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Development and analysis of vehicle trajectories and speed profiles along horizontal curves

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Development and analysis of vehicle trajectories and speed profiles along horizontal curves

by

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DEDICATION

This document is dedicated to my parents and sister, extended family, friends, current mentors, coauthors, and graduate student colleagues on the third and fourth floors of Town Engineering Building.

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ABSTRACT

Vehicle crashes at horizontal curves account for 42 percent of lane departure crashes on roadways. The risks of crashes on horizontal curves have been reported to be about 1.4 to 5 times greater than that for tangent sections. Twenty-five percent of the total number of fatal crashes in the United States occurred on horizontal curves. Driver error due to situational complexity has been cited as major factors run-off-road or cross-centerline crashes at horizontal curves. Major causes of crashes on horizontal curves include abrupt changes in vehicle operating speed and failure to maintain proper lane position within the horizontal curve, as well as other factors. The literature documents many investigations of these factors. This dissertation presents a methodology to develop and analyze vehicle trajectories and speed profiles at horizontal curves. Key research objectives included evaluating appropriate methods and equipment to gather and analyze data for individual vehicles, developing statistical models to predict vehicle speed and lateral position, and comparing speeds and lateral positions of different types of vehicles as they traverse a horizontal curve.

To compare the accuracy and efficiency of commonly used traffic data collection methods, pneumatic road tubes and video data recording systems were used to gather data related to vehicle speed and lateral position. After initial tests on a closed parking lot, a more extensive experiment was conducted on a horizontal curve that was closed to traffic. The setup for this had seven stations with each station consisting of a set of pneumatic tubes placed in a z-configuration, and a trailer with the video equipment placed on the roadway shoulder. The video equipment consisted of 4 cameras: 2 cameras on a mast at about 35 feet above the roadway and 2 cameras placed on the trailer at a height of about 7 feet above the roadway surface. Observations were made during day time and night time based on capabilities afforded by the equipment. Potential impacts of the data collection equipment on driver behavior were also examined. A repeated measures analysis of variance was used to compare vehicle trajectories and speed profiles to evaluate the accuracy of the measurements. The results from this study showed that pneumatic road tubes could be used to obtain vehicle speeds, lateral positions and trajectories along horizontal curves at a high degree of accuracy in a cost effective and time efficient manner. The presence of the trailer with the video recording equipment seemed to affect driver behavior. Also, it was felt that 7 stations (with z-configurations) may affect driver behavior. So, fewer stations would minimize such impacts on driver behavior.

In the second study, vehicle, roadway, and environmental factors at two horizontal field locations are analyzed (one urban and one rural). An OLS model is developed to predict vehicle speed and lateral position along a curve based on a vehicle's curve entry speed and lateral position.

Variables such as direction of travel, time of day, type of vehicle, pavement condition (wet/dry), and opposing vehicles are found to significantly influence vehicle trajectories and speeds.

The third study of this dissertation presents an exploratory analysis of vehicle trajectories and speed profiles. Trajectory data from both curve sites primarily reveal cutting or normal pathways. The analyses show that deviations vehicle speeds and lateral position varied as drivers traverse the curve, and that these changes were statistically significant at the 95 percent confidence level. Further, the means of the maximum speed and lateral deviation of passenger cars were greater than those for heavy vehicles along the horizontal curves.

Key Words: horizontal curve safety; lane and speed deviation along horizontal curves; vehicle speed and lateral position models for horizontal curves; vehicle trajectories; speed profiles

CHAPTER 1. INTRODUCTION

1.0 Background / Magnitude of the Problem

Horizontal curves are an important and necessary aspect of roadway systems. Smith et al. (1983) estimated there were over 10 million rural two-lane curves in the United States in 1983. Horizontal curves are segments of roadway that connect two tangent segments. As illustrated in FIGURE 1-1, rural curves typically consist of two paved travel lanes with or without shoulders. Generally, passing is not allowed on such horizontal curves, traffic volumes are low, and low-cost safety measures are used to help communicate to the driver the change in alignment prior to or within the curve. Examples of low-cost safety measures include advance signage, chevron alignment signs, paved shoulders, centerline and shoulder rumble strips, and edge line pavement markings.

FIGURE 1-1 Rural horizontal curve on State Highway 510 in Washington outside of the Nisqually Indian Community with paved shoulders and chevron alignment signs

Historically, research into crash trends has shown that horizontal curves, particularly in rural settings, are associated with higher numbers of severe crashes and have been considered a safety problem for many years (Torbic et al., 2004). Often, these crashes are shown to be roadway departure crashes in which the vehicle departs its traveled lane either by crossing the center line or by leaving the roadway via the shoulder. Torbic et al. (2004) reported that the roadway departure crash rates on horizontal curves are about three times higher than on tangent sections, and 25 percent of the fatal crashes in the United States in 2004 occurred on sharp horizontal curves, mostly on two-lane rural highways.

American Association of State Highway and Transportation Officials (AASHTO) reported that 42 percent of lane departure crashes occur on curves, and 50 percent of those are in rural areas (AASHTO, 2008). Additionally, Torbic et al. (2004) reported that about 76 percent of curve-related fatal crashes involve single-vehicle run-off-road events, and 11 percent involve multi-vehicle cross-centerline head-on crashes. Farmer and Lund (2002) investigated rollover crashes using the Fatality Analysis Reporting System (FARS) between 1995 and 1998 in three states and found using an odds ratio that rollover risk was highest at horizontal curves, although urban curves posed a high risk as well with younger drivers and light trucks. McGwin and Brown (1999) also found that older drivers were less likely to have crashes on level, down-grade, or up-grade horizontal curves.

The Federal Highway Administration (FHWA) reported that crashes on horizontal curves stem from a combination of factors related to the driver that can lead to a vehicle drifting off the road or departing the roadway (Staplin et al., 2001):

- Inability to negotiate curves with a superelevation greater than 3 degrees
- Exceeding the design speed of the horizontal curve and creating a dangerous trajectory through the curve
- Inability to adjust speed prior to or through the curve
- Lack of awareness of the sudden change in roadway geometry

The Michigan Department of Transportation (1979) undertook a study to investigate tree–vehicle crashes at rural horizontal curves in Michigan. They found that 77 percent of the 10,067 tree–vehicle crashes from 1971 to 1976 occurred at horizontal curves. The Michigan Department of Transportation developed FIGURE 1-2 based on the crash data and vehicle direction of travel. As shown, the highest number of fatal crashes and total number of crashes occurred on the outside lane when vehicles departed the roadway towards the shoulder. The least number of reported fatalities and crashes were reported for vehicles that were traveling on the inside lane and departed the roadway towards the shoulder. However, it was found that cross-centerline roadway departure crashes also accounted for a high proportion of the total number of crashes.

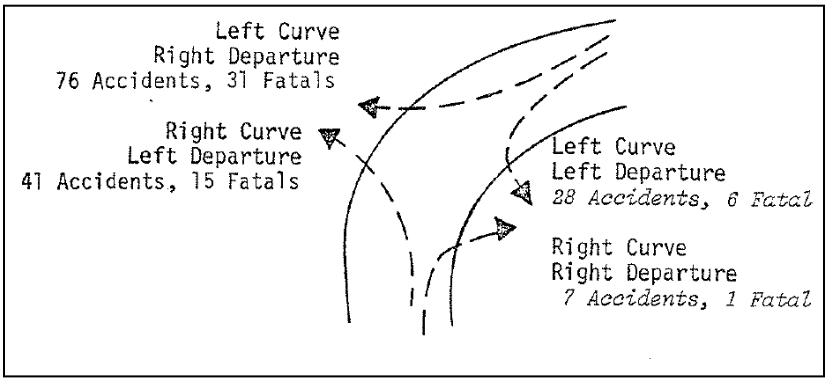
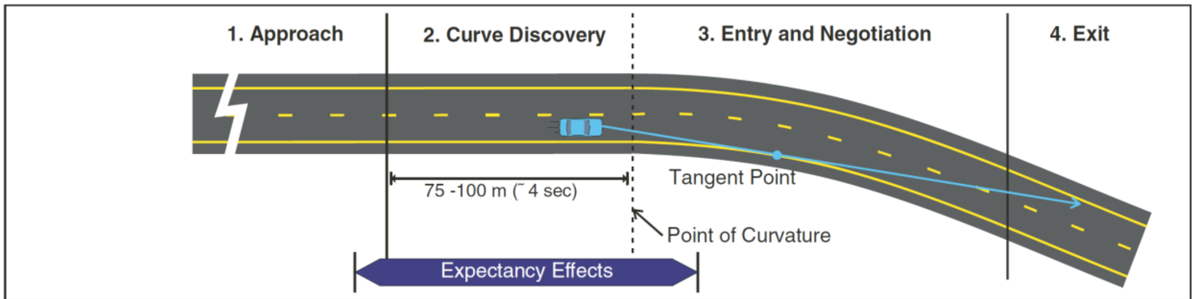


FIGURE 1-2 Fatalities and crashes at horizontal curves in Michigan (1971 to 1976) with respect to direction (Michigan Department of Transportation, 1979)

The study conducted by the Michigan Department of Transportation illustrated that roadway departure crashes are a serious problem on rural horizontal curves, and that the direction the vehicle negotiates the curve has an influence on the percentage of crashes. Other authors have stated that weather and traffic conditions may also affect crash outcomes on horizontal curves (Shankar, Mannering, and Barfield, 1995; Milton and Mannering, 1998). Milton and Mannering (1996) also reported that driver behavior on two-lane rural highways differs from behavior on other highway facilities.

To further understand the driver behavior of negotiating a horizontal curve, the National Cooperative Highway Research Program (NCHRP) Report 600B "Human Factors Guidelines for Roadway Systems" investigated the steps and key components of such movements (Campbell et al., 2008). Campbell et al. (2008) divided negotiating a horizontal curve into four distinct sections. The approach section allows drivers to locate the curve through visual cues such as curve warning signs, speed plaques, and pavement markings. The curve discovery section requires drivers to identify the curve, roadway conditions, and appropriate speed and adjust lateral position. The entry and negotiation section requires drivers to keep within the lane, watch for oncoming vehicles, and make adjustments to the speed based on lateral acceleration. Finally, the exit section allows drivers to transition into the tangent section and adjusts lane position once more.

As shown in FIGURE 1-3, the point of entry and negotiating the curve has the highest visual demand and requires judgment from the driver. The driver's actions here have a direct relationship to how the driver controls lateral placement and speed prior to, during, and at the exit of the horizontal curve. Several research studies investigated horizontal curve entry and exit transitions and change in vehicle lateral positions from the upstream tangent (Emmerson, 1969; Segal and Banney, 1980). These studies reported observing many vehicles moving laterally within the lane by 2 feet or greater on sharp curves between the point of curvature (PC) and the center of the curve (CC). This movement sets up a vehicle to potentially traverse the horizontal curve in an undesirable trajectory towards the shoulder or centerline.



	1. Approach	2. Curve Discovery	3. Entry and Negotiation	4. Exit
Key Driving Tasks	1.1 Locate bend 1.2 Get available speed information from signage 1.3 Make initial speed adjustments	2.1 Determine curvature 2.2 Assess roadway conditions 2.3 Make additional speed adjustments 2.4 Adjust path for curve entry	3.1 Adjust speed based on curvature/lateral acceleration 3.2 Maintain proper trajectory 3.3 Maintain safe lane position	4.1 Accelerate to appropriate speed 4.2 Adjust lane position
Visual Demands & Info Sources	**Low/Flexible** • Primarily environment driven	**Med. Increasing to High** • Curvature perception cues • Observing roadway conditions	**High** • Most fixations to tangent point	**Low** • Vehicle position information
Effective Info Modes	• Advisory/message signs	• Non-verbal (e.g., chevrons) and direct info (e.g., delineators)	• Direct info only (lane markings; raised markers)	• No constraints
Vehicle-Control Demands	• None	• Anticipatory positioning • Curve cutting	• Continuous heading adjustments	• Lane position adjustments
Primary Speed Influences	• Previous roadway elements & signage	• Expectations & curvature cues	• Expectations & lateral acceleration	• Posted speed or expectations

FIGURE 1-3 Horizontal curve segments, associated driving tasks, and identified constraints (Campbell et al., 2008)

As previously mentioned, the most critical step in curve negotiation occurs around the point of curvature in which the driver must make an appropriate decision in a matter of seconds regarding the vehicle speed and lateral placement within the lane. Stimpson et al. (1977) identified lateral placement and speed as the best indicators for assessing driver behavior on horizontal curves. They also recommended in the same study that data should be collected at the following locations: (1) in advance of the curve, (2) at the point of curvature, (3) at the center of the curve, and (4) at the point of tangency (PT). However, Terhune and Parker (1986) reported that annual average daily traffic (AADT) and degree of curvature were excellent indicators as well, based on a multiple regression analyses.

1.1 Research Objectives

The overall goal of this research is to support development of strategies, programs, policy, or countermeasures which aim to reduce the number of fatal and severe crashes at horizontal curves. While considerable research related to two-lane horizontal curves has been conducted, gaps in the body of knowledge exist limiting the extent of understanding of the complicated relationships between the driver, vehicle, roadway, and the environment. These relationships lead to actions taken by the driver resulting in either a successful or unsuccessful horizontal curve negotiation. This research is intended to answer specific questions to advance horizontal curve safety. This dissertation presents an exploratory analysis to answer the following research questions, which are the objectives of this research:

Research Question 1 / Paper 1: Vehicle Data Collection Proof of Concept Study	**How to acquire key data, in a cost effective manner with a desired level of accuracy, to develop vehicle trajectories and speed profiles along horizontal curves?**

A vehicle trajectory is the defined path a vehicle takes through a horizontal curve and is determined by projecting its known lateral position in the lane from predetermined stations. For this study, the distance from a vehicle's passenger-side front tire to the edge of the travel lane is defined as the vehicle's lateral position. Similarly, a vehicle's speed profile is defined by its speed along its trajectory and is determined by projecting its observed speed from the same predetermined stations along the horizontal curve. Key variables to answer research question one are:

- Lateral distance: measurement from the front passenger-side tire of vehicles to the edge of the travel lane at each station along the horizontal curve.
- Speed: measurement of vehicle speed at each station along the horizontal curve.

The first objective of this dissertation is to evaluate possible equipment used in transportation engineering practice that can collect vehicle lateral distance and speed measurements. Equipment selected for evaluation are pneumatic road tubes setup in a z-configuration and digital Autoscope video cameras with a TerraVision Rack video analysis unit housed in a video surveillance trailer. A series of closed and open course studies are proposed to evaluate the equipment. Closed course studies will be conducted in a parking lot or city street closed to public travel with a test vehicle, while open course studies will be conducted on a horizontal curve open to public travel. Secondary questions to be answered by these proofs of concept tests include:

- How does the accuracy of vehicle lateral distance measurements from the pneumatic road tubes and digital video compare to real world measurements of vehicle lateral distance?

- How does the accuracy of vehicle speed measurements from the automated video speed extraction software compare to the pneumatic road tube speed measurements?
- What is the relative level of effort required to reduce, process, clean, and verify the collected data from the different collection methods?
- Does the visibility of the data collection equipment in the field affect driver behavior?
- Are the overall mean vehicle trajectories and speed profiles between measurement methods and time of day statistically equivalent?

Secondary variables needed for the open-course study include: the time of day when daylight and darkness (nighttime) occur and when the video surveillance trailer and road tubes are present at the curve site.

The outcomes of this research are expected to add to the existing body of knowledge regarding vehicle operational data collection. The confirmation of accuracy, data reduction time, and cost-effectiveness of such data collection methodologies are critically important to other areas of transportation research including the Strategic Highway Research Program 2 (SHRP2), countermeasure effectiveness, work zone safety research, traffic calming applications, and bicycle lane applications.

Research Question 2 / Paper 2: Prediction Model Development	**What variables affect vehicle lateral positioning and speed along horizontal curves? Can vehicle lateral position and speed be predicted at stations through the curve to a certain degree of accuracy based on the vehicle's lateral position and speed at the initial point of curvature?**

The second objective of this dissertation is to investigate vehicle, traffic, and environmental variables which may affect vehicle trajectories and speed profiles through horizontal curves. Key factors that could potentially influence vehicle operations at horizontal curves will be evaluated. These include:

- Type of vehicle (motorcycle, passenger car, school bus and truck),
- Wheelbase length of the vehicle,
- Vehicle's lateral position and speed at the point of curvature,
- The presence and number of opposing vehicles encountered within the curve,

- If the vehicle is free-flowing or its positioned within a platoon of vehicles,
- Time of day,
- Whether the pavement was wet while the vehicle was within the horizontal curve,
- Location of the curve site (urban or rural),
- Direction of travel (inside or outside lane),

Field observations will be collected to evaluate the influence of these factors on vehicle trajectories and speed profiles. Data required include: extracted vehicle speed, lateral distance, vehicle type, number of axles, headway gap, wheelbase length, and time of day. To determine other key variables such as opposing lane vehicle presence, platoon position, and free-flowing conditions, time-stamped data will be extracted for each vehicle and reduced. Precipitation data to determine if the pavement is wet will be extracted from the Iowa Environmental Mesonet state-wide precipitation model.

A vehicle database will be created based on data collected in the field and a statistical model will be developed to predict vehicle lateral position and operating speed at stations along the horizontal curve based on curve entry point speed and lateral position. The resulting models will not include horizontal alignment geometric features. Therefore, the outcomes of this research should provide unique insight into predicting vehicle operations along a horizontal curve and serve as a framework for future research. Additionally, such a prediction tool can aid in the selection of appropriate countermeasures at horizontal curves and provide support to advance future driver assistance systems.

Research Question 3 / Paper 3: Trajectory and Speed Profile Projection and Descriptive Analyses	**How do vehicle trajectories and speed profiles vary along horizontal curves? Are there common “segments” along the horizontal curve where the vehicle’s maximum speed deviation and maximum lane deviation occur? Are these maximum deviations similar for both passenger cars and heavy vehicles?**

A key aspect to this dissertation research is the ability to project vehicle trajectories and speed profiles. The vehicle database developed under question two will provide individual vehicle lateral distance and speeds along the horizontal curve. Trajectories and speed profiles will be created for curve sites and both directions of travel using the mean values of both variables. Additionally, the 85^{th} percentile mean speed profiles will be projected. These mean vehicle trajectories, mean speed profiles, and 85th percentile speed profiles will be evaluated at urban and rural horizontal curve sites. Key variables required to achieve the first research objective under question three include:

- Mean lateral distance: the average lateral distance at each station along the horizontal curve calculated from observations in the vehicle database.
- Mean speed: the average vehicle speed at each station along the horizontal curve based on collected speeds in the vehicle database.
- 85th percentile speed: the 85th percentile speed at each station along the horizontal curve based on collected speeds in the vehicle database.
- Type of horizontal curve: urban or rural.

Similar to the prediction models developed under research question two, the projected mean vehicle trajectories, mean speed profiles, and 85th percentile mean speed profiles will provide overall insight into how vehicles traverse the horizontal curves. Additionally, this effort provides a relatively easy way to compare trajectories and speed profiles along curves and between lanes.

The second and third objectives under research question three provide are to further investigate vehicle trajectories and speed profiles. This is done by determining where the maximum speed deviation (positive or negative) and maximum lane deviation (positive or negative) occur along a horizontal curve and if these maximum deviation locations differ between passenger cars and heavy vehicles. Key variables evaluated to address the second and third objectives under research question three include lateral distance, speed, and:

- Interval: the distance between two successive data collection stations.
- Maximum lane deviation: the maximum positive or negative value found by calculating the difference of vehicle lateral distance between data collection stations. Positive lane deviation is the movement of the vehicle towards the centerline; negative lane deviation is the movement of the vehicle towards the edge line.
- Maximum speed deviation: the maximum positive or negative speed value found by calculating the difference of speed between data collection stations. Positive speed deviation indicates a vehicle's speed is increasing; a negative speed deviation indicates a vehicle's speed is decreasing.

- Passenger car and heavy vehicle: passenger cars will be coded as 1 in the vehicle database, heavy vehicles (school buses and trucks) will be coded either 2 or 3. Motorcycles are expected to be discarded from the analysis due to small samples at each location.

1.2 Dissertation Layout

This dissertation consist of six chapters, including the general introduction presented in this chapter which introduces horizontal curves, crash experience at horizontal curves in the United States, reasons for lane departure crashes at horizontal curves, and required tasks that must be performed by the driver at horizontal curves. Chapter two contains the literature review that discusses previous research conducted to develop speed prediction models at horizontal curves, vehicle lateral position models, and equipment used to collect vehicle operational data at horizontal curves. This chapter also includes a short discussion on previous research that has explored the effects of scientific equipment on driver behavior.

Chapter three presents a proof of concept study in which two types of equipment were evaluated to determine accuracy, amount of time needed to reduce data, whether vehicle trajectories and speed profiles could be constructed based on the selected equipment, and the effects of the equipment on driver behavior. These topics were explored using both open- and closed-course environments, and pneumatic road tubes and video were the selected equipment to be tested. Chapter four presents results of a study in which observations were made on vehicle operations on horizontal curves at two sites in Iowa. Data were collected in both the inside and outside lanes along information on the presence of opposing vehicle. The purpose of the study was to determine if a vehicle's lateral position and speed at the point of entry at a horizontal curve could be used to project its trajectory and speed profile by predicting the vehicles lateral position, speed, at subsequent stations along the curve.

Chapter five presents results of a study that utilizes the same dataset used in chapter four to investigate vehicle trajectories and speed profiles at horizontal curves. The maximum speed and lateral position data from each vehicle were examined and the location of the highest deviation for each vehicle was identified. The goal of the analysis was to explain how vehicles negotiate horizontal curves and report locations of significant change in operation. Chapter six provides conclusions, limitations, and recommendations for future research.

1.3 Attributions

Dr. Shashi Nambisan and Dr. Reginald Souleyrette, professors of civil engineering at Iowa State University and co-major advisors, aided in the organization, conceptual design, and execution of the research discussed in Chapters 3, 4, and 5; therefore, both listed as co-authors. Vanessa Kvam, Ph.D student in the Department of Statistics at Iowa State University is listed as the second author of Chapter 4 for her assistance in the construction and coding of the statistical models. Dr. Douglas Bonett, professor of statistics and psychology at Iowa State University, is listed as a co-author for chapter 4 for the guidance he provided for statistical analyses model development.

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CHAPTER 2. LITERATURE REVIEW

2.0 Overview

Two important vehicle operational characteristics related to drivers negotiating horizontal curves are vehicle operating speed and associated lateral placement within the lane. These have been cited by numerous research studies related to horizontal curve safety and driver behavior. The following three sections provide specific details of key research studies that have investigated and developed vehicle speed prediction models at or within the horizontal curve. In addition, cited studies have investigated vehicle lateral placement as an effectiveness measure, understanding overall driver behavior within a horizontal curve, and developing and classifying vehicle trajectories along horizontal curves. The studies also investigated significant factors such as roadway, traffic, and environmental factors that affect prediction models. However, these studies did not investigate how the number of crashes or the expected number of crashes relates to the developed models. The developed models were also to provide insights into design consistency of horizontal curves. Many of the prediction models have at least one geometric variable that is significant. Lastly, key items from the literature about different methods and potential biases with various types of equipment that have been used by researchers to collect vehicle operational data are also discussed.

2.1 Vehicle Speed Modeling on Horizontal Curves

A review of the literature identified a number of efforts related to modeling of vehicle operating speeds at horizontal curves over the past 30 years in the United States. Most studies have successfully developed a horizontal curve vehicle speed prediction model that have utilized data from only passenger cars, multiple locations, free-flowing conditions, and sample sizes between 30 and 100 at each site (Misaghi and Hassen, 2005). However, Nie and Hassen (2007) stated that speed prediction models developed utilizing smaller sample sizes, limited number of sites, and lack of cross-sectional data and should be used with caution. Studies have also investigated speed prediction models for light and heavy trucks on rural highway tangent sections and horizontal curves (Leisch and Leisch, 1977; Donnell et al., 2001). Important aspects of developing vehicle speed prediction models at horizontal curves include not only investigating driver behavior, but also verifying roadway design consistency, determining speed advisory signage, or measuring effectiveness.

Several significant factors have been identified by researchers that potentially influence the operational speed prior to, within, and after a horizontal curve (Oppenlander, 1966). Most of the literature expresses a vehicle's predicted speed (dependent variable) in terms of the 95^{th} or 85^{th} percentile speeds for a roadway design element, such as a horizontal curve, tangent section, transition zone, vertical curve, or a combination of roadway design elements. McLean (1981) and Nie and Hassen (2007) explained that determining the 85^{th} percentile speed on highway alignments can provide great insight into the design approach and consistency since the 85^{th} percentile speed will generally be higher than the design speed. The predicted vehicle speed specifically at a horizontal curve is typically a function of roadway or traffic characteristics that are collected in the field at predetermined sites. Constructed models included variables such as curve radius or degree of curvature, length of curve, the vertical alignment grade, superelevation, upstream and downstream tangent speeds, if the vehicle is a passenger car or truck, weather conditions, sight distance through the curve, the presence of an intersection, or lighting conditions.

However, Bonneson and Pratt (2009) also found that vehicle side friction factor and the vehicle's path radius through the curve were also significant in a developed speed prediction model. Also, many developed models assumed and were constructed around the idea that vehicle acceleration and deceleration only occur on the tangent sections, which has been shown to be inaccurate by recent research studies (Nie and Hassan, 2007; Figueroa Medina and Tarko 2004, 2005).

Figueroa Medina and Tarko (2004) stated that many of the models developed to predict vehicle speed at horizontal curves have been based on an ordinary least squares (OLS) linear regression. This is a standard linear method of representing the effects many parameters have on a dependent variable. The model is as follows:

$$V_i = \sum_k b_k X_{ik} + \varepsilon \tag{2-1}$$

Where V_i is the mean or specific vehicle percentile speed, individual speed estimate, or mean speed at site i; X_{ik} is the value of the k exogenous variable at site i; b_k is the regression parameters associated with variable k; and ε is the normally distributed disturbance term. Using an OLS model, five assumptions must hold true to prevent unbiased relationship between parameters and the dependent variable. These assumptions include no omitted variables, no serial correlation, heteroskedasticity, endogeneity, or multicollinearity (Washington, 2003). Statistical tests and or variable transformation can be utilized to prevent violation of these assumptions.

A limitation identified by Figueroa Medina and Tarko (2005) to using a linear regression is that the model cannot predict any other vehicle speed percentile than the one it was created for. However, modeling a speed percentile does not distinguish between mean speed factors and speed dispersion factors. Researchers have suggested that modeling the entire speed distribution and its variance might provide stronger prediction variable (Figueroa Medina and Tarko, 2005; Tarris et al., 1996, and Fitzpatrick et al., 2003). The following is a summary of the literature about how researchers have modeled vehicle speed in and around horizontal curves. Many of these studies have also investigated tangent sections and transition sections around the horizontal curve, but these results are not reported herein. Also reported for the selected studies are the significant variables found for data points within the horizontal curve and the utilized data collection methodologies.

Islam and Seneviratne (1994) developed speed prediction models to investigate data collection points located at the point of curvature (PC), center of the curve (CC), and point of tangency (PT) at eight two-lane rural horizontal curves in Utah. Sample sizes of 125 passenger car speeds were collected at each point using video capturing technology and a radar gun. The study sites selected exhibited grades less than five percent and no adverse alignment changes such as lane narrowing, pavement deterioration, or inadequate sight distance. The selected horizontal curve sites exhibited a degree of curvature between 4 and 28 degrees. OLS models were developed to predict 85th percentile vehicle speed (km/hr) for each of the three data collection points along the curve. Three models were developed for PC, CC, and PT points of the curve, and the only significant variable found was the degree of curvature that resulted in R-squared values between 0.98 and 0.99.

The authors concluded that vehicles decelerate and accelerate at different points within the horizontal curve and fail to keep a constant speed through the curve. The models also explained that the relationship between degree of curvature and vehicle speed is not always linear and that the lowest predicted 85th percentile speed occurred at the center of the curve for horizontal curves with a degree of curvature that was less than 6 degrees.

Lamm et al. (1990) developed a vehicle speed prediction model by investigating 322 horizontal curve sites in the state of New York. Speeds were collected for free-flowing vehicles by calculating the time each vehicle took to traverse a defined trap setup in the center of the horizontal curve using a stopwatch. Sample sizes from 120 to 140 vehicles were recorded at each curve location along with various roadway geometric characteristics. A multiple linear stepwise regression technique was used to determine significant variables in the OLS model. An overall 85th percentile vehicle speed prediction model found that the following parameters were significant at the 95 percent level of confidence: the degree of curvature (ranging from 0 to 27), lane width, shoulder with, and AADT. The model resulted in an R-squared value of 0.84 and sum of squares error value of 2.81 mph.

The authors then reduced the model by removing all parameters except degree of curvature to determine if a simpler form of the model could produce similar results and prediction power. The developed model resulted in an R-squared value of 0.78 and sum of squares error value of 3.25 mph.

They concluded that although extra parameters may help the regression model, minimal parameters may produce just as strong of a model.

Lamm et al. (1990) also investigated the effect of wet and dry pavements on vehicle speeds through horizontal curves. Out of the original 322 curve locations, 24 were selected for further analysis, and an additional speed study in wet pavement conditions was conducted at each of the locations. Speed distributions for dry and wet pavement conditions were plotted. The authors concluded that operating speed distributions for wet and dry pavement conditions were not significantly different and found that drivers do not change their speeds during adverse weather conditions.

In an extensive data collection effort conducted by Krammes et al. (1995), 138 horizontal curve sites and 78 approach sites were identified for analysis in five states (New York, Pennsylvania, Washington, Oregon, and Texas) that represented four regions of the United States. Speeds of free-flowing vehicles were collected using a radar gun at the midpoint of the approach tangent, midpoint of the horizontal curve, and midpoint of the departure tangent. The minimum tangent length was 800 feet. At least 50 paired vehicle speed measurements were taken at each site including both directions of travel. A paired speed measurement was defined as collecting multiple speed measurements for one vehicle. Twelve potential roadway and traffic parameters were tested and an OLS model was developed. The following parameters were found to be significant at the 95 percent level of confidence to predict the 85th vehicle speed percentile (km/hr) on the horizontal curve: degree of curvature, curve length (meters), and the curve deflection angle. The resulting model included an R-squared value of 0.90.

A follow-up study by Ottesen and Krammes (2000) using the same database confirmed the model developed by Krammes et al. (1995) and concluded that the developed model showed that predicted vehicle speeds on the inside and outside lanes at most curves were not statistically different. Investigating Krammes et al. (1995) model further, the parameter horizontal curve superelevation was investigated by Voigt and Krammes (1996). This parameter was found to be significant; however, it was only able to explain 1 to 2 percent of additional variability. McFadden et al. (2001) explored the same database created by Krammes et al. (1995) by utilizing back propagation artificial neural networks (ANN) for predicting 85th percentile vehicle operating speeds at horizontal curves instead of an OLS model. Two ANNs were developed from the vehicle speeds collected at 62 horizontal curve sites. Vehicle speed data from an additional 38 horizontal curve sites were used to validate the two models. One ANN model included only the parameter degree of curvature, while the second model included the parameters degree of curvature, length of curve, and deflection angle, which were the same significant parameters found by Krammes et al. (1995). Results of numerous iterations of both ANNs found the predictive power comparable to the OLS models developed by Krammes et al. The authors suggested ANNs could help future prediction models by predicting multiple outputs simultaneously.

Fitzpatrick et al. (2000) conducted an extensive study to validate and expand on research conducted by Krammes et al. (1995). One hundred seventy-six rural two-lane highway sites located in six states (Minnesota, New York, Pennsylvania, Oregon, Washington, and Texas) were selected for evaluation. One hundred and three sites were exclusively used to develop multiple prediction models, 73 sites were used to validate the models, and 21 sites were used for development of vehicle acceleration and deceleration models. A sample of 100 free-flowing vehicles in daylight hours were collected using either multiple radar meters or piezo strips at each horizontal curve. Trucks data were also collected at sites; however, speed prediction models were not developed due to the low percentage of trucks found at every horizontal curve site. It was mentioned by the authors that trucks exhibited a parallel speed behavior as passenger cars; however, the influence of vertical grade on trucks was larger than on passenger cars, and it would be somewhat difficult to quantify the performance of the truck to the load being carried. Several speed prediction models were developed to predict 85th percentile vehicle speeds for different alignment conditions, as shown in Table 2-1.

As shown in Table 2-1, each model represents the 85th percentile predicted passenger car speed at the midpoint of the horizontal curve assuming the vehicle is traveling at a constant speed through the curve. The inverse of the curve radius was the only statistically significant parameter for almost all of the models. Under equations 8 and 9, the predicted speed was also assumed to be the desired speed; this value was determined by the authors to be 100 km/hr, or the 85th percentile speed on the tangent section. R^2 is defined as the coefficient of determination and indicates the fraction of the variability in the dependent variable explained by the independent variables. The mean square error (MSE) compares the predicted value to observed values.

Fitzpatrick et al. (2000) also found in the same study that the predicted speed profile along a horizontal curve with a radius greater than 1,640 feet was similar to the predicted speed profile along a tangent section. The research study also concluded that it was possible to explain the effects of vertical grade on predicted operating speed through horizontal curves. In addition to the vertical grade parameter, other significant parameters included the inverse radius, length of the horizontal curve, length of the vertical curve, superelevation, grade, and the inverse of the rate of vertical curvature.

Table 2-1 Vehicle operating speed prediction models for passenger cars (Fitzpatrick et al. 2000)

Equation #	Alignment Condition	Formula	No. of Sites	R^2	MSE
1	Horizontal Curve on Grade: -9% ≤ G ≤ -4%	$V_{85} = 102.10 - \frac{3077.13}{R}$	21	0.58	51.95
2	Horizontal Curve on Grade: -4% ≤ G ≤ 0%	$V_{85} = 105.98 - \frac{3709.90}{R}$	25	0.76	28.46
3	Horizontal Curve on Grade: 0% ≤ G ≤ 4%	$V_{85} = 104.82 - \frac{3574.51}{R}$	25	0.76	24.34
4	Horizontal Curve on Grade: 4% ≤ G ≤ 9%	$V_{85} = 96.61 - \frac{2752.19}{R}$	23	0.53	52.54
5	Horizontal Curve Combined with Sag Vertical Curve	$V_{85} = 105.32 - \frac{3438.19}{R}$	25	0.92	10.47
6	Horizontal Curve Combined with Non-Limited Sight Distance Crest Vertical Curve (K > 43 m/%)	(see note 3)	13	n/a	n/a
7	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (K ≤ 43 m/%)	$V_{85} = 103.24 - \frac{3576.51}{R}$ (see note 4)	22	0.74	20.06
8	Sag Vertical Curve on Horizontal Tangent	$V_{85} =$ assume desired speed	7	n/a	n/a
9	Vertical Crest Curve with Non-Limited Sight Distance on Horizontal Tangent	$V_{85} =$ assume desired speed	6	n/a	n/a
10	Vertical Crest Curve with Limited Sight Distance on Horizontal Tangent	$V_{85} = 105.08 - \frac{149.69}{K}$	9	0.60	31.10

NOTES:
1. AC EQ# = Alignment Condition Equation Number
2. V85 = expected 85th percentile speed of passenger cars at curve midpoint (km/h)
   R = radius of horizontal curve (m)
   K = rate of vertical curvature (K)
   G = grade (%)
3. Use lowest of the speeds predicted from equations 1 or 2 (for the downgrade) and equations 3 or 4 (for the upgrade).
4. Check the speeds predicted from equations 1 or 2 (for the downgrade) and equations 3 or 4 (for the upgrade) and use the lowest speed. This will ensure that the speed predicted along the combined curve will not be better than if just the horizontal curve was present (i.e. that the inclusion of a limited sight distance crest vertical does not result in a higher speed)

Donnell et al. (2001) developed operating speed prediction models for trucks based on 13 rural two-lane highway sites in Pennsylvania that included a horizontal curve. Vehicle speed data were collected using three lidar meters, which tracked vehicles approaching, departing, and moving through the horizontal curve and continuously collected speed data. Site identified for analysis showed a high percentage of trucks, and their associated speed data were extrapolated from the data set which included passenger cars as well. Averages of 20 speed observations were collected at each site for each truck. Thirteen predefined data reduction points upstream, within, and downstream of the horizontal curve were determined with a maximum upstream and downstream distance of 656 feet away from the horizontal curve.

Vehicle speeds at each predefined data reduction point, along with collected roadway and traffic characteristics, were inputted into Two Lane Passing (TWOPAS) traffic modeling software. TWOPAS provides additional stochastic vehicle data by running simulations with different random number speeds and specified vehicle flow rates. If the maximum speed difference in the predicted 85^{th} percentile speed (km/hr) from TWOPAS exceeded ±4mph at each point the 85^{th} percentile speeds determined from real observations, the model was recalibrated or the site was not used. The authors removed two sites from the analysis, which resulted in 11 sites for analysis. OLS regressions were created for each of the 13 data collection points which were defined prior to, within, and following the horizontal curve.

Using data from the 11 horizontal curve sites, along with additional speed data provided by the simulation runs, speed prediction models were developed for the 13 data collection points. Within the horizontal curve, five models were developed for the PC, quarter point (QP), CC, three-quarter point (3QP), and PT. Significant parameters that were found included the curve radius (meters), grade of the departure tangent (percent), and length of the departure tangent (meters). Resulting R-squared values ranged from 0.562 to 0.611.

Donnell et al. (2001) concluded that TWOPAS adequately simulates truck operating speed on tangent sections and horizontal curves; however, the program was found to overestimate the speed reduction with the presence of a horizontal curve. The truck prediction models considered the effects of the vehicles and roadway characteristics; however, the models did not consider the effects of combining horizontal and vertical alignments at each site where the truck capabilities might affect the results.

Nie and Hassan (2007) investigated driver behavior at predefined horizontal curves in Eastern Ontario, Canada. A test vehicle was equipped with a magnetic wheel speed sensor, lidar meter to detect free-flowing conditions, a GPS antenna to collect vehicle position, and a video camera to monitor any unusual events during the experiment. Thirty drivers were given instructions to follow a specified path which included various types of roadway facilities. A total of 10 rural two-lane horizontal curves were selected. Averages of 25 free-flowing speed observations were collected around each horizontal curve. Geometric features were also recorded as possible model parameters.

The authors also noted that the presence of intersections and the posted speed limits where not taken into consideration at the horizontal curves located in urban areas. An OLS regression model was developed for each point within the horizontal curve to estimate the 85th percentile speed (km/hr).

Parameters within the horizontal curve found to be significant included the curvature change rate (degrees/km) and length of the departure tangent (meters). Models were developed for the PC, CC, and PC points of the curve. Both the PC and CC models found that the curvature change rate was the only significant parameter, while the model for the PT found both parameters significant. R-squared values between 0.714 and 0.938 were found for the three models. Also it was concluded that drivers do not maintain a constant speed through a horizontal curve, and it was hypothesized that drivers would be more cautious negotiating a series of horizontal curves rather than an isolated curve.

Studies performed by Tarris et al. (1996), Fitzpatrick et al. (2003), and Figueroa Medina and Tarko (2004, 2005) suggested that roadways, especially two-lane highways, may exhibit the same 85th percentile speed under very different traffic conditions. For example, Figueroa Medina and Tarko (2005) suggested that a roadway with a high vehicle distribution mean speed and low speed variability exhibits the same 85th percentile speed as a roadway with much lower distribution mean speed but higher speed variability. To explore this claim, Figueroa Medina and Tarko developed a speed prediction model that utilized any speed percentile as a dependent variable rather than a set percentile such as the 85th or 95th.

Figueroa Medina and Tarko (2005) developed a free-flowing OLS–panel data (OLS–PD) speed prediction model for horizontal curves. The advantage of this model included the ability to include many roadway characteristics as speed factors, the ability to separate the impacts on speed dispersion and mean speed, and also the ability to predict any specified speed percentile. Data were collected at 158 sites of rural two-lane highway in Indiana, and an average number of 360 speed observations were taken on the approach tangent, horizontal curve, and departing tangent at each site. The model developed for the horizontal curve speed prediction included 14 spot locations on horizontal curves. The horizontal curve model investigated six roadway geometric variables, and an additional six variables were considered both mean speed and speed dispersion factors. Panel data were created by determining the 5th through the 95th percentile speed at each site. Explanatory variables were also multiplied by a corresponding standard normal value for each of the speed percentiles. The resulting OLS–PD model took the following form:

$$V_{ip} = \sum_j a_j \times \sum_j b_k \times \left(Z_p \times X_{ij}\right) + \varepsilon \qquad (1\text{-}2)$$

where V_{ip} equals the p^{th} percentile speed at site i, X_{ij} and X_{ik} equal the exogenous variables affecting mean speed and standard deviation of speed, respectively, z_p equals the standard normal value to the p^{th} percentile, a_j and b_k equal parameters quantifying the relationship between X_{ij}, X_{ik}, and V_{ip}, and ε equals the random disturbance.

Two models were developed, including a separate model to predict mean operating speed on horizontal curves. Significant parameters included: sight distance, residential development indicator, degree of curvature, superelevation, superelevation squared, speed dispersion factor constant. The authors found the R-square value to be 0.93 and the model standard deviation to be 1.7 mph, which demonstrated to provide a reasonable predicted mean speed estimate. It was also concluded that utilizing the entire speed distribution may provide better insight into predicting operating speeds over determining a set percentile.

Gibreel et al. (2001) believed that many of the previous research studies that developed OLS speed prediction models for sections of roadway with horizontal curves lacked the important parameter "vertical alignment," which would add a third dimension to the prediction model. Two 85^{th} percentile vehicle speed prediction models were developed from 32 curve sites on two highways in Ontario, Canada. Data were collected at five points at each site located on the approach tangent, within the horizontal curve, and on the departure tangent. Data were collected for one hour at each site using a radar gun, and only free-flowing passenger cars were considered.

Multiple prediction models were developed that included points upstream, downstream, and within the curve for a crest vertical curve with a horizontal curve and a sag vertical curve with a horizontal curve. Models developed specifically for three points within the curve (PC, CC, and PT) included the following significant parameters: curve radius (meters), deflection angle (degrees), horizontal distance between the point of horizontal intersection and the point of vertical intersection (meters), length of the vertical curve (meters), first and second grade in direction of travel (percent), algebraic difference in grades (percent), and superelevation rate (percent). R-squared values between 0.94 and 0.98 were reported.

In summary, a significant amount of research has been conducted to develop vehicle speed prediction models under a variety of conditions, traffic composition, and site characteristics. The most common models developed have been constructed using an OLS model; however, research studies have also relied on exponential, inverse, and polynomial models to determine expected vehicle speed.

The selected literature specifically investigated models that predicted a specified percentile speed (typically the 85^{th} percentile) or mean speed at a single or multiple points within the horizontal curve and/or included upstream and downstream tangent points. The literature also found that curve geometry was a significant variable in almost every OLS regression, specifically the horizontal curve radius or degree of curvature. However, a review of literature found that minimal speed prediction models took into account the vehicle's lateral position or entry speed prior to or at the beginning of the horizontal curve. Furthermore, developed models have not fully explained the potential changes and maximum changes in speed within the horizontal curve. Lastly, no literature could be found that fully explains speed prediction models for other modes of transportation, such as motorcycles, school buses, and trucks. Considering the inconsistencies in cited speed prediction models and heavy reliance on horizontal curve geometry, a need to continue to understand and further predicted vehicle speed at horizontal curves is necessary.

2.2 Vehicle Lateral Distance / Vehicle Trajectory Analysis at Horizontal Curves

Vehicle lateral distance is defined as the lateral position of the vehicle within a travel lane. This distance can be measured from either the centerline of the roadway or edge of pavement to the vehicle's front passenger's side tire, driver's side tire, or the center of the vehicle, depending on the type of equipment used. Similar to collecting vehicle speed data, many types of equipment have been utilized to collect lateral distance, including high vantage point video, piezo strips, infrared delineator posts, human observers, chase vehicles, and pneumatic road tubes. Donnell and Gemar (2005) reported previous research studies that collected vehicle lateral distance using pneumatic road tubes, magnetic sensors, or piezo strips. They reported that most studies have utilized three sensors in various patterns that included sensors being placed across the travel lane perpendicular or 45 degrees to the roadway.

A broad body of research exists that have relied on evaluating vehicle lateral distance specific points along the horizontal curve to determine if the magnitude and direction of the overall vehicle shift is statistically significant. Typically these studies are performed in a before-and-after analysis, in which data is collected at either a single point within or prior to treatment area. The resulting change can be used to determine a countermeasure's effectiveness, to determine an overall change in driver behavior at locations, or as a crash surrogate in place of crash data. Examples of research studies that have utilized vehicle lateral distance as part of the analysis at horizontal curves are discussed below.

In an extensive study, Stimpson et al. (1977) investigated lateral placement and speeds on ten horizontal curves in five states, of which two sites were isolated horizontal curves. The data collection was performed using electronically calibrated tape switches adhered to the roadway in z-configured pattern. Both the inside and outside lane were investigated separately, with traffic classifiers located 750 feet upstream of the curve, at the point of curvature, and at the center of the curve, as illustrated in FIGURE 2-1. Two studies were performed, including investigating the change in vehicle lateral distance between the day time and nighttime conditions, as well as evaluating the effectiveness of various delineation treatments.

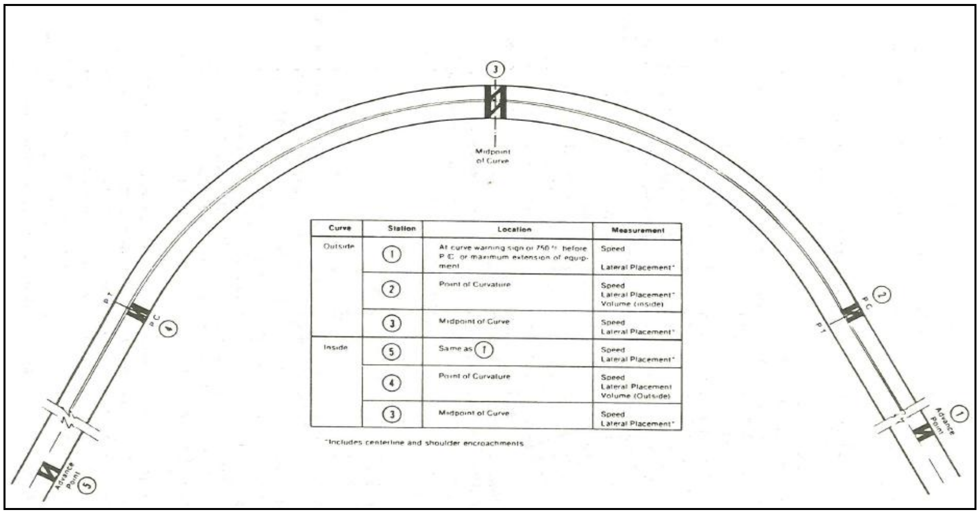

FIGURE 2-1 Data collection sites on a horizontal curve (Stimpson et al., 1977)

Overall, the authors found that vehicle lateral placement data between the advance data collection point and the point of curvature exhibited minimal change. However, between the point of curvature and the center of the curve, lateral placement analysis showed that vehicles drifted as much as 3.2 feet, and lateral placement differences between data collection points were found to be not statistically significant. Additionally, it was found that vehicles drifted towards the centerline more frequently at night. Stimpson et al. also concluded that speed and longitudinal shift in lateral distance variance were the two most sensitive indicators of hazard at horizontal curves.

Krammes and Tyer (1991) investigated the short- and long-term effectiveness of post-mounted delineators and raised pavement markers at five rural two-lane horizontal curves in Texas. Speed, lateral placement, and centerline encroachment were collected on the outside lane at the beginning, midpoint, and end of each horizontal curve using tape switches. Instead of developing a statistical model, chi-squared test was performed on each of the measures of effectiveness and a before-and-after comparison experiment. The researchers found that, for vehicles traveling on the outside lane, lateral placement moved away from the centerline 1 to 2 feet further and that the mean speed increased 1 to 3 miles per hour. A similar study conducted by Re' et al. (2010) found that driver moved an average of 15 inches away from the centerline when enhanced chevron signs were installed at two rural horizontal curves in Texas in a before-and-after analysis. The authors used a multivariate analysis of variance (MANOVA) to explore the relationship between average vehicle lateral distance and significant roadway and environmental parameters between sights and treatments. The authors noted that curve location, direction of travel, and time of day were found to be significant parameters.

Miles et al. (2005) investigated before-and-after vehicle lateral position on five two- and four-lane Texas curves on which centerline rumble strips were installed. A mobile video trailer was setup at a location within the curve, and tape markers were placed every six inches away from the centerline. Three hours of before and three hours of after data were collected. Vehicle encroachment data were binned and broken down into different vehicle classifications. The authors found that vehicles in the outside lane moved towards the centerline and that vehicles in the inside lane moved towards the inside edge line of the curved sites. The researchers also found that both directions of travel experienced an average shift of approximately 6 inches for all curved sites.

A similar study to investigate rumble strips was conducted by Hallmark et al. (2009). The authors investigated the effectiveness of four-inch painted shoulder rumble strips at high-crash horizontal curve locations in Iowa. One method of effectiveness used in the study involved determining the change in lateral placement one month prior to and one month after the installation of the rumble strips. Pneumatic road tubes were placed near the center of the curve in a z-configuration. One site was selected for evaluation, and a total of 1,328 vehicles were included in the before study and 702 vehicles were included in the after study. The researchers found that the percentage of vehicles traveling within 1 foot of the pavement edge decreased from 2 percent to 0 percent after installation, and the percentage of vehicles within 2 feet of the pavement edge decreased from 22 percent to 16 percent.

However, statistical models for vehicles and their change in lateral placement were not developed for the above-cited literature. One basic requirement to develop a statistical model as explained in the previous section is to trace vehicles though the horizontal curve to develop individual vehicle trajectory or path database. The next set of selected cited research explored the idea of tracing vehicles through two-lane horizontal curves. Unique data collection methodologies were utilized, and most studies reported similar conclusion on how vehicles negotiate horizontal curves.

2.3 Development and Classification of Vehicle Trajectories through Horizontal Curves

Stonex and Noble (1940) stated, “Very few drivers maintain a truly accurate course and are inclined to drive around a curve in chords.” The critical methodology to develop a statistical model that analyzes the magnitude of change in vehicle shift and potentially predicts with a certain level of confidence on how a vehicle will negotiate a curve in terms of vehicle lateral distance, a vehicle trajectory, or path must be created for each observation. Limited research has addressed this research gap on horizontal curves. However, a broad range of research studies have explored ways to detect and develop vehicle trajectories using site-based video data collecting systems with pixel extrapolation software on tangents of roadway only (Davis and Pei, 2005; Kim et al., 2005; Li, 2009). Finally, Glennon et al. (1969) noted there are potential variables that affect vehicle paths that cannot be measured or quantified easily in the field, which include tire temperature, wind conditions, faulty vehicle characteristics, foreign material on the pavement, and excessive water depth in low areas. The following cited literature has been identified as studies that have either quantified vehicle movement by calculating instantaneous vehicle radius within the travel lane or have created vehicle trajectories based on extrapolating vehicle lateral distance through a horizontal curve. The equipment utilized for these studies includes chase vehicles, instrumented vehicles, equipped delineator posts, driver simulators, and site-based video data collection.

Glennon and Weaver (1971) investigated five two-lane horizontal curves outside of College Station, Texas, that had a degree of curvature between two and seven degrees. A 16 mm movie camera was mounted in a plywood box constructed in the bed of a pickup truck to capture the vehicle path, as illustrated in FIGURE 2-2.

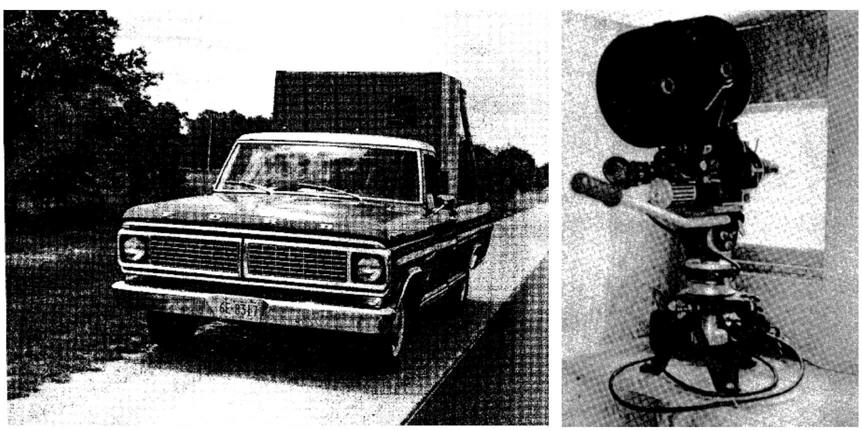

FIGURE 2-2 Data collection chase vehicle and camera (Glennon and Weaver, 1971)

Reference lines were placed on top of the curve centerline, and vehicle lateral position was recorded from outside of the back driver’s side tire. One hundred vehicles were recorded at each curve, and the speed and lateral position were recorded every 20 feet by the chase vehicle traveling 60 to 100 feet behind the sample vehicle. From the data collected, the instantaneous radius was estimated by computing the radius of the circular curve through three data collection points. Also, the speed distribution was estimated at each point for each vehicle. After plotting the relationship between vehicle speed and radius for each point, no correlation was found. The authors developed a relationship between the curve radius and observed vehicle instantaneous radius and found that most vehicles were cutting the curve by having a path radius through the horizontal curve less than the actual curve radius. Similar results were also found by Emmerson (1969) who noted vehicles shifting by 2 to 3 feet between the point of curvature and the middle of the curve with horizontal curves having a radius less than 500 feet.

A study performed by Segal et al. (1980) in Buffalo, New York, used a chase car and motor-driven camera to measure lateral position on three selected high-crash curves at entrance/exit ramps on limited access highways. Speed data were collected in three locations along the curve, and pictures of lateral placement were taken every 20 feet throughout the curve. The researchers noted that considerable time constraints, traffic characteristics, and film quality limited their sample size to 30 vehicles per curve. The study concluded that many drivers cut corners on curves; this conclusion was based on finding the mean vehicle path via the mean lateral placement measurements. However, a statistical analysis of the lateral placement data's standard deviation showed a possible lack of reliability associated with the calculated mean lateral placement measurements.

Glennon et al. (1985) investigated lateral position and vehicle speed at six curves in Illinois and Ohio and found similar results to those of Segal et al. (1980). Right and left horizontal curves were selected with various degrees of curvature, roadway widths between 20 and 22 feet, appropriate transition design, and various curve approach conditions, ranging from restricted to open. FIGURE 2-3 illustrates the equipment setup at each of the curves. The research team selected recreational vehicles in which the high-speed cameras were located. The research team marked the centerline and outside edge line every 25 feet prior to and after the point of curvature with reflective tape and verified elevation with a transit and level rod. When a vehicle came into the site, each camera tracked it through the system, and lateral position and speed were recorded at the tangent approach, PC of the curve, and within the curve.

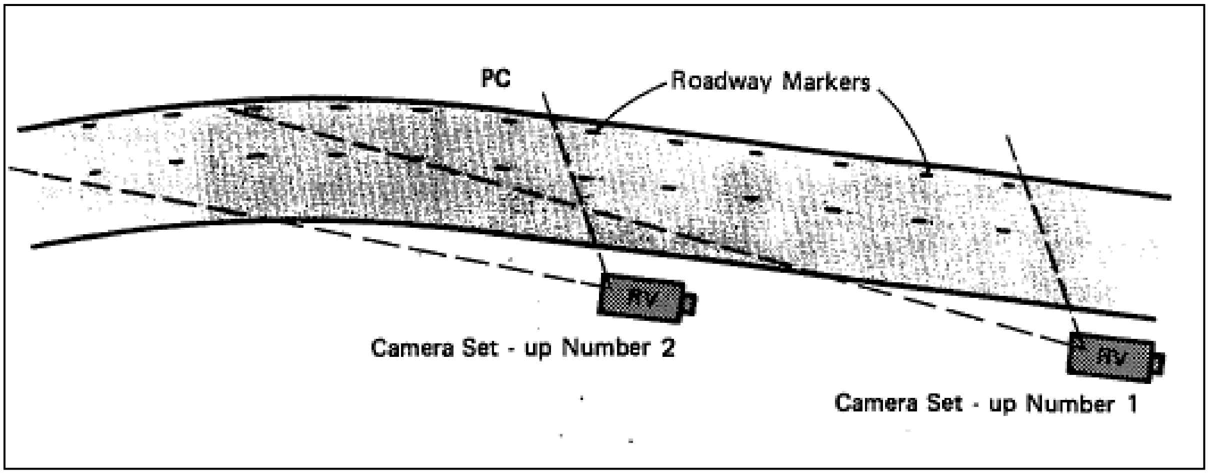

FIGURE 2-3 Location of cameras at horizontal curve sites (Glennon et al. 1985)

Data reduction occurred in two steps. The first step involved creating overall vehicle distributions of speed, total lateral movement, and identified erratic behavior at each site. The second step was to evaluate the top 20 percent of vehicles with the highest speed and lateral movement through the curve (about 1/3 of the total sample). Additionally, 10 to 15 vehicles were identified and extracted that exhibited median speeds and lateral movement. The vehicle path radii were calculated for every vehicle through the curve at 25-foot intervals. The authors found that these same vehicles drifted towards the centerline of left curves and shoulder of right curves with a mean lateral movement of 2.8 feet from the PC of the curve. The increased standard deviation of lateral distance within the curve was also found to be significant and indicated greater variability in vehicle behavior in the curve as compared to the approach tangent.

Similarly, a more recent study conducted by Felipe and Navin (1998) also found that drivers tend to follow the center of the lane of large radii curves. Drivers were also found to “cut” the horizontal curve with small radii to minimize speed reduction. A study conducted by Guny and Woodward (2007) used video data to investigate how drivers in Northern Ireland traversed horizontal curves and roundabouts. Data were collected at eight different sites, and by visually inspecting video data the researchers found that vehicles shifted towards the convex side of the curve. These results show that vehicles traveling in the outside lane of the horizontal curve shift towards the centerline and that the vehicles traveling in the inside lane of the horizontal curve shift towards the inside edge line. The researchers also concluded that the shift distance increased with a decreasing horizontal curve radius.

Vehicle lateral distance can also be extrapolated from a driving simulator as used by Gawron and Ranney (1990). Twelve male drivers between ages 21 and 55 were subjected to driving in the simulator for two hours each night for three nights with blood alcohol content (BAC) levels of 0.0, 0.7, and 0.12. Data were collected at five horizontal curves out of 150 possible horizontal curves in the simulation with radii between 188 and 356 feet. Once the vehicle entered the horizontal curve, vehicle lateral distance was recorded by determining which of 11 zones the driver's side of the vehicle traveled in, as illustrated in FIGURE 2-4.

The general results of this study showed that decreases in curve radii resulted in decreases in curve entry speed and increases in curve cutting. Specific results reported indicated that a higher BAC resulted in an increase in lane position error and overall poor vehicle control.

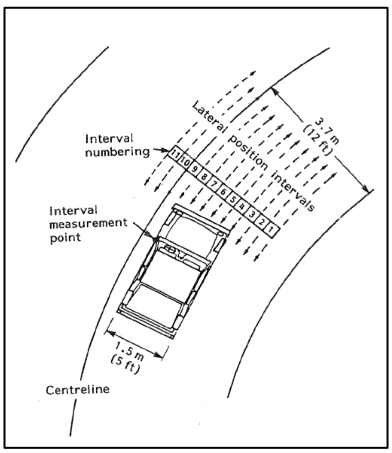

FIGURE 2-4 Vehicle lateral distance zones (Gawron and Ranney, 1990)

Spacek (1998) investigated vehicle trajectories at seven two-lane horizontal curves in Switzerland. This study specifically investigated how vehicles negotiate horizontal curves by collecting, projecting, and classifying vehicle trajectories in both the inside and outside lanes of two-lane horizontal curves. Additionally, Spacek (1998) was trying to determine if any relationships existed between trajectories and other variables such as crashes, speed, and lateral acceleration. The report created six distinct trajectory classifications, including "ideal," "normal," "correcting," "cutting," "swinging," and "drifting." A seventh classification "other" was defined as any trajectory not falling into one of the six classifications. An earlier study conducted in Switzerland (ArbeitsgruppeVerkehrssicherheit, 1980) evaluated night-time horizontal curve trajectories under certain lighting conditions and defined four classifications with Spacek, adding "ideal" and "normal" in his study. Other research studies have commented that the ideal path a vehicle can take along a horizontal curve is parallel to the center line and centered within the middle of the lane. (Stimpson et al. 1977; Land and Horwood, 1995; Riersma, 1981).The six trajectory classifications for the outside lane are shown in FIGURE 2-5, and the six trajectory classifications for the inside lane area shown in FIGURE 2-6.

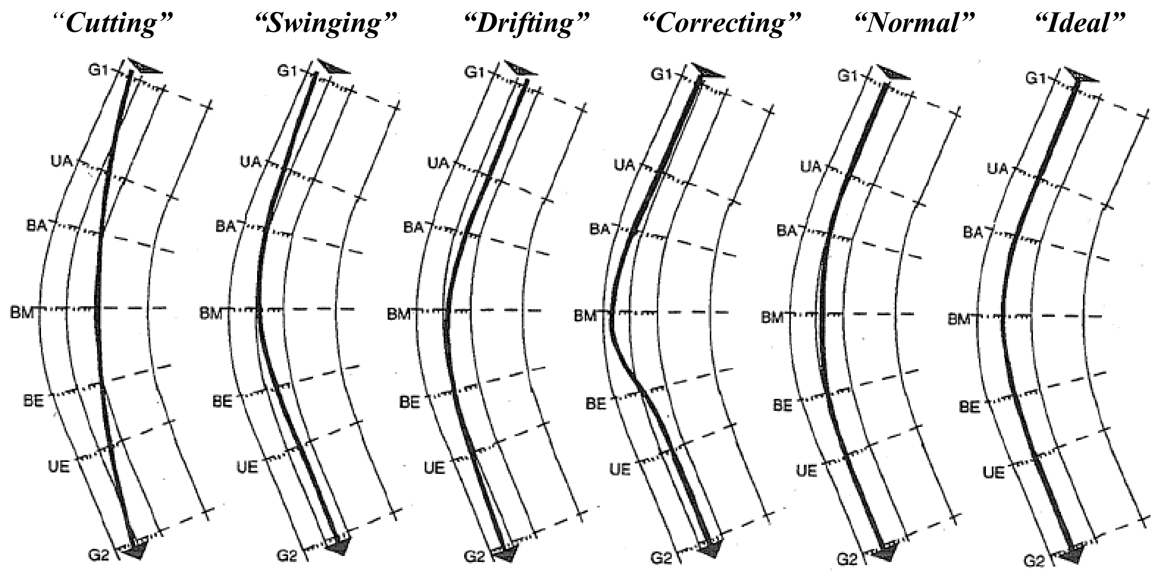

FIGURE 2-5 Outside lane vehicle trajectory classifications (Spacek, 1998; Lindenmann et al. 1976)

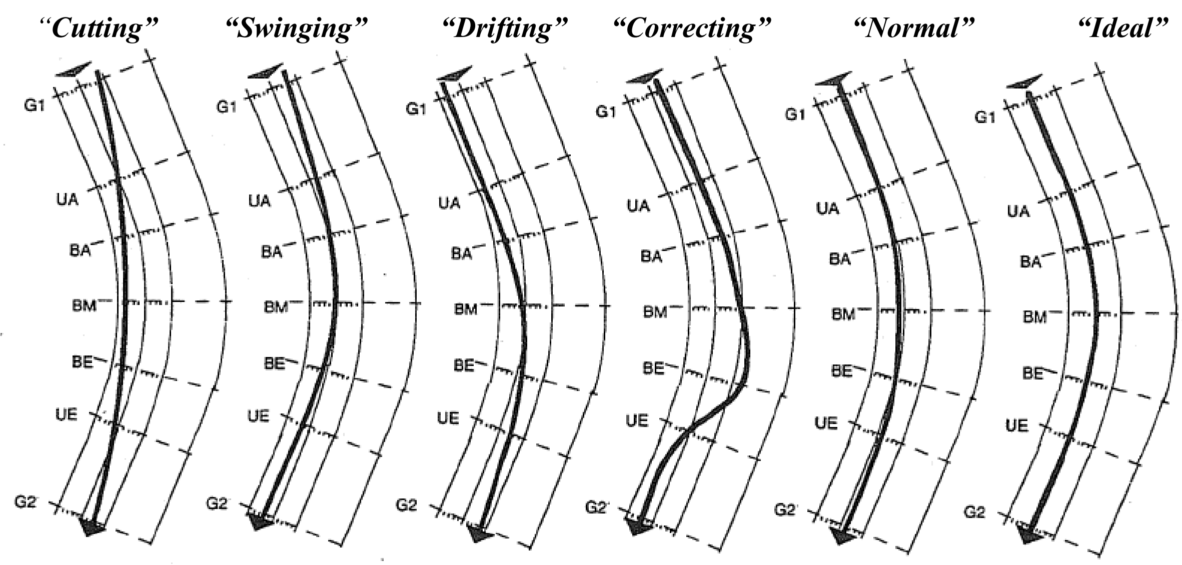

FIGURE 2-6 Inside lane vehicle trajectory classifications (Spacek, 1998; Lindenmann et al. 1976)

Horizontal curves selected in Switzerland had radii between 65 m and 200 m (213 ft and 656 ft). Data were collected at five locations within the horizontal curve and at two locations 30m (100 ft) upstream and downstream of the horizontal curve. Data were collected using up to 12 equipped delineator posts in which 7 stations were recorded (up to 2 posts per station within the curve to account for equipment failure), as illustrated in FIGURE 2-7.

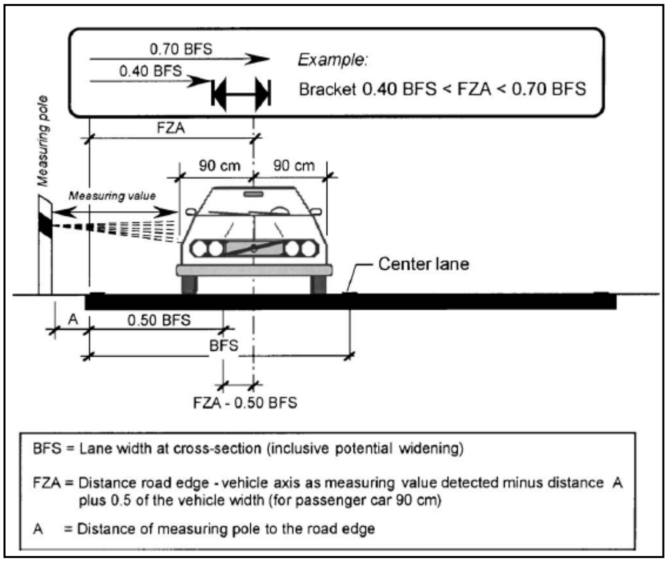

FIGURE 2-7 Delineator post and assumed vehicle dimensions (Scheifele and Spacek, 1992)

A custom software package processed the delineator posts data and classified the vehicle trajectories based on the six classifications (Lindenmann et al. 1976; Scheifele and Spacek, 1992). The software also filtered the collected data and removed trajectories in which data were not collected at all seven locations for individual vehicles (Scheifele and Spacek, 1992). Each classification included a set of seven upper and lower limits for each station along the horizontal curve. Out of the seven studied curves, five outside lanes and four inside lanes were investigated, and a sample for each lane ranged between 90 and 206. It was concluded that “Cutting” and “Normal” were found to be classifications with the highest number of trajectories in both directions. Additional conclusions were made by the author after investigating the result further:

- No clear relationship could be found between trajectory pattern frequency and the curve’s geometry or crash history.
- Significant influences are speculated to affect vehicle trajectories, including sight distance, warning signs, opposing vehicle traffic, and traffic volume within the curve in either direction.
- The data suggested that smaller radius curves impacted vehicle speed, while larger radius curves showed minimal impact on speeds.
- The data also suggested that geometry might have a significant role in classifying trajectories, and the authors cautioned that many trajectories may not fall into one of the six identified behaviors.

Park et al. (2003) developed two linear regressions to predict two separate dependent variables extracted from vehicle lateral distance data at 12 Korean curves. The report did not specify the number of observations, but it did mention that the researchers only investigated free-flowing vehicles. Data were collected on the outside lane using seven video cameras, five of which were located in the circular curve, and seven Nu-metric plates to record speed, as illustrated in FIGURE 2-8.

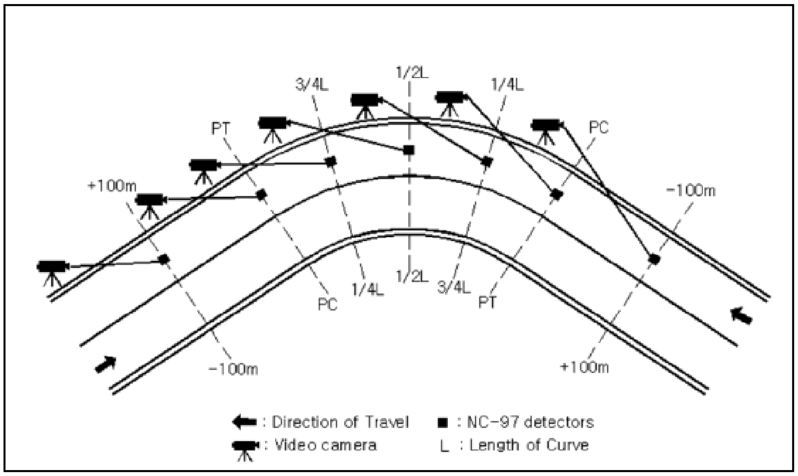

FIGURE 2-8 Video and Nu-Metric data collection points (Park et al., 2003)

Two dependent variables were extrapolated for each vehicle: the Path Detection Index (PDI) and Path Trajectory Ratio (PTR). The PDI indicates the 85th percentile value in the cumulative distribution of an individual vehicle's deviation of lateral placement within the curve, and the PTR indicates the ratio between the representative of a curve site's minimum path radius and the curve's deflection angle. The authors developed statistical models for both dependent variables using a single significant parameter. For PDI, it was found that the horizontal curve deflection angle parameter resulted in the best prediction model with an R-squared value of 0.71. For PTR, the curve radius was found to produce a model with the highest possible R-squared value of 0.77. Another important conclusion the authors explained was that the larger was the vehicle's maximum speed difference, the greater was the deviation of lateral distance of the vehicle on the curve.

Stodart (2006) and Donnell et al. (2007) investigated vehicle lateral placement and speeds at 23 horizontal curves on two-lane roadways in Pennsylvania at night as part of a larger project to evaluate pavement markings at night. Data were collected through video cameras which monitored the vehicle's speedometer and rear tires in respect to the edge and centerline of the roadway. Sixteen participants ranging in ages from 18 to 79 were instructed to traverse a closed roadway for approximately 30 minutes. Two nights of data were collected in which one night was considered baseline conditions, while the second night was considered enhanced conditions. Data were extracted continuously using video tracking software, and speed profiles and vehicle trajectories were developed. Visually inspecting the plots, the Stodart hypothesized that a possible relationship might exist between vehicle lateral placement and speed. It was noted that at some locations when the vehicle shifted away from the centerline the speeds decreased; however, it was also found that vehicles speeds also increased as vehicles shifted from the centerline. Along with operational and participant data, roadway characteristics were also recorded. An OLS model was developed for both speed and vehicle lateral distance at the center of the curve, and the vehicle lateral distance model is as follows.

$$LVP = 69.407 + 2.521\ (DumAge) + 3.340(DumTanLess300) + 2.831(DumAvgVertGrade) + 9.591(DumCurveDirection) + 11.066(PreviousRadiusInMiles) + \varepsilon$$

The regression model for vehicle speed at the center of curve is as follows:

$$SPEED = 19.085 - 1.467(DumAge) + 1.730(DumCurveDirection) + 0.437(SpeedAtPreviousMC) + 22.971(RadiusInMiles) + 5.353(DumTanLess300) - 14.864(PreviousRadiusInMiles) + \varepsilon$$

where *LVP* = estimated lateral vehicle placement at the CC from the centerline of the roadway (inches)

Speed = estimated vehicle speed at the CC (mph)

DumAge= dummy variable for age (1=old, 0=otherwise)

DumTanLess300= dummy variable for the approach tangent length (1=less than 300, 0=otherwise)

DumAvgVertGrade= dummy variable for average vertical grade (1=greater than 5%, 0=otherwise)

DumCurveDirection= direction of curve (1=left, 0=otherwise)

PreviousRadiusInMiles= previous curve radius affects site curve by the equation (11*n feet/5280 feet), where n=site curve radius (inches)

SpeedAtPreviousMC = speed of the vehicle at the previous curve's middle of the curve

RadiusInMiles = curve radius (miles)

For the speed prediction and lateral vehicle placement models, R-squared values of 0.27 and 0.59 were determined. As shown, both models rely heavily on previous traversed curve characteristics and geometry. Additionally, driver age, curve direction, and previous radius in miles variables were found in both models. To test whether speed influenced the vehicle's lateral placement at the center of the curve, Stodart inserted the speed variable into the OLS, which was found to be insignificant. The same result was found when the variable vehicle lateral placement was inserted into the OLS speed prediction model. The author also reported other conclusions that were not explained by the model. Previous study have reported driver's tendency to shift the vehicle inwards on horizontal curves; however, it was found that driver shifted outwards in both the inside and outside lane of the studied curves. It was also found in the OLS regression that if no external forces were acting, the constant term was reported to be the exact center of the lane.

In summary, a considerable amount of research has been conducted to understand and utilize vehicle lateral placement as an indicator of countermeasure effectiveness, driver behavior at horizontal curves, or the development of vehicle classifications. Much of the existing literature utilizes vehicle lateral placement as a crash surrogate measure, and the magnitude in vehicle shift as a countermeasure is either found to be statistically significant or not, leading researchers to hypothesize the device's effectiveness. However, limited research has developed prediction models to determine what factors affect vehicle lateral placement at or within the horizontal curve. However, unlike speed prediction models, the ability to capture the lateral distance with existing technology can limit the amount of data that can be acquired. Furthermore, it is unclear based on the current literature if speed and vehicle lateral placement are significantly related to each other.

2.4 Type and Arrangement of Methods to Collect Vehicle Operational Data

Different types of Methods have been utilized to collect vehicle speed data at both tangent sections and within horizontal curves. All studies have reported that the goal of data collection is to collect as much data as possible, without affecting driver behavior. Methods that have been used includes pneumatic road tubes, piezo strips, video data, lidar gun, radar run, vehicle-based data collection, stop watches, and chase vehicles. McFadden and Elefteriadou (2000) and Misaghi and Hassen (2005) noted that although the radar gun has been used for many speed prediction model development studies, researcher must account for cosine errors when recording speed data within the horizontal curve. Also Nie and Hassen (2007) suggested that some developed speed prediction models are questionable due to a human error when collecting manual speed measurements.

Pneumatic road tubes and piezo strips have been utilized extensively as an economical way to collect vehicle operational data when a high vantage point is not available (Chrysler, 2009; Krammes and Tyer, 1991; Meyer, 2003; Finley et al., 2008; Donnell et al., 2009). Vehicle lateral distance is calculated using the front passenger tire time-stamps recorded by each of sensors (or tubes). The trap, illustrated in FIGURE 2-9, consists of two perpendicular sensors and a single sensors setup in a 45 degree angle stretched across the travel lane.

FIGURE 2-9 Pneumatic road tubes setup in a z-configuration

The z-configuration also offers researchers the ability to determine speed and vehicle characteristics by analyzing the two perpendicular sensors spaced 16 feet apart using data reduction software. However, Crowther et al. (1961) stated that pneumatic road tubes may give biased vehicle speed results after testing various combinations of road tubes, concealment, and placement on certain highway alignments. Researchers have successfully used video data collection for a variety of situations, including estimating roadside encroachment (Miaou and Lum, 1993), lateral placement, speed distributions, and lane keeping at curved sites (Miles et al., 2006). A study conducted by Miles et al. (2010) used an instrument vehicle equipped with cameras mounted over the rear tires to capture video while the vehicle was negotiating horizontal curves in a closed course at night. Illustrated in FIGURE 2-10 is the lateral placement of the vehicle with respect to the centerline. Also shown is the calibration board used to calibrate the video cameras each night prior to data collection.

Davis and Pei (2005) have also developed a robust methodology to collect video data of crashes on highway segments and used sophisticated software to reconstruct vehicle trajectories by estimating lateral distance at specified points along the roadway. Video-based observations require a good vantage point to place the camera—either an elevated position or a camera positioned on a raised pole. The reliability of the collected data depends on how drivers behave while traversing a segment of roadway and whether any distractions are present to affect driver behavior.

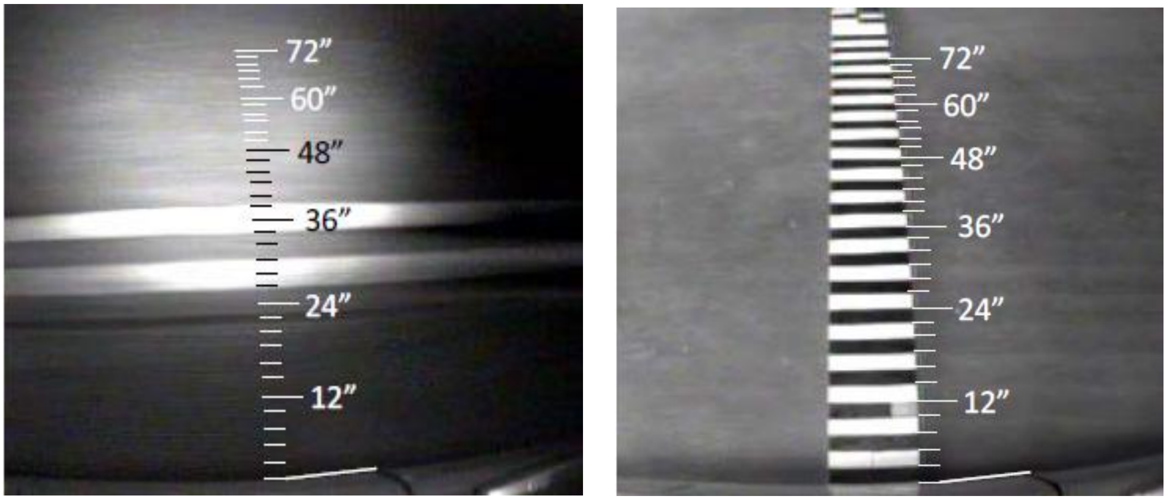

FIGURE 2-10 Video-based centerline encroachment data collection and video calibration board (Mies et al. 2010)

2.5 Effects of Equipment on Driver Behavior

One area of transportation safety that has not been thoroughly investigated is quantifying the effect that data collection devices on or near the roadway may have on driver behavior. There are numerous data collecting devices, including a radar or lidar speed detection device, pneumatic road tubes, electronic tape switches, or microwave devices. Misaghi and Hassen (2005) mentioned that careful consideration should be made regarding not only the effect of the device on driver behavior, but also what equipment is appropriate for the roadway geometry. The authors mentioned in their research an excellent example of a data collection error involving the collection of speed data on a horizontal curve. In that case, the data collectors did not consider that reading the radar signals along a curved roadway does not recognize the degree of curvature (cosine error). In contrast, other studies that have investigated speed and lateral placement using tape switches on rural and urban roadways found no driver behavior changes throughout the study (Dudek et al., 1988; Porter et al., 2004).

Poe et al. (1996) investigated the effect that research equipment has on driver behavior, specifically in terms of speed data collection. Six devices were set up on an urban corridor in State Park, Pennsylvania, including pneumatic road tubes, magnetic sensors, a human observer, radar, tape switches, and lidar. To quantify the effect of each of the devices, an observer counted the number of drivers that applied their brake lights prior to reaching the equipment. Vehicles that applied their brakes lights in a platoon or due to unusual circumstances were disregarded. Between 500 and 700 vehicles were observed for each device, and the researchers found that the pneumatic road tubes and tape switches had the highest percentage of observed brake lights, with 5.45 percent and 1.51 percent, respectively. The researchers also noted that many drivers decelerated prior to reaching the equipment by letting up on the accelerator and forcing the vehicles to change gears. Additionally, the researchers hypothesized that drivers reacted to equipment placed on the roadway, which was unlike the reaction to radar and lidar devices. Similar to the lidar device, the human observer had the least number of observed brake lights. However, the researchers noted that the human observer blended into the urban environment and might have had different results if the study had been performed in a rural environment.

In summary, researchers have utilized diverse equipment to collect vehicle operational data. Cited research studies have utilized pneumatic road tubes and piezo strips that stretch across the roadway and can easily collect time-stamp data but are noticeable to drivers while they negotiate the roadway. Studies have also utilized video technology to capture and extract operational data through computer software. Limitations have been identified, such as obscure viewing angles, the effects of nighttime darkness, various weather conditions, data reduction time, and the changes in driver behavior if the equipment is noticed by the driver.

Finally, researchers have utilized simpler data collection equipment, such as stopwatches, radar guns, and lidar devices. Although these devices may be low cost and can easily be hidden from the driver, researchers have hypothesized a possible human error in recording data, such as not accounting for the cosine error when collecting data along a horizontal alignment (McFadden and Elefteriadou, 2004) or other noise that may affect the device at the data collection site. A careful balance between accuracy, data reduction time, and the effects the equipment has on driver behavior must be accounted for to produce accurate vehicle operational data.

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CHAPTER 3. A COMPARISON OF TEHCNIQUES TO COLLECT VEHICLE OPERATIONAL DATA AND DEVELOP TRAJECTOIES AND SPEED PROFILES THROUGH HORIZONTAL CURVES

A paper prepared for submission to the *American Society of Civil Engineering Journal of Transportation Engineering*

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and Reginald R. Souleyrette, M.ASCE[3]

Abstract

Horizontal curves present drivers with numerous tasks that, if not performed while approaching and negotiating the curve, may result in a roadway departure crash. A vehicle's lateral position within the lane and its speed are two indicators of interest from safety and operational perspectives. These can be measured simultaneously at multiple locations along the curve. However, researchers face the challenge of collecting operational data while minimizing impacts on driver behavior, and developing robust, efficient, and accurate means to obtain the data. This paper presents the findings of a series of pilot studies on closed and open courses that investigated the effectiveness and accuracy of pneumatic road tubes and digital video cameras for collecting such data. These devices generally intended for other various purposes in traffic engineering. Closed-course studies investigated a single data collection station setup, while an open-course study investigated multiple data collection stations on a horizontal curve. The data were reduced manually and automatically, and tests were performed to evaluate the statistical significance of the analyses. The results of the pilot studies showed that pneumatic road tubes provided a higher level of accuracy than video data. Mean vehicle trajectories and 85th percentile speed profiles were also created. Furthermore, it was found that drivers moved away from the edge of the travel lane in the presence of the video equipment, and the nighttime speeds being nominally lower than daytime speeds. Vehicle speeds at the center of the curve were also noted to be lower when seven sets of pneumatic road tubes were used compared to only two sets of road tubes being used.

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3.1 Introduction

Vehicle crashes at horizontal curves have been recognized for many years as a considerable safety problem. Campbell et al. (2008) explained that drivers are faced with multiple tasks while approaching and traversing a horizontal curve. They also noted that between the point of curvature (PC) and the center of the curvature (CC), important tasks that must be carried out include keeping proper lane position and speed. Staplin et al. (2001) suggested that most horizontal curve crashes result from a lack of controlling these tasks, which could lead vehicles to drift within their lanes and potentially off the roadway. To investigate how well drivers perform these tasks, trajectory and speed profiles can be created using data collected in the field. One of the most important aspects of collecting field data is to test the limitations and effectiveness of the data collection equipment. The aim of this paper is to present the groundwork and proof of concept for selected equipment typically used.

Identifying a vehicle's lateral position within the lane and its speed are common data collection practices in transportation research fields such as work zone studies, studies of streets with bicycle lanes, and roadway shoulder design. Typical equipment utilized used in previous studies include pneumatic road tubes/piezo strips and video cameras. Researchers have successfully used video data collection for a variety of situations, including estimating roadside encroachment (Miaou and Lum, 1993), lateral placement, speed distributions, and lane keeping at curved sites (Miles et al., 2006). Davis and Pei (2005) have also developed a robust methodology to collect video data of crashes on highway segments and use of sophisticated software to reconstruct vehicle trajectories. Video based observations require a good vantage point to place the camera, either an elevated position or a camera positioned on a raised pole.

Pneumatic road tubes and piezo strips have also been utilized extensively as an economical way to collect vehicle operational data when a high vantage point is not available. Pneumatic tubes have been utilized to evaluate countermeasure safety and determine whether drivers react to the countermeasure by increasing their lateral distance away from the edge line and changing their speed at one or two points (Chrysler, 2009; Krammes and Tyer, 1991; Finley et al., 2008; Donnell et al., 2006). Crowther et al. (1961) stated pneumatic road tubes may give biased vehicle speed results after testing various combinations of road tubes, concealment, and highway design. Additionally, Poe et al (1996) also noted that the density of equipment on the roadway might influence the results of the data as well. However, these studies generally utilized only one or two data collection points at the countermeasure and did not fully develop a trajectory and speed profile through a curved or straight tangent segment of roadway.

A review of the literature identified the need to develop vehicle trajectories and speed profiles at horizontal curves using commonly available tools in a cost effective and time efficient manner. This includes locations do not have a high vantage point and avoiding the need to use advanced software packages to reduce the data. Two previous studies attempted to address this need. Park et al. (2003) created vehicle trajectories and speed profiles at 12 curves in South Korea using seven digital cameras and Nu-metric plates set up along the horizontal curves. Spacek (1998) used infrared delineator posts at six horizontal curves in Switzerland to collect vehicle operational data. These were used to develop seven distinct vehicle trajectories through horizontal curves. Both the studies were based on small datasets. Thus, there is a need to evaluate the effectiveness and relative accuracies of equipment used typically to determine the lateral position and speed of vehicles traversing horizontal curves. An approach to address this need is presented herein.

3.2 Research Approach

On a general level, the underlying methodology for creating a vehicle trajectory and speed profile is to trace individual vehicles through a roadway section and then plot their speed and lane position against time or location. This process can be complicated in rural settings, where high vantage points or areas to set up equipment and draw power may be limited or non-existent. However, researchers have utilized pneumatic road tubes and video cameras to collect and reduce vehicle operational data such as vehicle type, speed, lateral distance, gap, and wheelbase length. This study examined and compared these two types of equipment and developed a methodology for effectively obtaining key speed and trajectory data with these devices at horizontal curves. Closed- and open-course studies were utilized to test these methodologies and determine the variables that could be collected and the variables' accuracy. Data obtained from pneumatic road tubes and video cameras were compared against manual measurements of the tire location.

3.3 Closed-Course Studies

3.3.1 Background

Two closed-course studies were conducted to test the effectiveness and accuracy of pneumatic road tubes set up in a "z" configuration for collecting lateral distance data, as illustrated in FIGURE 3-1 (Cottrell, 1986; Dudek et al. 1988; Mahoney et al. 2003; Miles et al. 2005). A study conducted by Moen et al (1993) also investigated the effectiveness of using a z-configured data collection setup to determine vehicle lateral distance. Important findings included that a vehicle is assumed to travel at a constant rate over the setup, and that the setup must be spaced at a distance that is relatively close to a passenger car's wheelbase length. Pneumatic road tubes operate on the principle that when a wheel compresses the tube, a time-stamp is recorded by the traffic classifier (accurate to a thousandth of a second). As FIGURE 3-1 shows, the data collection setup is 16 feet long, with two perpendicular tubes at either end and a single diagonal tube between the two with a changing lane width "W". To create a right triangle and proper angle for tube 3, "Wb" was set to 8 feet and L2 set at 6 feet. The tubes are extended from the edge of the roadway to the center of the roadway.

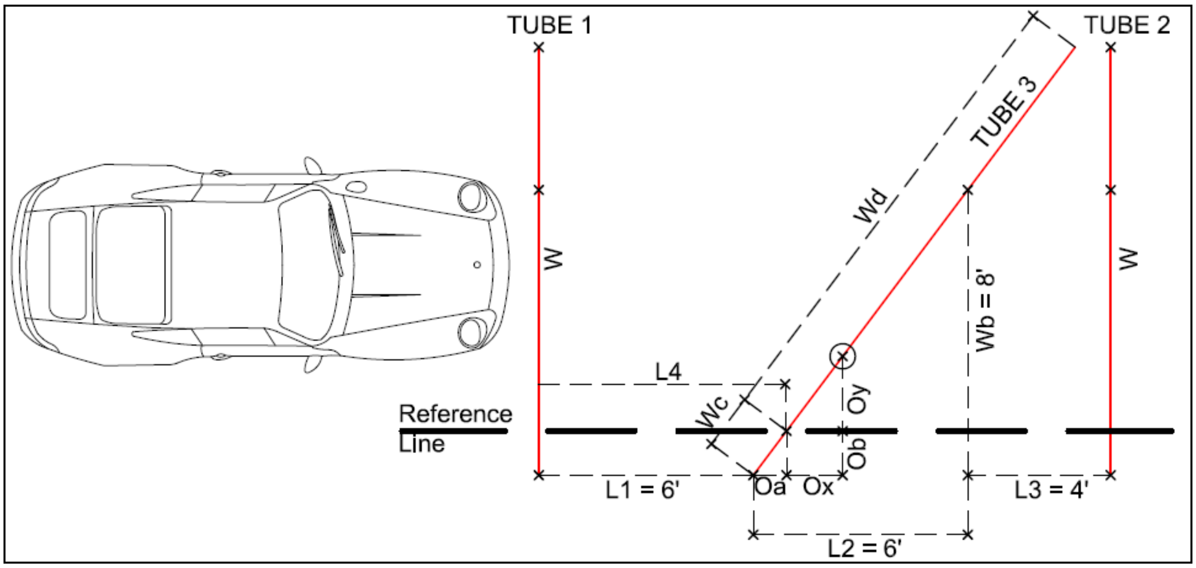

FIGURE 3-1 Dimensions of the z-configured road tubes

A careful installation technique must be followed to ensure that the pneumatic road tubes are properly secured and stretched tightly across the roadway; poor installation will give false or inconclusive readings. Air in the tube travels in two directions as the compression occurs, hitting either the tube pinched off by the other tire on the same axle, the end of the tube, or the traffic classifier. Setting up the tubes perpendicular to the roadway provides a single air pulse to the traffic classifier and gives a high accuracy rate in determining vehicle speed and classification. If a speed study was being conducted using only two tubes, the time stamp chronological sequence for the two tubes (Tubes 1 and 2) for a two-axle vehicle would be **1122**. This sequence indicates Tube 1 detected the vehicle's front axle, then the rear axle followed by Tube 2 detecting the front and rear axle. If three tubes are installed (Tubes 1, 2, and 3), the error-free chronological sequence would be **13312332**. However, due to the unsteady state of the air pulses along the diagonal tube, chronological sequences can be a variation of the previous sequence, including, for example, **1333212333323** or **132331332,** which are valid observations to extract lateral distance.

To determine vehicle lateral distance from time-stamp-based data and trap dimensions, and assuming that the diagonal tube was installed to make a right triangle, the following equation can be utilized (Chrysler, 2009):

$$O_y = \frac{8}{6}\left(\left(\frac{L}{t_2 - t_3}\right)(t_3 - t_1) - L_4\right) \tag{3-1}$$

Where O_y = Vehicle lateral distance from the pavement marking to the outside front tire of the vehicle

L = Length over the entire setup (16 feet)

L_4 = Distance between Tube 1 to the point where Tube 3 intersects the reference line (typically the inside of the pavement marking)

T_i = Time-stamp recorded at each tube

Generally, the procedure to reduce vehicle lateral distance data involves multiple steps of data cleaning and filtering. Along with collecting data from three tubes, a speed study can be performed at the same time by utilizing the time-stamp data from the two perpendicular tubes. A custom macro to apply Equation 3-1 to the present study's data set was created based on a macro developed by researchers at the Texas Transportation Institute (Johnson, 2008) to analyze piezo strips in a z-configuration. The macro identifies individual vehicles based on large gaps in the running time-stamp data; separates the vehicles and extracts the first 1, 3, and 2 of the chronological sequence for each vehicle while disregarding any other time-stamp data in the sequence; and applies Equation 3-1.

The results of the lateral distance data extraction can easily be compared to the speed study data. The speed study is used to identify unknown vehicle classifications, and the macro often identifies these vehicles as well. When the lateral distance data and speed data are combined, the unknown vehicle data are discarded. The previous vehicle data are also discarded because the data for this vehicle likely tripped the unknown classification. Finally, outlier data are removed, including vehicles well over 100 mph and vehicles whose width is beyond the lane width. The following is a summary of the experiment to enable comparisons of data obtained from the pneumatic road tubes with manual measurements of the tire position in the lateral direction.

3.3.2 Experiment Design

The first closed-course study was performed in a closed parking lot, as illustrated in the top left of FIGURE 3-2. The course was a tangent section 240 feet long with 180 feet of acceleration distance. Vehicle speeds were kept to less than 35 miles per hour. The second closed-course study was performed on a closed roadway with plenty of acceleration and deceleration distance, and vehicle speeds were kept under 55 mph. A total of 36 observations were made and recorded at each location.

FIGURE 3-2 Closed-course setup (parking lot: top left, city street: top right) and crushed limestone aggregate ridge (bottom left and right)

In addition to using the pneumatic road tubes to obtain O_y, manual measurements were used to compare the data. As illustrated in the bottom of FIGURE 3-2, a crushed limestone aggregate ridge was placed adjacent to Tube 1 of the setup to help measure with a tape measure the lateral distance from the edge line, O_b. The ridge was reset after every observation. This method proved to be an excellent way to imprint where the vehicle's passenger-side tires passed as the vehicle moved through the trap.

3.3.3 Analysis and Results

The lateral distance data collected by the pneumatic road tubes were then compared to the manual measurements. A matched-pair statistical analysis was used with the assumption that the data sets' two distributions were similar, though not normally distributed because the research team was in control of the speed and lateral position of the car. A paired t-test was selected because the statistical model is robust when analyzing similar distributions. The null hypothesis tested that the mean difference between observations is zero at a 90 percent level of significance. Table 3-1 shows the results of the analysis.

Table 3-1 Analysis of closed-course studies

Test Location	Sample Size	Speed, mph	Difference in Lateral Distance (Oy), ft.			90% Confidence Interval	Parametric Paried t-test p-value	Reject Null Hypothesis
			Minimum	Maximum	Averge			
Parking Lot	36	19 to 32	-1.30	0.90	-0.10	(-0.24, 0.38)	0.38	**No**
Closed Street	36	27 to 51	-1.80	1.50	0.30	(-0.09, 0.52)	0.18	**No**

Note: All values in Table 3-1 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 90 percentile level of confidence

Two important observations can be extrapolated from Table 3-1. First, the paired t-test indicated that the pneumatic road tubes, with the aid of the macro for data reduction, provide accurate measurements. Second, the accuracy of these measurements hold true for a broad range of vehicle speed ranging from 19 to 51 mph.

3.4 Open-Course Studies

3.4.1 Background

The objective of the open-course studies was to utilize the methodologies verified in the closed-course study and apply them to typical conditions at a horizontal curve. The secondary objectives included the following:

- Determine a systematic methodology to trace vehicles through a system of seven z-configured pneumatic road tube setups on the outside lane of the curve
- Investigate the accuracy and effectiveness of video-based data collection compared to pneumatic road tubes for individual speeds and lateral distances
- Plot mean vehicle trajectories and 85th percentile speed profiles from PC to CC and determine statistically significant changes
- Investigate whether equipment presence and the amount of equipment affects driver behavior and when based on the data collected by each type of equipment

A two-lane horizontal curve in Ames, Iowa, was selected as a test site for the open-course study. The horizontal curve provided a safe area for the researchers. It has a radius of 1,146 feet and length of 1,137 feet. The geometry has travel lanes are separated at the CC by a double yellow center line and then diverge with the aid of a painted median to a left turning lane at the PC of the curve, as shown in FIGURE 3-3. The posted speed limit is 45 mph for the outside lane. Countermeasures installed proximate to the horizontal curve include an upstream curve warning sign and chevron alignment signs.

3.4.2 Experiment Design

The study was conducted over a two-weekday time frame using types of equipment, z-configured pneumatic road tubes and a mobile video trailer. The mobile video trailer, as illustrated in the right image of FIGURE 3-3, consists of a four-channel digital video recorder that captures video from two cameras positioned at a lower elevation and two elevated cameras located 30 feet above the ground. Video was captured at 30 frames per second in .mp4 format and stored on internal memory.

The left side of FIGURE 3-3 shows the setup utilized at the horizontal curve. Data were collected and reduced from the PC to the CC in the outside lane using seven sets of z-configured pneumatic road tubes were installed 100 foot intervals. Opposing vehicle traffic was not considered for this experiment. Three days prior to utilizing the seven sets of pneumatic road tubes, baseline data were collected with pneumatic road tubes set up at the PC and CC. The pneumatic road tubes operated for 19 hours and captured both daytime and nighttime traffic. The video trailer was utilized during the daylight hours only and set up at the CC on the gravel shoulder, approximately 4 feet from the edge of the pavement. The video trailer was present at the curve for approximately 6 hours.

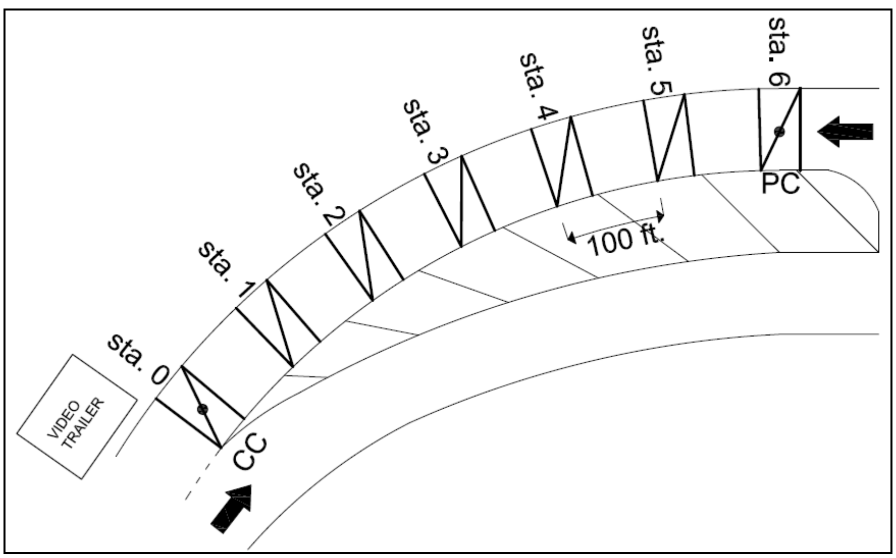

FIGURE 3-3 Open-course setup (left) and digital video trailer at the study site (right)

3.4.3 Road Tube Data Preparation

To be able to trace a vehicle through a set of pneumatic road tubes that is traveling in a platoon, it is important to consider that internal traffic classifiers' clocks are synchronized. However, a vehicle negotiating the curve that is isolated, it is easy to trace a vehicle through the set of pneumatic road tubes if the internal clocks have drifted. Similar to other research studies that utilized traffic classifiers together, this study also noted clock drift over the 19 hours of data collection. Stations 2 and 6, which included two traffic classifiers manufactured during the same time period, experienced a clock drift up to 3 minutes, while the other five traffic classifiers experienced a 10 to 40 second clock drift. Stations 2 and 6 also produced a greater amount of data with errors, and it is suspected that mechanical issues were affecting the data collection process.

Data of interest were extracted using the process described in the previous section. Vehicles were traced through the curve from station to station by aligning the adjusted clock, wheelbase length, speed, and vehicle type. Over the 19 hours of data collection, data for a total of 1,586 vehicles were collected by most of the counters. To be included in the final dataset that would compare vehicle trajectories and speed profiles, a vehicle must have been detected by all seven counters, a condition that brought the total number of vehicles to 1,391. Finally, this data set needed to consist of only free-flowing vehicles. A free-flowing vehicle was defined as having a minimum headway of 5 seconds and a vehicle following headway of 5 seconds. A total of 573 vehicles did not meet this condition, thus yielding a final data set of 818 vehicles, or 58 percent of the original data set.

3.4.4 Digital Video Data Preparation

Two Autoscope AIS cameras located on top of a 30 foot mast above a trailer were utilized for testing specified number of stations. Because two cameras could not monitor seven pneumatic road tube stations, it was decided that Camera 1 would focus a single station at a time and Camera 2 would monitor two stations at a time. A total of 65 vehicles were captured at each station by both cameras, with a target number of 50 vehicles with a headway time greater than 15 seconds for further analysis. A larger headway was selected to limit the interference by adjacent vehicle's shadows and features in the same video frames. A sample size of 653 daytime vehicles that met the headway criteria were manually extracted including vehicles that were deleted from the pneumatic road tube observations. Extraction was performed by creating a scale based on the known lane width of the station, and then the lateral distance was measured off of the front pneumatic road tube at each station, as illustrated in the left image of FIGURE 3-4.

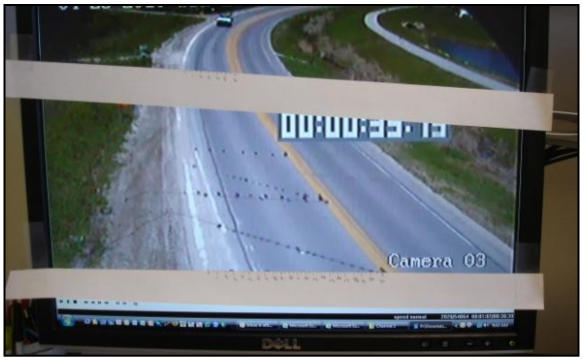

FIGURE 3-4 Manual lateral position reduction (left) and automated speed reduction (right)

The data reduction process proved to be time consuming work; an average of five minutes per vehicle was used to stop the video and take a measurement. The accuracy of the measurements depended greatly on the researcher's best estimate of the outside of the tire, and such variables as vehicle shadows and the estimated time when the vehicle hit the pneumatic tubes needed to be overcome. To verify the distances measured by one analyst, two other analysts also performed the data reduction process, and the results compared using a paired t-test which showed not enough evidence the mean between observers were statistically different.

3.4.5 Data Analysis and Summary

To determine the accuracy of the data collected by the digital video based only on individual vehicle lateral distance, a paired distribution tests were used to evaluate the accuracy of the digital video against the pneumatic road tube data. For comparison purposes, it was assumed that the pneumatic road tubes provided the most accurate measurement short of physically measuring the vehicles during the video data collection process. Data were extracted from the pneumatic road tube set for each video segment, and data sets were created for both cameras. As shown in Table 3-2, two analyses were performed for both Camera 1, which investigated only one station, and Camera 2, which investigated two stations at once.

First, the average difference was determined between the video observations and pneumatic road tube observations. The null hypothesis tested whether the mean difference between observations was zero using a 95 percent confidence level. A Shapiro-Wilk test was performed on the average difference distribution to determine normality, and if the distribution was normal, a two-tailed paired t-test was performed. If the distribution was found to be non-normal, the non-parametric test of matched-pairs Wilcoxon sign rank was performed. This test is equivalent to the paired t-tests, except the test is investigating the shift in distributions based on the change in medians.

As shown in Table 3-2, generally the data collected by the pneumatic road tubes and digital video were normally distributed. However, the p-values for both the parametric and non-parametric tests indicated the changes in means and medians of the distributions to be were significant at the 95 percent confidence level. It should be noted that during the pneumatic road tube raw data reduction a higher than usual error rate was found in the traffic classifiers at Stations 2 and 6. This error is believed to have affected the results presented in Table 3-2; however, further analysis is needed to verify this proposition. Finally, the Camera 2 analysis identified four station observations showing non-normal data distributions, and over half of the station observations' distribution means were found not to be equal. It can be concluded that the video data showed a maximum difference of 3 feet, and the statistical analysis showed overall that the pneumatic road tubes were collecting more accurate lateral distance data.

It should be noted that at least 2 out of every 50 observations in each data set collected by the pneumatic road tubes in the z-configuration were off by more than 2 feet. This finding was confirmed by the video data analysis and error checked in the macro. Further analysis is needed to fully understand this error in the data collection setup.

To determine the accuracy of the data collected by the digital video cameras based only on individual vehicle speed, a matched-pair comparison was used to test the accuracy of the automated vehicle extraction against the pneumatic road tube speed data. Individual vehicle speed data were automatically extracted from the video by use of Autoscope processing software. Two analyses were performed for the present study, including automated speed data collection of 47 observations at a single station and 46 observations each at two stations, as illustrated in the right image of FIGURE 3-4. Tape, to define detection zones, was placed manually on top of the pneumatic road tubes, and the detection area was created based on visual inspection of the camera's viewing area along the curve geometry. The results of the analyses are shown in Table 3-2 and Table 3-3.

The automated vehicle speed detection data were compared to the pneumatic road tube data. The null hypothesis tested whether the mean difference between observations is zero using a 95 percent confidence level. As shown in Table 3-2, the minimum, maximum and average speed differences are quite high. A Shapiro-Wilk test was performed on the average difference distribution and revealed that both cameras' two datasets were not normally distributed. Parametric and non-parametric tests were performed on the observation distributions, and these tests showed that the distribution means between the video data and pneumatic road tube data were not equal. Comparing the two types of equipment in terms of collecting and reducing vehicle speed, the video data automated extraction provided different values for vehicle speeds than the pneumatic road tubes found. It is believed that due to the curve geometry and viewing height of the cameras, it was difficult for the Autoscope processing software to accurately detect vehicles. Further analysis would be needed to confirm this by testing multiple observation angles.

3.4.6 Mean Trajectory and 85th Percentile Speeds

Based on the closed- and open-course studies, pneumatic road tubes in a z-configuration were found to be more accurate for collecting individual vehicle lateral distance and speed data; additionally, other variables of interest could also be extracted from the same data set. Using the free-flowing data set collected by the pneumatic road tubes at the open-course study site and known daylight times, the data were categorized into day and night observations. Additionally, data for the periods when the video trailer was present at the curve during the daytime were separated out. Illustrated in FIGURE 3-5 is the 85th percentile speed for the open-course study site.

As shown in FIGURE 3-5, the posted speed limit for the horizontal curve was 45 mph. Results for three types of equipment are shown, including the baseline: two pneumatic road tubes (shown in dark blue and red with a connected dashed line), seven pneumatic road tubes every 100 feet (shown in dark and light blue), and seven pneumatic road tubes with the video trailer present (shown in green). As illustrated, 85th percentile vehicle speed decreased as vehicles approached the CC (station 0). It can also be shown that, when the data collected with two pneumatic road tubes are compared to the data collected with seven tubes, the number of pneumatic road tubes, as well as with the presence of the video trailer, had an impact on 85th percentile speed. A repeated measures analysis of variance model was created to evaluate the change in overall speed profiles, combining the seven stations. The results of an analysis of variance indicated the change in overall mean between 7 tubes during the day and 7 tubes during the night was not significant at the 90 percent level of confidence. The overall change in mean between 7 tubes during the day and seven tubes with the trailer present was found to be significant at the 90 percent level of confidence. Overall, based on the collected data, it was found that the density of data collection equipment had an effect on driver behavior in terms of the overall decrease in 85th percentile speed, especially near the CC by about 5 mph.

Table 3-2 Analyses of pneumatic road tube and video data evaluating equal means and medians for lateral position

	Station	Sample Size	Difference in Lateral Distance (Oy), ft.			Shaprio-Wilk p-value	Normal	95% Confidence Interval	Parametric	Non-Parametric Test	Reject Null Hypothesis:
			Minimum	Maximum	Averge				Paired t-test p value	Matched-pairs Wilcoxon test p-value	
CAMERA 1: ONE STATION OBSERVATION	**0**	50	0.47	0.89	0.66	0.74	Yes	(0.63, 0.69)	<0.01		**Yes**
	1	44	-0.29	1.70	0.42	<0.01	No	(0.35, 0.45)		<0.01	**Yes**
	2	47	-2.04	0.58	-0.08	<0.01	No	(-0.06, 0.04)		0.73	No
	3	49	-0.25	0.37	0.99	0.98	Yes	(0.29, 0.45)	<0.01		**Yes**
	4	47	-0.26	0.72	0.18	0.69	Yes	(0.12, 0.24)	<0.01		**Yes**
	5	50	-0.99	1.61	0.29	0.13	Yes	(0.17, 0.40)	<0.01		**Yes**
	6	50	-0.95	0.98	-0.07	0.23	Yes	(-0.21, 0.06)	0.27		No

	Station	Sample Size	Difference in Lateral Distance (Oy), ft.			Shaprio-Wilk p-value	Normal	95% Confidence Interval	Parametric	Non-Parametric Test	Reject Null Hypothesis:
			Minimum	Maximum	Averge				Paired t-test p value	Matched-pairs Wilcoxon test p-value	
CAMERA 2: TWO STATIONS e.g. View 1 = sta. 0+1, View 2= sta. 2+1	**0**	51	0.30	0.90	0.58	0.68	Yes	(0.55, 0.61)	<0.01		**Yes**
	1	49	-0.63	0.89	0.04	0.03	No	(-0.03, 0.10)		0.31	No
	1	47	-0.13	0.76	0.22	0.13	Yes	(0.55, 0.61)	<0.01		**Yes**
	2	47	-1.80	0.88	0.01	<0.01	No	(-0.03, 0.12)		0.27	No
	2	49	-2.10	0.50	0.03	<0.01	No	(0.07, 0.18)		<0.01	**Yes**
	3	49	0.16	0.99	0.55	0.46	Yes	(0.49, 0.61)	<0.01		**Yes**
	3	47	-0.93	0.81	0.26	<0.01	No	(0.22, 0.34)		<0.01	**Yes**
	4	47	-0.50	0.57	0.11	0.57	Yes	(0.03, 0.17)	0.18		No
	4	51	-0.44	0.57	-0.05	0.15	Yes	(-0.12, 0.01)	0.10		No
	5	51	-0.61	1.07	0.13	0.40	Yes	(0.01, 0.24)	0.03		**Yes**
	5	49	-0.81	0.98	-0.05	0.41	Yes	(-0.16, 0.5)	0.30		No
	6	51	-0.91	0.41	-0.25	0.88	Yes	(-0.34, -0.16)	<0.01		**Yes**

Note: All values in Table 3-2 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 90 percentile level of confidence

Table 3-3 Analyses of pneumatic road tube and video data evaluating equal means and medians for speed

	Station	Sample Size	Speed, mph			Shaprio-Wilk p-value	Normal	95% Confidence Interval	Parametric	Non-Parametric Tests	Reject Null Hypothesis:
			Minimum	Maximum	Averge				Paired t-test p value	Matched-pairs Wilcoxon test p-value	
Camera 1	**0**	47	0.15	1.87	1.72	0.39	Yes	(-3.33, -0.11)	0.04		**Yes**
Camera 2	**1**	46	-5.12	2.83	-3.97	<0.01	No	(3.01, 5.49)		<0.01	**Yes**
	2	46	1.95	3.64	2.80	<0.01	No	(-3.49, -1.99)		<0.01	**Yes**

Note: All values in Table 3-3 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 90 percentile level of confidence

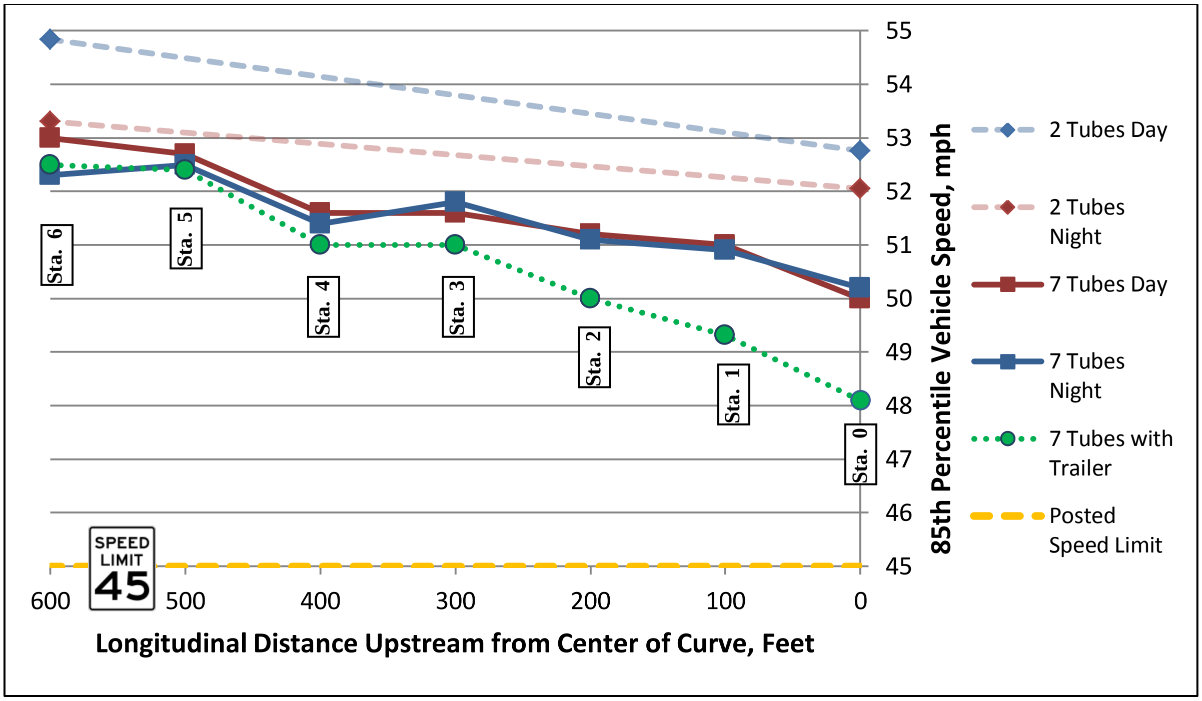

FIGURE 3-5 85th percentile speed profile for combinations of equipment and time of day

Using the same pneumatic road tube data and the time of day variable, normalized mean vehicle trajectories and one standard deviation were plotted along the horizontal curve. FIGURE 3-6 and FIGURE 3-7 illustrate the results of the study. The x-axis is the lateral distance from the edge of the edge line pavement marking (feet), and dark dashed lines is the center of the roadway (normalized to 12 feet for all stations). The y-axis is the longitudinal distance away from the CC, with 0 feet being the CC and 600 feet being the PC, a z-configured road tube setup was spaced at every 100 feet. In both figures, the gray dashed line indicates the vehicle passenger front tire center of the lane. This constant trajectory of 3 feet away from the edge line pavement marking is defined as the path a six foot wide vehicle would travel if it negotiated the horizontal curve exactly in the middle of the 12 foot travel lane.

As shown in FIGURE 3-6, the daytime average lateral distance from the outside pavement marking for all types of equipment deviated from the ideal line towards the center of the roadway. A repeated measures analysis of variance model was created to evaluate the change in overall vehicle trajectories, combining the seven stations. The results of an analysis of variance of that model indicated the change in overall mean between 7 tubes during the day and 7 tubes during the day with the trailer present was significant at the 90 percent level of confidence. Furthermore, it can clearly be seen that vehicles moved closer to the centerline of the roadway as they approached the video trailer

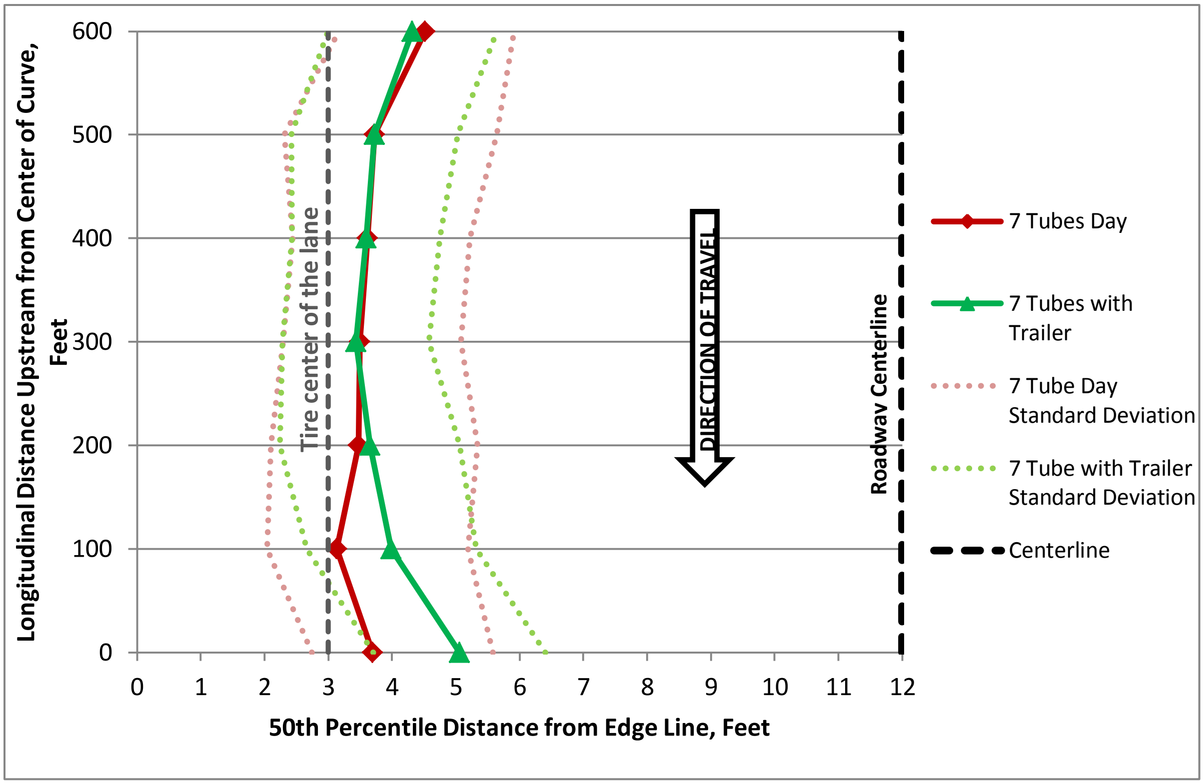

FIGURE 3-6 Mean lateral distance and one standard deviation for daytime hours

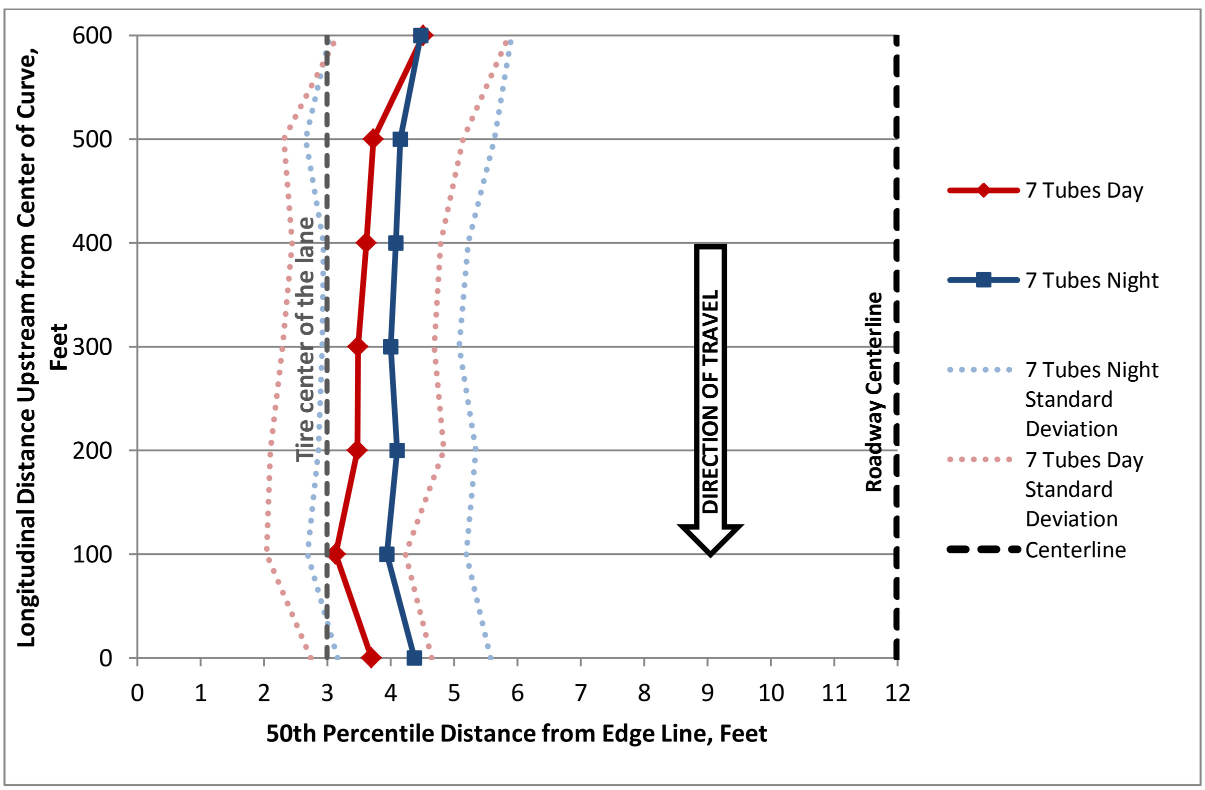

FIGURE 3-7 Mean nighttime versus daytime lateral position for seven pneumatic road tubes

from 200 feet away, as illustrated by the green line. This result shows that the trailer parked on the gravel shoulder affected the lateral position of the vehicles as they traversed the curve.

Illustrated in FIGURE 3-7is a comparison of daytime and nighttime data collected by the seven pneumatic road tubes, with one standard deviation and the passenger tire middle of the lane trajectory. As shown, the average lateral distance of the vehicles at night is closer to the center of the roadway than for vehicles during the daytime. The daytime trajectories were closer to ideal assuming a passenger car is six feet wide. A repeated measures analysis of variance model was created to evaluate the change in overall vehicle trajectories, combining the seven stations. The results of an analysis of variance of that model indicated the change in overall mean between 7 tubes during the day and 7 tubes during the night was not significant at the 90 percent level of confidence. As stated earlier, opposing vehicles and only free-flowing vehicles were not taken into consideration, and most likely the recorded vehicles' trajectories would be somewhat different if these two parameters were included. However, the plots in FIGURE 3-6 and FIGURE 3-7 ultimately show that pneumatic road tubes are an excellent means to collect vehicle operational data and plot vehicle trajectories and speed profiles. FIGURE 3-6 and FIGURE 3-7 also indicate that data collection equipment does alter driver behavior, though further analysis is needed to properly quantify the effects.

3.5 Discussion/Conclusions

This study evaluated two technologies to gather vehicle data to constructed vehicle trajectories and speed profiles. The study evaluated pneumatic road tubes setup in a z-configuration and video data captured by elevated cameras mounted on a mobile trailer. The data were collected on both closed and open-courses. Vehicle lateral position and speed data were recorded. Raw data obtained were processed and quality assurance checks performed to obtain cleaned datasets. The clean datasets were analyzed using parametric and non-parametric statistical tests and the results are as follows.

Two closed-course tests evaluated the accuracy of pneumatic road tubes setup in a z-configuration as compared to physical measurements. Low speeds tests were performed in a parking lot while higher speeds were tests on a closed roadway. The means of the distributions were tested for normality and the results of the paired t-test indicated there was not enough evidence to reject the null hypothesis that the z-configured road tube calculated vehicle lateral position measurements were different than physical measurements. These results demonstrate that both pneumatic road tubes specifically setup in z-configuration as described in this study provide a low-cost, cost effective, and time efficient approach to obtain large volumes of vehicle lateral position data.

The open-course evaluated the accuracy of the z-configured pneumatic road tubes as compared to digital video. Since the pneumatic road tubes were demonstrated to provide a high level of accuracy, manually reduced video data captured at seven stations along a horizontal curve were compared to the lateral position data obtained using road tubes that were recorded simultaneously. A parametric paired t-test (which is valid for data with normal distributions) or matched-pairs Wilcoxon Signed-Rank test (which is valid for data whose distributions cannot be ascertained to be normal) were used to the means of the data. The results of these tests indicated the road tubes provided a higher level of accuracy as compared to the video data. Similar results were found when the video cameras were focused on two adjacent observation stations.

Vehicle speed was also automatically extracted from the video data at both one and two stations and compared to the speed obtained from the pneumatic road tubes. The road tubes provided a higher level of accuracy when the sample distribution means were compared. The results of the study also indicated that pneumatic road tubes provided a higher level of accuracy as compared to video data.

Lastly, this study investigated if vehicles can be traced through a set of pneumatic road tubes to create vehicle trajectories and speed profiles. It was found this could be accomplished quite easily by lining the data up from the road tubes and tracing vehicle using characteristics recorded in the field such as speed, vehicle length, and gap. A significant advantage to using pneumatic road tubes to develop vehicle trajectories and speed profiles is the ability to collect data during nighttime hours with limited energy consumption. Additionally, the data reductions efforts were significantly more cost and time efficient that the video-based data.

A repeated measures analysis of variance test was used to compare vehicle trajectories and speed profiles to evaluate the accuracy of the measurements. The results from this study show that pneumatic road tubes could be used to obtain vehicle speeds, lateral positions along horizontal curves at a high degree of accuracy in a cost effective and time efficient manner. Potential impacts of the data collection equipment on driver behavior were also examined. Although there are indications that the increased presence of the video recording equipment affects driver behavior, it is recommended that additional studies be conducted to further investigate this observation. Also, it was felt that 7 stations (with z-configurations) may affect driver behavior. So, fewer stations would minimize such impacts on driver behavior.

The authors acknowledge that the studies performed in some cases had relatively small sample sizes. This work could be enhanced and that further analyses are needed to quantify the findings. Therefore, caution should be used in applying the results.

3.6 Acknowledgements

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CHAPTER 4. VEHICLE OPERATING SPEED AND LATERAL POSITION MODELS ALONG HORIZONTAL CURVES

A paper prepared for submission to the *American Society of Civil Engineering Journal of Transportation Engineering*

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ABSTRACT

Crashes at horizontal curves are a serious safety problem and represent a significant percent of the total number of highway fatalities in the United States. Previous research studies have suggested that lane departure crashes at horizontal curves are typically single-vehicle run-of-road or cross-centerline crashes in which a driver fails to negotiate the change in alignment through either improper lane position, exceeding the design speed, or other situational factors. The ability to develop a relationship between factors that affect either a crash or successful curve negotiation are complicated and not well understood by researchers.

A large body of knowledge exists that has developed speed prediction models to verify design consistency at horizontal curves. Often, the developed linear models have relied on geometric characteristics; however, limited research has been conducted on traffic, roadway, and environmental characteristics. Very few site-based research studies have investigated vehicle lateral position through a horizontal curve and the effects similar characteristics (roadway, traffic, and environment) have on lane keeping.

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The research project developed a procedure to construct vehicle trajectories and speed profiles at horizontal curves using pneumatic road tubes to capture vehicle data. Important traffic parameters, such as opposing vehicle presence, type of vehicle, and platoon position, were extracted from the data. Using vehicle speed and lateral position at the point of curvature, vehicle speed and lateral position at subsequent stations through the horizontal curve were estimated using a linear model.

4.1 Introduction

Roadway departure crashes comprise a significant percentage of the total number of highway crashes and the majority of fatal crashes in the United States. The Federal Highway Administration (2009) reported that 53 percent of all fatal crashes are due to vehicles departing the roadway, and 40 percent are single-vehicle run-off-road crashes. American Association of State Highway and Transportation Officials (AASHTO) reported that 42 percent of lane departure crashes occur at horizontal curves, and 50 percent of those are in rural areas (AASHTO, 2008). Torbic et al. (2004) reported that over 25 percent of the total number of fatal crashes in 2004 occurred at horizontal curves. Other studies have reported that crashes on horizontal curves are 1.5 to 4 times higher than on tangent sections (Staplin et al., 2001; Neuman, 1992). However, driver behavior and the interaction between variables that affect driver behavior through curves is complicated and not well understood.

Campbell et al. (2008) explained that drivers are expected to complete important tasks between the point of curvature and the center of the curve to successfully negotiate the curve. Staplin et al. (2001) reported that failure to control vehicle speed prior to and within the horizontal curve and lack of awareness in the sudden change in roadway geometry can certainly lead to drifting and possible departure from the travel lane. Stimpson et al. (1977) concluded that speed and longitudinal shift in lateral distance were the two most sensitive indicators of hazard at horizontal curves. Ruediger et al. (1988) stated that abrupt deviations in consistent operating speeds because of horizontal alignment on rural roads are the leading cause.

Drivers negotiating horizontal curves are influenced by many factors, including vehicle, environment, roadway characteristics, and prevailing traffic conditions. Many previous studies have developed prediction models to understand vehicle speed in terms of horizontal curve design consistency which have found various cross-sectional and overall geometric features to be significant parameters. Similarly, very limited numbers of research studies have developed models that have investigated vehicle lateral position within a horizontal curve. Many of these studies are also constrained by the number of sites selection, sample size, and in some cases not having the ability to construct trajectories and speed profiles due to equipment constraints.

Although many speed prediction models and a limited number of vehicle lateral position models have been developed as a method to validate design consistency, a significant gap exists in the body of knowledge that relates the two variables along with other traffic and roadway characteristics in a prediction model. This study adds to the understanding of how different types of vehicles negotiate horizontal curves and how traffic and environmental conditions affect prediction models. Understanding these characteristics is important as design engineers, vehicle manufacturers, and policymakers predict potentially hazardous situations and design appropriate lane departure countermeasures, develop improved vehicle control systems, and set appropriate speed limits.

4.2 Literature Review

4.2.1 Vehicle Operating Speed Models at Horizontal Curves

Despite a large body of knowledge that has investigated and developed speed prediction models at horizontal curves, much should still be investigated. Research studies have relied on a variety of explanatory data and various collection methodologies under varying conditions and geometry. Researchers have studied rural isolated horizontal curves, horizontal curves in a series along a two-lane highway, and horizontal curves located in an urban setting. Radar guns and laser units are the most common devices used to collect vehicle speeds at horizontal curves, with research assuming that driver behavior is not compromised by the use of this equipment. However, research studies have found human bias in data collecting and recording with wave-emitting devices used to collect vehicle operational data (McFadden and Elefteriadou, 2000; Misaghi and Hassen, 2005). Almost all of the data collection occurs at the point of curvature (PC), center of the curve (CC), and point of tangency (PT), along with points upstream and downstream on tangent section.

Speed prediction models at horizontal curves generally follow the same format in utilizing an ordinary least squares (OLS) linear regression model, which assumes a linear relationship between explanatory variables and a dependent variable (Figuroa Medina and Tarko, 2005). Research studies have relied mainly on dependent variables, such as the expected vehicle 85^{th} or 95^{th} percentile operating speed at the center of the curve, the predicted change in 85^{th} percentile speed between the tangent section and the midpoint of the curve (transition zone), or the predicted 85^{th} percentile speed within the curve using upstream tangent speed data. However, many studies have relied on small sample sizes and in many cases a limited number of sites.

Krammes et al. (1995) developed an 85th percentile speed model for horizontal curves using 138 sites in five states. Vehicle data were collected using a radar gun at the upstream tangent, midpoint of the curve, and downstream tangent with at least 50 paired observations. Significant parameters found to affect the predicted speed percentile included degree of curvature, curve length, deflection angle, and the 85th percentile speed upstream of the curve. Multiple research studies have built on the developed model using the same data and found other significant parameters, including approach grade (Fitzpatrick et al. 2003), that direction of travel (Ottesen and Krammes, 2000), and superelevation (Voigt and Krammes, 1996). Speed prediction models at horizontal curves have also been developed for other vehicle classes. Leisch and Leisch (1977) and Donnell et al. (2001) found that the predicted operating speeds of trucks at horizontal curves were affected by the performance of the truck in relationship to geometric parameters, specifically the vertical alignment. These studies found grade and length of the approach and departure tangents to be significant along with curve radius when only studying trucks.

Islam and Seneviratne (1994) found that vehicle speeds differ significantly at different locations within the horizontal curve, based on data collected at 8 Utah horizontal curves. Three 85th percentile speed models were developed for the PC, CC, and PT points of the curve. They found the radius of the curve to be the only significant parameter. It was concluded that the larger the curve radius above eight degrees, the larger the difference in predicted speed between models. Similar results were found by Poe and Mason (2000) in which three models developed to predict vehicle speeds at the PC, CC, and PT found that as the degree of curvature increases, the predicted speed decreases, with the large decrease predicted to occur at the CC.

Other researchers have suggested an OLS regression model prediction power may be hindered. Figueroa Medina and Tarko (2004) developed models based on the entire collected speed distribution, and the dependent variable was either mean speed or a specific percentile speed at horizontal curves sites in Indiana. The models included an OLS-pane data model and generalized least squares (GLS) random effects model. Similar to previous research studies, geometric characteristics of the curve were found to be significant parameters. An increase in the degree of curvature predicted a lower operating speed at the horizontal curve, and increases in superelevation rates were found to lower the speed deviation along the horizontal curve.

4.2.2 Vehicle Lateral Distance Models at Horizontal Curves

Very limited research has been conducted to investigate vehicle lateral placement within a horizontal curve. Generally, vehicle lateral placement is defined as the lateral distance from the edge of the roadway pavement to the passenger side of the vehicle with the equipment collecting data from the outside lane of the roadway. Numerous research studies in a before-and-after design have relied on capturing vehicle lateral distance at or near a horizontal curve safety countermeasure to determine effectiveness (Chrysler et al., 2009; Krammes and Tyer, 1991; Donnell et al., 2006). Vehicle average lateral shift is compared using statistical tests rather than by developing a statistical model. Many research studies have relied on site-based data collection strategies to collect natural lateral position, including video, pneumatic road tubes, and piezo strips. However, Poe (1996) stated that careful consideration of the type of equipment should be made to minimize changes in driver behavior. Closed course studies using test subjects have also used instrumented vehicles with video cameras monitoring the rear wheels in relationship to the center and edge lines (Stodart, 2006; Miles, 2010).

Research has also developed vehicle trajectories at horizontal curves by tracing vehicles through a set of data collection stations using a variety of data collection methodologies, including video, pneumatic road tubes, and infrared equipped delineator posts. Previous research has suggested that drivers do not have the ability to steer the vehicle through properly designed horizontal curves. This results in the driver having to negotiate the horizontal curve that is less than the design radius to prevent lane departure. This action results in encroachment towards the inside of the curve in both directions. (Stimpson et al., 1977; Glennon et al., 1985; Segal et al., 1980; Felipe and Vain, 1998). Similar conclusions were found by Spacek (1998) in which he stated that vehicles demonstrated a “cutting behavior” trajectory in both the inside and outside lanes at rural Swiss horizontal curves. The author utilized infrared delineator posts along seven horizontal curves to collect, project, and classify vehicle trajectories into six distinct classifications. Additionally, only weak relationships could be found between a vehicle’s trajectory classification within the horizontal curve and such dependent variables as speed, historical crashes, and lateral acceleration through the horizontal curve.

Stodart (2006) investigated vehicle lateral position during nighttime conditions on a closed course in Pennsylvania using an instrument vehicle test. Vehicle lateral distance was captured using video cameras mounted over the rear tires with a clear view of the edge and centerline. An OLS regression model was developed to predict the vehicle lateral position at the center of the curve. Driver age, approach tangents less than 300 meters, vertical grade, the direction of travel, and previous curve radius were all found to be significant. Park et al. (2003) developed an OLS regression that predicted the 85th percentile of the cumulative lane deviation distribution in South Korea using digital video. The authors found curve deflection angle and maximum speed difference between the tangent section and horizontal curve to be significant.

The literature review identified several efforts to develop vehicle speed prediction models on horizontal curves. Many of these studies rely on limited sample sizes and large site selection. The current state-of-practice includes developing linear models to predict vehicle 85th percentile speeds to verify design consistency. These are based on a single vehicle type and roadway geometric features within and upstream of a horizontal curve. The literature review also revealed limited research on vehicle lateral position modeling and site-based data collection beyond observing and classifying vehicle paths through horizontal curves. There is a need to develop models for vehicle speed and lateral position along horizontal curves based on broader considerations such vehicle, roadway, and environmental characteristics at multiple points within the curve. Such models would provide better understanding of vehicle operations within horizontal curves based on curve entry characteristics. An approach to address this need is presented herein.

4.3 Empirical Setting

4.3.1 Site Selection

Data were collected at two horizontal curve sites located in central Iowa. This study was limited to two-lane horizontal curves with standard Manual on Uniform Traffic Control Devices (MUTCD) safety enhancements. Both sites included curve ahead warning signs in both directions and chevron alignment signs located on the outside lane of the curves. The first study site, as illustrated in FIGURE 4-1, was located on State Highway 925 near Dexter, IA. The rural isolated two-lane horizontal curve included straight tangent approach sections greater than 3 miles. Both directions of travel within the curve were separated by no-passing and one-lane allowed passing pavement markings, and lane widths ranged from 10.6 to 11.2 feet, with greater lane widths found on the outside lane. As-built plans reported the following curve characteristics: the curve radius was 682.8 feet; the roadway had steep embankments on each side, and paved and gravel shoulders were two feet wide. The posted speed limit for both directions of travel was 55 mph. This horizontal curve site was selected for evaluation based on numerous characteristics that included a rural setting on a farm-to-market route, smaller curve radius, reduced sight distance around the curve, and also its high-profile fatal crash reputation in the community. The curve was found to also exhibit mixtures of vehicle classes throughout the day that included a high number of school buses, various heavy vehicles, motorcycles, and inexperienced drivers, with a high school located close by.

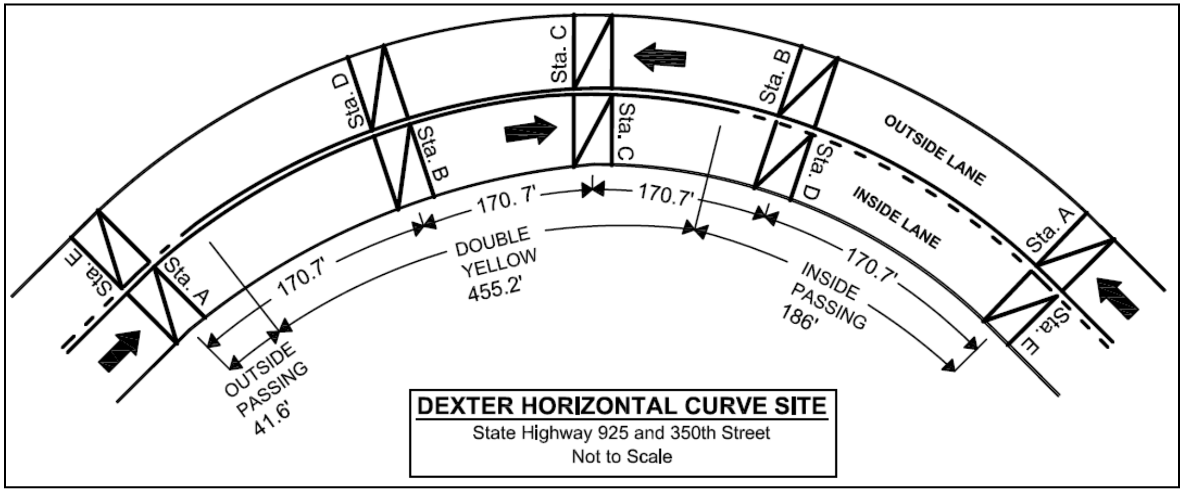

FIGURE 4-1 Z-configured road tube location and pavement marking distance for Dexter, IA study site

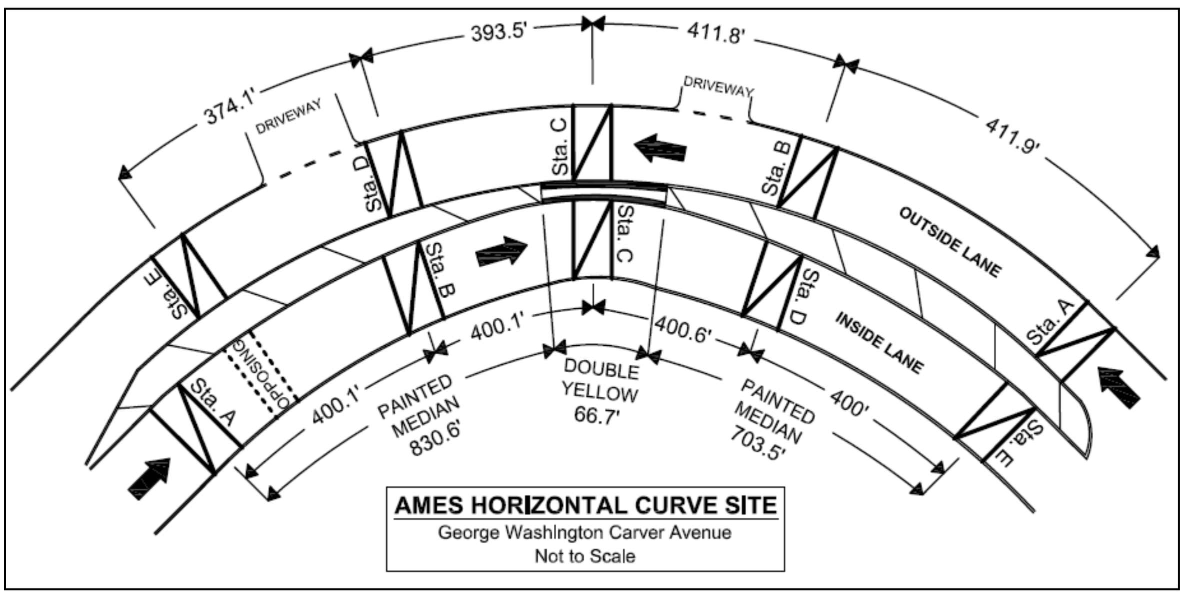

FIGURE 4-2 Z-configured road tube location and pavement marking distance for Ames, IA study site

The second horizontal curve site, as illustrated in FIGURE 4-2, was located on George Washington Carver Avenue in Ames, IA. This urban two-lane horizontal curve included two intersections located at the both the point of curvature (PC) and point of tangency (PT) that lead into dense residential housing developments. Both lanes were separated by a converging painted median to a no-passing pavement marking at the center of the curve. Lane widths were measured at between 10.2 and 13 feet, with wider lanes found on the outside lane of the curve. The inside lane consisted of a curb and gutter, and the outside lane included two private driveways located adjacent to the center of the curve with gravel shoulders. As-built plans reported the curve radius to be 1,600 feet. The curve was widened in 2002 to accommodate the addition of left-turning lanes into growing housing developments at both intersections. The posted speed limits were 45 mph for both the inside and outside lane, and chevron alignment signs were located on the outside lane. This location was selected because it exhibited high commuter traffic volumes during the morning and evening peak hours, which provided vehicle platoon data. In addition, no signalized intersections were in the vicinity of the curve site that may have affected traffic flow into or out of the curve.

4.3.2 Data Collection Protocol

Data were collected during the summer months, and no adverse traffic conditions were reported or found that would have affected normal traffic operations. Time-stamped data were collected in one direction at a time at each horizontal curve site for at least 70 hours using pneumatic road tubes set up in a z-configuration. The reason such an extended period of time was used to collect data was to account for any unusual occurrence that could not be controlled. The pneumatic road tubes were stretched across the lane to the centerline and adhered to the roadway using mastic tape in dry pavement conditions. The setup included two parallel tubes spaced 16 feet apart perpendicular to the roadway with a third tube stretched diagonally at a 45 degree angle between the two tubes. Setting up a road tube at a 45 degree angle can lead to misfires in the data collection process because of the unstable air inside the angled tube only, which results in unneeded time-stamped data. Each traffic classifier’s dead time setting for the diagonal road tube was adjusted down to compensate for this error. The road tubes were checked once a day to ensure that no dramatic movement occurred in the diagonal tube, that tube tension remained tight, and that all five traffic classifiers were detecting vehicle axles in each of the road tube sets.

As illustrated in FIGURE 4-1and FIGURE 4-2, a total of five equally spaced data collection stations (Sta.) were defined at each curve site based on the length of the curve and known PC and PT points. It was believed that utilizing five stations could accurately capture any significant movement within the lane and sudden changes of vehicle speed without significantly affecting driver behavior. Station A (Sta. A) was located at the PC, Sta. C was located at the CC, and Sta. E was located as close to the PT as possible. As illustrated in FIGURE 4-2, adjustments to the location of the data collection stations were made to accommodate private driveways and physical features.

In addition to the five stations through the horizontal curve, vehicle operational data without lateral distance data were collected in the opposing direction across of Sta. E for each direction using two perpendicular tubes adhered to the roadway and spaced 8 feet apart. An example of where the opposing pneumatic road tubes were located is illustrated in FIGURE 4-2 with dashed lines.

4.4 Description of Data/Data Reduction Process

Before a meaningful analysis of the collected data could be performed, the data at each site had to be downloaded, interpolated, joined, and screened to isolate observations that included potential disturbances. The time-stamp data were downloaded from all of the traffic classifiers using Jamar's Trax Pro software, and the data were reduced using various methods as described in the following section.

4.4.1 Extracted Variables

In the direction of data collection, individual vehicle characteristics from each set of two perpendicular tubes spaced 16 feet apart were extracted using Trax Pro software. These variables included individual vehicle speed, number of axles, gap, class, length, time of day, and the direction of travel. Similar data were also recorded from the pneumatic road tubes spaced 8 feet apart in the opposing lane. The smaller road tube spacing was utilized in the opposing lane since a diagonal tube to determine vehicle lateral distance was not needed because vehicle lateral position or its trajectory in the opposing lane was not taken into consideration in this study.

Along with extracting vehicle data from two perpendicular road tubes at each station, time-stamped data from all three road tubes in the direction of data collection was evaluated without Trax Pro. Time-stamped data are recorded data points of when a vehicle's axle (perpendicular tube) or individual tire (diagonal tube) hit the road tube. Using an excel macro written by the Texas Transportation Institute (Johnson, 2008) and customized for curve data collection applications by researchers at Iowa State University, individual vehicle lateral distance could be determined. Since both described data reduction processes utilized the same time-stamped dataset, road tube data collection errors could easily be identified. These errors included vehicles traveling over 100 mph or a calculated lateral position greater than the lane width, which was not possible since the pneumatic road tubes stretched to the center of the lane.

An intensive screening process of the data included developing a methodology to trace vehicles through the horizontal curve using the data from the traffic classifiers. Vehicles were traced through the set of five traffic classifiers utilizing each vehicle's recorded physical features rather than time due to errors identified in clock synchronization. These features included the length, speed, gap, and numbers of axles between sets of data. It was found that the traffic classifiers collected similar data for each vehicle which allowed each vehicle to be traced quickly and identify when a traffic classifier did not detect a vehicle. For a vehicle to be considered for the final data set, all five counters had to detect the vehicle. If a single or a set of counters were unable to accomplish this, the vehicle data were removed from the dataset. Overall, between 16 and 18 percent of the potential total number of vehicles were discarded due to this screening process.

The traffic classifiers reported both vehicle class and vehicle length. Trax Pro uses the Federal Highway Administration (FHWA) 13-vehicle classification scheme to identify vehicle type based on wheelbase length (FHWA, 2001, 2004). Additionally, a 14^{th} classification in which the software package could not recognize the vehicle was reported as "unknown." Vehicles that were classified as "unknown" in the dataset were found to have missing axle hits in the time-stamped data. The 13 vehicle classes used by the software package were aggregated into four vehicle classes for this study: motorcycle, passenger car, school bus, and truck. A free-flowing vehicle was defined as having a headway and tailway gap greater than or equal to five seconds. Vehicles with a headway gap time of less than five seconds were traveling in a platoon. These vehicles were assigned a number based on their following position behind the lead vehicle of the platoon. To properly assign platoon number, discarded vehicles in the initial screening process were kept in the database temporarily to assign proper platoon position before being discarded.

Another interpolated variable from opposing lane data collection effort was determining the number of opposing vehicles experienced within the horizontal curve by the direction of data collection. Since only one data collection station was setup in the opposing lane, the entry time into the curve was recorded; however, it was unknown when the opposing vehicle exited the curve. To determine the exit time, the opposing lane curve length was used and the vehicle's speed was recorded at the point of entry. A safe assumption was made that each opposing vehicle's speed remained constant through the length of the curve, and the exit time was determined. The opposing vehicle's entry and exit times were compared to the vehicles traveling in the direction of data collection. Two variables were determined from this comparison. These included whether a vehicle traveling in the direction of data collection experienced an opposing vehicle within the horizontal curve and how many opposing vehicles it experienced between the curve entry and exit times.

To determine if the pavement was wet within the curve, rain data were extrapolated from an Iowa state-wide precipitation model developed by the Iowa State University Department of Agriculture and the Iowa Environmental Mesonet. This model is based on data collection stations around the state. Five-minute intervals were extrapolated from the model based on the days the road tubes collected the data and the latitude and longitude of the center of the horizontal curve.

A database of 24,210 vehicle trajectories and speed profiles along with roadway and traffic characteristics was created based on the data collected at both sites and in both directions of travel. This number represented approximately 91 percent of the total potential number of vehicles collected in the field. For this study and developed associated models, only vehicle operational data, environmental conditions, and opposing vehicle characteristics will be utilized. As described in the literature review, geometry has been found to be a significant parameter in previous models. However, geometry will not be utilized due to the limited number of horizontal curve sites. Table 4-1offers a summary of data collected at both sites and in both directions of travel.

As shown in Table 4-1, a balanced number of vehicles were collected at both sites and in both directions. Passenger cars were found to be the dominating vehicles collected; however, the number of motorcycles, school buses, and trucks were also found to be high.

4.5 Results of the Analysis

In the following analysis, it was hypothesized that vehicle curve entry speed and lateral position could serve as independent variables to predict vehicle speed and lateral position at subsequent stations along the curve. It was also hypothesized that the type of vehicle, roadway, and environmental changes also affect driver behavior and also contributes to prediction power of the developed model. Unlike many previous research studies, it was assumed that a relationship existed between speed and lateral position within the curve. Vehicle's lateral position and speed at stations B through E served as the dependent variables for each of the developed models. These dependent variables were selected for two reasons. First, predicting speed and lateral position through the curve can provide design engineers potential guidance on countermeasure selection and placement. Secondly, vehicle manufacturers would be interested in the prediction power of the models for a vehicle entering a horizontal curve and automatically determining if a control system is needed if the predicted speed or lane position exceeds the achieved design standards.

Table 4-1 Vehicle database descriptive statistics

Independent Continuous Variables	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Sta. A vehicle lateral distance (in)	27.5	15.5	-18.5	111.2
Sta. A vehicle speed (mph)	48.0	6.3	13.0	80.0
Number of Opposing Vehicles	1	1	0	11
Vehicle Length (in)	128	68	48	835
Position in Platoon	0.6	1	0	10
Independent Categorical Variables	**Observations**			
	Yes (1)	**No (0)**		
Location	11,200	12,940		
(1 = Dexter (rural); 0 = Ames(urban))				
Lane	12,814	11,326		
(1 =Inside; 0 = Outside)				
Opposing Vehicle	13,006	11,134		
Motorcycle	148	23,992		
Passenger Car	22,329	1,811		
School Bus	156	23,984		
Truck	1,507	22,930		
Time of Day	7,400	16,740		
(1 = Night; 0 = Day)				
Free Flowing	15,472	8,668		
Wet Pavement	1,234	22,906		
Dependent Variables	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Sta. B vehicle lateral distance (in)	27.4	17.9	-26.5	123.9
Sta. C vehicle lateral distance (in)	28.6	17.9	-20.1	137.7
Sta. D vehicle lateral distance (in)	30.8	18.8	-22.6	134.7
Sta. E vehicle lateral distance (in)	45.9	26.9	-23.5	135.9
Sta. B vehicle speed (mph)	48.0	5.3	18.0	79.0
Sta. C vehicle speed (mph)	47.0	5.2	12.0	78.0
Sta. D vehicle speed (mph)	48.0	5.5	19.0	81.0
Sta. E vehicle speed (mph)	47.0	6.3	11.0	81.0

Note: All values in Table 4-1 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

4.5.1 Linear Regression

Ordinary Least Squares (OLS) method was used to fit several linear models that represent the effects explanatory variables have on a dependent variable in a cause-and-effect relationship. The OLS method was used to develop linear regression models based on variables shown in Table 4-1. Numerous assumptions are made when developing a linear regression model and the OLS method involves several properties that must hold true to develop an optimal model. These include no admitted variables, serial correlation, heteroskedasticity, endogeneity, and multicollinearity (Washington et al., 2003). The general form of the OLS linear regression models developed for this study was of the following structure:

$$Y_{Speed(i)} = \alpha_0 + \sum_{k=1\ to\ p} \alpha_k X_{ik} + \varepsilon_i \quad (4\text{-}1)$$

$$Y_{Lateral\ Position(i)} = \beta_0 + \sum_{k=1\ to\ p} \beta_k X_{ik} + \varepsilon_i \quad (4\text{-}2)$$

Where $Y_{Speed(i)}$ *and* $Y_{Lateral\ Position\ (i)}$ are speed and lateral distance dependent variables at Sta. *i* (B through E), α_0 and β_0 is the constant term, α_0 and β_k are the regression parameters to be estimated based on the dependent variable, X_{ik} is the explanatory variable, and ε_i is the normally distributed disturbance term. A stepwise technique was utilized for model development by initially inserting all possible independent variables and eliminating variables that were not significant at the 95 percent confidence level.

The only categorical variable in the model development process was "vehicle type," which included vehicle classes: motorcycles, passenger cars, school buses, and trucks. PROC GLM in SAS was used to compute Type III F-values to test whether the model fit the data significantly better than the same model excluding the categorical variable "vehicle type." If this test proved to be significant, the reduced model was significantly improved by adding the variable "vehicle type." Including this categorical variable resulted in a less-than-full-rank model. Therefore, a restriction was imposed where it was defined that the effect of the vehicle type "truck" be set at zero. Truck was referred to as the baseline parameter.

The t-statistic computed for an estimate of a vehicle type regression coefficient tests for a difference between the effect of the particular vehicle and truck, given what is already explained in the model. Although not all of these tests reveal a significant difference, the information does not warrant combination of vehicle types. Furthermore, it does not negatively affect the prediction power of the models. The arbitrary choice of the baseline parameter could be chosen such that significance tests would give different information. For this research study, the horizontal curve sites were evaluated separately, resulting in a model for a rural condition and a model for an urban condition.

4.5.2 Operating Speed Prediction Models

Table 4-2 explains the speed prediction models for Sta. B through Sta. E based on the lateral position and speed at Sta. A for Dexter, IA (rural isolated curve). The resulting coefficients of determination were high, indicating that between 74.6 and 94.4 percent of the variability could be explained by the independent parameters. This was determined to be accurate in that the prediction power of the model decreased as models were developed further away from the entry point of the curve. Similarly, the standard deviation of the expected value increased as models were developed through the curve with values between 1.3 and 2.7 mph.

The models described in Table 4-2 also were found to have logical explanations for the effect of each independent variable on the predicted vehicle speed at each station. It was found between Sta. B and C that the presence of opposing vehicles lowered the expected speed. At the end of the curve, it was found that vehicles traveling in a platoon also were expected to have a lower speed. Throughout the curve, it was found that vehicles were expected to travel at a higher speed at night and at a lower speed in the inside lane.

Vehicles other than in the baseline truck condition showed an expected speed increase with the exception of the motorcycles at Sta. B, which is most likely due to curve discovery and adjustments prior to the center of the curve. In general, it is expected that trucks will traverse the rural horizontal curve slower due to their size and need for increased accuracy in lane keeping. Vehicle length was found to be a significant parameter at three of the four stations, which meant that the longer the wheelbase, the higher was the expected speed. However, the estimate at each of the stations was very small.

Table 4-3 explains the speed prediction models for Sta. B through Sta. E based on the lateral position and speed at Sta. A for Ames, IA (urban horizontal curve). The resulting coefficients of determination were lower than on the rural curve, with the independent variables being able to explain between 23.9 and 70.7 percent of the variability. The standard deviation of the expected value also increased as models were developed through the curve and ranged between 2.5 to 3.1 mph. It is hypothesized that the intersections at either end of the horizontal curve affected the prediction power of the model with vehicles suddenly increasing and decreasing speeds; however, the effects were not quantified.

The models described in Table 4-3 resulted in an overall lower goodness of fit compared to the models in Table 4-2. Unlike Table 4-2, the models explained that vehicles were expected to have lower speeds at night, vehicle wheelbase length predicted lower speeds, and vehicle type was not found to be significant. Similar to Table 4-2, vehicle speeds were also expected to be lower in the inside lane, with the presence of opposing vehicles, and when traveling in a platoon. Wet pavement conditions at stations B and C showed to decrease the expected speeds at the stations, which showed that wet pavement does affect speed. Finally, vehicles that were traveling through the curve and were considered free flowing were found to have a higher expected speed.

Table 4-2 Vehicle operating speed prediction models for Dexter, IA (rural horizontal curve site)

	Dependent Variables							
	V_B		V_C (CC)		V_D		V_E (PT)	
Significant Parameters	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Constant	0.8197		3.4217		5.7103		8.3948	
Opposing Vehicles Present	-0.0597	0.0470	-0.0880	0.0386	.	.	.	.
Motorcycle[b]	-0.1233	0.3993	0.1322	0.5055	1.0284	<0.0001	1.7560	<0.0001
Passenger Car[b]	0.0959	0.0680	0.1554	0.0364	0.2134	0.0211	0.0896	0.2999
School Bus[b]	0.3261	0.0060	0.5485	0.0011	0.6255	0.0028	0.7358	0.0025
Vehicle Length (in)	0.0005	0.0034	0.0007	0.0028	0.0009	0.0041	.	.
Time of Day	0.2324	<0.0001	0.4314	<0.0001	0.5932	<0.0001	0.6486	<0.0001
Platoon Position	.	.	.	.	-0.1200	<0.0001	-0.1728	<0.0001
Lane	-0.4953	<0.0001	-1.0563	<0.0001	-0.8047	<0.0001	-0.1313	0.0126
Lateral Position at Sta. A (PC)	0.0048	<0.0001	.	.	0.0046	0.0138	.	.
Speed at Sta. A (PC)	0.9658	<0.0001	0.9008	<0.0001	0.8712	<0.0001	0.8306	<0.0001
Goodness of Fit Measures								
R^2	0.9441		0.8809		0.8160		0.7465	
Root Mean Square Error (mph)	1.3302		1.8829		2.3428		2.7384	

Note: All values in Table 4-2 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

[a]V_{si} = predicted operating speed at a specific station along the curve (mph)

[b]Baseline condition is a truck

Table 4-3 Vehicle operating speed prediction models for Ames, IA (urban horizontal curve site)

	Dependent Variables							
	V_B		V_C (CC)		V_D		V_E (PT)	
Significant Parameters	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Constant	13.2840		22.1754		26.8339		30.3385	
Opposing Vehicles Present	-0.0384	0.0035	0.3106	0.0010	0.2930	0.0053	.	.
Number of Opposing Vehicles	.	.	-0.1005	<0.0001	-0.1130	<0.0001	-0.1223	<0.0001
Wet Pavement	-0.2141	0.0240	-0.2543	0.0486	.	.	.	.
Free-Flowing Vehicle	0.8710	<0.0001	1.0050	<0.0001	1.0126	<0.0001	0.7331	<0.0001
Vehicle Length (in)	.	.	.	.	.	.	-0.0038	0.0112
Time of Day	-0.4554	<0.0001	-0.5377	<0.0001	-0.4755	<0.0001	-0.7878	<0.0001
Platoon Position	0.1872	<0.0001	.	.	-0.2121	0.0001	-0.5277	<0.0001
Lane	.	.	-2.2839	<0.0001	-4.5375	<0.0001	-4.1209	<0.0001
Lateral Position at Sta. A (PC)	0.0218	<0.0001	0.0225	<0.0001	0.0229	<0.0001	0.0149	0.0007
Speed at Sta. A (PC)	0.6425	<0.0001	0.5250	<0.0001	0.4620	<0.0001	0.3899	<0.0001
Goodness of Fit Measures								
R^2	0.7072		0.4650		0.4200		0.2395	
Root Mean Square Error (mph)	2.5811		3.4765		3.8596		5.3100	

Note: All values in Table 4-3 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence
[a]V_{si} = predicted operating speed at a specific station along the curve (mph)

4.5.3 Lateral Position Predilection Models

Table 4-4 explains the lateral position prediction models for Sta. B through Sta. E based on the lateral position and speed at Sta. A for Dexter, IA (rural isolated curve). The resulting coefficients of determination ranged between 22 and 74.1 percent. As shown, the R-squared value increases at Sta. D and then decreases significantly at Sta. E. One hypothesized explanation for this is when the vehicle mean trajectories were plotted for the inside lane, a sudden positive lateral movement was found between stations D and E, most likely due to sudden changes in horizontal alignment exiting the horizontal curve. The standard deviation of the expected value increased as models were developed further away from Sta. A, which ranged from 10.94 to 14.19 inches.

The models described in Table 4-4 were found to have logical explanations for the effects of each independent variable on the predicted vehicle lateral position. As described previously, the dependent variable is measured from the white edge line pavement marking to the passenger-side front tire. A positive value in each direction means the vehicle is moving towards the center of the roadway. However, a negative value would suggest that the passenger-side front tire is expected to travel outside of the lane on the shoulder. It was found for the Dexter, IA, site that lateral position is expected to be lower with the presence of opposing vehicles near the center of the curve. Wet pavement at Sta. D was found to be significant, which also lowered the predicted lateral position. At night and in the inside lane, vehicles were found to encroach the center of the roadway. Motorcycles and passenger cars were also found to travel closer to the center of the roadway as compared to trucks; however, school buses were found to travel closer to the edge line than trucks.

Table 4-5 explains the lateral position models for Sta. B through Sta. E based on the lateral position and speed at Sta. A for Ames, IA (urban horizontal curve). The resulting coefficients of determination were found to be lower than on the rural curve, with a range between 27.9 and 41.6 percent. The root-mean-square error was also found to be larger, with a range between 10.6 to 21.6 inches. Similar to the hypothesis related to the lower goodness of fit of the speed prediction models, it was also assumed that vehicle turning onto the curve or decelerating from the curve to turn at the intersections at both ends of the horizontal curve affected the results of the analysis.

The models described in Table 4-5 are similar to Table 4-4 in that the significant parameters made logical sense in affecting the dependent variable estimation. Opposing vehicles and the number of opposing vehicles at stations B through E showed to lower the predicted lateral placement. Similarly, vehicles traveling at night and in the inside lane were shown to have a higher predicted lateral position.

Table 4-4 Vehicle lateral position prediction models for Dexter, IA (rural horizontal curve site)

	Dependent Variables							
	LP_B		LP_C (CC)		LP_D		LP_E (PT)	
Significant Parameters	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Constant	-3.1490		5.8070		2.4490		15.9910	
Number of Opposing Vehicles	.	.	-0.5592	0.0251	-0.5377	0.0130	.	.
Motorcycle[b]	6.0546	<0.0001	19.8307	<0.0001	22.2128	<0.0001	31.2952	<0.0001
Passenger Car[b]	0.5291	0.1268	1.3374	0.0046	1.5476	0.0002	1.5189	0.0007
School Bus[b]	-2.3883	0.0143	-3.1553	0.0173	-1.9493	0.0898	-3.5930	0.0045
Time of Day	1.1918	<0.0001	3.9852	<0.0001	5.0947	<0.0001	5.1354	<0.0001
Wet Pavement	.	.	.	.	-1.4307	0.0306	.	.
Lane	13.6172	<0.0001	14.9881	<0.0001	25.8321	<0.0001	-1.4905	0.0002
Lateral Position at Sta. A (PC)	0.7356	<0.0001	0.5143	<0.0001	0.4111	<0.0001	0.3477	<0.0001
Speed at Sta. A (PC)	0.0981	<0.0001	.	.	0.0507	0.0195	0.1749	<0.0001
Goodness of Fit Measures								
R^2	0.7413		0.5327		0.6873		0.2209	
Root Mean Square Error (inches)	10.9429		14.8892		12.9056		14.1906	

Note: All values in Table 4-4 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence
[a]LP_{si} = predicted lateral position from edge line at a specific station along the curve (inches)
[b]Baseline condition is a truck

Table 4-5 Vehicle lateral position prediction models for Ames, IA (urban horizontal curve site)

	Dependent Variables							
	LP_B		LP_C (CC)		LP_D		LP_E (PT)	
Significant Parameters	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Constant	8.9015		18.5803		16.6082		57.9925	
Opposing Vehicles Present	.	.	.	.	.	.	-1.6506	0.0049
Number of Opposing Vehicles	-0.2998	<0.0001	-0.3243	<0.0001	-0.4620	<0.0001	.	.
Motorcycle[b]	23.4942	<0.0001	23.8942	<0.0001	28.0125	<0.0001	29.6719	<0.0001
Passenger Car[b]	1.4315	0.0235	2.1988	0.0005	1.4514	0.0178	5.9996	<0.0001
School Bus[b]	-4.0406	0.1803	-0.9378	0.7557	0.7484	0.8223	-1.9214	0.7944
Wet Pavement	.	.	1.3100	0.0009	.	.	13.2793	<0.0001
Free-Flowing Vehicle	.	.	.	.	.	.	1.6161	0.0008
Vehicle Length (in)	-0.0126	0.0003	-0.1516	<0.0001	.	.	.	.
Time of Day	.	.	2.1672	<0.0001	2.5692	<0.0001	7.7141	<0.0001
Platoon Position	-0.4330	<0.0001	.	.	-0.3599	0.0003	.	.
Lane	9.6180	<0.0001	10.3649	<0.0001	4.3602	<0.0001	-33.7020	<0.0001
Lateral Position at Sta. A (PC)	0.3995	<0.0001	0.3057	<0.0001	0.3392	<0.0001	0.1692	<0.0001
Speed at Sta. A (PC)	0.0791	<0.0001	-0.0736	<0.0001	0.0587	0.0008	.	.
Goodness of Fit Measures								
R^2	0.4161		0.3834		0.2404		0.2799	
Root Mean Square Error (inches)	10.6615		10.6545		11.8090		26.1356	

Note: All values in Table 4-5 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence
[a] LP_{si} = predicted lateral position from edge line at a specific station along the curve (inches)
[b] Baseline condition is a truck

However, it was also shown that at Sta. E the expected lateral distance would be less, which is most likely due to the transition from the curved alignment to the tangent alignment. Similar to the rural curve, motorcycles and passenger cars were expected to travel closer to the centerline as compared to trucks and school buses. Furthermore, for the vehicles traveling in a platoon and as vehicle wheelbase length increased near the center of the curve, the lateral position of the vehicle was expected to move towards the edge line. Free-flowing vehicles at Sta. E were expected to have a higher lateral position, and vehicles negotiating the curve while the pavement was wet at the center and end of the curve were expected to have a higher lateral position.

4.6 Discussion/Conclusions

Crashes at horizontal curves are recognized as a serious safety concern, especially in rural areas. The relationship between driver, vehicle, roadway, and environmental factors are complex. The driver must make critical decisions to safely negotiate the curve, including maintaining proper lane position, maintaining speed, and identifying the changes in roadway alignment. These decisions are required at various points from the entry point to exit point of the curve. Previous research developed speed prediction models primarily as a way to verify design consistency. Such efforts relied almost exclusively on horizontal curve geometry and cross-sectional data at a limited number of points. Limited research has been documented in the literature on investigations of the relationship between vehicle operating speed and lateral position within the lane. Site-based and non-site-based research studies have suggested that drivers have several possible reasons for path deviation along a horizontal curve, including such variables as speed choice, comfort, vehicle dimensions, driver education, weather, and time of day.

Two horizontal curves in central Iowa were selected to conduct field observations for the study. One curve was in a rural site and the other was at an urban site. Data on vehicle speeds and lateral positions were recorded at five stations along each curve in both the inside and outside lanes of travel separately. Pneumatic road tubes in z-configurations were used to collect data. The presences of vehicles in the opposing lane were identified. Speed and lateral position data for 24,410 vehicle observations were recorded. A series of linear models were developed to predict vehicle speed and lateral position along the horizontal curves based on the vehicle's speed and lateral position at the entry point to the curve. Ordinary least squares method was used to fit linear models along the curve using a stepwise technique. Table 4-6 provides a summary of the speed and lateral position models for the rural and urban sites. The table identifies the level of statistical significance of the variables.

Table 4-6 shows that most of the variables were significant in all of the models. Vehicle type, time of day, and travel lane were significant in many, or if not all, of the models for speed and lateral position at both sites. Motorcycles, passenger cars, and school buses were found to have a higher expected speed than trucks, and motorcycles and passenger cars were expected to have a greater lateral deviation in lane position. Vehicle speeds were noted to be higher during nighttime hours as was the deviation in lateral position. Finally, vehicles traveling in the outside lane had a lower speed and greater lateral deviation than the inside lane.

Table 4-6 Significant variables at rural and urban sites, their signs that indicate effects on the dependent variables, and if significant in all models along the curve

	Speed		**Lateral Position**	
Variable	**Rural**	**Urban**	**Rural**	**Urban**
Motorcycle[c]	+/-[a]	.	+[a]	+[a]
Passenger Car[c]	+[a]	.	+[a]	+[a]
School Bus[c]	+[a]	.	-[a]	-[a]
Time (Dark)	+[a]	-[a]	+[a]	+[b]
Traveling Outside Lane	-[a]	-[b]	+[a]	+/-[a]
Lateral Position at Sta. A	+[b]	+[a]	+[a]	+[a]
Speed at Sta. A	+[a]	+[a]	+[b]	+/-[b]
Number of Opposing Vehicles	.	-[b]	-[b]	-[b]
Pavement is Wet	.	-[b]	-[b]	+[b]
Vehicle is Free-Flowing	.	+[b]	.	+[b]
Opposing Vehicle Present	-[b]	+/-[b]	-[b]	-[b]
Vehicle Length	+[b]	-[b]	.	-[b]
Vehicle is in a Platoon	-[b]	.	.	-[b]

[A]Variable is significant in all models along the curve at study site at the 95 percent confidence level
[B]Variable significant in some, but not all models along the curve at study site at the 95 percent confidence level
[c] Baseline condition is a truck

Overall, as may be expected, the coefficient of determination decreased as for models further downstream from the point of curve entry. However, the root-mean-square error was found to slowly increase with increase in distance from the PC, around a realistic standard deviation suggesting that the prediction power of the model was still adequate. It is therefore recommended that future studies explore the use of adding data from stations other than that at the PC to develop.

Agencies faced with limited highway safety funding are tasked with selecting appropriate and economical countermeasures for horizontal curves. The findings of this research provide information to support safety studies and selection of appropriate countermeasure at horizontal curves. Instead of selecting a blanket countermeasure that meets costs limits, the models developed provide decision makers information to select appropriate countermeasure and utilize highway safety funds. If for example the mean trajectories for the outside lane indicated encroachment or crossing the centerline, centerline rumble strips would be an appropriate choice over shoulder rumble strips. Similarly, if the mean speed profile indicated vehicle in the inside lane exceeding the posted speed limit through the curve at night, target enforcement, lower the posted speed limit, or posting curve advisory speeds may be an appropriate countermeasure.

This exploratory analysis was intended to provide preliminary insights regarding key vehicle, roadway, and environmental factors that affect vehicle speed and lateral position on horizontal curves. While previous studies developed models that estimate the 85^{th} percentile vehicle speed (mostly based on small sample sizes), this study was more extensive. Speed and lateral position data were collected for more than 24,000 vehicles at multiple stations within the horizontal curve. Both the inside lane and the outside lane were considered. This study also evaluated some important variables such as the effect of vehicles in the opposing lane, vehicles traveling in a platoon along the curve, multiple vehicle classes, and if the pavement was wet or dry. These have not been addressed in previous studies. Finally, the large sample size developed in this study is significantly larger than those used in other studies. Previous research studies have relied on small sample sizes at many curve sites ranging between 50 and 200 passenger cars or trucks. However, the current study was limited by the number of study sites and it is recommended that future studies include more than a single rural and urban curve site. This is to potentially include in the model other geometric design factors such as curve radius and length of curve.

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CHAPTER 5. ANALYSES OF VEHICLE TRAJECTORIES AND SPEED PROFILES ALONG HORZIONTAL CURVES

A paper prepared for submission to the 91st Annual Meeting of the Transportation Research Board and consideration for publication in *Transportation Research Record*

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ABSTRACT

A significant number of highway crashes occur at horizontal cures. Previous research has suggested that the crash rates on horizontal curves are three to four times higher than those on tangent sections. Many of these crashes are single-vehicle run-off-road crashes which are the result of drivers departing the travel lane either via the shoulder or centerline of the roadway. Vehicle speed and lane position are two of the many possible factors that lead to such crashes. Thus, Vehicle trajectory and speed through horizontal curves are of great interest to many areas of traffic engineering including countermeasure design, design consistency, and policy.

This paper discusses the results of an exploratory analysis of vehicle trajectories and speed profiles at two horizontal curves in Iowa. The sites included an urban and rural curve. Data were collected at five stations within the curve in both directions using pneumatic road tubes setup in a z-configuration.

Overall, vehicles were found to cut the horizontal curve in both the inside and outside travel lanes. However, the trajectories were seen to be different between the curve sites. Vehicle mean speed profiles found that vehicles at the rural curve site decelerated prior to the center of the curve and accelerated past the center of the curve. Speed deviations of individual vehicles as they traversed the curve were evaluated. More vehicles were found to adjust their speeds and lateral position in the vicinity of the center of the curve, and then at the end of the horizontal curve. Other physical characteristics such as the horizontal curve geometry and the presence of intersections proximate to the study site possibly influenced the results.

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5.1 Introduction

Vehicle crashes at horizontal curves are a serious safety concern. Most crashes at horizontal curves are single-vehicle run-off-road or cross-centerline type crashes. These are often the result of drivers failing to adjust vehicle speeds and trajectories to account for changes in horizontal alignment. Torbic et al (2004) reported that roadway departure crashes at horizontal curves were about three times higher those that on tangent sections. A five year crash analysis performed by the Michigan Department of Transportation (1979) found the highest number of crashes and fatalities occurred in the outside lane of horizontal curves when the vehicle departed the roadway towards the outside. The FHWA reports that crashes on horizontal curves stem from a combination of factors including the inability to adjust the vehicle's speed prior to the horizontal curve and exceeding the design speed within the curve which results in a potentially dangerous trajectory (Staplin et al. 2001). Other studies have suggested that traffic conditions and weather are significant factors in crashes at horizontal curves (Shanker et al. 1995; Milton and Mannering, 1998).

This paper presents the results of an exploratory investigation in which vehicle trajectories and speed profiles were evaluated at two horizontal curves in central Iowa. Data were collected using low-cost pneumatic road tubes. Specifically, this study investigated changes in vehicle speed and lateral deviation as an integral part of the trajectory and speed profile within the horizontal curve. The study also investigated the differences between passenger cars and heavy vehicles. Previous studies have noted the need to study differences operational characteristics at horizontal curves (Leische and Leisch, 1977; Donnell et al., 2001).

5.2 Relevant Literature

5.2.1 Site-Based Vehicle Trajectory Projection

Vehicle lateral position is the location of a vehicle within the travel lane with respect to the edge line or centerline of the roadway. A vehicle trajectory consists of traces of a vehicle along a segment of a roadway based on multiple vehicle lateral position observations over the segment. Limited efforts are noted in the literature to investigate vehicle trajectories using site-based data collection equipment as compared to instrumented vehicles. Glennon (1971) developed a relationship between horizontal curve radii, observing 500 vehicle radii every 20 feet captured at five marked horizontal curves outside of College Station, Texas using a video camera mounted to a chase car. It was concluded that vehicles were cutting the horizontal curve by tracing a path with a radius less than the actual curve radius. Similar results were found by Segal and Banney (1980) by calculating the mean vehicle path through three high-crash horizontal curves in New York.

A study conducted by the Swiss Federal Police Department (Arbeitsgruppe Verkehrssicherheit, 1980) investigated driver behavior at horizontal curves at night under different levels of roadway illumination. Part of the investigation included development of possible trajectories vehicles took at horizontal curves in the inside lane. These trajectories included "swinging", "drifting", "cutting" and "correcting". The researchers found most drivers followed the cutting trajectory at larger radii curves and correcting trajectory type at smaller radii.

Spacek (1998) further investigated vehicle trajectories at seven two-lane horizontal curves in Switzerland. This study specifically investigated how vehicles negotiate horizontal curves by collecting, projecting, and classifying vehicle trajectories. Additionally, the study investigated if any significant relationships existed between trajectories and other factors such as crash history, lateral acceleration, and speed profiles could be found. Six distinct trajectory classifications were identified: "ideal", "normal", "correcting", "cutting", "swinging", and "drifting". A seventh classification "other" was defined in the study as any trajectory not falling into one of the six classifications. Horizontal curves selected in this study had radii between 65m and 200m (213 feet and 656 feet). Data were collected at five locations within the horizontal curve and two locations 30m (100 feet) upstream and downstream of the horizontal curve. Spacek only investigated passenger cars with a set vehicle width of 5.90 feet. In the seven curves studied, five outside lanes and four inside lanes were investigated and the sample size for each lane ranged between 90 and 206 vehicles.

Data were collected using up to 12 ultrasonic equipped delineator posts at 7 defined stations. Based on the defined classifications and the sample size, Spacek was able to classify between 50 and 80 percent of the vehicles. The proportion of vehicle trajectories that fell into "other" was between 23 and 60 percent. "Cutting" and "normal" were found to be classifications with the highest number of trajectories in both directions. Additionally, no clear relationships could be found between trajectory classification and crash history or geometry. Spacek suggested other factors may influence the vehicle trajectory including sight distance, curve geometry, warning signs, opposing vehicle traffic, traffic volume within the curve.

Other research studies have also used vehicle trajectories to evaluate countermeasure effectiveness. Charlton (2007) investigated the changes in vehicle trajectories in New Zealand through horizontal curves using a driver simulator to test various treatment options. The data were aggregated and an overall analysis showed that drivers in the outside lane moved towards the centerline of the roadway while drivers in the inside lane moved towards the inside edge line of the curve. Similar results were found in studies conducted by Emmerson (1969) and Segal and Banney (1980).

5.2.2 Site-Based Vehicle Speed Profile Projection

A vehicle speed profile, similar to a vehicle trajectory traces an individual vehicle's speed as it traverses a segment of roadway. A review of the literature found that vehicle speed profiles have be utilized in a variety of traffic engineering applications including signal coordination, countermeasure before-and-after studies, and roadway design consistency analysis.

Hassen (2002) developed speed profiles for both lanes at three horizontal curve sites in Canada. Data were collected at three stations within the curve and two stations outside of the curve on the approach tangents. Sample sizes ranged from 5,494 to 14,258 with over 89 percent of the total sample from all three sites having only two axles. Speed changes due to vehicles type and ambient lighting were compared. The author found the speeds through the curves were not dependent on ambient lighting, and two-axle vehicles had a higher operating speed. The author cautioned about comparing two-axle vehicles to mutli-axle vehicles because of lower sample sizes. Charlton (2007) investigated vehicle mean speed profiles at horizontal curves using a driver simulator. Six horizontal curve scenarios were developed with four types of countermeasures and advance warning signs tested for each scenario using a small group of participants. It was found that advance warning signs did not significantly reduce mean speed. However, the addition of shoulder rumble strips to each scenario did produce a statistically significant reduction in mean speeds.

Ottesen and Krammes (2000) developed speed profile models for estimating reductions in the 85th percentile speeds on long tangents and within horizontal curves as a feedback loop for design consistency of rural highways with design speed less than 62.1 mph. Data were collected at 138 horizontal curves on 29 rural highways in five states using a radar gun at the midpoint of the horizontal curve and at tangent sections. A linear model was developed with degree of curvature, length of curvature, and deflection angle as statistically significant variables. It was found that the 85th percentile speeds on the inside and outside lanes were not significantly different at most curves. It was also found that the 85th percentile speeds on horizontal curves with degrees of curvature equal to or less than 4 degrees did not differ significantly from the 85th percentile speeds on tangent sections. Further investigating speed profiles as a tool to explain vehicle speed reduction between tangent section and horizontal curve, Figueroa Medina and Tarko (2007) found that 66% of vehicle speed reduction and 72% of vehicle speed acceleration occur only on the tangent sections before and after a horizontal curve. This was based on 1,606 vehicle observations at 10 Indiana curve sites.

The literature review identified limited efforts to develop and analyze vehicle trajectories and speed profiles from site-based studies. The literature documents prior efforts to trace vehicles through horizontal curves and classify their paths into six categories. However, such efforts have not fully investigated and reported where maximum deviations in speed and lateral position occur within the curve the. Additionally, most had small sample sizes (under about 300 vehicle observations) and they studied passenger cars and trucks separately. Thus, there is a need to conduct more extensive evaluations based on significantly larger sample sizes, and to compare operations of passenger cars and heavy vehicles (e.g., trucks).

5.3 Empirical Setting

5.3.1 Site Selection

One urban and a rural curve site were selected for investigation for this exploratory analysis. Crash history and roadway geometric characteristics were not taken into consideration and the research focused on selecting two sites with varying traffic conditions. The urban curve site had to be close to an incorporated area without the influence of a traffic signal. The site selected was located in Ames, Iowa bordering two residential areas. It was also on a primary commuter route to and from Iowa State University during the peak hours. The rural curve site had to be isolated, located on a two-lane state highway or paved secondary roadway, and at least 4 miles outside of an incorporated area. The site selected was located near Dexter, Iowa and was considered a farm-to-market route which provided higher truck volumes.

A 2009 traffic count showed the average daily traffic (ADT) at the urban curve site was 4,380 vehicles. The curve has a radius of 1,600 feet. The posted speed limit was 45 mph and advance warning signs were located in both directions upstream of the curve. Chevron alignment signs were located on the outside of the curve which met MUTCD requirements. This curve included two intersections located close to the point of curvature (PC) at each end of curve leading into a residential area. These intersections included left turning lanes with a 13 foot wide painted median at both ends of the curve. These converged into a no passing pavement marking for 66 feet at the center of the curve. There was also a curb and gutter located on the inside lane and there were no sight distance restrictions.

The rural horizontal curve site 2008 traffic count showed an ADT of 1,830 vehicles and the posted speed limit was 55mph. It also had a high school was located within three miles of the site. This curve had limited sight distance and a radius of 682.8 feet. Advance warning signs were located upstream of the curve and chevron alignment signs were located outside of the curve. Steep embankments were present on each side of the curve and a 2 foot paved shoulder was located on the edge of both directions of travel. A no passing double yellow line was present for three-quarters of the length of the curve, and a passing allowed marking for the inside lane was present between the center of the curve (CC) and the point of tangency (PT) for the inside lane.

5.3.2 Data Collection Protocol

The strategy used to construct and evaluate vehicle trajectories at horizontal curves was based on previous research that utilized site-based equipment to collect vehicle lateral position at both curves and tangent sections (Miles et al. 2006; Mahoney et al. 2003; Chrysler et al. 2009; Cottrell, 1986). The equipment selected for data collection was pneumatic road tubes. Data were collected in each direction of travel separately at five equally spaced stations within the curve between the PC and PT. Stationing began at the PC with “Station A” (Sta. A) and ended at the PT with “Station E” (Sta. E).

Each station consisted of three pneumatic tubes attached to a traffic classifier that recorded the time-stamp when each axle of the vehicle crossed the tube. A z-configuration setup was utilized which included two perpendicular tubes spaced 16 feet apart stretched tightly between the centerline and edge line of the roadway. Between the two perpendicular tubes, a third tube was stretched across the lane to the centerline at a 45 degree angle. Data were collected between 70 and 100 hours at each site and included both weekday and weekend days. The pneumatic road tubes and roadway sections were checked every 24 hours to ensure no physical damage or tube lateral movement had occurred.

5.3.3 Data Description/Data Reduction

Time-stamped vehicle data were downloaded from the traffic classifiers using the manufacturer’s software to a .csv file. Multiple steps were performed to extrapolate, trace, and screen the data to identify outliers, errors, and potentially unrealistic conditions.

Variables were extracted from the two perpendicular tubes utilizing the software package provided by the traffic classifier’s manufacturer. These included vehicle length, speed, and class. Vehicle length ranged from 50 inches to 853 inches and the software interpreted these lengths and classified each vehicle as part of the FHWA’s 13 vehicle classification scheme (FHWA 2001, 2004). Along with the 13 classes of vehicles, a 14 class was also included which was termed “unknown” based on recording errors. Four classes of vehicles were utilized for this study which included combining various classes of the original 13 FHWA classes. The initial four classes used included motorcycles, passenger cars, school buses, and trucks.

Vehicle lateral position for this study was the distance measured from the inside of the white edge line pavement marking to the vehicles outside front (passenger side) tire. This was determined for each vehicle using a series trigonometric functions based on the time-stamp for each tire crossing each of the tubes. A macro written by the Texas Transportation Institute (Johnson, 2008) was modified and customized for this study. It was used to apply the trigonometric function to each vehicle's data so as to identify errors which were the result of inaccurate time stamps, vehicles traveling over 100 mph, and lateral distances measured past the distance the tubes were stretched.

A vehicle was considered valid for this study if it could be traced through the five traffic classifiers (i.e. stations A to E). Between 16 to 20 percent of the potential number of vehicles were removed from the dataset because a complete trace could not be found. A total of 24,410 observations were recorded at the two curve sites in both directions. Table 5-1 provides summary statistics for both curve sites including vehicle mean speed, 85th percentile speed, and mean lateral position at each station in both directions of travel.

5.4 Projection of Trajectories and Speed Profiles

To visually illustrate the lateral position data at each of the horizontal curve sites (as shown in Table 5-1) for all classes of vehicles combined, trajectories of the location of the passenger front tire were plotted. FIGURE 5-1 and FIGURE 5-2 illustrate the trajectories for both the inside and outside lanes at each curve site. Additionally, one standard deviation of the distribution is shown which represents where 68.2 percent of the observations were observed. As shown in both figures, the centerline of roadway is the dashed vertical line at 11 feet. The center of lane tire position is the dashed vertical line at 2.5 feet. The travel lane was 11 feet wide and the center of the travel lane was located at a lateral position of 5.5 feet. If a conservative average vehicle width of 6 feet is assumed, and the passenger front tire would then be at 2.5 feet from the edge line.

As shown in FIGURE 5-1, vehicles enter the horizontal curves at station A towards the outside of the travel lane. Between stations D and E at both curves, vehicles were found to move towards the centerline of the roadway. This may be because near the end of each horizontal curve drivers are identify the end of the curve and reposition the vehicle towards the center of the lane into the tangent section. Another possibility is that drivers at this point of the curve recognized their lateral position was unsafe or had overcorrected within the curve and needed to reposition the vehicle prior to exiting the curve. Additionally, it can be clearly seen at both curves that drivers cut the curve in the inside lane.

Table 5-1 Vehicle class observations, mean speed, and lateral position at each station and study site

OUTSIDE LANES

Study Site	Dexter Site								Ames Site							
Vehicle Type →	Motorcycles		Passenger Cars		School Buses		Trucks		Motorcycles		Passenger Cars		School Buses		Trucks	
Number of Observations →	60		4,087		56		512		29		6,383		6		197	
	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th
Sta. A Speed *(mph)*	51.4	55.4	50.2	55.9	50.9	55.2	51.7	57.0	48.0	54.7	47.2	52.6	43.8	49.1	46.6	51.8
Sta. B Speed *(mph)*	50.4	55.4	49.2	55.1	49.5	53.6	50.4	56.1	49.2	56.7	47.7	52.3	44.6	48.6	47.3	51.8
Sta. C Speed *(mph)*	48.8	53.2	47.9	53.4	48.4	51.4	48.9	54.2	47.5	53.6	45.8	50.5	42.9	47.2	45.4	49.5
Sta. D Speed *(mph)*	50.9	55.3	49.2	54.6	49.7	52.8	50.0	55.6	46.8	56.3	45.0	49.8	42.3	47.1	44.7	48.6
Sta. E Speed *(mph)*	52.9	58.2	50.1	55.4	50.4	53.4	50.8	56.7	46.0	54.8	44.0	49.0	41.7	46.9	43.7	47.9
Sta. A Mean Lateral Position *(inches)*	80.9		39.0		23.1		32.5		64.1		37.0		37.2		32.8	
Sta. B Mean Lateral Position *(inches)*	78.2		44.8		32.2		39.9		71.1		36.0		23.5		31.7	
Sta. C Mean Lateral Position *(inches)*	85.5		42.9		31.9		38.0		68.2		37.6		35.2		33.0	
Sta. D Mean Lateral Position *(inches)*	92.7		49.5		38.2		43.6		73.6		37.8		42.9		34.3	
Sta. E Mean Lateral Position *(inches)*	82.4		39.8		28.9		33.7		71.0		40.2		37.4		36.1	

INSIDE LANES

Study Site	Dexter Site								Ames Site							
Vehicle Type →	Motorcycles		Passenger Cars		School Buses		Trucks		Motorcycles		Passenger Cars		School Buses		Trucks	
Number of Observations →	60		4,087		56		512		29		6,383		6		197	
	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th	Mean	85th
Sta. A Speed *(mph)*	47.7	51.5	50.6	56.0	50.5	54.0	50.3	55.5	44.3	46.6	44.4	49.8	36.9	44.3	43.7	49.7
Sta. B Speed *(mph)*	46.9	50.4	49.9	55.2	50.1	53.1	49.7	54.6	43.9	47.2	45.8	50.4	40.1	45.8	45.5	50.5
Sta. C Speed *(mph)*	46.5	50.5	49.2	54.5	49.6	52.7	49.1	53.9	44.1	46.4	46.5	51.3	42.2	47.2	46.5	50.9
Sta. D Speed *(mph)*	48.9	53.3	50.1	55.4	50.2	53.3	49.9	54.9	45.4	48.0	48.2	53.1	42.6	47.3	48.2	52.8
Sta. E Speed *(mph)*	49.5	53.1	50.4	55.6	51.0	54.0	50.3	55.5	46.7	48.9	47.1	52.8	41.7	46.5	46.6	52.9
Sta. A Mean Lateral Position *(inches)*	41.7		13.4		4.9		12.5		67.5		23.3		18.7		23.8	
Sta. B Mean Lateral Position *(inches)*	72.1		12.5		1.7		10.8		55.7		20.8		15.0		18.5	
Sta. C Mean Lateral Position *(inches)*	46.5		14.8		3.8		12.6		57.5		22.9		13.3		19.4	
Sta. D Mean Lateral Position *(inches)*	37.0		12.9		5.4		11.6		66.5		28.0		23.9		27.3	
Sta. E Mean Lateral Position *(inches)*	71.9		31.9		22.7		31.4		88.9		71.1		53.7		62.1	

Note: All values in Table 5-1 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

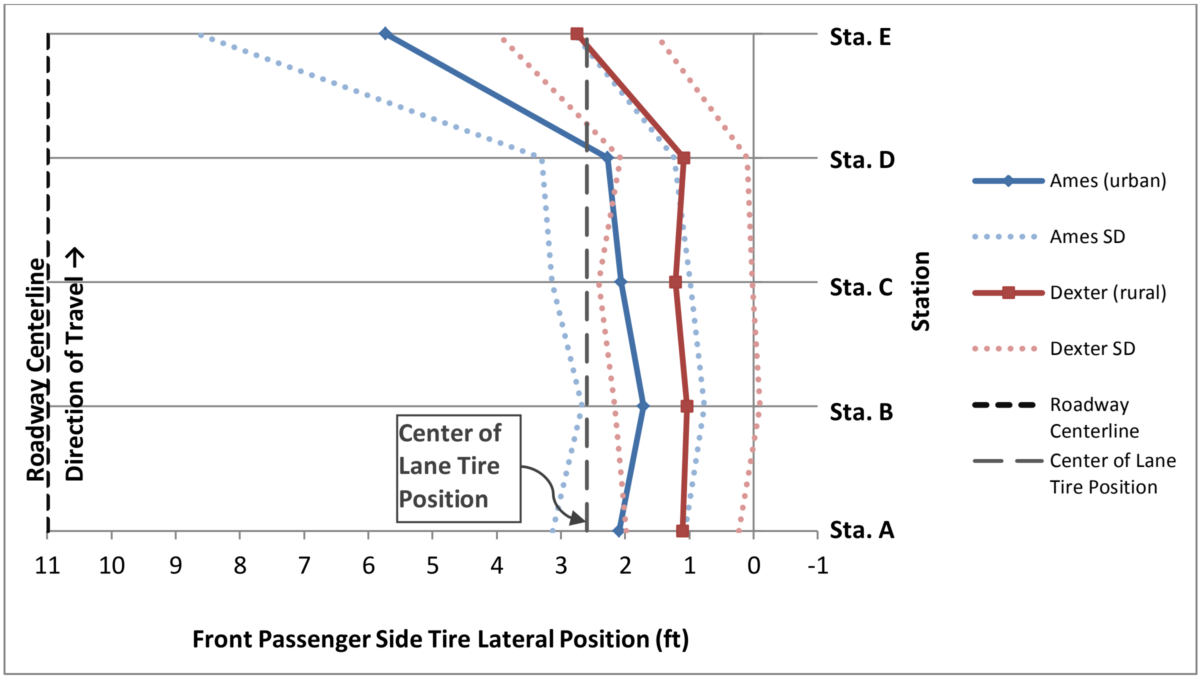

FIGURE 5-1 Inside lane mean vehicle trajectories

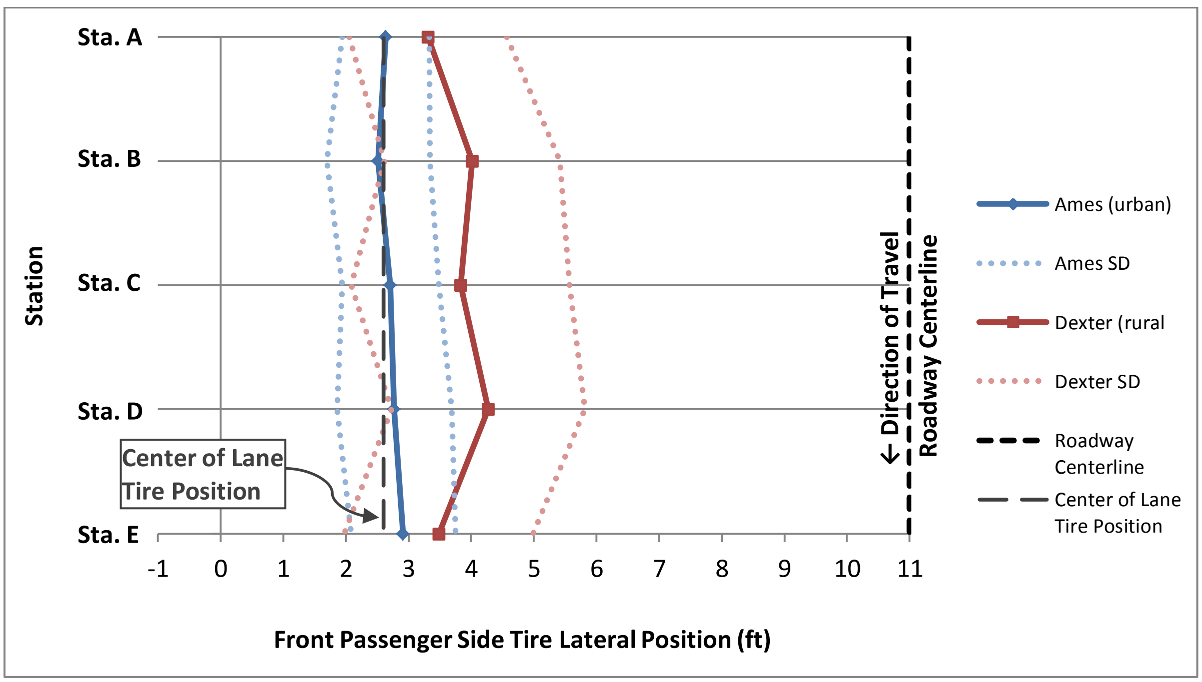

FIGURE 5-2 Outside lane mean vehicle trajectories

FIGURE 5-2 shows the outside lane trajectories for both horizontal curve sites. As shown, the vehicle trajectory for the Ames curve site followed the center of the lane with a slight deviation towards the centerline of the roadway near Sta. E. The trajectory for vehicles at the Dexter site clear shows vehicles traveling closer to the centerline of the roadway. One important aspect FIGURE 5-2 shows is that drivers the standard deviation of the Dexter curve site. As previously stated, the vehicle width was assumed to be 6 feet and the lane widths were normalized to 11 feet. The driver's left side of the vehicle would cross the centerline if the lateral position of the front outside tire was found to be greater than 5 feet. As shown, many vehicles at the Dexter curve site crossed this 5 foot lateral position between stations B and E. However, it was found that drivers appeared to recognize the end of the horizontal curve and lateral position was shifted towards the center of the lane between stations D and E. This indicates a "cutting" trajectory.

FIGURE 5-3 and FIGURE 5-4 illustrate the speed profiles for each horizontal curve site. They show both the mean speed profile and the 85th percentile speed profile for both the inside and outside lanes. As illustrated in FIGURE 5-3, the overall mean speed profile at the Dexter site was found to be below posted speed limit of 55 mph. The overall mean speed at the Ames site was found to be above the posted speed limit of 45 mph. The inside lane of the Dexter site clearly shows a drop in the average within the horizontal curve until the center of the curve, and increasing after that point. Such change in speed has also been reported in past research studies that have investigated rural isolated curve. However, the speed profiles shown for the inside lane at the Ames site show an increasing trend with a slight decrease between stations D and E.

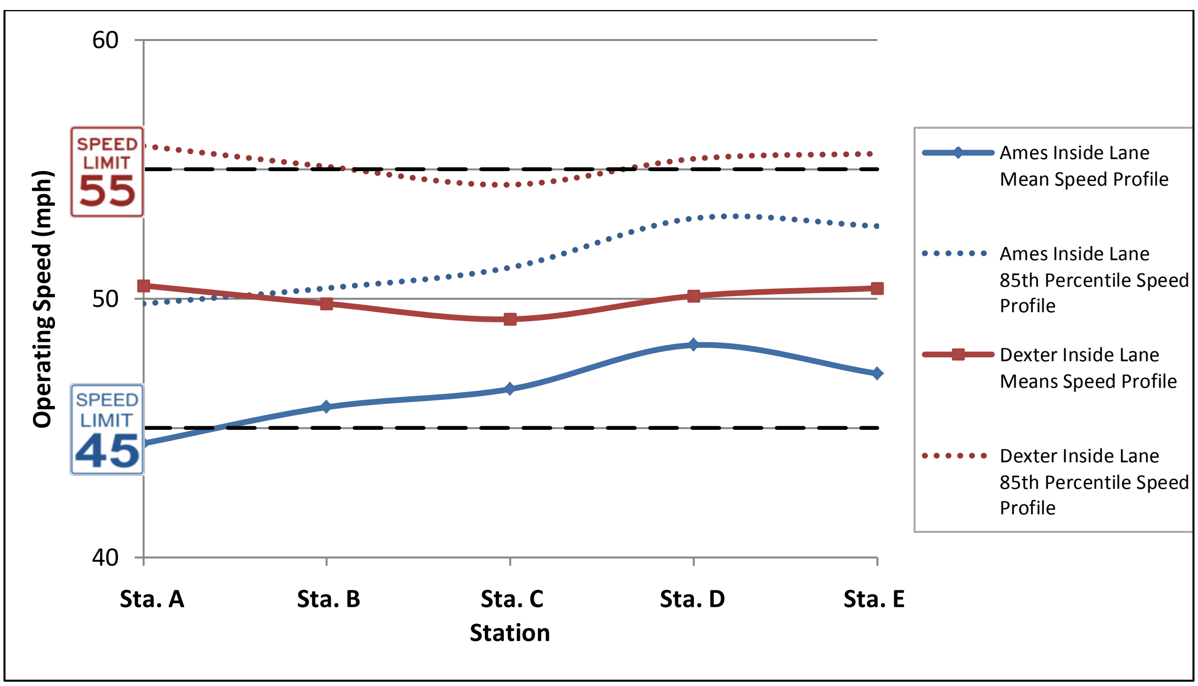

FIGURE 5-3 Inside lane vehicle mean and 85th percentile speed profiles

FIGURE 5-4 illustrates the speed profiles for the outside lane at both curve sites. As shown, the Dexter mean and 85th percentile speed profiles are very similar to the inside lane profiles with the exception of a lower mean speed at the center of the curve. Drivers are decelerating within the horizontal curve to the center of the curve and accelerating out of the curve. FIGURE 5-4 also shows that there is an overall drop in the mean and 85th percentile speed along the curve at the Ames site.

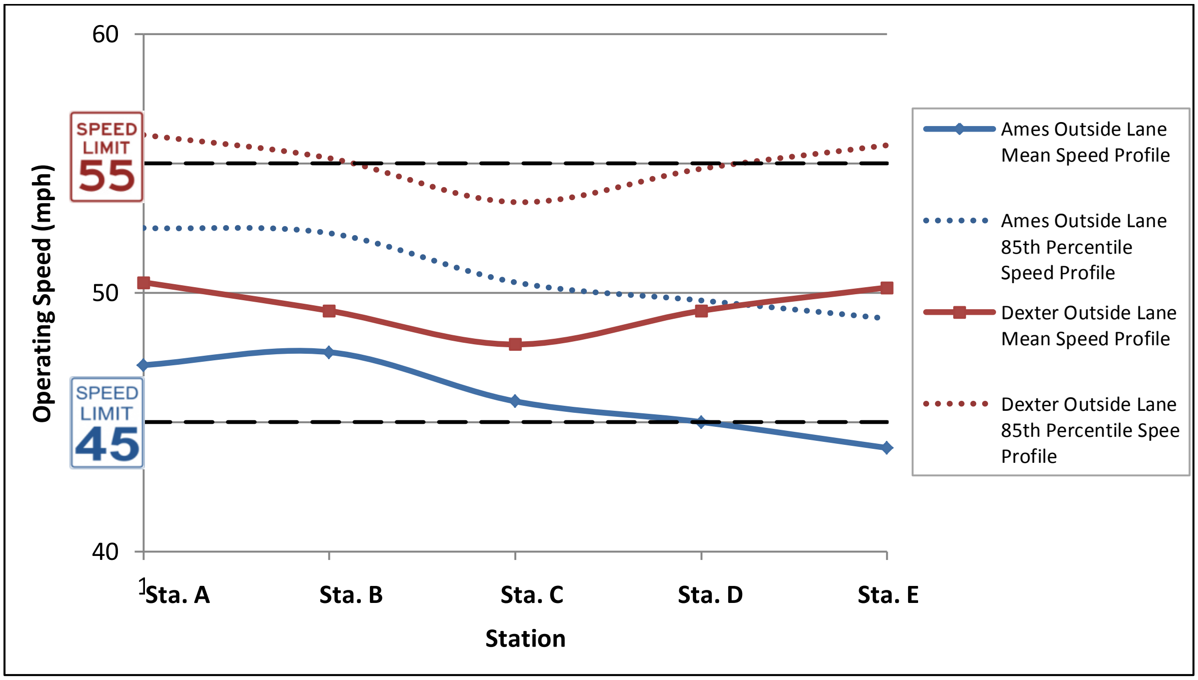

FIGURE 5-4 Outside lane vehicle mean and 85th percentile speed profiles

5.5 Segment Speed and Lateral Deviation

5.5.1 Definition

To investigate changes in vehicle trajectories and speed profiles between stations, data were initially combined into three vehicle classes. These classes were passenger cars, school buses, and trucks. Changes in vehicle speed and lateral position through the horizontal curves were defined in segments as illustrated on the left of FIGURE 5-5.

As shown on the left of FIGURE 5-5 for the outside lane, a segment was defined by the longitudinal distance between two adjacent stations. This resulted in four segments at each site. A deviation value for each segment was calculated by determining the difference in speed and lateral position between the two stations. A positive speed deviation value indicates that the vehicle speed increased within the segment and a negative value represents a reduction in the vehicle speed within the segment. Similarly, lateral deviation can be positive or negative. FIGURE 5-5 on the right defines positive and negative lateral deviation for each direction of travel. A positive lateral deviation value signifies that the vehicle moved towards the centerline of the roadway while a negative value represents a vehicle moving away from the centerline. If a value of zero is reported for speed or lateral deviation, this indicates that the vehicle made no changes in speed or lateral position between two stations defining the segment.

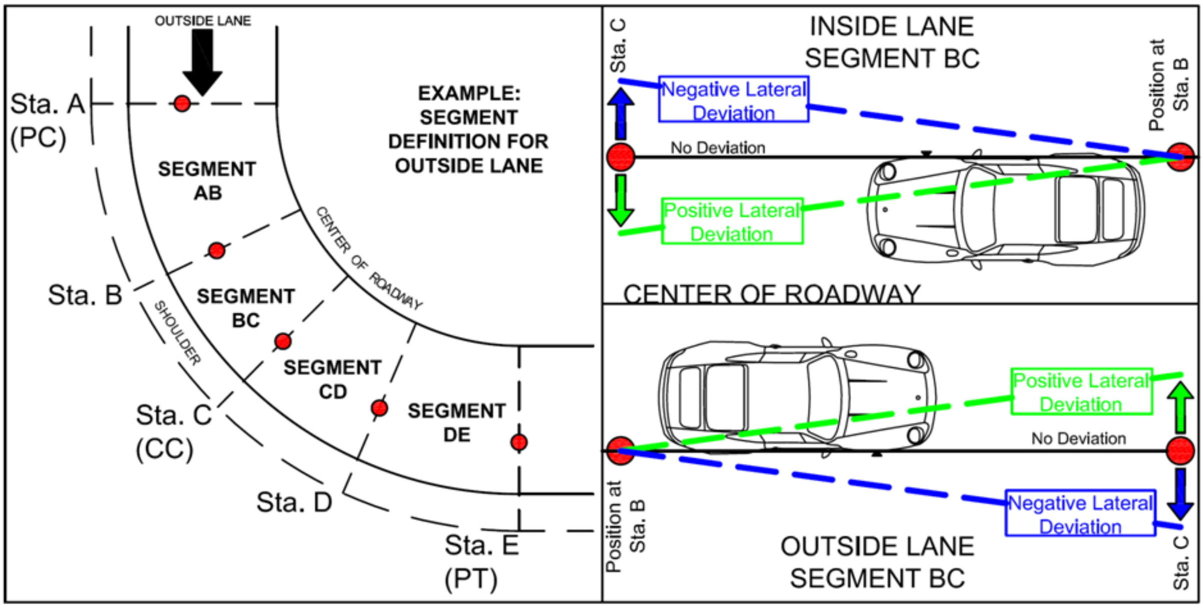

FIGURE 5-5 Left: Segment definition between stations; Right: Positive and negative lateral deviation definition both directions of travel

5.5.2 Segment Speed Deviation versus Lateral Deviation

FIGURE 5-6 and FIGURE 5-7 illustrate the speed and lateral deviation for each vehicle at each segment for both the inside and outside lanes at each horizontal curve site. Due to the limited number of motorcycles observations, this vehicle class was removed and only passenger cars, school buses, and trucks were considered.

FIGURE 5-6 illustrates the speed and lateral deviation plots for the inside lane at the two sites. For the Ames site, each segment plot consisted of 6,329 observations and the Dexter site segment plots consisted of 6,485 observations. Since both sites had a similar number of observations, each segment could easily be compared. FIGURE 5-6 suggests significant difference exist between the two sites in terms of speed deviation. However, lateral deviation seems to be similar with a range between -50 and 50 inches with the exception of the Ames site DE segment. As shown in the Ames DE segment, it can be seen that the lateral deviation was much higher than any other segment. As was shown in FIGURE 5-1, the average vehicle speeds showed a drop for this segment. Combined, these suggest drivers were making significant adjustments to safely transition to the tangent section.

Comparing speed deviations between sites, it was found the Ames segments showed a greater dispersion with higher positive and negative speed deviations as compared to the Dexter site. One possible reason for this is the difference in radius. The radius of the Dexter site is almost 1,000 feet smaller, making the curve tighter. This was also observed for the outside lane (FIGURE 5-2). The large speed deviation can be clearly seen at segments AB and DE with many vehicles showing a positive or negative speed deviation greater than 10 mph. This was also found for the outside lane at segments as illustrated in FIGURE 5-7.

FIGURE 5-7 illustrates the speed and lateral deviation plots for the outside lane at the two sites. They show 6,612 observations for the Ames site and 4,715 observations for the Dexter site. Many of same characteristics seen for the inside lanes were also noted here. However, unlike the segment DE with the large positive lateral deviation in FIGURE 5-6, segment DE in FIGURE 5-7 does not illustrate a large increase in positive lateral deviation.

An important observation that can be noted from both FIGURE 5-6 and FIGURE 5-7 is the difference in the speed and lateral deviation between vehicle types. As shown in both figures, school buses and trucks are illustrated by the green and red observation points. They have an overall lower speed and lateral deviation through the curve as compared to passenger cars with many observations having a speed deviation between -2 mph and 2 mph with the exception of a few outliers. Likewise, their lateral deviations are generally smaller than those of passenger cars. One possible explanation for this is that drivers of school buses and trucks are required to have commercial driver's licenses (CDL). Drivers with CDLs generally have higher skill levels to operate larger vehicles, and manure them on curves.

5.6 DATA ANALYSIS

5.6.1 Comparison of Vehicle Mean Speed and Mean Vehicle Lateral Position between Stations

Vehicle mean speed and lateral position were compared between adjacent stations along the horizontal curve. Two statistical tests were selected which included the paired t-test and Wilcoxon Signed-Rank tests. The paired t-test was selected because of its robust characteristics to analyze large paired samples. The Wilcoxon Signed-Rank test was also selected to investigate the shift in distributions by comparing the paired sample medians. This is a non-parametric test equivalent to the paired t-test that does not make any assumptions regarding the normality of the distributions.

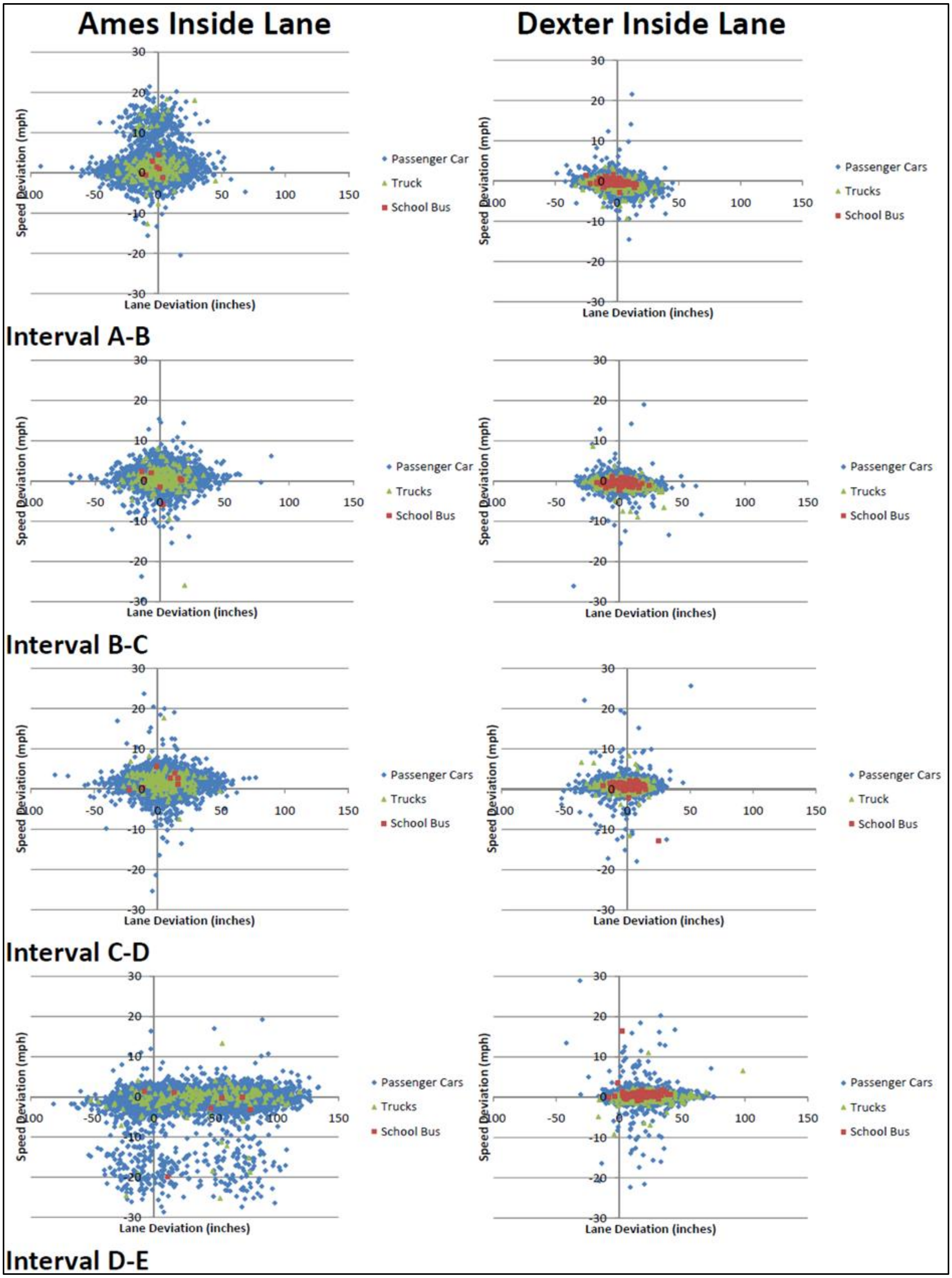

FIGURE 5-6 Inside lane interval speed and lane deviation for both horizontal curve sites

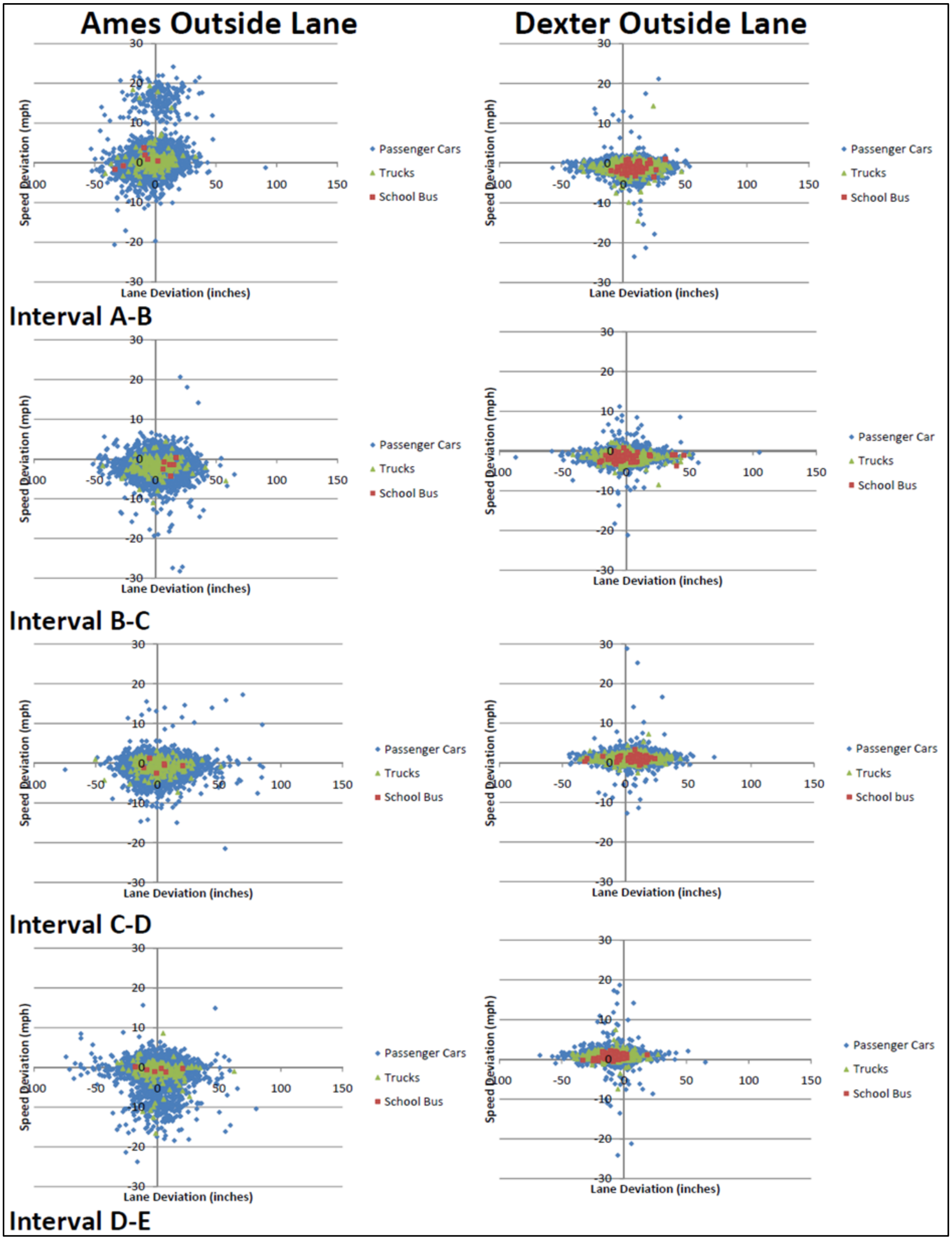

FIGURE 5-7 Outside lane interval speed and lane deviation for both horizontal curve sites

For both tests, the null hypothesis *(H_o)* states that the mean of the speed distribution at the first station ($\bar{v}_i$) equals the mean of the speed distribution at station ($\bar{v}_{i+1}$). The alternative hypothesis *(H_a)* states that the mean of the speed distribution at the first station *($\bar{v}_i$)* is not equal to the mean of the speed distribution at the second station *($\bar{v}_{i+1}$)*. For speed, hypotheses are expressed as follows:

$$H_o: \bar{v}_i - \bar{v}_{i+1} = 0 \quad (5\text{-}1)$$

$$H_a: \bar{v}_i - \bar{v}_{i+1} \neq 0 \quad (5\text{-}2)$$

For testing lateral position means between adjacent stations along the curve, the hypotheses become:

$$H_o: \bar{d}_i - \bar{d}_{i+1} = 0 \quad (5\text{-}3)$$

$$H_a: \bar{d}_i - \bar{d}_{i+1} \neq 0 \quad (5\text{-}4)$$

Table 5-2 and Table 5-3 show the results of the statistical tests comparing each station in the inside and outside lanes. Results include both distribution means, 95 percent confidence interval of the calculated difference in distribution means, the paired t-test p-value, and the Wilcoxon Sign-Rank p-value. The null hypothesis is rejected if the p-value is <0.05 (for the 95 percent level of confidence).

As shown in Table 5-2, results of testing both the mean speed and lateral position between adjacent stations for the inside lane indicate there is enough evidence to support rejecting the null hypothesis for both variables tested at the 95 percent level of confidence. These results were expected since the vehicle trajectories and speed profiles explained earlier did not indicate vehicles maintained a constant mean speed or trajectory through the curves.

Similar results were reported in Table 5-3, the results of testing both the vehicle mean speed and lateral position distribution means between adjacent stations for the outside lane. These results indicate there is enough evidence to reject the null hypothesis at the 95 percent level of confidence for both variables tested for most stations. However, it was found there was not enough evidence to reject the null hypothesis at the 95 percent level of confidence when lateral position was compared at stations C and D.

5.6.2 Comparison of Vehicle 85th Percentile Speed between Stations

Vehicle 85th percentile speeds were compared between adjacent stations along the horizontal curve using a two-sided t-test. The 85th percentile speed is a commonly used in transportation engineering in which 85 percent of the vehicles at the station within the curve are traveling at or below the determined 85th percentile speed.

Table 5-2 Comparing vehicle mean speed and lateral position between stations at each study site for the inside lane

Stations Comparing	Observations	Station	Mean Speed (mph)	Mean Lateral Position (inches)	95% CI $(\bar{v}_{i+t} - \bar{v}_i)$; $(\bar{d}_{i+t} - \bar{d}_i)$	Paired t-test p-value (Speed, Lateral Pos.)	Wilcoxon Signed-Rank p-value (Speed, Lateral Pos.)	Reject Null Hypothesis (Speed, Lateral Pos.):
Dexter Inside Lane								
Sta. A-B	6,485	Sta. A	50.5	13.2	(0.62, 0.67);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. B	49.8	12.4	(0.78, 1.28)			
Sta. B-C	6,485	Sta. B	49.8	12.4	(0.59, 0.65);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. C	49.2	14.6	(-2.45, -1.99)			
Sta. C-D	6,485	Sta. C	49.2	14.6	(-0.95, 0.90);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. D	50.1	13.1	(1.57, 2.04)			
Sta. D-E	6,485	Sta. D	50.1	13.1	(-0.35, -0.30);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. E	50.4	33.1	(-19.49, -18.92)			
Ames Inside Lane								
Sta. A-B	6,329	Sta. A	44.4	25.2	(-1.43, -1.27);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. B	45.8	20.6	(2.31, 2.97)			
Sta. B-C	6,329	Sta. B	45.8	20.6	(-0.75, -0.65);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. C	46.5	24.8	(-2.41, -1.78)			
Sta. C-D	6,329	Sta. C	46.5	24.8	(-1.76, -1.66);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. D	48.2	27.2	(-5.49, -4.81)			
Sta. D-E	6,329	Sta. D	48.2	27.2	(0.96, 1.17);	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
		Sta. E	47.1	68.8	(-43.74, -41.89)			

Note: All values in Table 5-2 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

Table 5-3 Comparing vehicle mean speed and lateral position between stations at each study site for the outside lane

Stations Comparing	Observations	Station	Mean Speed (mph)	Mean Lateral Position (inches)	95% CI $(\bar{v}_{i+t} - \bar{v}_i)$; $(\bar{d}_{i+t} - \bar{d}_i)$	Paired t-test p-value (Speed, Lateral Pos.)	Wilcoxon Signed-Rank p-value (Speed, Lateral Pos.)	Reject Null Hypothesis (Speed, Lateral Pos.):
Dexter Outside Lane								
Sta. A-B	4,715	Sta. A Sta. B	50.4 49.3	39.7 48.2	(0.96, 1.06); (-6.33, -5.61)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Sta. B-C	4,715	Sta. B Sta. C	49.3 48.0	48.2 45.9	(1.26, 1.32); (1.44, 2.15)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Sta. C-D	4,715	Sta. C Sta. D	48.0 49.3	45.9 51.2	(-1.34, -1.29); (-6.84, -6.17)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Sta. D-E	4,715	Sta. D Sta. E	49.3 50.2	51.2 41.8	(-0.93, -0.88); (9.41, 10.02)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Ames Outside Lane								
Sta. A-B	6,612	Sta. A Sta. B	47.2 47.7	31.6 30.2	(-0.58, -0.42); (0.68, 1.23)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Sta. B-C	6,612	Sta. B Sta. C	47.7 45.8	30.2 32.5	(1.85, 1.95); (-1.94, -1.35)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes
Sta. C-D	6,612	Sta. C Sta. D	45.8 45.0	32.5 33.2	(0.68, 0.78); (-0.51, 0.09)	(<0.01, <0.01)	(<0.01, 0.17)	Yes, **No**
Sta. D-E	6,612	Sta. D Sta. E	45.0 44.0	33.2 35.0	(1.00, 1.12); (-2.62; -2.03)	(<0.01, <0.01)	(<0.01, <0.01)	Yes, Yes

Note: All values in Table 5-3 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

The null hypothesis *(H_o)* states that the 85th percentile speed at the first station ($85\bar{v}_i$) equals the 85th percentile speed at the adjacent station ($85\bar{v}_{i+1}$). The alternative hypothesis *(H_a)* states that the 85th percentile speed distribution at the first station *($85\bar{v}_i$)* is not equal to the mean of the speed distribution at the second station *($85\bar{v}_{i+1}$)*. The hypotheses are expressed as follows:

$$H_o: 85\bar{v}_i - 85\bar{v}_{i+1} = 0 \tag{5-5}$$

$$H_a: 85\bar{v}_i - 85\bar{v}_{i+1} \neq 0 \tag{5-6}$$

Table 5-4 and Table 5-5 show the results of the statistical tests comparing each station in the inside and outside lanes. Results include both station 85th percentile speeds, 95 percentile confidence interval of the calculated difference between 85th percentile speeds, and the t-test p-value. The null hypothesis is rejected if the p-value is <0.05 (for the 95 percent level of confidence).

As shown in Table 5-4 and Table 5-5, results of the testing the 85th percentile speed between adjacent stations for the inside and outside lanes indicate there is enough evidence to support rejecting the null hypothesis for both lane at each study site. The results of this analysis are similar to the statistical tests which evaluated the mean speed between stations as shown in Table 5-2 and Table 5-3.

5.6.3 Comparison of Vehicle Maximum Speed and Lateral Position Means between Segments

As previously stated, each of the 24,410 vehicle observations included four speed and lateral deviation values which corresponded to the changes in speed and lateral position between successive observations stations along the horizontal curve. The maximum speed and lateral deviation value was identified out of the four values along with its corresponding segment along the horizontal curve where it happened. The maximum values for both variables were either positive or negative, and in many cases the value did not occur on the same segment.

To analyze the maximum speed and lateral deviation for each curve site and in each lane, two vehicle categories were constructed: passenger cars and heavy vehicles. Heavy vehicles included both school buses and trucks. These two vehicle classes exhibited similar speed and lateral deviation at each segment as shown in FIGURE 5-6 and FIGURE 5-7, and also the drivers of these vehicles are generally required to have a commercial driver’s license. Motorcycles were discarded from the dataset due to their smaller sample size at each curve site.

Table 5-4 Comparing vehicle 85th percentile speeds between stations at each study site for the inside lane

Stations Comparing	Observations	Station	85th Percentile Speed (mph)	95% CI $(85\bar{v}_{i+t} - 85\bar{v}_i)$	Two-sided t-test p-value	Reject Null Hypothesis:
Dexter Inside Lane						
A-B	6,485	Sta. A Sta. B	55.9 55.2	(0.58, 0.95)	<0.01	Yes
B-C	6,485	Sta. B Sta. C	55.2 54.4	(0.57, 0.94)	<0.01	Yes
C-D	6,485	Sta. C Sta. D	54.4 55.4	(-1.17, -0.80)	<0.01	Yes
D-E	6,485	Sta. D Sta. E	55.4 55.6	(-0.19, -0.01)	0.03	Yes
Ames Inside Lane						
A-B	6,329	Sta. A Sta. B	49.8 50.4	(-0.78, -0.41)	<0.01	Yes
B-C	6,329	Sta. B Sta. C	50.4 51.2	(-0.96, -0.63)	<0.01	Yes
C-D	6,329	Sta. C Sta. D	51.2 53.1	(-2.06, -1.73)	<0.01	Yes
D-E	6,329	Sta. D Sta. E	53.1 52.8	(0.10, 0.49)	<0.01	Yes

Note: All values in Table 5-4 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

Table 5-5 Comparing vehicle 85th percentile speeds between stations at each study site for the outside lane

Stations Comparing	Observations	Station	85th Percentile Speed (mph)	95% CI $(85\bar{v}_{i+t} - 85\bar{v}_i)$	Two-sided t-test p-value	Reject Null Hypothesis:
Dexter Outside Lane						
A-B	4,715	Sta. A Sta. B	56.1 55.2	(0.66, 1.13)	<0.01	Yes
B-C	4,715	Sta. B Sta. C	55.2 53.5	(1.46, 1.94)	<0.01	Yes
C-D	4,715	Sta. C Sta. D	53.5 54.7	(-1.42, -0.97)	<0.01	Yes
D-E	4,715	Sta. D Sta. E	54.7 55.7	(-1.22, -0.77)	<0.01	Yes
Ames Outside Lane						
A-B	6,612	Sta. A Sta. B	52.5 52.3	(0.01, 0.38)	0.03	Yes
B-C	6,612	Sta. B Sta. C	52.3 50.4	(1.73, 2.06)	<0.01	Yes
C-D	6,612	Sta. C Sta. D	50.4 49.7	(0.53, 0.86)	<0.01	Yes
D-E	6,612	Sta. D Sta. E	49.7 49.0	(0.52, 0.87)	<0.01	Yes

Note: All values in Table 5-5 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

Table 5-6 provides information for passenger car and heavy vehicle mean maximum speed deviation at both curve site and in both lanes of travel. The sum of the observations across the segments at each curve site equals the total sample size collected.

The segment with the highest number of vehicle observations provides insight into the location where the highest positive or negative maximum speed deviation is occurring. Additionally, the mean maximum speed deviation is reported for each segment. As shown in Table 5-6 it is reported that the mean maximum speed deviations follow the general trends earlier reported for the mean vehicle speed profiles for both lanes at each curve site. Table 5-7 provides similar information as Table 5-6 except the variable under consideration is the mean maximum later deviation. As shown, both curve sites experienced higher number of vehicle observations with the greatest mean maximum lateral deviations at segment DE as compared to other segments at each curve site.

The means of maximum speed and lateral deviation distributions were compared between segments along the curve. Unlike the statistical tests performed to compare mean maximum speed and lateral deviation distributions between stations along the curve, these statistical tests compare all possible segments in a lane with each other. The goal of the analysis was to investigate if any specific segments along the curve exhibited similar maximum deviation means. As reported in Table 5-6 and Table 5-7, the numbers of observations for each vehicle category varied between segments. As shown, segments reported between 11 and 18 heavy vehicles and other segments reporting over 4,000 passenger car observations. To maximize observations at each segment, passenger car and heavy vehicle observations were combined. Due to the variation in observations at each segment, a paired t-test could not be utilized.

It was assumed all segment maximum speed and lateral deviation distributions were normally distributed based on the large number of observations. A two-sided t-test was selected to evaluate two independent sample means between segments. For both tests, the null hypothesis *(H_o)* states that the mean of the maximum speed deviation distribution at a specific segment ($\overline{sv}_i$) equals the mean of the maximum speed deviation distribution mean of an adjacent segment, or other segment within the curve ($\overline{sv}_{i+1}$). The alternative hypothesis *(H_a)* states that the mean of the maximum speed distribution a station *($\overline{sv}_i$)* is not equal to the mean of the speed distribution at the second station *($\bar{v}_{i+1}$)*. For vehicle speed, hypotheses are expressed as follows:

$$H_o: \overline{sv}_i - \overline{sv}_{i+1} = 0 \qquad (5\text{-}7)$$

$$H_a: \overline{sv}_i - \overline{sv}_{i+1} \neq 0 \qquad (5\text{-}8)$$

Table 5-6 Maximum speed deviation descriptive statistics for passenger car and heavy vehicle at curve segments in each direction of travel

	Inside Lane							
	Dexter				**Ames**			
Segment →	**AB**	**BC**	**CD**	**DE**	**AB**	**BC**	**CD**	**DE**
Passenger Car Observations[a] →	**1,075**	**1,621**	**2,546**	**496**	**1,626**	**629**	**2,567**	**1,298**
Mean Maximum Speed Deviation *(mph)*	-1.48	-1.33	1.47	0.72	3.78	0.99	2.57	-5.07
Heavy Vehicle Observations[a] →	**131**	**223**	**290**	**54**	**52**	**27**	**73**	**45**
Mean Maximum Speed Deviation *(mph)*	-1.42	-1.59	1.36	0.90	4.78	-1.04	2.66	-4.64
	Outside Lane							
	Dexter				**Ames**			
Segment →	**AB**	**BC**	**CD**	**DE**	**AB**	**BC**	**CD**	**DE**
Passenger Car Observations[a] →	**748**	**1,562**	**1,576**	**201**	**1,395**	**2,921**	**944**	**1,123**
Mean Maximum Speed Deviation *(mph)*	-2.26	-2.12	1.94	2.48	2.66	-2.98	-2.08	-4.27
Heavy Vehicle Observations[a] →	**116**	**270**	**162**	**20**	**47**	**100**	**25**	**28**
Mean Maximum Speed Deviation *(mph)*	-2.44	-2.12	1.89	1.68	3.15	-2.87	-1.47	-3.55

Note: All values in Table 5-6 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

Table 5-7 Maximum lateral deviation descriptive statistics for passenger car and heavy vehicles at curve segments in each direction of travel

	Inside Lane							
	Dexter				**Ames**			
Segment →	**AB**	**BC**	**CD**	**DE**	**AB**	**BC**	**CD**	**DE**
Passenger Car Observations[a] →	**518**	**623**	**503**	**4,094**	**467**	**366**	**542**	**4,745**
Mean Maximum Lateral Deviation *(inches)*	-0.37	11.57	-11.63	23.83	-8.10	5.67	17.41	54.85
Heavy Vehicle Observations[a] →	**69**	**72**	**65**	**492**	**19**	**11**	**18**	**149**
Mean Maximum Lateral Deviation *(inches)*	0.83	12.67	-9.28	23.06	-5.56	0.17	20.05	53.81
	Outside Lane							
	Dexter				**Ames**			
Segment →	**AB**	**BC**	**CD**	**DE**	**AB**	**BC**	**CD**	**DE**
Passenger Car Observations[a] →	**1,109**	**727**	**1,058**	**1,193**	**1,475**	**1,807**	**1,518**	**1,583**
Mean Maximum Lateral Deviation *(inches)*	12.55	-6.00	15.19	-18.25	-1.93	3.69	2.40	6.79
Heavy Vehicle Observations[a] →	**135**	**119**	**155**	**159**	**43**	**54**	**50**	**53**
Mean Maximum Lateral Deviation *(inches)*	12.86	-5.68	16.15	-18.39	-5.94	4.39	8.84	8.06

[a]Sum of vehicle max deviation observations equals the total number of observations

Note: All values in Table 5-7 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

For testing the maximum lateral deviation means between segments along the curve, the hypotheses become:

$$H_o: \overline{sd}_i - \overline{sd}_{i+1} = 0 \quad (5\text{-}9)$$

$$H_a: \overline{sd}_i - \overline{sd}_{i+1} \neq 0 \quad (5\text{-}10)$$

Table 5-8 and Table 5-9 show the results of the statistical tests comparing every segment in both the inside and outside lanes. Results include the segment maximum speed and lateral deviation distribution means, 95 percent confidence interval of the calculated difference in distribution means, and the determined p-value for the t- test. The null hypothesis is rejected if the p-value is <0.05 (for the 95 percent level of confidence).

As shown in Table 5-8 and Table 5-9, there was enough evidence to reject the null hypothesis at every segment comparison in both lanes of travel at the 95 percent level of confidence. Overall, the following conclusions regarding vehicle operating speed at horizontal curves can be drawn from the previous two sections which include the following:

- Vehicle operating speeds changed as they traversed the horizontal curve in both lanes of travel,
- Changes in maximum speed deviation were significant along segments on the curve.

The following conclusions regarding vehicle lateral position at horizontal curves can be drawn from the previous two sections which include the following:

- Vehicle lateral position changed as they traversed the curve in both lane of travel,
- Changes in maximum lateral deviation were significant along segments on the curve.

5.6.4 Comparison of Maximum Speed and Lateral Deviation Means between Vehicle Type

Vehicle maximum speed and lateral deviation means were compared between vehicle classes at adjacent segments in each lane. As stated in the previous section in Table 5-6 and Table 5-7, the sample size of passenger cars was much higher than heavy vehicles at all of the segments at both curve sites. Each segment vehicle class maximum deviation distribution was tested for normality using a Shapiro-Wilk test at the 95 percent level of confidence. The results did not support the normality assumption and a non-parametric test was needed.

A one-sided Wilcoxon Rank-Sum test is the equivalent of a one- sided t-test, except the test is investigating the shift in distributions based on the change in medians. This is a non-parametric test that does not make any assumptions regarding normality of the unpaired data.

Table 5-8 Comparison of maximum speed and lateral deviation means between segments for the inside lane

Ames Inside

Comparison	Maximum Speed Deviation Mean: Means	Maximum Speed Deviation Mean: 95% CI $(\overline{sv}_{i+t} - \overline{sv}_i)$	Maximum Speed Deviation Mean: t-test p-value	Maximum Speed Deviation Mean: Reject Null Hypothesis:	Maximum Lateral Deviation Mean: Means	Maximum Lateral Deviation Mean: 95% CI $(\overline{sd}_{i+t} - \overline{sd}_i)$	Maximum Lateral Deviation Mean: t-test p-value	Maximum Lateral Deviation Mean: Reject Null Hypothesis:
AB, BC	3.82, 0.90	(2.53, 3.29)	<0.01	Yes	-7.98, 6.06	(-17.13, -10.97)	<0.01	Yes
AB, CD	3.82, 2.58	(0.98, 1.49)	<0.01	Yes	-7.98, 17.50	(-28.10, -22.88)	<0.01	Yes
AB, DE	3.82, -5.06	(8.40, 9.36)	<0.01	Yes	-7.98, 54.82	(-65.09, -60.53)	<0.01	Yes
BC, CD	0.90, 2.58	(-1.97, -1.37)	<0.01	Yes	6.06, 17.50	(-14.22, -8.67)	<0.01	Yes
BC, DE	0.90, -5.06	(5.46, 6.47)	<0.01	Yes	6.06, 54.82	(-55.22, -46.29)	<0.01	Yes
CD, DE	2.58, -5.06	(7.22, 8.06)	<0.01	Yes	17.50, 54.82	(-39.15, -35.47)	<0.01	Yes

Dexter Inside

Comparison	Maximum Speed Deviation Mean: Means	Maximum Speed Deviation Mean: 95% CI $(\overline{sv}_{i+t} - \overline{sv}_i)$	Maximum Speed Deviation Mean: t-test p-value	Maximum Speed Deviation Mean: Reject Null Hypothesis:	Maximum Lateral Deviation Mean: Means	Maximum Lateral Deviation Mean: 95% CI $(\overline{sd}_{i+t} - \overline{sd}_i)$	Maximum Lateral Deviation Mean: t-test p-value	Maximum Lateral Deviation Mean: Reject Null Hypothesis:
AB, BC	-1.47, -1.35	(-0.22, -0.01)	<0.01	Yes	-0.24, 11.68	(-13.80, -10.05)	<0.01	Yes
AB, CD	-1.47, 1.47	(-3.04, -2.83)	<0.01	Yes	-0.24, -11.36	(9.10, 13.12)	<0.01	Yes
AB, DE	-1.47, 0.77	(-2.59, -1.90)	<0.01	Yes	-0.24, 23.77	(-25.61, -22.77)	<0.01	Yes
BC, CD	-1.35, 1.47	(-2.90, -2.75)	<0.01	Yes	11.68, -11.36	(-3.31, -2.76)	<0.01	Yes
BC, DE	-1.35, 0.77	(-2.46, -1.79)	<0.01	Yes	11.68, -11.36	(21.41, 24.67)	<0.01	Yes
CD, DE	1.47, 0.77	(0.35, 1.03)	<0.01	Yes	11.68, 23.77	(-13.16, -11.01)	<0.01	Yes

Note: All values in Table 5-8 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

Table 5-9 Comparison of maximum speed and lateral deviation means between segments for the outside lane

Ames Outside Lane

	Maximum Speed Deviation Mean				Maximum Lateral Deviation Mean			
Comparison	**Means**	**95% CI** $(\overline{sv}_{i+t} - \overline{sv}_i)$	**t-test p-value**	**Reject Null Hypothesis:**	**Means**	**95% CI** $(\overline{sd}_{i+t} - \overline{sd}_i)$	**t-test p-value**	**Reject Null Hypothesis:**
AB, BC	2.67, -2.97	(5.31, 5.98)	<0.01	Yes	-1.92, 3.70	(-6.84, -4.41)	<0.01	Yes
AB, CD	2.67, -2.08	(4.38, 5.12)	<0.01	Yes	-1.92, 2.65	(-5.89, -3.24)	<0.01	Yes
AB, DE	2.67, -4.24	(6.52, 7.32)	<0.01	Yes	-1.92, 6.79	(-9.95, -7.47)	<0.01	Yes
BC, CD	-2.97, -2.08	(-1.08, 0.69)	<0.01	Yes	3.70, 2.65	(-0.21, 2.33)	<0.01	Yes
BC, DE	-2.97, -4.24	(1.02, 1.52)	<0.01	Yes	3.70, 6.79	(-4.26, -1.89)	<0.01	Yes
CD, DE	-2.08, -4.24	(1.87, 2.46)	<0.01	Yes	2.65, 6.79	(-5.43, -2.83)	<0.01	Yes

Dexter Outside

	Maximum Speed Deviation Mean				Maximum Lateral Deviation Mean			
Comparison	**Means**	**95% CI** $(\overline{sv}_{i+t} - \overline{sv}_i)$	**t-test p-value**	**Reject Null Hypothesis:**	**Means**	**95% CI** $(\overline{sd}_{i+t} - \overline{sd}_i)$	**t-test p-value**	**Reject Null Hypothesis:**
AB, BC	-2.29, -2.13	(-0.36, 0.03)	<0.01	Yes	12.56, -5.78	(16.65, 20.05)	<0.01	Yes
AB, CD	-2.29, 1.94	(-4.44, -4.04)	<0.01	Yes	12.56, 15.29	(-3.95, -1.50)	<0.01	Yes
AB, DE	-2.29, 2.41	(-5.20, -4.22)	<0.01	Yes	12.56, -18.27	(29.74, 31.93)	<0.01	Yes
BC, CD	-2.13, 1.94	(-4.16, -3.99)	<0.01	Yes	-5.78, 15.29	(-22.69, -19.47)	<0.01	Yes
BC, DE	-2.13, 2.41	(-5.01, -4.09)	<0.01	Yes	-5.78, -18.27	(10.96, 14.01)	<0.01	Yes
CD, DE	1.94, 2.41	(-0.92, -0.01)	<0.01	Yes	15.29, -18.27	(32.61, 34.52)	<0.01	Yes

Note: All values in Table 5-9 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

For both tests, the null hypothesis (Ho) states that the maximum speed distribution mean of passenger cars at segment $(p\bar{v}_i)$ is greater than the maximum speed distribution mean of heavy vehicles at segment$(h\bar{v}_i)$. The alternative hypothesis (Ha) states that the maximum speed distribution mean of passenger cars at segment $(p\bar{v}_i)$ is not greater than that maximum speed distribution of heavy vehicle as segment$(h\bar{v}_i)$. For vehicle maximum speed, the hypotheses are expressed as follows:

$$H_o: p\bar{v}_i - h\bar{v}_i > 0 \quad (5\text{-}11)$$

$$H_a: p\bar{v}_i - h\bar{v}_i \ngtr 0 \quad (5\text{-}12)$$

For testing maximum lateral deviation means between vehicle classes at adjacent segments along the curve, the hypotheses become:

$$H_o: p\bar{d}_i - h\bar{d}_i > 0 \quad (5\text{-}13)$$

$$H_a: p\bar{d}_i - h\bar{d}_i \ngtr 0 \quad (5\text{-}14)$$

Table 5-10 shows the results of the statistical tests comparing the maximum speed and lane deviation mean between passenger cars and heavy vehicles at segments along the curve. Results include the one-sided Wilcoxon Rank-Sum p-value. The null hypothesis is rejected if the p-value is <0.05 (for the 95 percent level of confidence).

As shown in Table 5-10, results of the tests showed there was enough evidence to support the null hypothesis at almost all of the segments along the horizontal curve for both variables tested at the 95 percent level of confidence. These results were expected as passenger cars have the ability to accelerate and decelerate quicker than heavy vehicles. Also, passenger cars have a narrower width, giving more room within the lane to deviate than heavy vehicles. However, there was not enough evidence to support the null hypothesis at segment BC at the Ames inside lane where the passenger car was found to not be higher than the heavy vehicle.

5.6.5 Segments with Largest Numbers of Maximum Speed and Lateral Deviations

To determine if the maximum speed and lateral deviation were occurring at similar segments along the curve at each site and it both lanes, maximum deviation data were combined for both lanes and plotted. This was performed to investigate if the physical location of the curve site affected where the driver made significant adjustments to vehicle operations. FIGURE 5-8 illustrates segments along the curve in the outside lanes and the frequency of maximum lateral and speed deviations.

Table 5-10 Comparison of maximum speed and lateral deviation means between passenger cars and heavy vehicles at segments

Ames Inside Lane				
	Maximum Speed Deviation Mean		**Maximum Lateral Deviation Mean**	
Segment	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**
AB	0.77	No	0.57	No
BC	0.03	**Yes**	0.67	No
CD	0.88	No	0.85	No
DE	0.72	No	0.48	No
Dexter Inside Lane				
	Maximum Speed Deviation Mean		**Maximum Lateral Deviation Mean**	
Segment	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**
AB	0.60	No	0.61	No
BC	0.06	No	0.78	No
CD	0.13	No	0.63	No
DE	0.79	No	0.11	No
Ames Outside Lane				
	Maximum Speed Deviation Mean		**Maximum Lateral Deviation Mean**	
Segment	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**
AB	0.85	No	0.07	No
BC	0.66	No	0.51	No
CD	0.88	No	0.99	No
DE	0.75	No	0.78	No
Dexter Outside Lane				
	Maximum Speed Deviation Mean		**Maximum Lateral Deviation Mean**	
Segment	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**	**One-sided Wilcoxon Rank-Sum p-value**	**Reject Null Hypothesis:**
AB	0.69	No	0.52	No
BC	0.59	No	0.39	No
CD	0.21	No	0.74	No
DE	0.22	No	0.33	No

Note: All values in Table 5-10 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m), all parameters tested at the 95 percentile level of confidence

FIGURE 5-8 shows that the highest maximum speed deviations occurred immediately prior to the center of the curve at segment BC at both curve sites. FIGURE 5-8 also shows the most maximum lateral deviations for the Dexter site were occurring near the end of the horizontal curve. It is speculated that the smaller radius at the Dexter curve may influence how driver exit the curve and the need to quickly reposition the vehicle while transitioning to the tangent section. The highest numbers of maximum lateral deviation for the Ames site were occurring at segment BC, prior to the center of the curve. FIGURE 5-9 illustrates segments along the curve in the inside lanes and the frequency of maximum speed and lateral deviations.

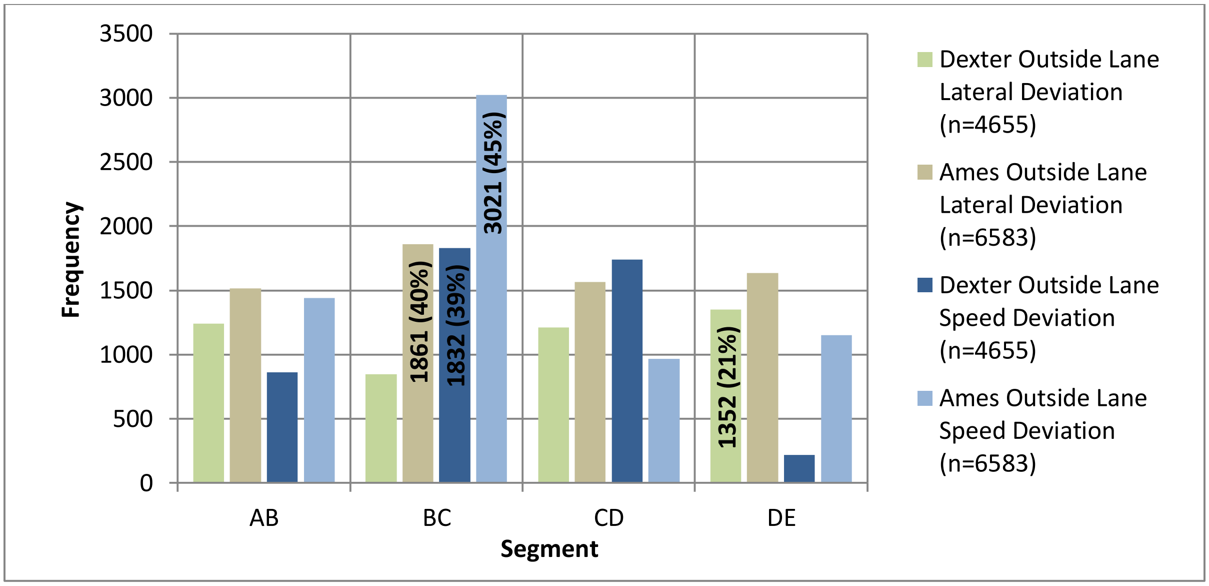

FIGURE 5-8 Maximum speed and lateral deviation location for the outside lane at Ames and Dexter sites

FIGURE 5-9 shows that the highest maximum speed deviations occurred at segment CD after the center of the horizontal curves. This was expected in that the vehicle profiles showed drivers at both curve accelerated immediately following the center of the curve. FIGURE 5-9 also shows the most maximum lateral deviations for both curve sites occurred at segment DE. The maximum lateral deviations at this segment were assumed to either be positive or negative as drivers identified the end of the horizontal curve and adjusted their lateral position to transition to the tangent section.

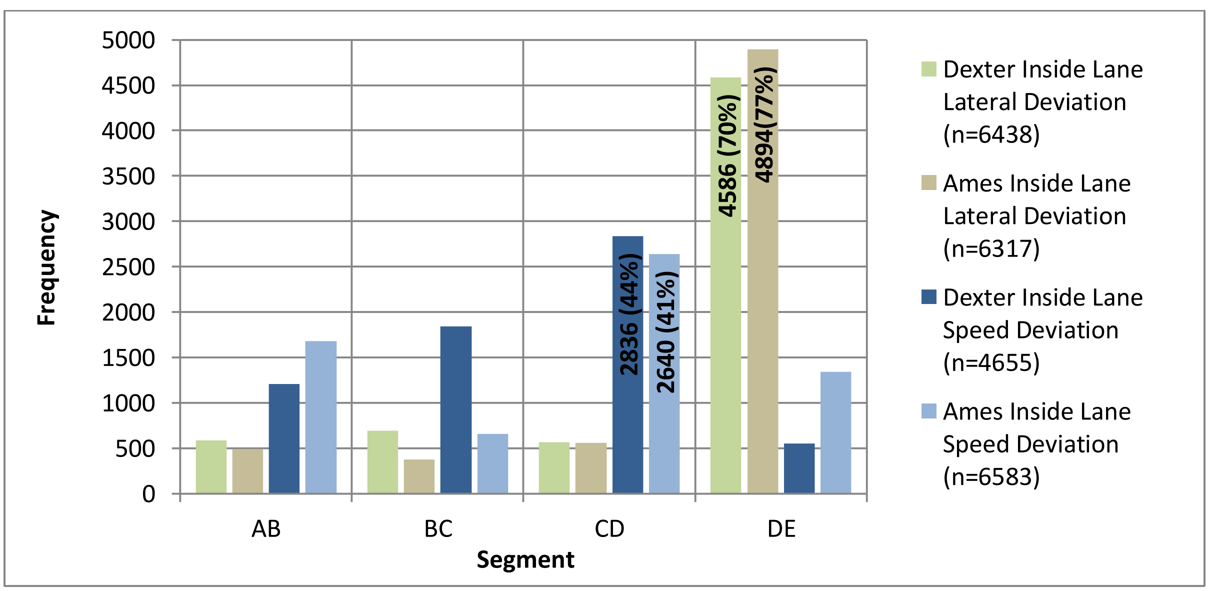

FIGURE 5-9 Maximum speed and lateral deviation location for the inside lane at Ames and Dexter sites

5.6.6 Location of Maximum Positive and Negative Deviation Values

The previous analyses reported the maximum speed and lateral deviation means which included both positive and negative values. The final analysis to investigate vehicle trajectories and speed profiles at both horizontal curve sites was to report what percentage of the maximum speed and lateral deviation values were positive and negative. Additionally, the analysis determined which segments experienced the highest number of maximum positive and negative speed and lateral deviation for both vehicles classes in the inside and outside lanes. Table 5-11 and Table 5-12 report the results of the analysis.

Table 5-11 shows the numbers and segments of the maximum lateral deviation for both passenger cars and heavy vehicles. The table is divided by the inside and outside lane for each horizontal curve site. To understand how both tables are interrupted, the outside lane for Dexter heavy vehicles will be explained. As shown, the total number of heavy vehicles observed was 568. Of these 568 vehicles, the maximum lateral deviations were positive for 295 vehicles (51.9 percent) and negative for the remaining 273 vehicles (48.1 percent). The segment which reported the highest number of positive lateral deviation values in the outside lane was segment CD, just after the center of the curve. The percentage reported with segment CD is the percent of the total number of total possible positive max lateral deviation observations for heavy vehicles. The segment which reported the highest number of negative lateral deviation values in the outside lane was segment DE at the end of the curve. Similar to the positive segment, the percentage reported for segment DE is the percentage of the total number of maximum negative lateral deviation observations. This same interpretation can be applied to the remaining results shown in Table 5-11 and Table 5-12.

Table 5-11 shows the segments with highest number of maximum positive and negative lateral deviations for both passenger cars and heavy vehicles at both study sites in the outside and inside lanes. If the inside and outside lanes at both curve sites are examined simultaneously, the following observations are notable. Positive maximum lateral deviations for both heavy vehicles and passenger cars were found to occur after the center of the curve, specifically in segments CD and DE. The previous section reported that drivers tend to cut the curve in both lanes. With the maximum positive lateral deviations occurring in these two segments, it verifies the trajectory findings with drivers moving towards the center of lane of the lane to exit the curve safely. Furthermore, it was found that a higher percentage of vehicle observations exhibited positive maximum lateral deviations for both vehicle classes at both curve sites.

Table 5-11 Location of highest number of maximum lateral deviations for heavy vehicles and passenger cars in each lane and at each site

	Outside Lanes		Inside Lanes	
	Dexter	Ames	Dexter	Ames
Heavy Vehicle Observations →	**568**	**200**	**698**	**197**
Maximum Deviation is Positive	295 (51.9%)[a]	118 (59.0%)	606 (87.9%)	167 (84.8%)
Segment with Highest Number of Maximum Positive Lateral Deviations	**CD:** 142 (48.1%)[b]	**DE**: 142 (30.5%)	**DE**: 488 (80.5%)	**DE**: 135 (80.8%)
Maximum Deviation is Negative	273 (48.1%)[a]	82 (42.2%)	92 (13.3%)	30 (15.2%)
Segment with Highest Number of Maximum Negative Lateral Deviations	**DE**: 155 (56.7%)[c]	**AB**: 27 (32.9%)	**CD**: 48 (52.1%)	**DE**: 14 (46.6%)
Passenger Car Observations →	**4087**	**6383**	**5738**	**6120**
Maximum Deviation is Positive	2142 (52.4%)[d]	3691 (57.8%)	4961 (86.4%)	5189 (77.5%)
Segment with Highest Number of Maximum Positive Lateral Deviations	**CD**: 956 (44.6%)[e]	**DE**: 1102 (29.8%)	**DE**: 4085 (82.3%)	**DE**: 4343 (83.6%)
Maximum Deviation is Negative	1945 (47.6%)[d]	2692 (42.2%)	777 (13.5%)	931 (15.2%)
Segment with Highest Number of Maximum Negative Lateral Deviations	**DE**: 1157 (59.4%)[f]	**AB**: 765 (28.4%)	**CD**: 411 (52.8%)	**DE**: 402 (43.1%)

[a]Number and percentage of vehicles of the total sample 568
[b]Segment, number, and percentage of 295
[c]Segment, number, and percentage of 273
[d]Number and percentage of vehicle for the total sample 4087
[e]Segment, number, and percentage of 2,142
[f]Segment, number, and percentage of 1,945

Note: All values in Table 5-11 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

Table 5-12 Location of highest number of maximum speed deviations for heavy vehicles and passenger cars in each lane and at each site

	Outside Lanes		Inside Lanes	
	Dexter	Ames	Dexter	Ames
Heavy Vehicle Observations →	**568**	**200**	**698**	**197**
Maximum Deviation is Positive	184 (32.4%)[a]	48 (24.0%)	341 (49.4%)	134 (68.0%)
Segment with Highest Number of Positive Maximum Speed Deviations	**CD:** 162 (88.0%)[b]	**AB**: 34 (70.8%)	**CD**: 282 (82.6%)	**CD**: 70 (52.2%)
Maximum Deviation is Negative	384 (67.6%.1)[a]	152 (76.0%)	357 (51.8%)	63 (32.0%)
Segment with Highest Number of Positive Negative Speed Deviations	**BC**: 270 (70.3%)[c]	**BC**: 99 (65.1%)	**BC**: 219 (61.3%)	**DE**: 35 (55.5%)
Passenger Car Observations →	**4087**	**6383**	**5738**	**6120**
Maximum Deviation is Positive	1809 (44.3%)[d]	1302 (20.3%)	3016 (52.5%)	4970 (81.2%)
Segment with Highest Number of Positive Maximum Speed Deviations	**CD**: 1570 (86.7%)[e]	**AB**: 938 (72.0%)	**CD**: 2516 (83.4%)	**CD**: 2468 (49.6%)
Maximum Deviation is Negative	2278 (55.7%)[d]	5081 (79.6%)	2722 (47.4%)	1150 (18.8%)
Segment with Highest Number of Positive Negative Speed Deviations	**BC**: 1550 (68.0%)[f]	**BC**: 2872 (56.5%)	**BC**: 1587 (58.3%)	**DE**: 1002 (87.1%)

[a]Number and percentage of vehicles of the total sample 568
[b]Segment, number, and percentage of 184
[c]Segment, number, and percentage of 384
[d]Number and percentage of vehicle for the total sample 4087
[e]Segment, number, and percentage of 1,809
[f]Segment, number, and percentage of 2,278
Note: All values in Table 5-12 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

It was also observed that a high percentage of the maximum negative lateral deviations observed were occurring after the center of the curve in segments CD and DE. However, Table 5-11 showed that at the Ames site in the outside lane, segment AB experienced the highest percentage of maximum negative lateral deviation. This may be due to vehicles turning onto the horizontal curve from the intersection near the PC in the outside lane. The driver would then reposition the vehicle in segment AB to safely traverse the curve. The high proportion of negative maximum lateral deviations after the center of the curve may be due to drivers who did not cut the curve in either lane who were repositioning the vehicle towards the center of the lane to safely exiting the horizontal curve without being forced to encroach on the centerline of the roadway.

Table 5-12 shows the numbers and segments of the maximum speed deviation for both passenger cars and heavy vehicles. As reported previously in FIGURE 5-3 and FIGURE 5-4, both study sites exhibited different types of vehicle speed profiles as compared to vehicle trajectories which were somewhat similar. So, both sites could not be compared together. The Ames site outside lane experienced the highest number of positive maximum speed deviations occurring at segment AB which suggest vehicles turning into the curve from the intersection were accelerating at this segment. The largest number of negative maximum speed deviations for the outside lane occurred at segment BC. This indicates that at this segment, vehicles slowed down prior to the center of the curve.

The Ames site inside lane experienced the opposite findings of the outside lane where over 68 percent of the total number of maximum positive speed deviations were occurring after the center of the curve at segment CD. It was found however that most of the negative maximum speed deviations were occurring at segment DE which suggests the higher number of observations decelerating were due to vehicles turning right into the residential area. Both the inside and outside lanes at the Dexter verified similar findings documented in the literature that the largest proportion of maximum positive speed deviation for both lanes and both vehicles classes occurred just past the center of the curve. The highest proportion of negative maximum speed deviation (e.g. slowing down) for both lanes occurred immediately prior to the center of the curve.

5.7 Discussion/Conclusions

The purpose of this study was to construct mean trajectories, mean speed profiles, and 85th percentile speed profiles. The study evaluated vehicle trajectories and speed profiles at two horizontal curves in Iowa based on observations of 24,410 vehicles. Mean speeds, the 85th percentile speeds of vehicles, and lateral position of vehicles at five stations along each curve were studied. Changes in vehicle speed and lateral at four adjacent segments along the horizontal curve were evaluated. The maximum speed and lateral deviation were identified by comparing the four deviation values. Finally, the means of the maximum changes (deviations) in speed and lateral position of passenger car s were compared to those of heavy vehicle.

Mean vehicle trajectories were constructed for both the inside and outside lanes for both the rural and urban horizontal curves. Using the trajectories categories reported by Spacek (1998), it was found that the mean vehicle trajectories in the inside and outside lanes at the rural curve site followed a “cutting” path. The inside lane at the urban curve site also exhibited a “cutting” path while the outside lane exhibited a “normal” path. Several other studies also have reported similar “cutting” paths followed by drivers. It is postulated that such a trajectory permits drivers to maintain a higher speed through the curve. Developing the mean vehicle trajectories provides an excellent preliminary evaluation of curve operations, and can support appropriate countermeasure selection based on the trajectories of concern (e.g., encroaching the center line or edge line).

Differences were also found in the mean and 85th percentile speed profiles at both curves. In both lanes at the rural curve site, the speed profiles exhibited characteristics similar to those documented in previous research where vehicle speeds decreased approaching the center of the curve and increased subsequently. The urban curve exhibited both increasing the decreasing mean and 85th percentile speed profiles depending on the direction.

Mean and 85th percentile vehicle speed and lateral position were compared between stations at both curve sites. A parametric paired t-test and non-parametric Wilcoxon Signed-Rank tests were used to compare distribution means. The results of the statistical tests indicate that changes in vehicle speed and lateral position was significant. Similarly, it was also found that changes in speed and lateral deviation between segments were also significant. These tests show that the overall changes in vehicle operations between stations within the curve are different between lanes at both sites. It is recommended that future research efforts include multiple rural and urban curve sites with varying geometric characteristics.

The means of the maximum deviations in speed and lateral position of passenger cars and heavy vehicles were compared for each e segment. Heavy vehicles consisted of school buses and trucks. Heavy vehicles differ from passenger car in terms of size, weight, and their drivers typically require a commercial driver’s license. It was tested that the passenger car maximum speed and lateral deviation mean was higher than the heavy vehicles means using. A one-sided t-test showed that the mean of the maximum deviations in speed and lateral position of passenger car was greater than those for heavy vehicles at every segment along the curve. This was true for both curve sites. The results suggest that future studies evaluate passenger cars and heavy vehicle separately. However, there is great benefit in studying the interactions between vehicle classes in operation analyses of curves. This would be particularly valuable for the interaction between passenger car and heavy vehicle when the opposing vehicle is a heavy vehicle.

The deviations in maximum speed and lateral position of both passenger cars and heavy vehicles were investigated at each curve site to determine where the highest number of positive and negative deviations occurs within the horizontal curve. The findings suggest that the maximum lateral deviation for both passenger cars and heavy vehicles occurred downstream of the center of the curve. This further supports the previously mentioned conclusion that drivers were found to follow a "cutting" path in which the driver shifts towards the centerline to exit the horizontal curve. The analysis also showed that the highest number of maximum speed deviation of vehicles occurred just upstream and downstream of the curve. This finding is consistent with findings from previous research.

Finally, it is recommended that future studies investigate potential relationships between vehicle trajectories and vehicle crash data. If relationships are found between mean trajectories and certain types of crashes, appropriate countermeasures could be selected to enhance safety and minimize risks of such crashes along the curve.

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CHAPTER 6. GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 General Discussion/Conclusions

Understanding the relationships between the driver, vehicle, roadway, and environmental at horizontal curves is complicated and not well understood. As stated in this research, the magnitude of crashes at horizontal curves in the United States is a safety concern. Chapter 2 provided extensive insight into previous research that had developed vehicle operating speed and lateral position models relating to horizontal curves, and also general trends found when vehicle trajectories and speed profiles were projected for horizontal curves. Specific gaps in the body of knowledge allowed for the development of research objective which included developing and analyzing vehicle trajectories and speed profiles along horizontal curves, developing vehicle speed and lateral position models along horizontal curves, and investigating where abrupt changes in speed and lane deviation occur between points along the horizontal curve.

A data collection protocol was presented in Chapter 3 in which pneumatic road tubes were selected over digital video to collect vehicle operational data which subsequently allowed to for the construction of trajectories and speed profiles by tracing a vehicle through a set of road tubes.

Chapter 4 presented a case study in which two horizontal curves in Iowa were selected for evaluation. A vehicle database for both curve sites and in both lanes of travel was created with vehicle, roadway, and environmental characteristics. Ordinary least Squares method was used to fit several linear models that represent what effects explanatory variables had on vehicle speed and lateral position along the horizontal curves in a cause-and-effect relationship based on the vehicle's curve entry speed and lateral position.

The trajectories and speed profiles of the vehicle collected in Chapter 4 were further analyzed in Chapter 5. Vehicle trajectories and speed profile were created in which overall trends of how vehicles traversed the curves were reported. The speed and lateral position of vehicles were compared between stations. The maximum speed and lateral deviation value for each vehicle was extracted and segments between data collection stations containing these values were compared to each other. The location of the maximum positive and negative speed and lane deviations along the curve were also reported. In the following sections, identified research limitations, advancements in highway safety, and immediate future research recommendations are discussed.

6.2 Advancements in Highway Safety

Based on the identified research objectives and the results of the analysis and conclusions of this study, engineering, policy and vehicle design have been identified. They are discussed in the following subsections.

6.2.1 Engineering and Policy Implications

As stated in the introduction, vehicle crashes at horizontal curves are a serious safety problem, especially in rural areas. Guidance to reduce crashes at horizontal curves has been established through programs such as the Manual on Uniform Traffic Control Devices (MUTCD), Highway Safety Manual (HSM), and Interactive Highway Safety Design Model (IHSDM).The current research would provide additional vehicle operational information to be considered in the IHSDM (Levison et al., 2001), which gives agencies guidance to evaluate horizontal curves and recommend specific countermeasures based on the expected number of crashes.

It is hypothesized that historical crashes at horizontal curves are possibly related to certain actions a driver takes while negotiating the horizontal curve. A sudden change in vehicle operating speed or lateral position towards may or may not result in a run-off-road crash, either to the shoulder or across the centerline into opposing vehicle traffic. The linear models developed along the horizontal curve, along with and the interval study between data collection stations, provide a unique insight into predicting and understanding vehicle lateral position and speed within the curve based on entry point characteristics. If a relationship could be established between the developed linear models and historical crashes, targeted countermeasures such as centerline rumble strips, edge line rumble strips, high-tension cable barrier, or targeted enforcement at a site could be appropriately selected and installed based on a simple traffic engineering study and applying the model. This ultimately could save a highway agency considerable funding if the appropriate countermeasure is selected after a traffic study occurs at the point of curvature, and then complimented with the prediction models developed. Additionally, the site-based research conducted will complement national research efforts such as the Strategic Highway Research Program 2 (SHRP2) to reduce fatal and severe crashes on the roadway.

6.2.2 Advanced Driver Assistance Systems (ADAS) Framework

Significant efforts by motor vehicle manufacturers and researchers in the past ten years have given rise to Advance Driver Assistance Systems (ADAS). ADAS are vehicle control systems that are designed to improve driving comfort and traffic safety by recognizing or predicting changes in driving patterns or potential hazards through the use of cameras, radars, or gyroscopic sensors (Gietelink et al. 2006). ADAS are built on current vehicle active safety systems as specified by the Federal Motor Vehicle Safety Standards (FMVSS) administered by the National Highway Transportation Safety Administration (NHTSA). These standards, which have reduced vehicle fatalities considerably since 1966 require both passive (shoulder belts, crumple zones, air bags) and active safety systems (anti-lock brakes and electronic stability control) to be installed in United States vehicles (Evans, 2004). Active safety systems are triggered by monitored-events detected by systems that constantly monitor vehicle operations. These systems are capable of deploying hydraulic differential braking, engine torque reduction, or suspension stiffening may be employed. ADAS alerts the driver using visual or auditory warnings and in some cases can intervene in the driving process. Current ADAS technologies found in vehicles includes system such as: lane departure warning, driver drowsiness, speed limit detection, blind spot warning, adaptive cruise control, pre-crash detection system, and night vision object identification. These systems are becoming more common on high-end vehicles where drivers are willing to pay for such systems.

This dissertation research provides and an initial framework to advance ADAS in vehicles by adding a prediction aspect to aid drivers in negotiating horizontal curves safely. This proposed system would include use of the onboard Global Positioning System (GPS) which would recognize the location of the vehicle and how far upstream it is to a horizontal curve. The vehicle computer then would cross-reference the position of the vehicle to a database of the upcoming horizontal curve characteristics proving an optimal speed and lateral position to safely negotiate the horizontal curve. An array of sensors would collect speed, lateral position, and other vehicle characteristics, and then input the data into the prediction model. If the prediction model was found to be dissimilar to the optimal model, the vehicle would either alert the driver, or apply existing vehicle control systems prior to or at the point of curvature to force the vehicle into a safe trajectory and speed. The important aspect to the proposed vehicle control system described is that all of the components exist in today's vehicle. The critical step to implementing such a system is the speed and lateral position prediction models as found in this research.

6.3 Immediate Future Research Recommendations

6.3.1 Development of a Less Intrusive Data Collection System

As discussed in the literature review, pneumatic road tubes are one of several data collection methods that have been used by researchers to collect vehicle operational data, specifically vehicle speed and lateral position. However, pneumatic road tubes are limited by environmental factors such as wet pavement, pavement deicing chemicals, or soil on the roadway. Additionally, pneumatic road tubes are susceptible to physical damage from parts hanging from the vehicle or vandalism. Furthermore, drivers see and physically feel the presence of pneumatic road tubes. On an instrument curve similar to the data collection methodologies described in the current research, changes in driver behavior were shown to occur in both the vehicle mean trajectory and 85th percentile speed profile.

A need exists to develop a data collection device that is less intrusive than pneumatic road tubes to collect vehicle operational and lateral position data. Video technology has been used by many researchers to extract vehicle data trajectories from high vantage points. However, in a rural area, a high vantage point may be impossible and local drivers will notice physical devices at the curve site. The research study conducted by Spacek (1998) provided insight into the use of ultrasonic vehicle data collection equipment built into delineator posts. Development of a similar device with ultrasonic, radar, or beam-breaking lasers is suggested. Since large delineator posts are not common in rural areas, it is also recommended the proposed device be concealed on or in chevron alignment posts, which are common in rural areas. It is also suggested a computer program be created to develop vehicle trajectories and speed profiles from the device data, and also have the ability to automatically filter out noise and errors, greatly reducing the time needed to process the data.

6.3.2 Expansion of Study

Expansion of the current research study is strongly recommended to continue refinement and validation of the developed prediction models and understanding driver behavior at horizontal curves. The models developed in this study predicted vehicle speed and lateral position throughout a curve based on the curve entry speed and lateral position. The next logical step for future research is to develop a model that predicts a vehicle's trajectory type and speed profile type. Spacek (1998) hypothesized that a vehicle negotiates a horizontal curve in one of six vehicle trajectory types; however, the author was unable to predict which type of trajectory they were expected to follow based on curve entry point characteristics. This research would greatly benefit the creation of an ADAS system as described in section 6.3.2, and also safety countermeasure design and implementation as described in section 6.3.1.

As stated in the limitations section, the findings presented were based on a two-site investigation which included a rural and urban horizontal curve with varying geometric characteristics. Literature cited has shown to study a high number of curve sites; however, many times this is dependent on the data collection devices used to collect vehicle operational data. Adding additional study sites will enable the models to include curve geometric characteristics such as the radius, length, lane width, vertical alignment, and pavement conditions.

Also, increasing the overall sample size with the addition of study sites would allow for further investigation of vehicle classes. In the present study, the vehicle class passenger car combined pickups, vans, sport utility vehicles, and various sizes of sedans. A larger sample would be able to target specific kinds of passenger cars. This would be an important study area since sport utility vehicles have different vehicle dynamics as compared to a sedan. Furthermore, a larger sample size would allow for further investigation of motorcycles and school buses, which were found to have a limited sample size in the present study.

Finally, it is also recommended that besides the five data collection points within the horizontal curve used in the present study, that vehicle speed and lateral position data be collected at each site 100 meters upstream and downstream of the horizontal curve. It is hypothesized that many drivers familiar with a certain horizontal curve will begin to shift their lateral position prior to the point of curvature and may not fully correct their position until after they exit the horizontal curve. Additionally, the data collection sites upstream and downstream of the horizontal curve would also allow for the development of transition zone vehicle operating speed models.

6.4 Limitations of Current Research

There are a number of limitations that were identified throughout the research project. They are discussed in the following subsections.

6.4.1 Identified Equipment Limitations

The current research relied heavily on the use of pneumatic road tubes to collect vehicle operational data at the horizontal curve sites. Specific limitations that directly affected the data collection process in the current research included the following: In the proof of concept study as described in Chapter 3, digital video data were compared to pneumatic road tube data. The video data was manually reduced by scaling the video display and the Jamar traffic classifier data was automatically reduced using TRAX Pro software. It is hypothesized that video data collection would have provided similar results, as the road tubes if high-definition video capturing equipment, extraction software, and control of environmental factors such as rain and wind were available at the time of testing.

As described in Chapters 4 and 5, vehicle operational data were collected using a set of five pneumatic road tubes and Jamar traffic classifiers at the horizontal curve sites. The maximum time any one of the traffic classifiers could be used in the field to collect data was limited around 110 hours, due to the electrical discharge rate of the provided 9 volt battery. The units included an attached solar cell; however, it was found it did not recharge the battery enough during daylight hours.

The lateral distance was limited in two directions at each data collection station which included the roadway centerline and edge of pavement. It was hypothesized that minimal numbers of vehicles would pass or travel completely in the opposing lane through the horizontal curve. Assuming this, the tubes were stretched to the centerline of the roadway in the direction of data collection. If the road tubes were extended into the opposing lane, unnecessary opposing vehicle data would be collected and potentially interfere with the direction of data collection. Tubes were also limited to the roadway edge of the pavement. From the roadway edge of pavement, the road tubes were placed across the shoulder to the traffic classifier approximately 6 to 8 feet away. Due to the light soil compaction of the gravel or soil shoulder, tension could not be set. Vehicles that were calculated and determined to be traveling outside of roadway pavement edge at the data collection station were removed from the dataset.

Limitations were also identified in the installation process. The road tubes were stretched across the roadway, tightened, and secured using 4 inch seal tape. The seal tape is an asphalt binder-constructed tape that cannot be adhered to the roadway under non-normal conditions. Each site had to be inspected prior to installation to ensure no water, deicer, or gravel was on the roadway. Additionally, pneumatic road tubes are easily susceptible to damage which includes debris from vehicles, lawn mowers, farm implements, and animal carcasses. Inspection of the site occurred every 24 hours to monitor uncontrollable events, damage, and traffic classifier malfunction.

6.4.2 Developed Model Limitations

The current research relies on data collected at two horizontal curve sites. The two sites were selected to represent an urban and rural environment with different traffic and geometric characteristics. The linear models developed where limited by the data collected and the absence of a model validation dataset. As explained in the conclusion section, the overall coefficient of determination for the models developed showed that the low percentage of the variation in the response variable could be explained. Since this study was limited to two sites, curve geometric features were not included in the model development. Including these features, along with the variables collected is hypothesized to increase the prediction power of the models along the horizontal curve.

Finally, the current research assumed a linear relationship existed between the dependent variables and the independent variables based on previous research studies conducted. Interactions between independent variables and the quadratic terms were added to the model which showed minimal improvement to the model. At the current time it is unknown if a different model form besides a linear model would be appropriate for the data collected.

6.5 References

Evans, L. Traffic Safety. 2nd edition, Science Serving Society, Bloomfield Hills, Michigan, 2004.

Gietelink, O., J. Ploeg, D. De Schutter, and M. Verhaegen. Development of Advanced Driver Assistance Systems with Vehicle Hardware-in-the-Loop Simulations. In *Vehicle Systems Dynamics*, Vol. 44, No.7, 2006, pp. 569-590.

Levison, W.H., A.C. Bittner, T. Robbins, and J.L. Campbell. Development of Prototype Driver Models for Highway Design, Task C: Develop and Test Prototype Driver Performance Model (DPM). Report FHWA: DTFH61-96-R-00065, FHWA, U.S. Department of Transportation Federal Highway Administration, Washington, D.C., 2001.

Spacek, P. FahrverhaltenunUnfallgeschehen in Kurven, Fahrverhalten in Kurvenbereichen. InStitutFürVerkehrsplanung, Transporttechnick, Strassen- unEisenbahnbaur, ETH Zürich, 1998.

APPENDIX A: DATA DICTIONARY AND EXAMPLE DATA

The following is the data dictionary for variables contained in the vehicle database which included 24,410 observations. All variables were considered in the statistical model development as described in the current research and SAS code shown in Appendix B.

Number: (placeholder) – count of every observation

Opposing: (0 = No, 1 = Yes) – did the vehicle experience an opposing vehicle while in the horizontal curve?

Number_Opposing: (0-11) – the total number of opposing vehicles experienced in the horizontal curve

Vehicle_Type: (0-3) – type of vehicle observed (0 = motorcycle, 1 = passenger car, 2 = school bus, 3 = truck)

Time_Day: (0 = Day, 1 = Night) – at what time did the vehicle travel within the horizontal curve?

Free_Flowing: (0 = No, 1 = Yes) – Is the vehicle free-flowing? Free-flowing was defined as a vehicle exhibiting a headway and tailway gap time greater than or equal to 5 seconds at all stations

Platoon_Position: (0 = free-flowing, 1-6 = position within the platoon) – if a vehicle is not free-flowing, what is its position in the platoon of vehicles (1 = lead vehicle)? Platoons positions over 6 were reduced to 6

Rain: (0 = No, 1 = Yes) – is it raining when the vehicle is within the horizontal curve?

Ldistance_0 through **Ldistance_4:** the lateral distance (in inches) of the vehicle at each station along the curve. The measurement is from the inside edge of the white edge line pavement marking to the passenger front tire edge

Speed_0 through **Speed_4:** the speed (in mph) of the vehicle at each station along the horizontal curve

Place: (0 = Ames, 1 = Dexter) – the city in which the vehicle observation was recorded

Lane: (0 = Inside, 1 = Outside) – the lane in which the vehicle observation was recorded

vlength: the length of the vehicle (in inches) at Sta. A

Table A-1 First 26 vehicle observations from the vehicle database

Number	Opposing	Number_ Opposing	Vehicle_Type	Time_Day	Free_Flowing	Platoon_ Position	Rain	Ldistance_0	Speed_0	Ldistance_1	Speed_1	Ldistance_2	Speed_2	Ldistance_3	Speed_3	Ldistance_4	Speed_4	Place	Lane	vlength
1	1	1	1	0	1	0	0	20.897	44.4	24.226	47.3	10.164	49.2	25.807	51.3	24.044	51.6	0	0	104
2	1	1	1	0	0	1	0	23.136	45.7	17.348	45.9	52.930	46.3	32.556	46.8	11.037	45.8	0	0	110
3	0	0	1	0	0	2	0	21.567	53.5	12.325	52.4	2.970	50.3	14.789	47.2	-1.589	45	0	0	121
4	1	2	1	0	1	0	0	15.283	41.1	12.680	42.8	15.726	43.8	26.040	44.8	24.984	43.7	0	0	139
5	1	1	1	0	1	0	0	31.236	50.8	6.558	50.2	5.947	53	16.436	54.8	19.743	54.7	0	0	105
6	1	1	1	0	1	0	0	27.084	54.3	10.756	51.6	27.839	52	51.661	54.1	36.151	55	0	0	107
7	1	1	1	0	1	0	0	36.525	44.7	36.384	45.7	30.514	45.6	60.000	44.3	53.225	29.1	0	0	111
8	1	1	1	0	1	0	0	18.951	44	5.575	43.7	20.110	47.5	40.829	50.2	13.922	50.4	0	0	116
9	1	1	1	0	1	0	0	24.883	45.1	36.430	46.1	23.024	47.3	24.212	50.6	20.910	51.8	0	0	119
10	1	1	1	0	0	1	0	22.039	42.5	23.127	44.1	29.392	45.9	35.742	47.9	35.375	47.8	0	0	118
11	1	1	1	0	0	2	0	16.177	35.9	33.961	42.2	22.355	45	23.292	46.6	30.818	49.5	0	0	110
12	1	1	1	0	0	1	0	14.416	36.8	26.579	37	16.682	38.5	21.016	40	4.691	28	0	0	135
13	1	1	1	0	0	2	0	27.960	42.8	24.587	41.4	42.335	40.2	40.736	42.3	25.584	29.8	0	0	121
14	1	2	1	0	0	3	0	35.433	48.3	33.857	48.8	43.858	48.1	48.953	46.4	24.312	26	0	0	103
15	1	3	1	0	0	1	0	27.084	54.3	27.840	52.6	36.702	52.5	43.398	53.8	48.582	52.8	0	0	115
16	1	3	1	0	0	2	0	34.188	51.5	28.376	54.5	35.505	53.5	48.604	54.8	46.362	53.9	0	0	103
17	1	3	1	0	1	0	0	17.220	40	32.399	40.4	18.269	42.4	60.444	44.2	25.489	43.9	0	0	98
18	0	0	1	0	0	2	0	33.838	46.1	25.702	49.3	17.972	49	40.809	48.5	18.204	50.2	0	0	116
19	1	1	1	0	1	0	0	31.526	47.7	11.538	48.2	17.725	49.9	27.444	51.9	20.336	51.6	0	0	119
20	1	1	1	0	0	1	0	17.623	50.5	26.871	49.3	16.260	48.8	22.412	52.4	20.543	53.9	0	0	134
21	0	0	1	0	0	2	0	24.910	47.3	9.168	47.1	28.753	47.3	29.174	47.2	32.465	46.7	0	0	108
22	0	0	1	0	0	3	0	42.927	42.2	19.902	44.4	32.157	44.6	26.081	46.4	28.860	28.5	0	0	103
23	0	0	1	0	0	4	0	9.052	43.3	2.296	43.2	12.096	43.6	12.135	47	-6.134	28.6	0	0	145
24	1	1	1	0	1	0	0	30.271	44.4	16.276	44.2	28.388	44.5	49.816	45.3	38.313	45	0	0	109
25	1	1	1	0	0	1	0	17.990	36.5	18.577	38.7	15.797	40.8	15.594	42.9	14.042	43.6	0	0	114
26	1	1	1	0	0	2	0	29.790	37.8	40.371	39.7	14.808	40.8	29.434	46	25.107	42.7	0	0	107

Note: All speed and lateral deviation values in Table A-1 are in U.S. unites (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

APPENDIX B: SAS CODE

```
/*==================================Ames==================================*/

ods pdf file = "modelstationsAmes.pdf";
ods graphics on;
proc glm  data=curves2;
  where place=0;
  class vehicle_type;
  model  Ldistance_1 =  Number_opposing Vehicle_Type vlength
speed_0 Platoon_Position Ldistance_0 lane/solution ss3;
title 'Ames prediction models';
output out = r1 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
  where place=0;
  class vehicle_type;
  model Speed_1 = number_opposing rain Free_Flowing
      Time_Day Platoon_Position Ldistance_0 Speed_0 /solution ss3;
  output out = r2 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
  where place=0;
  class vehicle_type;
  model Ldistance_2 = Number_opposing Vehicle_Type vlength
   Time_Day Rain Ldistance_0 Speed_0 lane/solution ss3;
  output out = r3 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
  where place=0;
  class vehicle_type;
  model  Speed_2 = opposing Number_opposing rain
 Free_Flowing Time_Day Ldistance_0 Speed_0 lane/solution ss3;
  output out = r4 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
where place=0;
  class vehicle_type;
  model  Ldistance_3 = Number_opposing Vehicle_Type
Time_Day Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
  output out = r5 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
  where place=0;
  class vehicle_type;
  model Speed_3 = opposing Number_opposing Free_Flowing Time_Day
      Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
  output out = r6 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
```

```
proc glm  data=curves2;
where place=0;
  class vehicle_type;
  model Ldistance_4 = opposing Vehicle_Type
Free_Flowing Time_Day Rain Ldistance_0 lane/solution ss3;
  output out = r7 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm data=curves2;
where place=0;
  class vehicle_type;
  model Speed_4 = Number_opposing vlength
Free_Flowing Time_Day Platoon_Position Ldistance_0 Speed_0 lane/solution
ss3;
  output out = r8 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
quit;
ods graphics off;
ods pdf close;

/*=================================Dexter===============================*/

ods pdf file = "modelstationsDexter.pdf";
ods graphics on;
proc glm  data=curves2;
  where place=1;
  class vehicle_type;
  model  Ldistance_1 =  Vehicle_Type time_Day Ldistance_0 Speed_0
lane/solution ss3;
title 'Dexter prediction models';
output out = r1 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
  where place=1;
  class vehicle_type;
  model Speed_1 = opposing Vehicle_Type vlength Time_Day
 Ldistance_0 Speed_0 lane/solution ss3;
output out = r2 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
where place=1;
class vehicle_type;
  model Ldistance_2 = Number_opposing Vehicle_Type Time_Day
  Ldistance_0 lane/solution ss3;
output out = r3 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
```

```
proc glm  data=curves2;
where place=1;
class vehicle_type;
  model  Speed_2 = opposing Number_opposing Vehicle_Type vlength
Free_Flowing Time_Day
Rain Platoon_Position Speed_0 lane/solution ss3;
output out = r4 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
where place=1;
class vehicle_type;
  model  Ldistance_3 = opposing Number_opposing Vehicle_Type vlength
Free_Flowing Time_Day
Rain Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
output out = r5 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
where place=1;
class vehicle_type;
  model Speed_3 = opposing Number_opposing Vehicle_Type vlength
Free_Flowing Time_Day
Rain Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
output out = r6 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm  data=curves2;
where place=1;
class vehicle_type;
  model Ldistance_4 = opposing Number_opposing Vehicle_Type vlength
Free_Flowing Time_Day
Rain Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
output out = r7 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
proc glm data=curves2;
where place=1;
class vehicle_type;
  model Speed_4 = opposing Number_opposing Vehicle_Type vlength
Free_Flowing Time_Day
Rain Platoon_Position Ldistance_0 Speed_0 lane/solution ss3;
  output out = r8 r = resid rstudent = rs p = yhat cookd = cookd dffits =
dffit h = h;
run;
quit;

ods graphics off;
ods pdf close;
```

APPENDIX C-1: DEXTER LATERAL POSITION SAS MODEL OUTPUTS

Dexter prediction models 11:55 Tuesday, March 8, 2011 **2**

The GLM Procedure

Dependent Variable: Ldistance_1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3839705.640	548529.377	4580.77	<.0001
Error	11192	1340198.949	119.746		
Corrected Total	11199	5179904.589			

R-Square	Coeff Var	Root MSE	Ldistance_1 Mean
0.741270	42.09472	10.94286	25.99580

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Type	3	4351.8192	1450.6064	12.11	<.0001
Time_Day	1	2572.4481	2572.4481	21.48	<.0001
Ldistance_0	1	835063.4320	835063.4320	6973.61	<.0001
Speed_0	1	3412.1187	3412.1187	28.49	<.0001
Lane	1	241677.8326	241677.8326	2018.25	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	-3.14904506	B	1.00803249	-3.12	0.0018
Vehicle_Type 0	6.05460834	B	1.15663440	5.23	<.0001
Vehicle_Type 1	0.52908335	B	0.34652317	1.53	0.1268
Vehicle_Type 2	-2.38825090	B	0.97429150	-2.45	0.0143
Vehicle_Type 3	0.00000000	B	.	.	.
Time_Day	1.19180683		0.25713627	4.63	<.0001
Ldistance_0	0.73560658		0.00880880	83.51	<.0001
Speed_0	0.09812827		0.01838285	5.34	<.0001
Lane	13.61718080		0.30310952	44.92	<.0001

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

The GLM Procedure

Dependent Variable: Ldistance_2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	2828012.086	404001.727	1822.39	<.0001
Error	11192	2481128.861	221.688		
Corrected Total	11199	5309140.947			

R-Square	Coeff Var	Root MSE	Ldistance_2 Mean
0.532668	56.13563	14.88918	26.52358

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	1113.1265	1113.1265	5.02	0.0251
Vehicle_Type	3	37646.2905	12548.7635	56.61	<.0001
Time_Day	1	28743.3692	28743.3692	129.66	<.0001
Ldistance_0	1	409376.4231	409376.4231	1846.64	<.0001
Lane	1	293116.5892	293116.5892	1322.20	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	5.80703660	B	0.48476340	11.98	<.0001
Number_Opposing	-0.55915633		0.24953519	-2.24	0.0251
Vehicle_Type 0	19.83074920	B	1.57389965	12.60	<.0001
Vehicle_Type 1	1.33741652	B	0.47146901	2.84	0.0046
Vehicle_Type 2	-3.15532031	B	1.32559609	-2.38	0.0173
Vehicle_Type 3	0.00000000	B	.	.	.
Time_Day	3.98516974		0.34998449	11.39	<.0001
Ldistance_0	0.51426637		0.01196734	42.97	<.0001
Lane	14.98813057		0.41219059	36.36	<.0001

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

The GLM Procedure

Dependent Variable: Ldistance_3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	4143109.961	460345.551	2763.92	<.0001
Error	11190	1863753.090	166.555		
Corrected Total	11199	6006863.052			

R-Square	Coeff Var	Root MSE	Ldistance_3 Mean
0.689729	45.73294	12.90563	28.21954

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	1026.9618	1026.9618	6.17	0.0130
Vehicle_Type	3	45561.0727	15187.0242	91.18	<.0001
Time_Day	1	46562.6037	46562.6037	279.56	<.0001
Rain	1	778.9500	778.9500	4.68	0.0306
Ldistance_0	1	260766.8823	260766.8823	1565.65	<.0001
Speed_0	1	908.8223	908.8223	5.46	0.0195
Lane	1	867972.0447	867972.0447	5211.32	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	2.44903722	B	1.19473312	2.05	0.0404
Number_Opposing	-0.53773977		0.21655797	-2.48	0.0130
Vehicle_Type 0	22.21279477	B	1.36433199	16.28	<.0001
Vehicle_Type 1	1.54761125	B	0.40874022	3.79	0.0002
Vehicle_Type 2	-1.94932573	B	1.14913263	-1.70	0.0898
Vehicle_Type 3	0.00000000	B	.	.	.
Time_Day	5.09465170		0.30470180	16.72	<.0001
Rain	-1.43074858		0.66158811	-2.16	0.0306
Ldistance_0	0.41109020		0.01038939	39.57	<.0001
Speed_0	0.05069151		0.02170076	2.34	0.0195
Lane	25.83210333		0.35783766	72.19	<.0001

The GLM Procedure

Dependent Variable: Ldistance_4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	638990.861	91284.409	453.31	<.0001
Error	11192	2253780.863	201.374		
Corrected Total	11199	2892771.724			

R-Square	Coeff Var	Root MSE	Ldistance_4 Mean
0.220892	40.25738	14.19064	35.24979

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Type	3	92015.6668	30671.8889	152.31	<.0001
Time_Day	1	47762.0935	47762.0935	237.18	<.0001
Ldistance_0	1	186613.0740	186613.0740	926.70	<.0001
Speed_0	1	10836.6052	10836.6052	53.81	<.0001
Lane	1	2895.3851	2895.3851	14.38	0.0002

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	15.99096473	B	1.30721114	12.23	<.0001
Vehicle_Type 0	31.29516478	B	1.49991729	20.86	<.0001
Vehicle_Type 1	1.51890748	B	0.44936939	3.38	0.0007
Vehicle_Type 2	-3.59296304	B	1.26345599	-2.84	0.0045
Vehicle_Type 3	0.00000000	B	.	.	.
Time_Day	5.13539948		0.33345294	15.40	<.0001
Ldistance_0	0.34774181		0.01142320	30.44	<.0001
Speed_0	0.17487540		0.02383878	7.34	<.0001
Lane	-1.49046562		0.39307080	-3.79	0.0002

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

APPENDIX C-2: DEXTER SPEED SAS MODEL OUTPUTS

The GLM Procedure

Dependent Variable: Speed_1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	334141.8265	37126.8696	20981.6	<.0001
Error	11190	19800.6534	1.7695		
Corrected Total	11199	353942.4799			

R-Square	Coeff Var	Root MSE	Speed_1 Mean
0.944057	2.679274	1.330224	49.64866

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Opposing	1	6.9809	6.9809	3.95	0.0470
Vehicle_Type	3	20.7297	6.9099	3.91	0.0084
vlength	1	15.1748	15.1748	8.58	0.0034
Time_Day	1	96.6052	96.6052	54.59	<.0001
Ldistance_0	1	35.4589	35.4589	20.04	<.0001
Speed_0	1	329149.9923	329149.9923	186013	<.0001
Lane	1	319.4932	319.4932	180.56	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	0.8197340202	B	0.13672870	6.00	<.0001
Opposing	-.0596710921		0.03004234	-1.99	0.0470
Vehicle_Type 0	-.1232732671	B	0.14624284	-0.84	0.3993
Vehicle_Type 1	0.0958529785	B	0.05252478	1.82	0.0680
Vehicle_Type 2	0.3260941934	B	0.11857157	2.75	0.0060
Vehicle_Type 3	0.0000000000	B	.	.	.
vlength	0.0005089567		0.00017380	2.93	0.0034
Time_Day	0.2324467371		0.03145922	7.39	<.0001
Ldistance_0	0.0047953435		0.00107123	4.48	<.0001
Speed_0	0.9658499420		0.00223943	431.29	<.0001
Lane	-.4952704669		0.03685839	-13.44	<.0001

The GLM Procedure

Dependent Variable: Speed_2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	293498.2228	36687.2779	10348.0	<.0001
Error	11191	39675.8483	3.5453		
Corrected Total	11199	333174.0711			

R-Square	Coeff Var	Root MSE	Speed_2 Mean
0.880916	3.863093	1.882906	48.74089

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Opposing	1	15.1788	15.1788	4.28	0.0386
Vehicle_Type	3	45.0168	15.0056	4.23	0.0054
vlength	1	31.7598	31.7598	8.96	0.0028
Time_Day	1	340.5540	340.5540	96.06	<.0001
Speed_0	1	287227.9097	287227.9097	81015.7	<.0001
Lane	1	3023.2826	3023.2826	852.75	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	3.421713572	B	0.19179309	17.84	<.0001
Opposing	-0.087985269		0.04252263	-2.07	0.0386
Vehicle_Type 0	0.132228657	B	0.19858373	0.67	0.5055
Vehicle_Type 1	0.155402720	B	0.07426582	2.09	0.0364
Vehicle_Type 2	0.548499864	B	0.16744640	3.28	0.0011
Vehicle_Type 3	0.000000000	B	.	.	.
vlength	0.000736045		0.00024592	2.99	0.0028
Time_Day	0.431407678		0.04401731	9.80	<.0001
Speed_0	0.900766811		0.00316466	284.63	<.0001
Lane	-1.056296798		0.03617223	-29.20	<.0001

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

The GLM Procedure

Dependent Variable: Speed_3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	272366.2607	30262.9179	5513.65	<.0001
Error	11190	61418.8421	5.4887		
Corrected Total	11199	333785.1028			

R-Square	Coeff Var	Root MSE	Speed_3 Mean
0.815993	4.701195	2.342803	49.83420

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Type	3	129.6182	43.2061	7.87	<.0001
vlength	1	45.1452	45.1452	8.23	0.0041
Time_Day	1	631.2307	631.2307	115.00	<.0001
Platoon_Position	1	114.8824	114.8824	20.93	<.0001
Ldistance_0	1	33.3037	33.3037	6.07	0.0138
Speed_0	1	267101.9436	267101.9436	48663.7	<.0001
Lane	1	841.8345	841.8345	153.38	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	5.710316459	B	0.24129167	23.67	<.0001
Vehicle_Type 0	1.028426318	B	0.25788438	3.99	<.0001
Vehicle_Type 1	0.213441735	B	0.09250973	2.31	0.0211
Vehicle_Type 2	0.625458982	B	0.20884979	2.99	0.0028
Vehicle_Type 3	0.000000000	B	.	.	.
vlength	0.000877888		0.00030610	2.87	0.0041
Time_Day	0.593165435		0.05531177	10.72	<.0001
Platoon_Position	-0.120004916		0.02623059	-4.57	<.0001
Ldistance_0	0.004647137		0.00188658	2.46	0.0138
Speed_0	0.871156473		0.00394906	220.60	<.0001
Lane	-0.804708754		0.06497722	-12.38	<.0001

The GLM Procedure

Dependent Variable: Speed_4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	247094.5545	35299.2221	4707.39	<.0001
Error	11192	83925.2451	7.4987		
Corrected Total	11199	331019.7996			

R-Square	Coeff Var	Root MSE	Speed_4 Mean
0.746465	5.432489	2.738372	50.40732

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Type	3	364.1784	121.3928	16.19	<.0001
Time_Day	1	776.0313	776.0313	103.49	<.0001
Platoon_Position	1	238.2812	238.2812	31.78	<.0001
Speed_0	1	244209.6014	244209.6014	32567.0	<.0001
Lane	1	46.7236	46.7236	6.23	0.0126

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	8.394810604	B	0.25165979	33.36	<.0001
Vehicle_Type 0	1.755991462	B	0.27647721	6.35	<.0001
Vehicle_Type 1	0.089638536	B	0.08646272	1.04	0.2999
Vehicle_Type 2	0.735784845	B	0.24324396	3.02	0.0025
Vehicle_Type 3	0.000000000	B	.	.	.
Time_Day	0.648567879		0.06375412	10.17	<.0001
Platoon_Position	-0.172823646		0.03065849	-5.64	<.0001
Speed_0	0.830558818		0.00460237	180.46	<.0001
Lane	-0.131284376		0.05259412	-2.50	0.0126

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

APPENDIX C-3: AMES LATERAL POSITION SAS MODEL OUTPUTS

Ames prediction models 11:55 Tuesday, March 8, 2011 **2**

The GLM Procedure

Dependent Variable: Ldistance_1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	1047352.663	116372.518	1023.80	<.0001
Error	12930	1469724.249	113.668		
Corrected Total	12939	2517076.912			

R-Square	Coeff Var	Root MSE	Ldistance_1 Mean
0.416099	37.29460	10.66151	28.58728

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	3484.0097	3484.0097	30.65	<.0001
Vehicle_Type	3	19172.1691	6390.7230	56.22	<.0001
vlength	1	1492.2471	1492.2471	13.13	0.0003
Speed_0	1	2856.4431	2856.4431	25.13	<.0001
Platoon_Position	1	3019.0565	3019.0565	26.56	<.0001
Ldistance_0	1	226786.2627	226786.2627	1995.17	<.0001
Lane	1	203625.6115	203625.6115	1791.41	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	8.90147961	B	1.18229333	7.53	<.0001
Number_Opposing	-0.29984236		0.05415917	-5.54	<.0001
Vehicle_Type 0	23.49418885	B	1.86419729	12.60	<.0001
Vehicle_Type 1	1.43145228	B	0.63182742	2.27	0.0235
Vehicle_Type 2	-4.04059147	B	3.01541748	-1.34	0.1803
Vehicle_Type 3	0.00000000	B	.	.	.
vlength	-0.01255071		0.00346391	-3.62	0.0003
Speed_0	0.07914634		0.01578835	5.01	<.0001
Platoon_Position	-0.43296033		0.08401003	-5.15	<.0001
Ldistance_0	0.39948960		0.00894367	44.67	<.0001
Lane	9.61797904		0.22724079	42.33	<.0001

The GLM Procedure

Dependent Variable: Ldistance_2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	912520.827	91252.083	803.85	<.0001
Error	12929	1467689.305	113.519		
Corrected Total	12939	2380210.132			

R-Square	Coeff Var	Root MSE	Ldistance_2 Mean
0.383378	34.98280	10.65454	30.45650

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	4022.2816	4022.2816	35.43	<.0001
Vehicle_Type	3	18986.8151	6328.9384	55.75	<.0001
vlength	1	2177.2385	2177.2385	19.18	<.0001
Time_Day	1	12664.1098	12664.1098	111.56	<.0001
Rain	1	1255.4054	1255.4054	11.06	0.0009
Ldistance_0	1	132763.7155	132763.7155	1169.53	<.0001
Speed_0	1	2452.3468	2452.3468	21.60	<.0001
Lane	1	212102.3640	212102.3640	1868.43	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	18.58029650	B	1.18948615	15.62	<.0001
Number_Opposing	-0.32427792		0.05447732	-5.95	<.0001
Vehicle_Type 0	23.89423260	B	1.86288864	12.83	<.0001
Vehicle_Type 1	2.19883933	B	0.63141106	3.48	0.0005
Vehicle_Type 2	-0.93780883	B	3.01374088	-0.31	0.7557
Vehicle_Type 3	0.00000000	B	.	.	.
vlength	-0.01515859		0.00346131	-4.38	<.0001
Time_Day	2.16721492		0.20518672	10.56	<.0001
Rain	1.30999250		0.39392307	3.33	0.0009
Ldistance_0	0.30565487		0.00893771	34.20	<.0001
Speed_0	-0.07355903		0.01582631	-4.65	<.0001
Lane	10.36490964		0.23978795	43.23	<.0001

The GLM Procedure

Dependent Variable: Ldistance_3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	570698.467	63410.941	454.71	<.0001
Error	12930	1803129.837	139.453		
Corrected Total	12939	2373828.303			

R-Square	Coeff Var	Root MSE	Ldistance_3 Mean
0.240413	35.69455	11.80903	33.08357

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	8162.9956	8162.9956	58.54	<.0001
Vehicle_Type	3	28136.3519	9378.7840	67.25	<.0001
Time_Day	1	15835.0803	15835.0803	113.55	<.0001
Platoon_Position	1	1836.7540	1836.7540	13.17	0.0003
Ldistance_0	1	163567.5266	163567.5266	1172.92	<.0001
Speed_0	1	1571.5457	1571.5457	11.27	0.0008
Lane	1	38108.4397	38108.4397	273.27	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	16.60816896	B	1.02170803	16.26	<.0001
Number_Opposing	-0.46204277		0.06039092	-7.65	<.0001
Vehicle_Type 0	28.01246016	B	1.99196144	14.06	<.0001
Vehicle_Type 1	1.45137507	B	0.61232391	2.37	0.0178
Vehicle_Type 2	0.74844546	B	3.33160505	0.22	0.8223
Vehicle_Type 3	0.00000000	B	.	.	.
Time_Day	2.56918852		0.24110159	10.66	<.0001
Platoon_Position	-0.35989481		0.09916635	-3.63	0.0003
Ldistance_0	0.33921989		0.00990483	34.25	<.0001
Speed_0	0.05874999		0.01750083	3.36	0.0008
Lane	4.36020832		0.26376119	16.53	<.0001

The GLM Procedure

Dependent Variable: Ldistance_4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	3432305.85	381367.32	558.32	<.0001
Error	12930	8832056.92	683.07		
Corrected Total	12939	12264362.77			

R-Square	Coeff Var	Root MSE	Ldistance_4 Mean
0.279860	47.33565	26.13555	55.21325

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Opposing	1	5419.545	5419.545	7.93	0.0049
Vehicle_Type	3	36045.969	12015.323	17.59	<.0001
Free_Flowing	1	7606.912	7606.912	11.14	0.0008
Time_Day	1	148987.407	148987.407	218.12	<.0001
Rain	1	128407.430	128407.430	187.99	<.0001
Ldistance_0	1	40743.043	40743.043	59.65	<.0001
Lane	1	2326967.283	2326967.283	3406.65	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	57.99248951	B	1.54658899	37.50	<.0001
Opposing	-1.65061528		0.58599796	-2.82	0.0049
Vehicle_Type 0	29.67187041	B	4.40657476	6.73	<.0001
Vehicle_Type 1	5.99960741	B	1.35469095	4.43	<.0001
Vehicle_Type 2	-1.92135717	B	7.37107346	-0.26	0.7944
Vehicle_Type 3	0.00000000	B	.	.	.
Free_Flowing	1.61607016		0.48427013	3.34	0.0008
Time_Day	7.71414501		0.52232966	14.77	<.0001
Rain	13.27928580		0.96852605	13.71	<.0001
Ldistance_0	0.16915548		0.02190236	7.72	<.0001
Lane	-33.70196043		0.57741983	-58.37	<.0001

APPENDIX C-4: AMES SPEED SAS MODEL OUTPUTS

Ames prediction models 11:55 Tuesday, March 8, 2011 **6**

The GLM Procedure

Dependent Variable: Speed_1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	208073.9139	29724.8448	4461.97	<.0001
Error	12932	86150.6239	6.6618		
Corrected Total	12939	294224.5379			

R-Square	Coeff Var	Root MSE	Speed_1 Mean
0.707194	5.516176	2.581050	46.79056

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	56.7920	56.7920	8.52	0.0035
Rain	1	33.9663	33.9663	5.10	0.0240
Free_Flowing	1	763.2716	763.2716	114.57	<.0001
Time_Day	1	529.3539	529.3539	79.46	<.0001
Platoon_Position	1	171.1437	171.1437	25.69	<.0001
Ldistance_0	1	924.6077	924.6077	138.79	<.0001
Speed_0	1	193600.2587	193600.2587	29061.2	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	16.28404852	0.18977391	85.81	<.0001
Number_Opposing	-0.03841648	0.01315741	-2.92	0.0035
Rain	-0.21405000	0.09479547	-2.26	0.0240
Free_Flowing	0.87100288	0.08137227	10.70	<.0001
Time_Day	-0.45536321	0.05108357	-8.91	<.0001
Platoon_Position	0.18723766	0.03694104	5.07	<.0001
Ldistance_0	0.02176179	0.00184719	11.78	<.0001
Speed_0	0.64250916	0.00376897	170.47	<.0001

The GLM Procedure

Dependent Variable: Speed_2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	135806.5429	16975.8179	1404.61	<.0001
Error	12931	156281.5579	12.0858		
Corrected Total	12939	292088.1007			

R-Square	Coeff Var	Root MSE	Speed_2 Mean
0.464951	7.531171	3.476465	46.16101

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Opposing	1	130.4377	130.4377	10.79	0.0010
Number_Opposing	1	262.3483	262.3483	21.71	<.0001
Rain	1	47.0005	47.0005	3.89	0.0486
Free_Flowing	1	2929.0078	2929.0078	242.35	<.0001
Time_Day	1	715.9287	715.9287	59.24	<.0001
Ldistance_0	1	741.2912	741.2912	61.34	<.0001
Speed_0	1	125139.2991	125139.2991	10354.2	<.0001
Lane	1	10278.2887	10278.2887	850.44	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	22.17544295	0.25558566	86.76	<.0001
Opposing	0.31062052	0.09455106	3.29	0.0010
Number_Opposing	-0.10050310	0.02157139	-4.66	<.0001
Rain	-0.25430778	0.12895734	-1.97	0.0486
Free_Flowing	1.00504030	0.06455963	15.57	<.0001
Time_Day	-0.53768683	0.06986060	-7.70	<.0001
Ldistance_0	0.02250564	0.00287366	7.83	<.0001
Speed_0	0.52501948	0.00515960	101.76	<.0001
Lane	-2.28390748	0.07831698	-29.16	<.0001

The GLM Procedure

Dependent Variable: Speed_3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	139475.3650	17434.4206	1170.38	<.0001
Error	12931	192624.4362	14.8963		
Corrected Total	12939	332099.8012			

R-Square	Coeff Var	Root MSE	Speed_3 Mean
0.419980	8.278396	3.859576	46.62227

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Opposing	1	116.05406	116.05406	7.79	0.0053
Number_Opposing	1	331.69981	331.69981	22.27	<.0001
Free_Flowing	1	1030.77058	1030.77058	69.20	<.0001
Time_Day	1	540.32128	540.32128	36.27	<.0001
Platoon_Position	1	219.80387	219.80387	14.76	0.0001
Ldistance_0	1	768.21359	768.21359	51.57	<.0001
Speed_0	1	96645.34784	96645.34784	6487.86	<.0001
Lane	1	41425.35503	41425.35503	2780.91	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	26.83387338	0.29538118	90.84	<.0001
Opposing	0.29304188	0.10498788	2.79	0.0053
Number_Opposing	-0.11298410	0.02394332	-4.72	<.0001
Free_Flowing	1.01260990	0.12173089	8.32	<.0001
Time_Day	-0.47552622	0.07895653	-6.02	<.0001
Platoon_Position	-0.21211822	0.05522045	-3.84	0.0001
Ldistance_0	0.02292717	0.00319263	7.18	<.0001
Speed_0	0.46199923	0.00573575	80.55	<.0001
Lane	-4.53753418	0.08604516	-52.73	<.0001

The GLM Procedure

Dependent Variable: Speed_4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	114833.1916	14354.1489	509.09	<.0001
Error	12931	364598.2051	28.1957		
Corrected Total	12939	479431.3966			

R-Square	Coeff Var	Root MSE	Speed_4 Mean
0.239520	11.65667	5.309959	45.55296

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Number_Opposing	1	570.78931	570.78931	20.24	<.0001
vlength	1	181.53233	181.53233	6.44	0.0112
Free_Flowing	1	539.57506	539.57506	19.14	<.0001
Time_Day	1	1488.45468	1488.45468	52.79	<.0001
Platoon_Position	1	1358.19250	1358.19250	48.17	<.0001
Ldistance_0	1	323.93799	323.93799	11.49	0.0007
Speed_0	1	68598.83459	68598.83459	2432.96	<.0001
Lane	1	34127.54144	34127.54144	1210.38	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	30.33846066	0.44928015	67.53	<.0001
Number_Opposing	-0.12225937	0.02717287	-4.50	<.0001
vlength	-0.00377263	0.00148682	-2.54	0.0112
Free_Flowing	0.73306105	0.16757353	4.37	<.0001
Time_Day	-0.78781229	0.10842917	-7.27	<.0001
Platoon_Position	-0.52771601	0.07603452	-6.94	<.0001
Ldistance_0	0.01490519	0.00439742	3.39	0.0007
Speed_0	0.38989446	0.00790460	49.33	<.0001
Lane	-4.12093783	0.11844992	-34.79	<.0001

APPENDIX D: EXAMPLE OF R CODE

Two-sided paired t-test, Shapiro-Wilk test of normality, non-parametric Wilcoxon rank sum test

```
# Read in paired data of video and road tube speeds – testing the
difference at 95% level of confidence
s1 = read.csv("speed.csv",header=TRUE)
diff1 = s1$sta2v - s1$sta2t
qqnorm(diff1)

# Shapiro-Wilk normality test
t1 = shapiro.test(diff1)
t1

# Non-parametric "Wilcoxon" test
test1 = wilcox.test(s1$sta2v,s1$sta2t,paired=TRUE, conf.int = TRUE,
conf.level = 0.95)
test1

# Paired t-test
test1a = t.test(s1$sta1v,s1$sta1t,paired=TRUE)
test1a
```

Two-sided t-test, Shapiro-Wilk test of normality, Non-parametric Wilcoxon rank sum test

```
# Read in 2 independent datasets – mean speed of passenger car versus
truck at Station A at 95% level of confidence
library(ggplot2)
s1 = read.csv("STA_A.csv",header=TRUE)

# Shapiro-Wilk normality test
t1 = shapiro.test(s1$PC)
t1
t2 = shapiro.test(s1$T)
t2

# Non-parametric "Wilcoxon Sum" test
test1 = wilcox.test(s1$PC,s1$T, conf.int = TRUE, conf.level = 0.95)
test1

# T-test
test1a = t.test(s1$PC,s1$T, var.equal = FALSE, conf.level = 0.95)
test1a
```

<u>One-sided t-test, Shapiro-Wilk test of normality, Non-parametric Wilcoxon rank sum test</u>

```
# Read in 2 independent datasets - passenger car means speed is greater
than truck mean speed at Sta. A
library(ggplot2)

s1 = read.csv("Sta_A_PvT.csv",header=TRUE)
head(s1)

# Shapiro-Wilk normality test
t1 = shapiro.test(s1$PC)
t1
t2 = shapiro.test(s1$T)
t2

# Non-parametric "Wilcoxon" test
test1 = wilcox.test(s1$PC, s1$T, con.int = TRUE, alternative = "greater")
test1

# T-test: one-one sided (car mean is greater than truck mean)
test2 = t.test(s1$PC, s1$T, var.equal=FALSE, alternative = "greater")
test2

# assuming unequal variance and normally distributed with large sample,
check normality with smaller sample sizes
# Hypothesis: Mean of car is greater than truck
# if p-value is greater than 0.05 Accept. If less, reject
```

<u>Repeated measures analysis of variance</u>

```
# Mixed model to compare day versus night vehicle trajectories as a whole
library(ggplot2)
library(nlme)

d1 = read.csv("Trajectory.csv",header=TRUE)
d1$vehicle = seq(1,nrow(d1))
dsb = melt(d1,id.var=c(1,16),measure.var=c(3,5,7,9,11,13,15))
dsb$Time = as.factor(dsb$Time)
dsb$vehicle = as.factor(dsb$vehicle)

dsb = dsb[order(dsb$vehicle,dsb$variable),]

m22 = gls(value ~ Time + variable + Time*variable,data=dsb,method="REML",
          correlation=corARMA(form = ~ 1|vehicle,p=1,q=0))
m22
# print(anova(m22))
# m22 is preferred
```

APPENDIX E: CURVE STATION DIMENSIONS

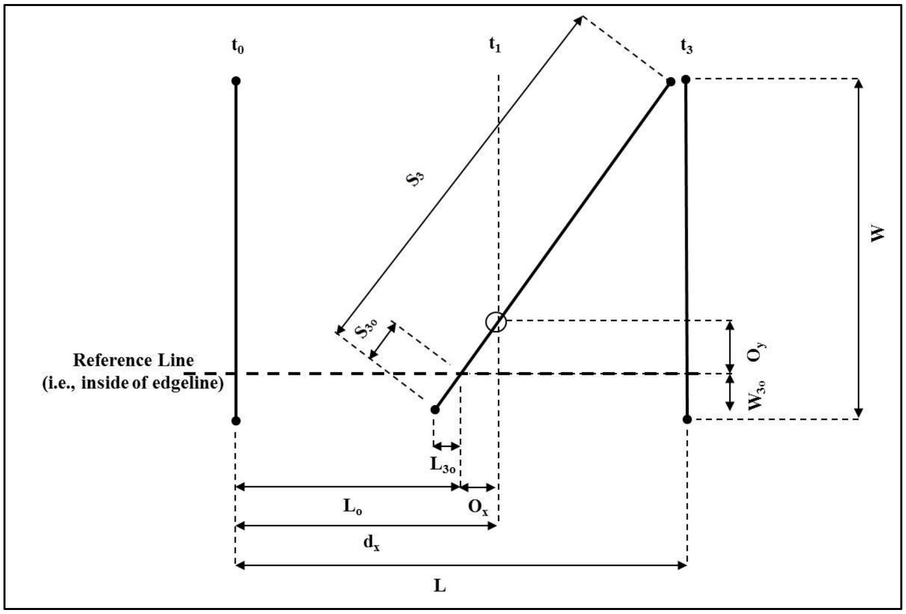


FIGURE E.1 Z-configured road tube variable definitions

Table E-1 Ames outside lane z-configuration dimensions at each station

Ames Outside Lane					
Station	**Sta. A**	**Sta. B**	**Sta. C**	**Sta. D**	**Sta. E**
Counter	**16547**	**21336**	**21390**	**19340**	**21337**
L (ft.)	16.50	15.96	15.92	15.92	15.96
L_0 (ft.)	6.13	6.04	5.83	5.88	5.96
S_3 (ft.)	17.33	17.08	17.08	16.25	16.92
S_{30} (ft.)	1.42	1.21	1.33	1.33	1.42
W (ft.)	14.08	14.13	14.00	13.67	13.71
W_{30} (ft.)	1.21	1.00	1.25	1.13	1.08
L_{30} (ft.)	1.17	0.96	1.17	1.17	1.25
Triangle X (ft.)[a]	7.25	6.50	7.08	6.83	6.88
Triangle Y (ft.)[a]	6.89	7.60	7.06	7.30	7.26

Table E-2 Ames inside lane z-configuration dimensions at each station

Ames Inside Lane					
Station	**Sta. A**	**Sta. B**	**Sta. C**	**Sta. D**	**Sta. E**
Counter	**20335**	**21569**	**20333**	**20332**	**20331**
L (ft.)	16.08	15.83	16.17	17.29	16.04
L_0 (ft.)	5.79	6.00	6.17	6.13	6.17
S_3 (ft.)	15.33	16.33	15.00	17.00	16.75
S_{30} (ft.)	2.17	2.17	2.17	2.67	2.58
W (ft.)	11.92	12.58	11.83	13.33	13.33
W_{30} (ft.)	1.67	1.67	1.67	2.00	2.00
L_{30} (ft.)	1.58	1.25	1.33	1.83	1.83
Triangle X (ft.)[a]	6.00	5.96	5.88	6.00	5.92
Triangle Y (ft.)[a]	8.00	8.03	8.09	8.00	8.06

Table E-3 Dexter outside lane z-configuration dimensions at each station

Dexter Outside Lane					
Station	**Sta. A**	**Sta. B**	**Sta. C**	**Sta. D**	**Sta. E**
Counter	**20332**	**20333**	**20335**	**20331**	**21569**
L (ft.)	15.17	15.88	16.08	15.92	16.00
L_0 (ft.)	6.00	6.75	6.96	6.75	6.96
S_3 (ft.)	15.50	14.50	14.58	14.88	14.83
S_{30} (ft.)	1.42	1.50	1.67	1.50	1.75
W (ft.)	12.00	11.58	11.63	11.75	11.92
W_{30} (ft.)	1.29	1.40	1.38	1.17	1.50
L_{30} (ft.)	1.17	1.00	0.94	1.21	1.00
Triangle X (ft.)[a]	5.92	6.00	6.00	6.00	5.92
Triangle Y (ft.)[a]	8.06	8.00	8.00	8.00	8.06

Table E-4 Dexter inside lane z-configuration dimensions at each station

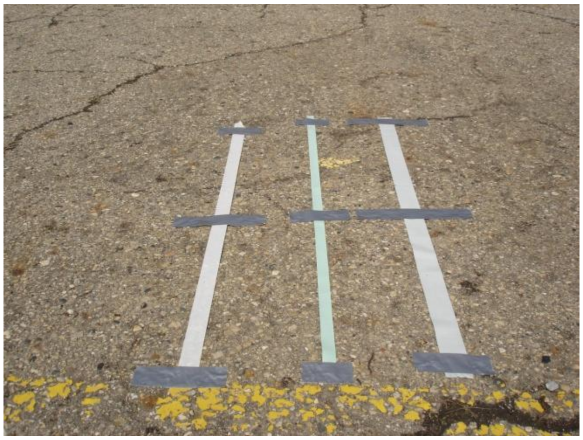
Dexter Inside Lane					
Station	**Sta. A**	**Sta. B**	**Sta. C**	**Sta. D**	**Sta. E**
Counter	**20335**	**20333**	**21569**	**20331**	**20332**
L (ft.)	15.75	16.00	15.63	15.67	15.75
L_0 (ft.)	7.25	7.58	6.96	7.08	7.42
S_3 (ft.)	15.96	16.42	15.25	15.33	15.58
S_{30} (ft.)	2.29	2.75	1.79	2.08	2.50
W (ft.)	13.08	13.33	12.79	13.00	12.67
W_{30} (ft.)	1.92	2.29	1.75	2.17	2.00
L_{30} (ft.)	1.33	1.67	1.42	1.38	1.42
Triangle X (ft.)[a]	6.54	5.96	5.75	5.92	6.00
Triangle Y (ft.)[a]	7.56	8.03	8.18	8.06	8.00

[a]Triangular adjustments to Equation 3-1. This adjustment was made cue to curvature of the roadway and known errors in the equipment setup. Equation 3-1 is based on the assumption the diagonal road tube is installed correctly and forms a right triangle with lateral length (Y) = 8 feet and longitudinal length (X) = 6 feet.

Note: All values in Table 4-1 are in U.S. units (1 mph = 1.61 km/hr; 1 ft = 0.305 m)

APPENDIX F: CHAPTER 3 DATA COLLECITON SITE PHOTOS

Closed-course study in the ISU north parking lot with lower speeds (April 13, 2010)




FIGURES F-1 and F-2 Tape test to determine tire lateral position (before and failure after)

FIGURE F-3 test bed for z-configured road tubes at low speeds


FIGURES F-4 and F-5 Z-configured road tube test setup with limestone aggregate ridge

Closed-course study at George Washington Carver Avenue with higher speeds (May 26, 2010)

FIGURE F-6 Closed-course looking south from z-configured road tubes

FIGURES F-7 and F-8 Z-configured road tube test bed with limestone aggregate ridge

FIGURE F-9 Aggregate ridge after vehicle crossing

Open-course study at George Washington Carver Avenue (8:10:54PM Apr. 27, 2010 to 4:46:14PM April 28, 2010)

FIGURE F-10 Seven z-configured road tubes from the CC to the PC

FIGURE F-11 Mobile video trailer at CC

Figure F-12 Setup from the PC

APPENDIX G: CHAPTERS 4 AND 5 DATA COLLECTION SITE PHOTOS

Dexter inside lane data collection (1:50:05PM Sept. 11, 2010 to 8:54:29AM Sept. 18, 2010)

FIGURE G-1: Sta. E with opposing lane station

FIGURE G-2 Sta. B z-configured road tubes

FIGURE G-3 Example of lane departure

FIGURE G-4 Heavy vehicle in the inside lane

FIGURE G-5 Sta. C z-configured road tubes

Dexter outside lane data collection (2:32:31PM Sept. 3, 2010 to 1:11:31AM Sept. 9, 2010)

FIGURE G-6: Sta. E with opposing lane station

FIGURE G-7 Sta. A through C

FIGURE G-8 Motorcycle in the outside lane

FIGURE G-9 Jamar TRAX plus HS counter

FIGURE G-10 Opposing lane station

<u>Ames Inside lane data collection (11:28:01AM Sept. 24, 2010 to 9:43:01AM Sept. 28, 2010)</u>

FIGURE G-11: Sta. A at point of curvature

FIGURE G-12 Truck at Sta. D

FIGURE G-13 Center of the curve (Sta. C)

FIGURE G-14 Sta. E z-configured road tubes

FIGURE G-15 Sta. B z-configured road tubes

Ames Outside lane data collection (12:27:45PM Oct. 11, 2010 to 10:50:57AM Oct. 14, 2010)

FIGURE G-16: Sta. E with opposing lane station

FIGURE G-17 Sta. D z-configured road tubes

FIGURE G-18 Center of the curve (Sta. C)

FIGURE G-19 Sta. B z-configured road tubes

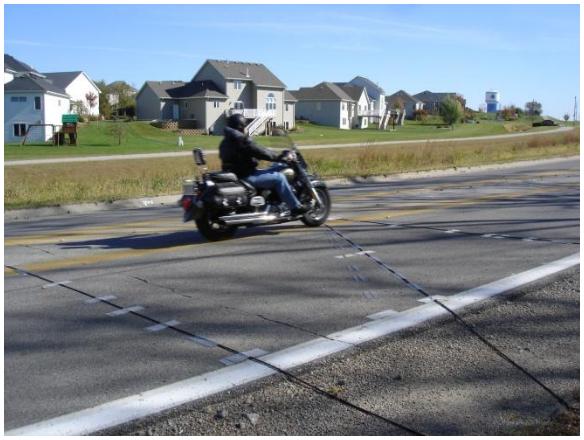


FIGURE G-20 Motorcycle at Sta. D