	5	5	4
number of observations over 10 degrees	0	0	0	0	0	0	5	5	4
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	4%	4%	4%
average number of 250ms periods over 10 deg			0.00			0.00			4.67
average time (sec) in curve over 10 deg			0.00			0.00			1.17
average max ball bank reading			0.0			0.0			7.0
maximum 250ms reiker reading			0.0			0.0			13.3

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18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	6	7	7	8	8	8
average of ball bank readings:			0.00			6.67			8.00
number of 250ms speed observations	0	0	0	160	160	159	124	130	131
number of 250ms periods over 10 degrees	0	0	0	0	0	0	1	0	0
number of observations over 10 degrees	0	0	0	0	0	0	1	0	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	1%	0%	0%
average number of 250ms periods over 10 deg			0.00			0.00			0.33
average time (sec) in curve over 10 deg			0.00			0.00			0.08
average max ball bank reading			0.0			6.7			8.0
maximum 250ms reiker reading			0.0			8.7			10.7

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp Samples	Average	85%'tile	Prior to First Curve Samples	Average	85%'tile	Middle of First Curve Samples	Average	85%'tile
IH 45 N. SB TO IH 610 WB	Pass Veh	61902	44.3	53.4	37951	54.2	60.5	55047	51.0	56.9
	Rigid Veh	1857	51.9	66.8	4823	55.0	61.8	9031	51.6	57.7
	Hvy Trks	1771	42.8	52.1	809	50.2	56.4	1437	47.3	52.6
	ALL	65530	44.5	53.6	43583	54.2	60.8	65515	51.0	56.9

Legend:
- Runs not made at this speed
- Runs corresponding to 85th percentile speed

Connector:
IH 45 SB to IH 610 WB

Passenger Car	45 mph Test Runs 45-1	45-2	45-3	50 mph Test Runs 50-1	50-2	50-3	55 mph Test Runs 55-1	55-2	55-3
manual ball bank reading:	9	10	9	11	11	10	13	13	14
average of ball bank readings:			9.33			10.67			13.33
number of 250ms speed observations	105	105	105	95	95	95	89	89	89
number of 250ms periods over 10 degrees	1	2	0	12	11	8	31	27	31
number of observations over 10 degrees	1	2	0	12	11	8	31	27	31
percent of time over 10 degrees	1%	2%	0%	13%	12%	8%	35%	30%	35%
average number of 250ms periods over 10 deg			1.00			10.33			29.67
average time (sec) in curve over 10 deg			0.25			2.58			7.42
average max ball bank reading			9.3			10.7			13.3
maximum 250ms reiker reading			10.7			13.0			15.8

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	9.5	9	8	11	11	12	15	14	13
average of ball bank readings:			8.83			11.33			14.00
number of 250ms speed observations	113	121	120	104	104	103	106	108	108
number of 250ms periods over 10 degrees	0	0	0	3	9	9	33	33	36
number of observations over 10 degrees	0	0	0	3	9	9	33	33	36
percent of time over 10 degrees	0%	0%	0%	3%	9%	9%	31%	31%	33%
average number of 250ms periods over 10 deg			0.00			7.00			34.00
average time (sec) in curve over 10 deg			0.00			1.75			8.50
average max ball bank reading			8.8			11.3			14.0
maximum 250ms reiker reading			8.8			11.5			14.8

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	10	10	10	13	13	13	0	0	0
average of ball bank readings:			10.00			13.00			0.00
number of 250ms speed observations	114	96	100	96	96	107	0	0	0
number of 250ms periods over 10 degrees	10	16	11	26	23	27	0	0	0
number of observations over 10 degrees	10	16	11	26	23	27	0	0	0
percent of time over 10 degrees	9%	17%	11%	27%	24%	25%	0%	0%	0%
average number of 250ms periods over 10 deg			12.33			25.33			0.00
average time (sec) in curve over 10 deg			3.08			6.33			0.00
average max ball bank reading			10.0			13.0			0.0
maximum 250ms reiker reading			16.7			19.3			0.0

18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	9	10	11	0	0	0	0	0	0
average of ball bank readings:			10.00			0.00			0.00
number of 250ms speed observations	128	131	127	0	0	0	0	0	0
number of 250ms periods over 10 degrees	2	7	7	0	0	0	0	0	0
number of observations over 10 degrees	2	7	7	0	0	0	0	0	0
percent of time over 10 degrees	2%	5%	6%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			5.33			0.00			0.00
average time (sec) in curve over 10 deg			1.33			0.00			0.00
average max ball bank reading			10.0			0.0			0.0
maximum 250ms reiker reading			14.1			0.0			0.0

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve Samples	Average	85%'tile	Middle of Second Curve Samples	Average	85%'tile
IH 45 SB TO IH 610WB	Pass Veh	29573	53.9	60.3	29555	46.4	51.2
	Rigid Veh	7091	54.2	60.5	1109	46.3	51.2
	Hvy Trks	501	50.3	56.6	363	43.0	47.6
	ALL	37165	54.0	60.3	31027	46.3	51

Legend:
Runs not made at this speed
Runs corresponding to 85th percentile speed

Connector:
IH 610 SB to SH 225 EB

	30 mph Test Runs			35 mph Test Runs			40 mph Test Runs		
Passenger Car	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-8	-9	-9	-10	-10	-10
average of ball bank readings:			0.00			-8.67			-10.00
number of 250ms speed observations	0	0	0	88	88	88	76	76	76
number of 250ms periods over 10 degrees	0	0	0	0	0	0	3	3	1
number of observations over 10 degrees	0	0	0	0	0	0	3	3	1
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	4%	4%	1%
average number of 250ms periods over 10 deg			0.00			0.00			2.33
average time (sec) in curve over 10 deg			0.00			0.00			0.58
average max ball bank reading			0.0			-8.7			-10.0
maximum 250ms reiker reading			0.0			-8.3			-10.7

Sport Utility	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-7	-7	-8	-11	-10	-9
average of ball bank readings:			0.00			-7.33			-10.00
number of 250ms speed observations	0	0	0	83	83	83	73	74	74
number of 250ms periods over 10 degrees	0	0	0	0	0	0	7	2	0
number of observations over 10 degrees	0	0	0	0	0	0	7	2	0
percent of time over 10 degrees	0%	0%	0%	0%	0%	0%	10%	3%	0%
average number of 250ms periods over 10 deg			0.00			0.00			3.00
average time (sec) in curve over 10 deg			0.00			0.00			0.75
average max ball bank reading			0.0			-7.3			-10.0
maximum 250ms reiker reading			0.0			-8.2			-11.5

Dump Truck	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-8	-8	-8	-10	-10	-10
average of ball bank readings:			0.00			-8.00			-10.00
number of 250ms speed observations	0	0	0	87	87	87	76	76	76
number of 250ms periods over 10 degrees	0	0	0	4	3	4	8	6	9
number of observations over 10 degrees	0	0	0	4	3	4	8	6	9
percent of time over 10 degrees	0%	0%	0%	5%	3%	5%	11%	8%	12%
average number of 250ms periods over 10 deg			0.00			3.67			7.67
average time (sec) in curve over 10 deg			0.00			0.92			1.92
average max ball bank reading			0.0			-8.0			-10.0
maximum 250ms reiker reading			0.0			-14.2			-20.7

18-Wheeler	30-1	30-2	30-3	35-1	35-2	35-3	40-1	40-2	40-3
manual ball bank reading:	0	0	0	-8	-9	-9	-12	-11	-11
average of ball bank readings:			0.00			-8.67			-11.33
number of 250ms speed observations	0	0	0	82	81	79	70	74	70
number of 250ms periods over 10 degrees	0	0	0	1	1	1	8	6	5
number of observations over 10 degrees	0	0	0	1	1	1	8	6	5
percent of time over 10 degrees	0%	0%	0%	1%	1%	1%	11%	8%	7%
average number of 250ms periods over 10 deg			0.00			1.00			6.33
average time (sec) in curve over 10 deg			0.00			0.25			1.58
average max ball bank reading			0.0			-8.7			-11.3
maximum 250ms reiker reading			0.0			-10.2			-15.3

Measured Vehicle Speeds on Connector Ramps

CONNECTOR RAMP	Type of Vehicle	Approach to Ramp			Prior to First Curve			Middle of First Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610 SBTO SH 225 EB	Pass Veh	22007	63.1	71.9	14051	51.5	57.0	46940	49.5	54.9
	Rigid Veh	7029	65.8	74.1	1664	50.9	57.5	10466	48.7	54.4
	Hvy Trks	3216	60.0	67.1	1270	47.2	52.6	6451	45.4	50.8
	ALL	32252	63.4	71.9	16985	51.1	56.9	63857	48.9	54.5

Legend:
- Runs not made at this speed (gray)
- Runs corresponding to 85th percentile speed (yellow)

Connector:
IH 610 SB to SH 225 EB

	45 mph Test Runs			50 mph Test Runs			55 mph Test Runs		
Passenger Car	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	0	-13	-13	-14	-15	-16	0	0	0
average of ball bank readings:			-13.00			-15.00			0.00
number of 250ms speed observations	0	75	75	67	67	67	0	0	0
number of 250ms periods over 10 degrees	0	12	22	41	44	39	0	0	0
number of observations over 10 degrees	0	12	22	41	44	39	0	0	0
percent of time over 10 degrees	0%	16%	29%	61%	66%	58%	0%	0%	0%
average number of 250ms periods over 10 deg			11.33			41.33			0.00
average time (sec) in curve over 10 deg			2.83			10.33			0.00
average max ball bank reading			-13.0			-15.0			0.0
maximum 250ms reiker reading			-12.4			-15.9			0.0

Sport Utility	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-12	-13	-14	-16	-16.5	-15	0	0	0
average of ball bank readings:			-13.00			-15.83			0.00
number of 250ms speed observations	68	68	68	66	66	66	0	0	0
number of 250ms periods over 10 degrees	29	32	29	44	43	38	0	0	0
number of observations over 10 degrees	29	32	29	44	43	38	0	0	0
percent of time over 10 degrees	43%	47%	43%	67%	65%	58%	0%	0%	0%
average number of 250ms periods over 10 deg			30.00			41.67			0.00
average time (sec) in curve over 10 deg			7.50			10.42			0.00
average max ball bank reading			-13.0			-15.8			0.0
maximum 250ms reiker reading			-15.1			-17.2			0.0

Dump Truck	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-13	-13	0	0	0	0	0	0
average of ball bank readings:			-13.00			0.00			0.00
number of 250ms speed observations	68	68	67	0	0	0	0	0	0
number of 250ms periods over 10 degrees	22	23	22	0	0	0	0	0	0
number of observations over 10 degrees	22	23	22	0	0	0	0	0	0
percent of time over 10 degrees	32%	34%	33%	0%	0%	0%	0%	0%	0%
average number of 250ms periods over 10 deg			22.33			0.00			0.00
average time (sec) in curve over 10 deg			5.58			0.00			0.00
average max ball bank reading			-13.0			0.0			0.0
maximum 250ms reiker reading			-18.2			0.0			0.0

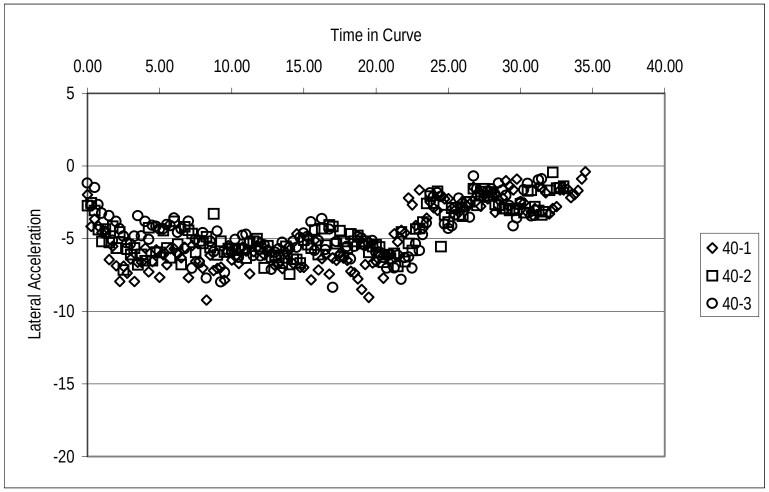
18-Wheeler	45-1	45-2	45-3	50-1	50-2	50-3	55-1	55-2	55-3
manual ball bank reading:	-13	-12	-13	-15	-14	-15	0	0	0
average of ball bank readings:			-12.67			-14.67			0.00
number of 250ms speed observations	69	67	70	63	62	64	0	0	0
number of 250ms periods over 10 degrees	16	18	15	34	22	32	0	0	0
number of observations over 10 degrees	16	18	15	34	22	32	0	0	0
percent of time over 10 degrees	23%	27%	21%	54%	35%	50%	0%	0%	0%
average number of 250ms periods over 10 deg			16.33			29.33			0.00
average time (sec) in curve over 10 deg			4.08			7.33			0.00
average max ball bank reading			-12.7			-14.7			0.0
maximum 250ms reiker reading			-16.2			-17.3			0.0

Measured Vehicle Speeds on Connector Ramps

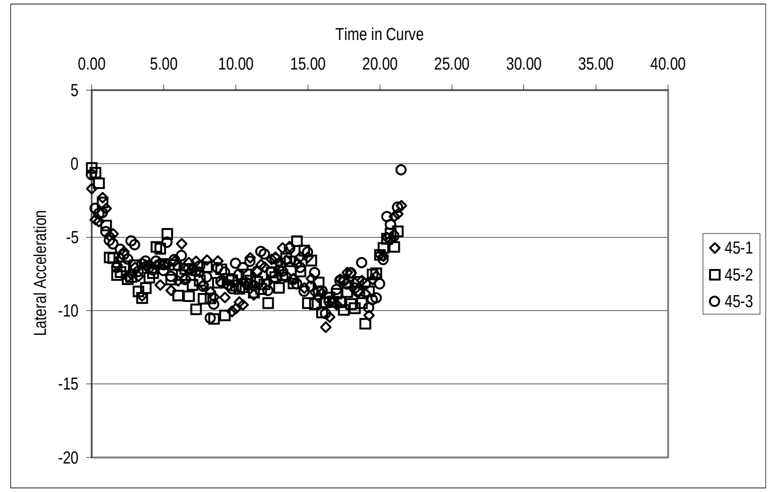
CONNECTOR RAMP	Type of Vehicle	Prior to Second Curve			Middle of Second Curve		
		Samples	Average	85%'tile	Samples	Average	85%'tile
IH 610 SB TO SH 225 EB	Pass Veh	0	0	0	0	0	0
	Rigid Veh	0	0	0	0	0	0
	Hvy Trks	0	0	0	0	0	0
	ALL	0	0	0	0	0	0

Legend:
Runs not made at this speed
Runs corresponding to 85th percentile speed

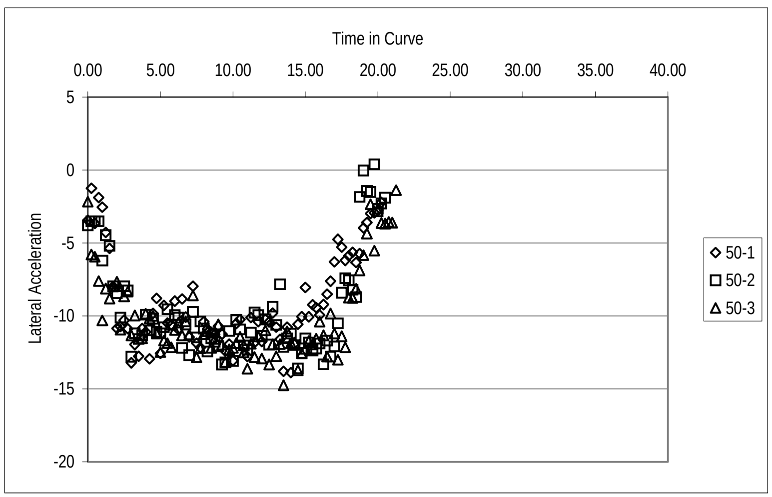
DIGITAL BALL-BANK GRAPHS
US 290 EB TO IH 610 EB
(TYPICAL OF ALL CURVES)



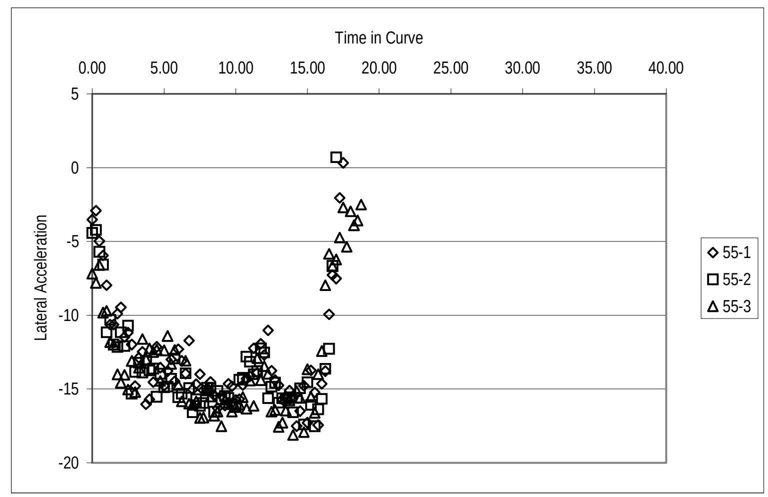
Speed in Curve: 40 mph



Speed in Curve: 45 mph

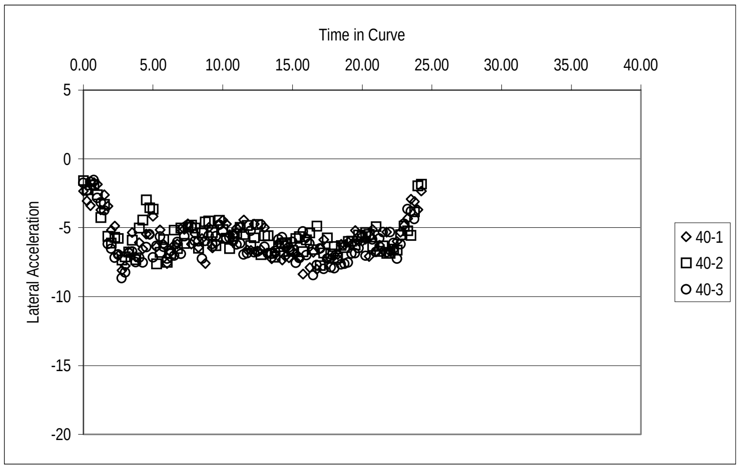


Speed in Curve: 50 mph

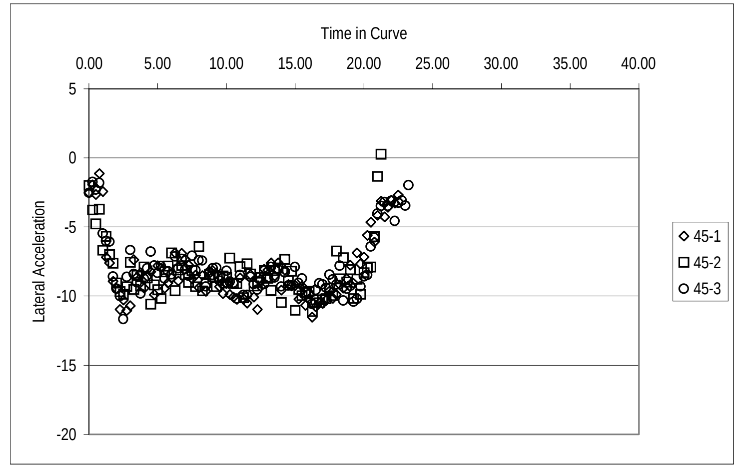


Speed in Curve: 55 mph

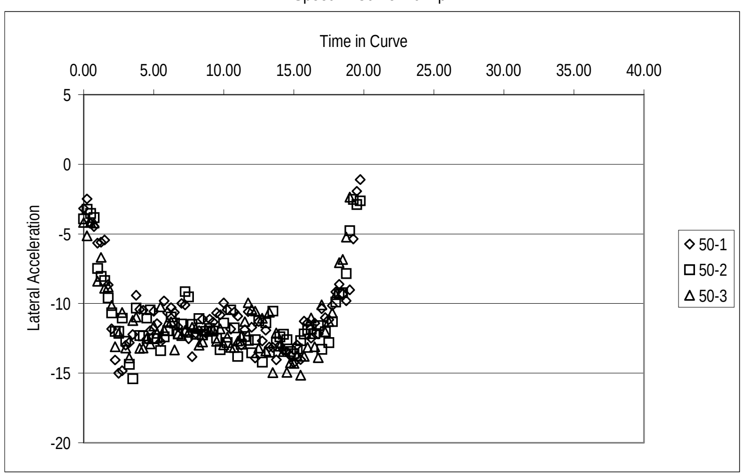
Lateral Acceleration (as read by Reiker Electronic Ball-Bank Indicator-degrees) versus Time In Curve (seconds)
Passenger Car - US 290 Eastbound to IH 610 Eastbound Freeway-to-Freeway Connector Ramp



Speed in Curve: 40 mph

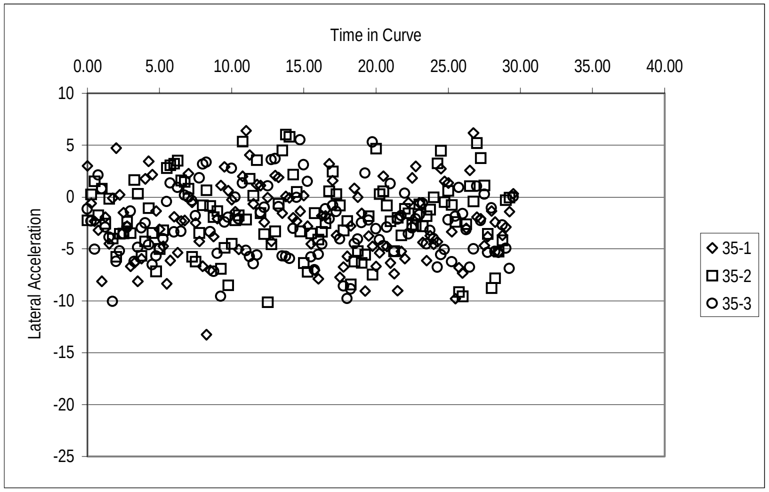


Speed in Curve: 45 mph

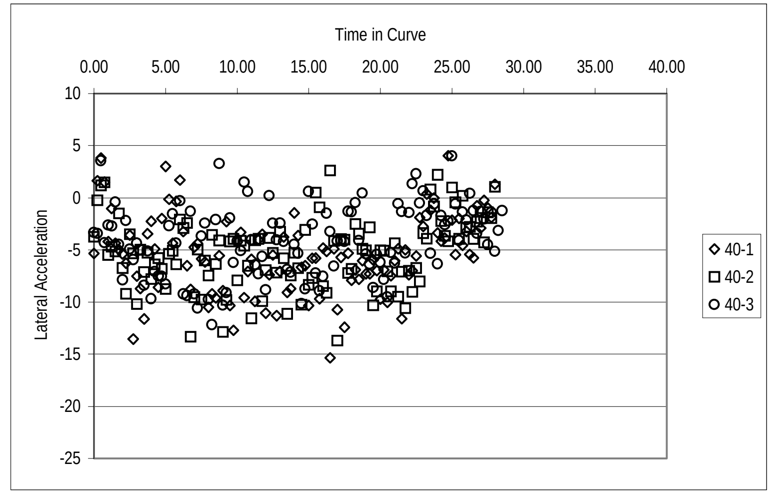


Speed in Curve: 50 mph

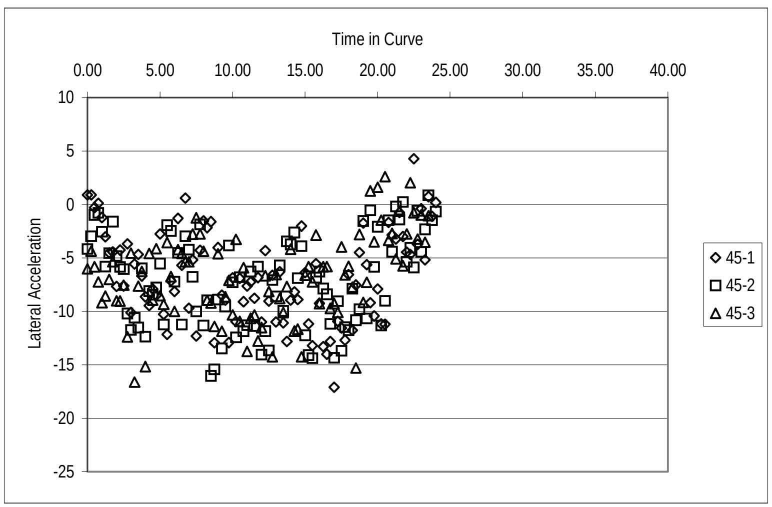
Lateral Acceleration (as read by Reiker Electronic Ball-Bank Indicator-degrees) versus Time In Curve (seconds)
Sport-Utility Vehicle - US 290 Eastbound to IH 610 Eastbound Freeway-to-Freeway Connector Ramp



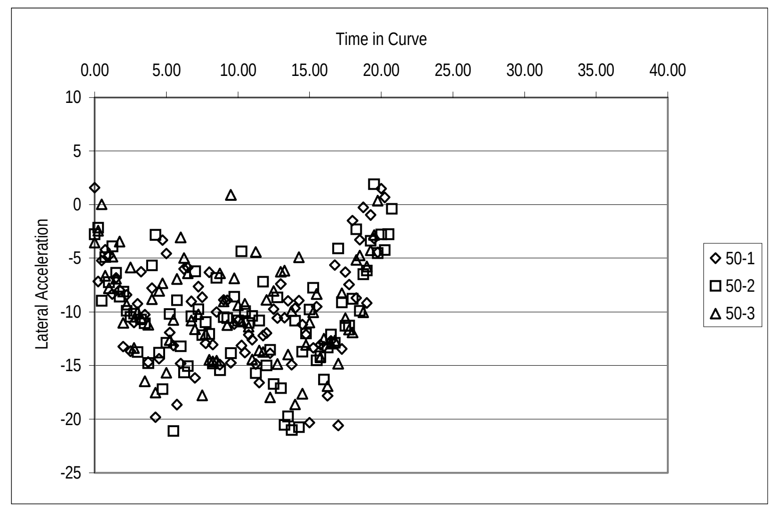
Speed in Curve: 35 mph



Speed in Curve: 40 mph

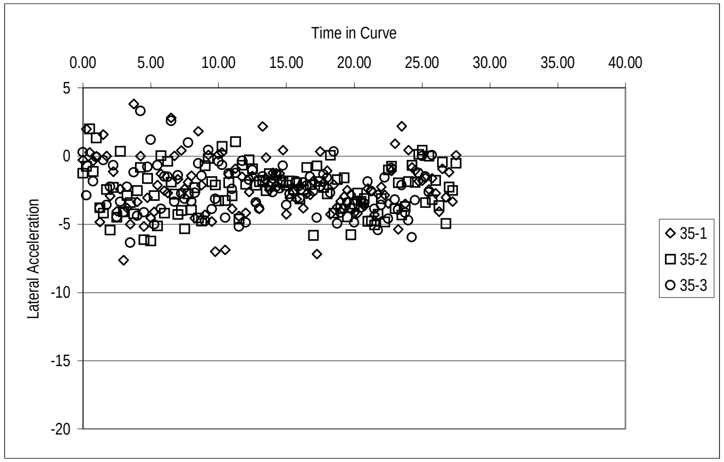


Speed in Curve: 45 mph

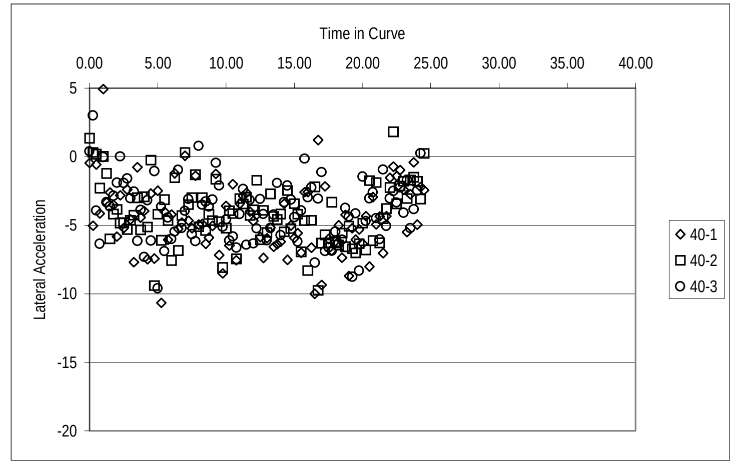


Speed in Curve: 50 mph

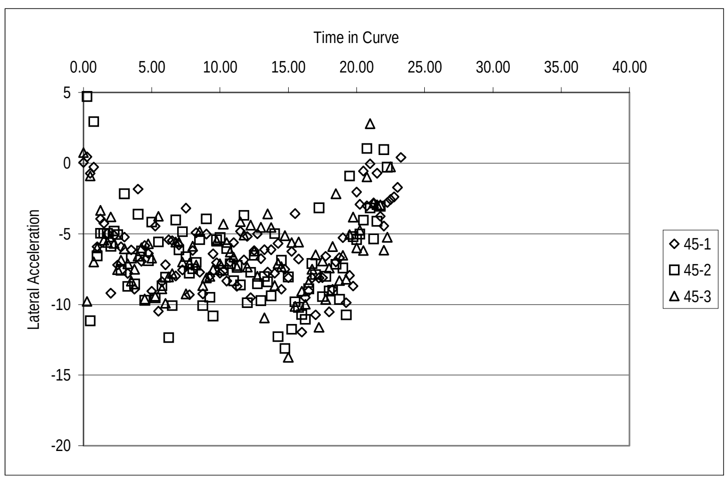
Lateral Acceleration (as read by Reiker Electronic Ball-Bank Indicator-degrees) versus Time In Curve (seconds)
Dump Truck - US 290 Eastbound to IH 610 Eastbound Freeway-to-Freeway Connector Ramp



Speed in Curve: 35 mph



Speed in Curve: 40 mph



Speed in Curve: 45 mph

Lateral Acceleration (as read by Reiker Electronic Ball-Bank Indicator-degrees) versus Time In Curve (seconds)
18-Wheeler - US 290 Eastbound to IH 610 Eastbound Freeway-to-Freeway Connector Ramp