AN INVESTIGATION OF PASSING OPERATIONS ON A RURAL, TWO-LANE, TWO-WAY HIGHWAY WITH CENTERLINE RUMBLE STRIPS

A Thesis

by

JEFFREY DAVID MILES

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Civil Engineering

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Conrad Dudek
(Chair of Committee)

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ABSTRACT

An Investigation of Passing Operations on a Rural, Two-Lane, Two-Way Highway with Centerline Rumble Strips. (December 2004)

Jeffrey David Miles, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Conrad Dudek

The research in this thesis was conducted to investigate the initial stage of passing maneuvers on a rural, two-lane, two-way (RTLTW) highway with centerline rumble strips (CRSs). Four measures of effectiveness were used: (1) number and type of erratic movements by a passing vehicle, (2) number of and time between centerline encroachments of a passing vehicle, (3) gap distance of a passing vehicle, and (4) centerline crossing time. Data were collected for a before-and-after analysis at one site, in Comanche County, Texas. The test section was on US 67 from Comanche, Texas to the county line south of Dublin, Texas. The posted speed limit for this RTLTW highway was 70 mph during the day.

CRSs were installed along approximately 15 miles of US 67. Only one test design for CRSs was installed. The design specification was for a CRS to be milled to a 0.5-inch depth, 7-inch length, and 16-inch width. This specification was developed from current state practices throughout the United States. CRSs were installed continuously through passing and no-passing zones, and they were spaced at 24 inches on-centers. Pavement markings were striped over the CRSs.

Data were collected using an innovative data collection system developed by the author through the Texas Transportation Institute (TTI). This system was mounted to a four-door sedan, and it consisted of four concealed cameras that recorded the entire passing maneuver around the data collection vehicle.

Data were collected at three different speeds during the daytime. The speeds were 55, 60, and 65 mph (15, 10, and 5 mph, respectively, under the posted speed limit).

Based on the assessment of the four MOEs, the overall finding of this thesis was that driver performance during the initial phase of passing maneuvers was not negatively impacted after the installation of CRSs on US 67.

The caveat is that differences in the weather conditions may have influenced the results. The weather was dry with clear skies at the study site during data collection prior to the installation of CRSs; however, the weather consisted of intermittent rain during the data collection after the installation of CRSs.

DEDICATION

This thesis is dedicated to my loving wife, Nora. Her support was essential to my success in graduate school, and it will continue to be important in my future professional practice. Nora's love and support add to the wind that drives my sails through both the dead calm seas and storms of life.

ACKNOWLEDGEMENTS

The research described in this thesis is an extension of a larger Texas Transportation Institute (TTI) project sponsored through the Texas Department of Transportation (TxDOT). I would like to thank Dr. Paul Carlson for the opportunity to participate in this research, and for the time that he invested in my development as a researcher.

I would also like to thank my thesis committee for their support and guidance that they provided me throughout the thesis academic process. Dr. Conrad Dudek, my committee chair, spent many hours working with me to develop my research proposal. As my proposal began to materialize, Dr. Carroll Messer and Dr. Philip Yasskin further aided in the development of my thesis. Periodically, I sought and received helpful direction from each member of my committee as I collected and analyzed my data. Dr. Conrad Dudek and I worked closely together to refine various drafts of my report prior to submitting a draft to my whole committee. The level of detail and the final quality of my research presented in this document were greatly impacted by my thesis committee.

In general, I would like to thank The Texas A&M University Department of Civil Engineering, TxDOT, and TTI. Each professor that has crossed my path through my academics has played some role in my development as a researcher; TxDOT sponsored the very research detailed in this document; and the various professionals within TTI further refined my abilities as a researcher.

Finally, I would like to thank the United States Navy. My various experiences throughout my military service further developed my drive for excellence and my ability to persevere through the most chaotic of storms.

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INTRODUCTION

In 2001, more than half of all fatal multiple vehicle crashes on rural, two-lane, two-way (RTLTW) highways in the U.S. involve drivers traveling in opposite directions (*1*). This is one reason why state departments of transportation (DOTs) have recently begun investigating countermeasures for crossover (opposite direction) crashes associated with RTLTW highways.

As engineers study possible countermeasures to help mitigate the frequency and severity of crossover crashes, they must consider countermeasures that are both efficient and economical. Centerline rumble strips (CRSs) are a relatively new countermeasure that is one of the least expensive and one of the simplest countermeasures to install and maintain (*2*).

The purpose and design of CRSs are similar to the widely used shoulder rumble strips (SRSs), a successful countermeasure for run-off-road (ROR) crashes. As vehicles pass over rumble strips, audible and tactile sensations are generated that warn drivers of changes in roadway alignment and vehicle departures from the travel path. The most common application of CRSs is intermittent, depressed, transverse areas along the centerline pavement markings (*2*,*3*,*4*,*5*). Figure 1 contains a photograph of CRSs from Kansas, and a profile view drawing of CRSs.

Various state DOTs, such Alaska, Delaware, Idaho, Oregon, and Texas, are in the process of installing and testing CRS applications. Early study findings from

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This thesis follows the style and format of the *Transportation Research Record*.

Delaware indicate that CRSs are effective at reducing not only the number of crashes with increasing average annual daily traffic (AADT), but also the number of fatalities (*6*).

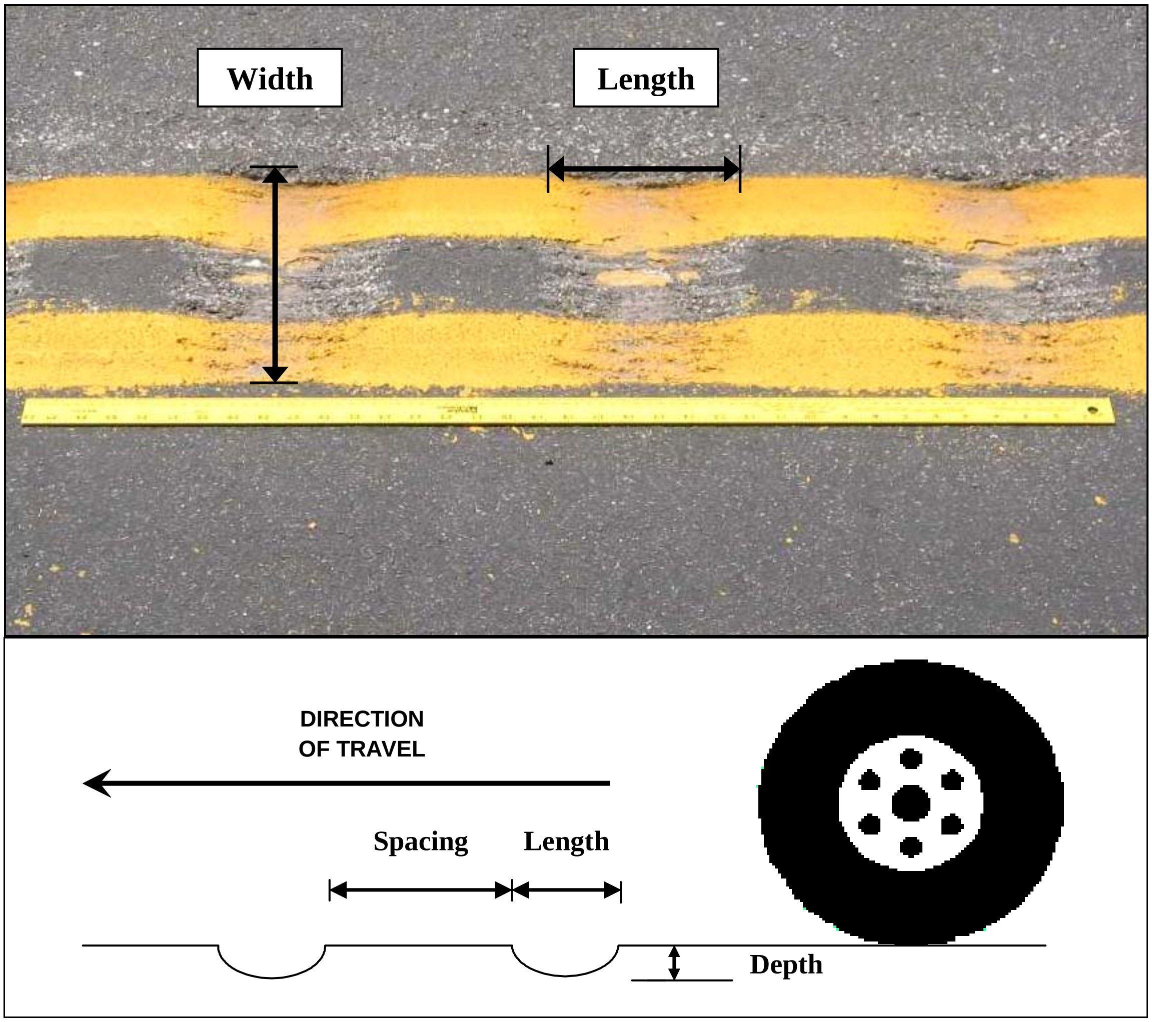


FIGURE 1 Centerline Rumble Strips (CRSs)

However, most of the current studies that have been published focused on crash data that can neither be used to explain how the traffic flow has changed, nor how the change in traffic flow impacted the improvement in safety by reducing crashes and/or severity of crashes. In particular, no research has been documented on the impact that CRSs may have on driver behavior during a passing maneuver.

PROBLEM STATEMENT

Concerns have been expressed about using CRSs in passing zones because of unknown driver reaction and performance (*2*,*3*,*7*). In particular, DOT representatives are concerned with the physical reaction of drivers when crossing CRSs in passing zones. Of the 22 state DOTs that have implemented CRSs, only Alaska, Delaware, Kentucky, Maryland, Oregon, Texas and Washington currently have CRSs in passing zones (*2*,*6*,*7*,*8*). The Texas Department of Transportation (TxDOT) is currently sponsoring research to determine the impacts on passing behavior for their statewide rumble strip study because a significant portion of the RTLTW highways in Texas are marked for passing. TxDOT is specifically concerned that drivers may perceive a conflicting message when they cross over CRSs to pass other vehicles, which may result in driver uncertainty and possibly erratic maneuvers during the initial phase of the passing maneuver. There is a need to study driver behavior in the before-and-after periods along RTLTW highways with CRSs to assess any changes during the passing maneuvers.

The Texas Transportation Institute (TTI) was selected by TxDOT to research the impacts of rumble strips on driver behavior. The TTI research project 4472 contained a study of all uses of rumble strips, and included a focused study of the impact of CRSs on driver behavior during passing maneuvers. The TTI project team selected six measures of effectiveness (MOEs) to study any changes in driver behavior along RTLTW highways after the installation of CRSs. The four MOEs that dealt with the initial stage of the passing maneuver were addressed in this thesis. These MOEs were:

- The number of passing maneuvers;
- Passing opportunity;
    - The amount of time that a passing vehicle is in a passing zone while queued behind a vehicle that the passing driver intends to pass less the amount of time that there is opposing traffic and all of this divided by the total amount of time that the passing driver is queued behind the passed vehicle;
- Number and type of erratic driving behavior during the initial stage of a passing maneuver;
- Number of centerline encroachments prior to a passing maneuver and the time between centerline encroachments;
- Gap distance between the front-end of a passing vehicle and the rear end of a vehicle being passed, prior to completing a passing maneuver; and
- Centerline crossing time.

OBJECTIVES

The research question for this thesis was: Does the installation of CRSs on highways marked for passing have an impact on driver performance during the initial stage of passing maneuvers? The initial stage of passing maneuvers denotes the elapsed time between the point that a passing vehicle first queues behind a vehicle to be passed and the point when the passing vehicle completely crosses into the opposing lane of travel prior to completing a pass. The specific research objectives were to:

1. Determine the relative differences of the following MOEs before and after CRSs are installed in no-passing and passing zones on a RTLTW highway:
    a. Number and type of erratic driving behavior during the initial stage of a passing maneuver;
    b. Number of centerline encroachments prior to a passing maneuver and the time between centerline encroachments;
    c. Gap distance between the front-end of a passing vehicle and the rear end of a vehicle being passed, prior to completing a passing maneuver; and
    d. Centerline crossing time during the initial stage of a passing maneuver; and
2. Design, develop, and calibrate an instrumented vehicle to measure the above MOEs and other MOEs for evaluating driver performance during passing maneuvers.

SCOPE

This research was limited to a study of the initial phase of passing maneuvers on US 67, a RTLTW highway in Comanche County, Texas. The study section was 15 miles long and the posted speed limit was 70 mph in the daytime. The average daily traffic (ADT) for the roadway was less than 4,122 vehicles per day (vpd) with approximately a 50/50 directional split for weekday traffic. One CRS design was tested.

LITERATURE REVIEW

A review of literature was conducted to investigate the state-of-the-art with respect to CRS use. This chapter is subdivided into the following topics:

- Crash Statistics and Countermeasures
- Rumble Strip Design
- Rumble Strip Application
- CRS Research
- Summary

CRASH STATISTICS AND COUNTERMEASURES

One of the main areas of concern related to crashes on undivided highways is the opposite direction or crossover crash (*2*). Opposite direction crashes occur when drivers cross the delineated roadway centerline into the opposing traffic flow and result in either sideswipe or head-on crashes. Opposite direction sideswipe and head-on crashes on RTLTW highways have a high percentage of fatalities making them a significantly hazardous class of crashes.

The National Highway Traffic Safety Administration (NHTSA) reported 37,795 fatal crashes in the United States during 2001 (*9*). Out of the total number of fatal crashes reported for 2001, 30 percent (11,235) occurred on RTLTW highways (speed limit ≥ 50 mph). In the State of Texas, 3,310 fatal crashes were reported and 32 percent (1,047) of those crashes were on RTLTW highways (*1*). Furthermore, 8 percent (266) of the fatal crashes in Texas involved either a head-on collision or opposite direction sideswipe (*9*).

Rumble strips milled along the centerline are a countermeasure under study by various state DOTs to mitigate head-on, opposite direction sideswipe, and single vehicle crossover run-off-road (SVCROR) crashes on RTLTW highways (*2*,*3*,*5*,*6*,*7*,*8*). Rumble strips are formed from intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface. Audio and vibratory sensations are generated when vehicle tires contact them. Through these sensations, drivers are alerted to unusual motor vehicle traffic conditions, such as unexpected changes in alignment and to conditions requiring a stop (*4*). State DOT agencies install rumble strips to warn drivers of the following conditions (*5*):

1. A need to stop;
2. A need to slow down;
3. A need to change lanes;
4. A change in roadway alignment;
5. A vehicle is leaving the roadway and/or the designated direction of travel; and
6. An unexpected change in traffic control devices.

Recently, Slack et al. summarized CRSs and other countermeasures for opposite direction crashes in a National Cooperative Highway Research Program (NCHRP) report *A Guide for Addressing Head-On Collisions* (*2*). The authors of that report emphasized that the cost of installing CRSs was considerably less expensive than either installing concrete barrier treatments (CBTs) or widening a roadway to allow for a median, wider lanes, and/or additional lanes. Furthermore, CRSs are one of the quickest countermeasures to implement (see Table 1).

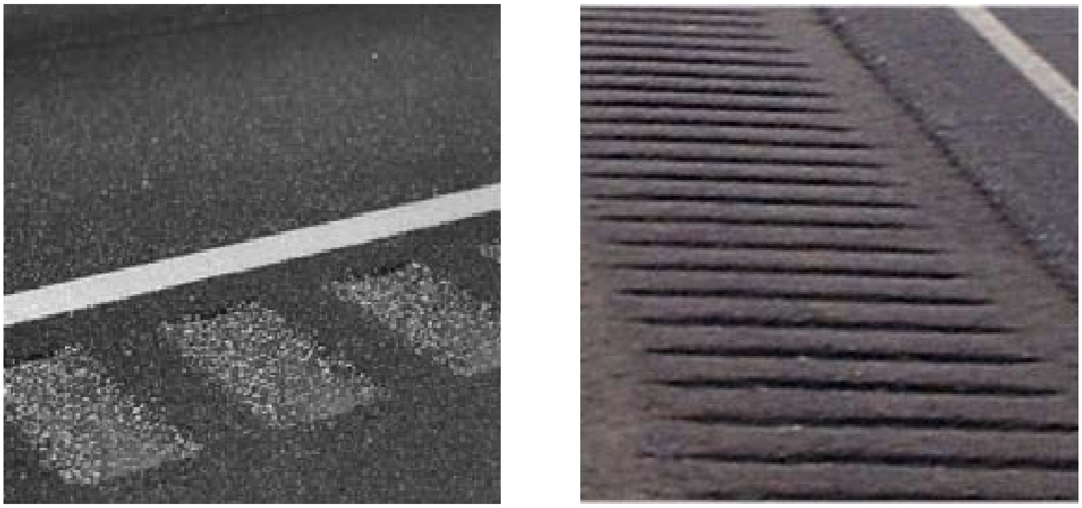
TABLE 1 Countermeasure Relative Cost Comparison (*2*)

Implementation Timeframe (2002)	**Strategy**	**Relative Cost to Implement and Operate**			
		Low	*Moderate*	*Moderate to High*	*High*
Short (<1 year)	CRSs for two-lane roads	☑			
	PTSs[1] for centerlines	☑			
	TWLTL[2] for two and four-lane roads		☑		
Medium (1-2 years)	Adjust lane and shoulder widths on two-lane roads to allow narrow "buffer median"	☑			
	Median barriers for narrow-width medians on multi-lane roads		☑		
	Alternating passing lanes or four-lane roadway sections at key locations[1]			☑	
Long (>2 years)	Redesign with wider cross-sections on two-lane roads[3]			☑	

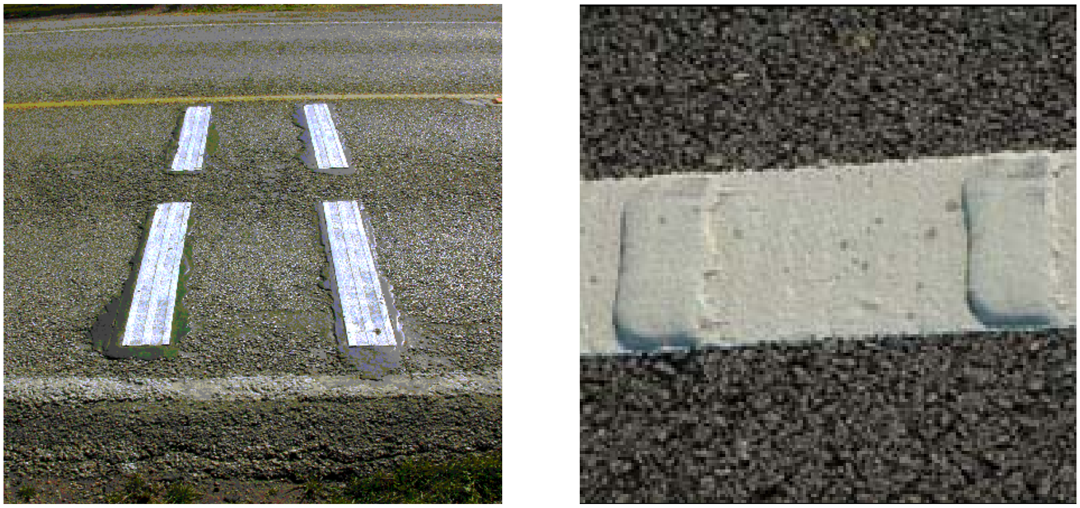
1 Profiled thermoplastic stripes (PTSs)
2 Two-way, left-turn lane (TWLTL)
3 This strategy will become high-cost if additional right-of-way (ROW) is required.

RUMBLE STRIP DESIGN

There are four types of rumble strips: milled, rolled, formed and raised (see Figure 2). Milled rumble strips are created by cutting into the pavement surface with a grinding machine. Rolled and formed rumble strips are pressed into the roadway surface shortly after the placement of new pavement. Rolled treatments are used on fresh asphalt concrete (AC) overlays during the compaction process, while the asphalt is still hot. The installation process uses a modified steel wheel compacting roller that has bars welded to the steel wheel to indent the roadway surface. Pressing corrugated forms into fresh Portland Cement Concrete (PCC) during the curing process produces formed rumble strips (*10*).



Milled (*11*) **Rolled (*12*)**



Raised (Prefabricated) **Raised (Profile Marking)**

FIGURE 2 Rumble Strip Design

The use of milled, rolled or formed rumble strips is limited by the depth, type, and quality of the pavement surface. If the pavement surface does not have the proper thickness, then none of these three methods may be used to install rumble strips. The recommended minimum pavement thickness varies among pavement types and the installation locations. While rolled and formed rumble strips can only be used on new construction or roadway retrofits, milled and raised rumble strips may be installed in preexisting pavement, or recently cured new pavement. One restriction that should be considered when installing rumble strips in new asphalt concrete is the quality of the composition of the asphalt. Certain asphalt binders may limit the practical use of milling rumble strips. In some cases, instead of grinding the surface to the design specifications, the milling machines remove chunks of asphalt concrete. The quality of a cured pavement surface will greatly impact whether to install rumble strips by milling. For instance, milling should not be used on roadways that show signs of advanced fatigue such as surface cracking and/or raveling. Milling would further aggravate the pavement degradation.

Raised rumble strips are the last installation type that is discussed herein (*5*,*10*). They may consist of raised pavement markings (RPMs), profile markings, or fabricated strips. Four-inch-diameter, ceramic buttons are traditionally used for RPM applications. Profile markings are formed by placing multiple layers of thermoplastic pavement marking material at set distances along the top of a thermoplastic pavement stripe. Fabricated strips consist of polyurethane and glass beads that are prefabricated into long strips of material that may be cut to requirements of a rumble strip installation project on-site.

RUMBLE STRIP APPLICATIONS

Milled, rolled and formed rumble strips are used as countermeasures to:

- Mitigate the number crashes on roadways; or
- Increase compliance with traffic control devices.

The most common use by state DOTs is as a countermeasure against run-off-the-road (ROR) crashes (*2*,*3*,*5*,*10*,*13*). Rumble strips are placed adjacent to or slightly offset from the outside edge of the pavement marking delineating the edge-line of the roadway, and they alert drivers to lane departures from the main driving lane onto the shoulder. These rumble strips are referred to as shoulder rumble strips (SRSs).

There are various causes for ROR crashes; however, a single vehicle crash resulting from a lane departure by an inattentive driver is the primary type of crash that researchers predict will be reduced by SRSs. At least 18 states have SRSs installed on a number of their roadways and these states either have set design standards or are in the process of testing their effectiveness. The associated reduction in ROR crashes ranges from 15 to 70 percent (see Table 2) (*10*).

Approach rumble strips (ARSs) traverse the main driving lanes and are intended to inform drivers that they are approaching an area along the travel path that requires additional attention (see Figure 3) (*5*). For instance, these rumble strips have been installed in advance of stop signs at rural highways intersections with limited sight distance to increase stop compliance.

TABLE 2 ROR Crash Statistics (*10*)

State/Date	Highway Type	Crash Reduction
Pennsylvania (1994)	Thruway - Rural	70%
New Jersey (1995[1])	Turnpike - Rural	34%
New York (1994)	Thruway - Rural	72%
Massachusetts (1997[1])	Turnpike - Rural	42%
Washington (1991[1])	Six Locations	18%
California (1985)	Interstate - Rural	49%
Kansas (1991[1])	Turnpike - Rural	34%
FHWA (1985[2])	Interstate - Rural	20%

1 Summary value from study

2 Data from rural Interstate locations in CA, AZ, MS, NV, and NC (***Error! Reference source not found.***).

FIGURE 3 ARS Seal Coat Treatment

Centerline rumble strips (CRSs) are the third treatment for rumble strips. This type is similar to SRSs except that they are placed along the centerline of undivided highways. The purpose of CRSs is to alert drivers to encroachments into lanes carrying traffic in the opposite direction. This application is relatively new when compared to the number of installed lane miles of SRSs in the United States (*2*,*5*).

CRS RESEARCH

Delaware and Colorado

Delaware DOT (DelDOT) was one of the first state agencies to document the effects of CRSs on a RTLTW highway. CRSs were installed on 2.9 miles of U.S. 301. DelDOT used a before-and-after period (3 years in the before period and 7 years in the after period) crash analysis. DelDOT recorded a 90 percent reduction in head-on crashes and a 100 percent reduction in fatalities. This result is even more significant because the AADT increased by 5 percent each year over the study period. Some additional results of the CRSs cited by DelDOT were (*6*):

- Effectively reduced the number of head-on collisions due to driver inattention, error and fatigue;
- Low cost countermeasure;
- No recorded degradation to pavement surface due to installation;
- Require minimal maintenance;
- Milled CRSs may be installed on new or existing pavement; and
- Many safety features decrease in effectiveness over time due to the novelty effect; however, this is not an issue with fatigued drivers with regard to CRSs.

Figure 4 contains a picture of CRSs installed in the DelDOT study (on the left) and a picture of CRSs installed in a study in Colorado (on the right). It should be noted that the centerline pavement markings were placed over the CRSs in both states. DelDOT has installed CRS in the passing and no-passing zones, while the Colorado

DOT (CDOT) only installs CRSs in no-passing zones (*6*,*14*). Again, states that have installed CRSs are divided on whether to install CRSs in passing zones and whether to install centerline pavement markings over CRSs (*2*,*7*). With respect to the dimensions of the CRSs installed in Delaware, the 12-inch, on-centers spacing, ½-inch depth and 7-inch longitudinal length in the direction of travel, are similar if not identical to most other states' policies and/or test applications (*3*,*14*).

FIGURE 4 Delaware and Colorado CRS Installations

Pennsylvania

Pennsylvania DOT has been a leader among the state DOTs to study rumble strips as cost-effective countermeasures. Lateral vehicle placement with respect to the installation of CRSs on RTLTW highways was investigated through PennDOT (*15*). One of the findings of the research was that drivers offset themselves farther laterally from the centerline after the installation of CRSs. Also, it was found that the variance of the lateral offset decreased.

Researchers in another study in Pennsylvania have shown that safety increases as drivers travel closer to the center of their specific lane of travel (*16*). The increased lateral offset of the vehicles in the PennDOT study put drivers closer to the center of their respective lane of travel, thus improving safety.

Alaska and Oregon

Alaska and Oregon state DOTs were initially hesitant to install CRSs in passing zones, but they have recently placed test sections in passing zones (*7*,*8*). Oregon DOT (ODOT) initially only installed CRSs in no-passing zones along US Highway 26 and State Highway 18, because they were concerned about how the installation of CRSs would affect passing maneuvers in passing zones (see left picture in Figure 5). However, because ODOT had seen the benefits of installing CRSs in no-passing zones, they decided to install one test section on US Highway 26 that contained CRSs in passing and no-passing zones (see the right picture in Figure 5). No results were available from their before-and-after crash analysis prior to the completion of this thesis.

FIGURE 5 Oregon CRSs Installations

The Alaska DOT (ADOT) had similar concerns (*8*). ADOT had also witnessed the benefits of CRSs in no-passing zones, but ADOT still had reservations with placement of CRSs in passing zones. Their current state policy on rumble strip use prohibits the installation of CRSs in passing zones.

However, ADOT did place CRSs in horizontal curves of greater than 2 degrees along a 16-mile segment of Seward Highway (State Route 1) (*8*). The specification for this installation included a 150-foot lead-in and lead-out section of CRSs on both sides of the horizontal curves. This resulted in CRSs overlapping into some portions of passing zones. It was stated that ADOT would conduct before-and-after crash analysis studies on CRSs throughout their state.

Texas

TxDOT recently installed the first of several miles of milled CRSs in Texas to investigate the benefits of CRSs. Currently, TxDOT allows the placement of CRSs in both no-passing and passing zones. One of the issues that TxDOT specifically wanted to study was whether drivers may interpret a conflicting message from the installation of CRSs in passing zones on RTLTW highways. In particular, it was thought that drivers would interpret the installation of CRSs in a passing zone as an indication of a no-passing zone regardless of the pavement markings. Subsequently, TxDOT believed that the total number of passes in a passing zone with CRSs would decrease which would theoretically decrease the capacity of the overall roadway. The study test section used to research TxDOT's concerns was along US 67 in Comanche County, and this test section was the same portion of RTLTW highway that was studied for this thesis.

Massachusetts

Elango and Noyce completed a safety evaluation of CRSs in 2003 for the state of Massachusetts (*3*). This was a three-part study that included: (1) a survey of current state practices with regard to CRSs; (2) a statistical analysis of crash data from roadways with CRSs in the state of Massachusetts; and (3) a simulator study on driver reactions to inadvertently crossing CRSs.

Two of the findings from the survey were (1) that most states are using similar dimensions in their CRS design and (2) that the primary reason for installation is to reduce crash frequency, and thereby improve safety. Table 3 contains the general findings and a graphical breakdown with regard to CRS use by DOTs in the United States (*3*).

TABLE 3 CRS Installation in the United States (*3*)

Survey Response (September 2002)	Number of States
Already installed[1]	20
Definitely will install	1
Considering installing	15
Probably will install	4
May test	1
Will not install	7
Have not considered	2

1 Since the completion of the survey in 2002, Idaho (*17*), Nebraska (*18*) and Texas have installed CRSs. Now there are at least 23 states with CRSs installed.

The simulator study appears to be the first documented attempt at evaluating driver reaction to CRSs. The tactile and audio sensations associated with crossing CRSs were simulated through four vibration motors (see Figure 6) and a comprehensive sound system placed in the simulator. The simulated driving environment was nighttime, foggy conditions, and it was believed that visibility was limited to approximately 20 feet (6 meters). The study subjects were given the task of reading simulated billboard signs while traveling through the simulated environment. The centerline was shifted at various points throughout the simulated study section. The combination of the limited sight distance and the reading task impaired the drivers' ability to notice the shift in the centerline. Subsequently, the researchers were able to gather data on driver reactions to inadvertently crossing CRSs.

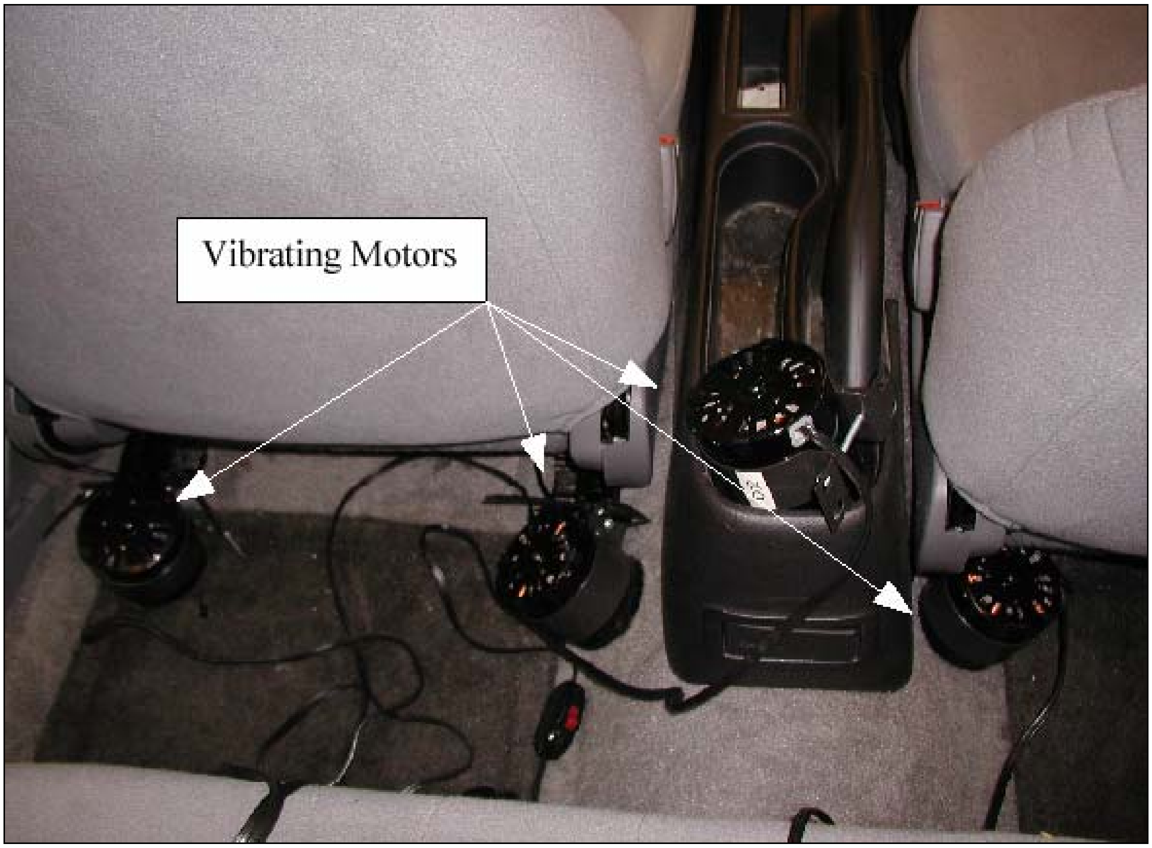
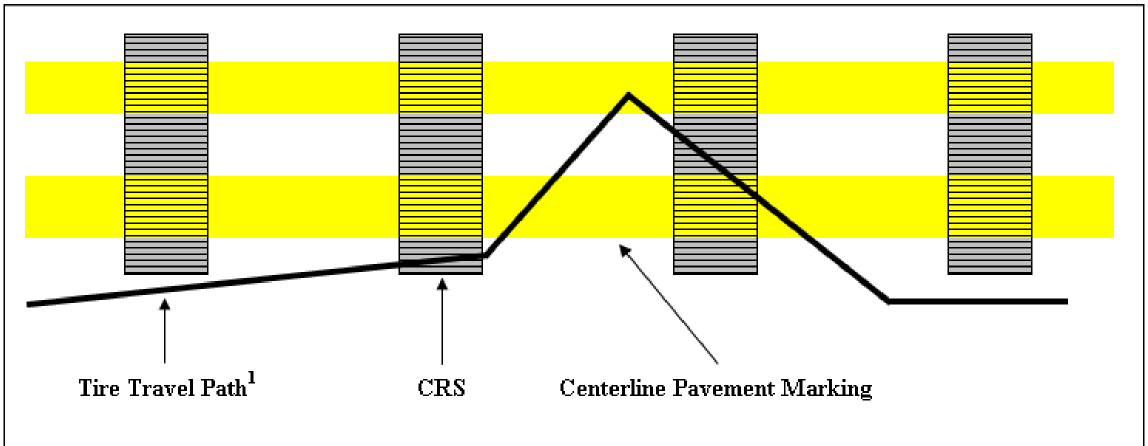


FIGURE 6 Simulator Vibrating Motors (*3*)

The purpose of this portion of the study by Elango and Noyce was to investigate whether drivers may respond erratically when unintentionally contacting CRSs. In particular, the researchers were concerned that drivers who inadvertently crossed CRSs may incorrectly steer their vehicle to the left instead of the right. It was hypothesized that drivers would react in this manner because of their exposure to SRSs and the associated corrective action (i.e., steering to the left). It was documented that 28 percent of the test subjects initially steered to the left when first crossing CRSs before returning to their intended lane positions. Figure 7 is a drawing of the travel path of the front, driver-side tire of a vehicle that is steered to the left after contacting CRSs before returning to the intended lane.



1 The travel path was not based on field data, and may be more or less conservative than a real-world corrective action.

FIGURE 7 Scenario of Incorrectly Steering to the Left

While the researchers speculated potential concerns with respect to driver response to crossing CRSs in passing maneuvers, it is important to note that they only studied driver reactions to inadvertently crossing CRSs. Passing maneuvers are intentional events, and driver reactions to intentionally crossing CRSs could be significantly different than speculated by Elango and Noyce.

SUMMARY

Driver behavior with respect to unintentionally crossing CRSs has been studied in a simulated condition; however, there has been no research documenting the effects on driving behavior when drivers intentionally cross CRSs during passing maneuvers. In particular, no one has studied driver behavior while crossing CRSs during the initial stage of passing maneuvers.

Furthermore, it is important to note that only seven states have even installed CRSs in passing zones. All of the state DOTs that have installed CRSs are concerned with how drivers react to CRSs and in particular when in passing zones. Two of the questions that have been asked are: (1) will drivers respond erratically when contacting CRSs; and (2) will passing maneuvers decrease with the installation of CRSs. In the later case, there was a question as to whether drivers would perceive a conflicting message if CRSs were installed in sections that are marked for passing. The later case was studied as a smaller portion of the TxDOT study, and it was not investigated in this thesis.

METHODOLOGY

This chapter is divided into four areas: (1) study design, (2) data collection, (3) data reduction, and (4) analysis approach.

STUDY DESIGN

Measures of Effectiveness

The purpose of this research was to ascertain whether the installation of CRSs in passing zones affects passing behavior in the initial stage of passing maneuvers. In order to investigate passing behavior, various MOEs and their respective data collection method were studied (*3*,*19*,*20*,*21*,*22*,*23*,*24*,*25*).

Previous research related to passing operations used distance, time, and speed as MOEs to study passing maneuvers. Passing maneuvers were also subdivided into four different segments for discussion in *A Policy on Geometric Design on Highways and Streets*, or the *Green Book*, produced by the American Association of State Highway and Transportation Officials (AASHTO) (*26*). Figure 8 is a drawing from the *Green Book* depicting the passing condition and the terms for distance, d_1 through d_4. The system that was developed to collect the data for this thesis accurately gathered data on the second portion (d_2) of passing maneuvers; however, it was believed by the author of this thesis that driver behavior during passing would be most affected during the initial stage of the pass.

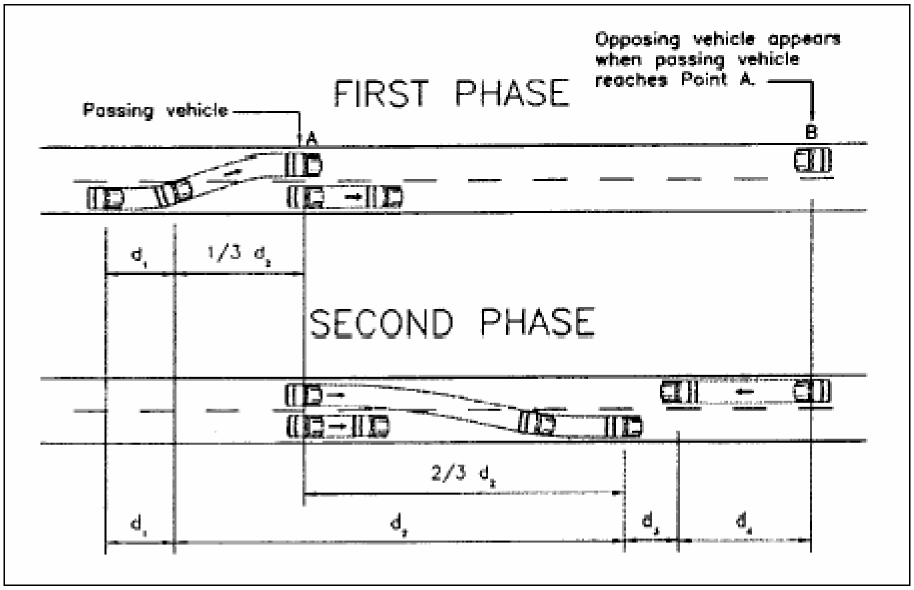


FIGURE 8 Passing Maneuver Diagram (*26*)

Hence, it was believed that the use of the passing maneuver criteria, as described in the *Green Book*, for the MOEs was not appropriate and different MOEs were generated that focused solely on the start of passing maneuvers. There were four MOEs selected to study driver reaction to CRSs prior to passing. They were:

1. Erratic movements;
2. Centerline encroachments;
3. Gap distance; and
4. Centerline crossing time.

Erratic movements

Erratic movements referred to movements that appeared to be outside what would be considered normal for the given roadway environment. For example, if a driver appeared to make a rapid alignment change or a wrong corrective action in his/her vehicle’s direction of travel, it was recorded as an erratic movement. An example of a wrong corrective action would be a driver initially moving farther to the left rather than to the right when inadvertently contacting CRSs, as speculated by Elango and Noyce (*3*).

Centerline Encroachments

The second MOE was the number of and the time between centerline encroachments. An encroachment referred to any moment that a passing vehicle was in contact with the pavement markings delineating the centerline. The point at which the front, driver-side tire first touched the centerline pavement markings was the start of an encroachment. The end of an encroachment was denoted when the front, driver-side tire last touched the centerline marking when returning to the appropriate lane of travel. Each encroachment was counted, and when multiple encroachments were made by passing drivers prior to completing a pass, the time between encroachments was calculated. The author believed that drivers would encroach the centerline less prior to passing after CRSs are installed.

Gap Distance

The third MOE was gap distance. Gap distance was the distance between a vehicle being passed and a vehicle attempting to pass at the time the passing driver initiated a pass. The author thought that gap distance would increase after CRSs were installed for at least two reasons. First, it was possible that drivers would perceive a need to have additional in-lane acceleration distance prior to crossing the CRSs to minimize their exposure to both the traffic in the opposing lane of travel and the sensations associated with crossing CRSs. Another possible reason was that drivers who prefer to encroach on the centerline to scan for on-coming traffic would increase the distance from the vehicle being passed. The additional gap distance would minimize the amount of visual information being processed by the passing driver, so that he or she could focus more on the visual input from the opposing travel lane. Figure 9 is a depiction of the passing gap distance measurement.

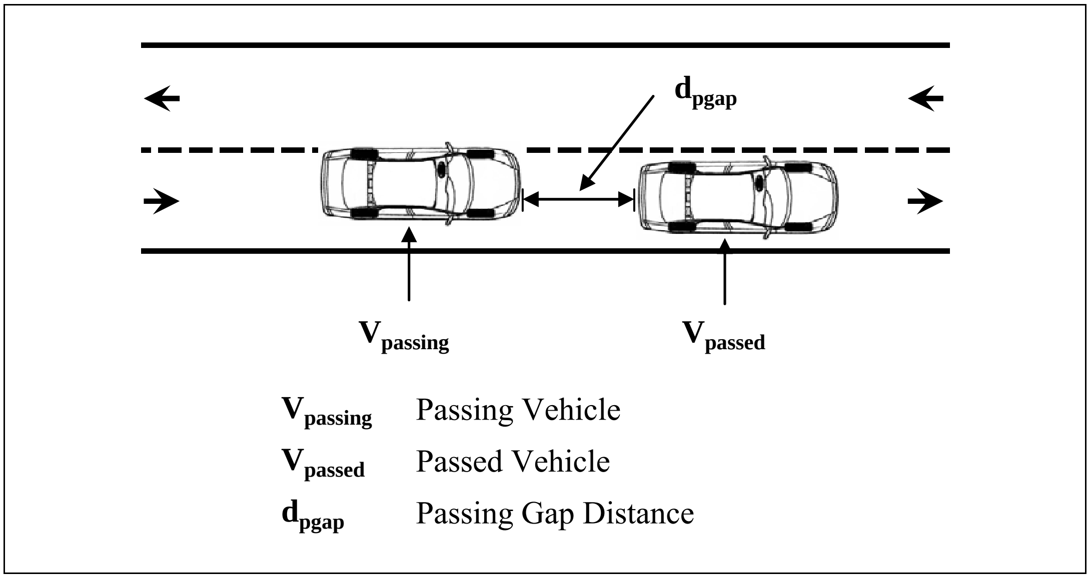


FIGURE 9 Passing Gap Distance

Centerline Crossing Time

Centerline crossing time was the fourth MOE, and it denoted the time that was taken by drivers to completely cross the centerline at the beginning of a passing maneuver. The elapsed time started when the front, driver-side tire first contacted the centerline, and it ended when the front, passenger-side tire last touched the centerline during the start of a pass.

This MOE was investigated because the author believed that drivers would cross the centerline more quickly when CRSs are present in order to minimize any discomfort that may be experienced by the driver. Figure 10 is a depiction of the previously described scenario, and the figure contains the equation was used in this study to calculate the values for centerline crossing time.

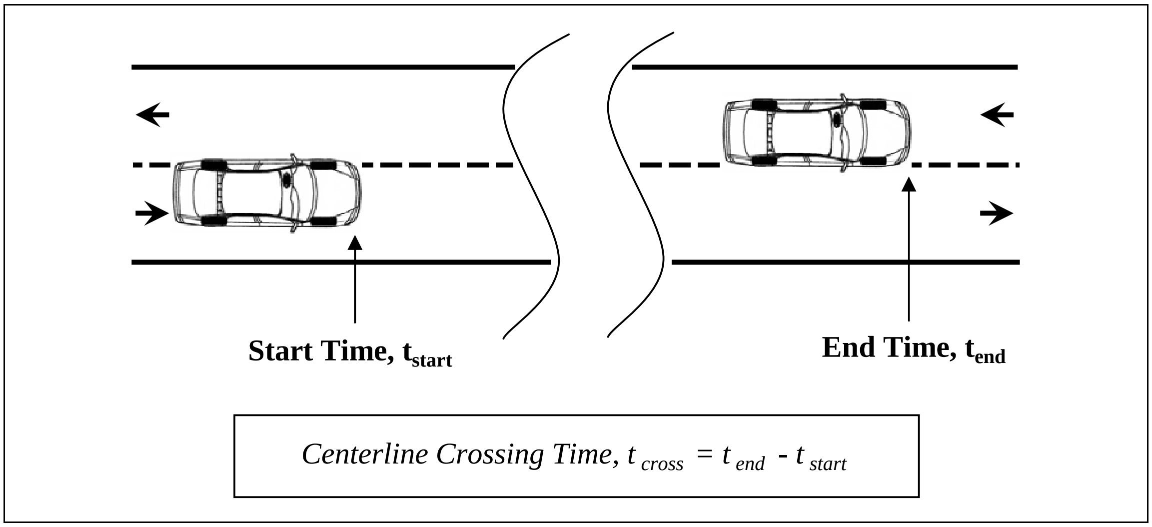


FIGURE 10 Centerline Crossing Time

Research Hypothesis

The general research null hypothesis (H_0) was that the installation of CRSs in passing zones would not significantly change passing behavior during the initial stage of passing maneuvers on RTLTW highways. It was developed from the concerns of various state DOTs and the research of Elango and Noyce (*3*,*7*,*8*). The general alternative hypothesis (H_1) was that passing behavior during the initial stage of passing maneuvers would significantly change after the installation of CRSs in passing zones. Passing behavior during the initial stage of passing maneuvers was investigated under the following specific hypotheses:

- Erratic movements
    - H_0: The number and type of erratic movements made by drivers prior to starting a passing maneuver on a RTLTW highway will be the same or decrease after installing CRSs; and
    - H_1: The number and type of erratic movements made by drivers prior to starting a passing maneuvers on a RTLTW highway will increase after installing CRSs;
- Encroachments
    - H_0: The number of and time between encroachments of the centerline by drivers prior to starting a passing maneuver on a RTLTW highway will be the same or decrease after installing CRSs; and
    - H_1: The number of and time between encroachments of the centerline by drivers prior to starting a passing maneuvers on a RTLTW highway will increase after installing CRSs;
- Gap Distance
    - H_0: The gap distance prior to starting a passing maneuver on a RTLTW highway will be the same after installing CRSs; and
    - H_1: The gap distance prior to starting a passing maneuvers on a RTLTW highway will decrease after installing CRSs; and

- Centerline Crossing Time
  - H_0: The centerline crossing time of drivers during the initial stage of a passing maneuver on a RTLTW highway will be the same after installing CRSs; and
  - H_1: The centerline crossing time of drivers during the initial stage of a passing maneuver on a RTLTW highway will decrease after installing CRSs.

DATA COLLECTION

Previous studies of passing maneuvers were reviewed in detail to determine the potential options for collecting data and their associated advantages and disadvantages. Road tubes (pneumatic sensors) were used in the earliest studies to collect data (*9*,*20*,*21*). Later studies were conducted using event recorders (*22*,*23*). In some of the more recent studies, passing maneuvers were videotaped from a either a moving vehicle (*24*) or a fixed point (*25*).

With the exception of the one study that videotaped passing maneuvers from a fixed point, the author believed that the study methodologies used previously might have influenced the drivers conducting passes. For instance, road tubes were placed at 50-foot intervals over approximately 0.5 mile in one of the earliest studies (*9*,*20*,*21*). Drivers would pass over more than 50 road tubes when passing through the study site, and they would see, hear and feel each one. Based on the experience of the author, this would impact driving behavior.

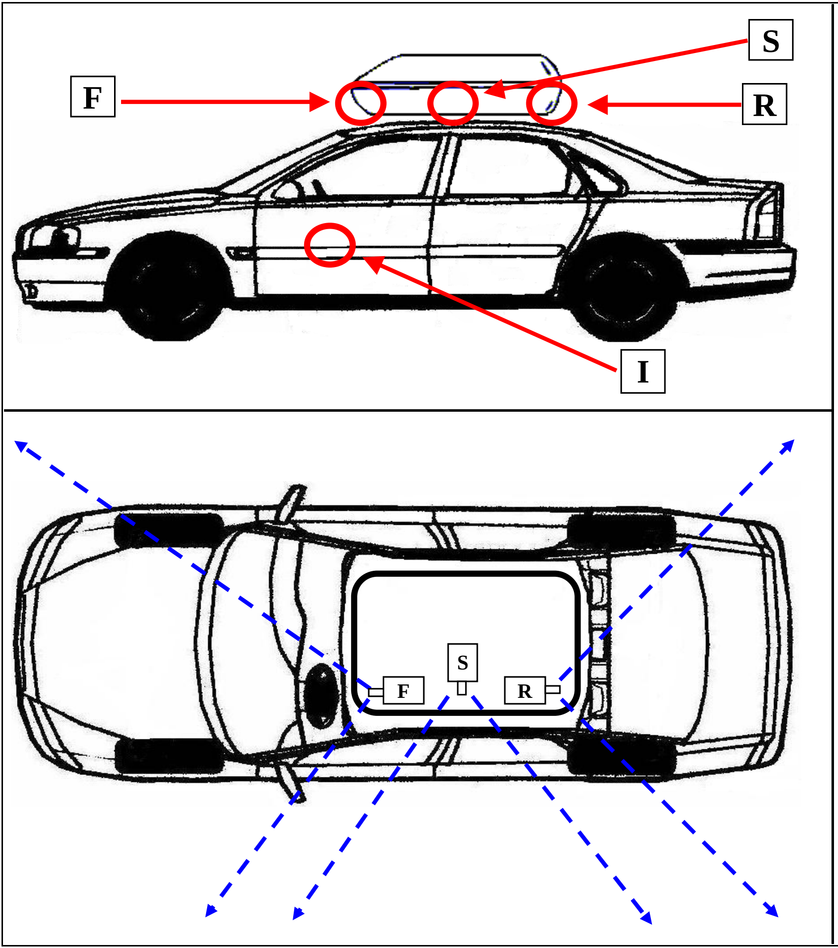
While it was believed that the study in which a fixed-point video camera was used to record passing maneuvers did not affect driver behavior, this data collection method was also not chosen (*25*). The fixed camera location was from an elevated point, such as a nearby mountain peak or a helicopter. The study location for this thesis did not provide the topography for monitoring traffic from an overlooking mountain peak, and the use of a helicopter was considered too expensive. Furthermore, the author thought that long distance video coverage would not provide sufficient resolution to study the MOEs.

Subsequently, the review of previous studies did not provide an acceptable means of data collection. Therefore, a unique study approach was developed.

Data Collection System Design

The author determined that the best form of field data to measure the four MOEs was video footage of passing maneuvers. Since TTI did not have the equipment readily available to collect this type of data, the author designed and developed an instrumented vehicle, referred to as the data-recording vehicle (DRV). The vehicle, a four-door sedan, had four concealed cameras mounted on it in locations that provided video coverage of vehicles passing around the DRV (see Figure 11). Three of the cameras were placed exterior to the vehicle to monitor passing maneuvers (see Figure 12). The fourth camera was placed inside the DRV, and it recorded the speed of and distances traveled by the DRV. Speeds and distances were calculated and displayed by a distance-measuring instrument (DMI) (see Figure 12).

The cameras monitoring passing maneuvers were enclosed in an aerodynamic, hard-body, cargo carrier and carried on the roof of the DRV. Camera “R” faced the rear of the vehicle and recorded encroachments and the beginning of passing maneuvers onto videotape. Camera “S” recorded onto videotape the opposing lane of travel by being placed on the left side of the cargo carrier and angled perpendicular to the travel direction. Camera “F” was affixed at the front of the cargo carrier, and it was angled in the direction of travel of the DRV. This camera recorded oncoming traffic and the completion of passing maneuvers. Figure 11 depicts the general orientation of the camera setup for cameras R, S and F.



KEY (Camera):

F - Forward View

S - Side View

R - Rear View

I - Internal View

FIGURE 11 Video Camera Setup

Cameras R, S, and F **Camera I**

FIGURE 12 Close-up View of the Cameras

Figure 13 is a picture of the fully instrumented, DRV.

FIGURE 13 Data Recording Vehicle

The three cameras affixed to the interior of the cargo container were mounted in a manner that did not alert drivers to the data collection efforts. The faces of each camera were painted black and symmetrical black ovals were painted on the cargo container to camouflage the viewing ports. Figure 14 contains various pictures of the DRV configuration with close-ups of the camouflaged viewing ports.

Front **Rear**

Side

FIGURE 14 External Close-up Views

Furthermore, the viewing angles of the cameras were adjustable to allow for variation in the vehicle height of the DRV being used for data collection (see Figure 12). The forward and rearward facing cameras were positioned as close as possible to the left (the driver-side of the vehicle) of the cargo carrier to capture the instant that vehicles encroach upon the centerline of the roadway.

The power supply and the video feed cables were sent internal to the vehicle through the trunk of the vehicle. The video recorder was located in the backseat, and it was restrained by harnesses. Power to the recording unit was supplied by a direct current to an alternating current (DC/AC) cigarette lighter power converter.

Camera "I" was placed in the interior of the DRV, and it was mounted on a stable platform with a DMI and a clock (refer back to Figure 12). The stable platform minimized the need to permanently attach any fastening devices to the interior of the vehicle for the camera, DMI and/or clock. The platform was not permanently mounted in the vehicle. Instead, technicians at TTI designed the platform to fit snuggly into the cup holders of the DRV. Consequently, the platform was very stable, yet easy to remove.

The instrumentation of the DRV was calibrated by the author in a controlled environment at the Riverside Campus at the Texas A&M University. The calibration procedure is discussed in detail in Appendix A.

Field Data Collection

Study Site Characteristics

Although the original intent was to collect data at three sites in Texas, TxDOT was not able to install CRSs on but one site as part of the main TTI research project. Thus, field data were collected at only one site. The site consisted of a 15-mile section of RTLTW highway on US 67 in Comanche County, Texas. US 67 runs approximately north and south. Data were collected in both directions. This section of roadway started at the northern edge of the town of Comanche, Texas, and it ended at the Comanche County line south of Dublin, Texas. The speed limit along this roadway was 70 mph with one short 55 mph speed zone approximately 10 miles north of the southern edge of the test section. The following site-specific details were:

- 44-foot roadway cross-section with:
    - 10-foot paved, asphalt concrete shoulders,
    - 12-foot paved, asphalt concrete lanes;
- Average daily traffic (ADT) was:
    - 4,122 vehicle per day (vpd),
    - Approximately a 50/50 directional split;
- Predominately passing zones (greater than 75 percent)
- Mean and 85th percentile speed
    - Northbound (63 and 70 mph)
    - Southbound (67 and 73 mph).

The climatic conditions and the timeframes of data collection were different for the before and after periods (see Table 4). This was not intended, but instead was the result of various uncontrollable circumstances. The circumstances included academic scheduling restrictions, TxDOT restrictions, installation delays, limited financial resources, and uncontrollable weather conditions. The academic scheduling problems consisted of coordinating data collection to minimize the number of days missed from classes and to avoid missing class examinations. This problem was complicated further in that two students were used in the data collection efforts, and they did not have identical schedules. TxDOT also requested that data be collected over a weekend with abnormally high traffic for the study location. Taking the student scheduling problems, the TxDOT request, and the installation delays into consideration, the optimal data collection period was for the week of academic spring break. The day after the researchers arrived at the study location, it began raining. The author decided to continue collecting data for the following reasons:

1. The forecasted probability of rain continuing was low, and the rain was to be intermittent;
2. Based on the previously mentioned restrictions, data collection would be delayed more than two months until May, and May and June are traditionally rainy months, so further delays would be expected;
3. The project funds were limited and the author believed that the cost to reschedule once on-site would strain the project funds; and
4. The author's academic financing ended in May, and he was scheduled to start working full-time in August, which would not allow sufficient time to reschedule data collection, and complete data reduction and analysis in order to complete this thesis prior to August.

TABLE 4 Data Collection Conditions

Category	Before Period	After Period
Number of Sites	1	1
Days of the Week	Wednesday, Thursday, Friday	Friday, Saturday, Sunday, Monday
Period of the Day	7:30 am to 6:00 pm	7:30 am to 6:00 pm
Weather	Ideal (clear skies)	Intermittent Rain
Roadway	Ideal (dry)	Dry to Wet

All of the field data were recorded on videotape. In addition to recording passing maneuvers, supplemental comments related to the field environment during data collection were recorded to videotape through a microphone built into the camera located inside the DRV. These comments included things such as: (1) direction of travel, (2) location, (3) possible erratic movements, and (4) acknowledging opposing traffic.

Collected Data

The DRV was driven northbound and then southbound along US 67 in Comanche County. Data were recorded continuously to videotape. The DRV induced drivers to pass by driving at 5, 10 and 15 mph below the posted daytime, speed limit of 70 mph.

There were two purposes in collecting data at three different speeds. First, it was not certain what speeds would provide a sufficient amount of data within the timeframe of the data collection efforts to conduct statistical testing on the data. Furthermore, it was believed that there would be a difference in the initial phase of the passing maneuvers with respect to the speed of the vehicle being passed.

A total of 723 vehicles were observed during the data collection; however, only 582 actually passed the DRV. Out of 582 passes, 103 vehicles were not analyzed because the passes were conducted by drivers who were in platoons or by drivers conducting multiple vehicle passes. All of the remaining passes recorded to videotape were isolated, single vehicle passes and the resulting study sample sizes were:

- DRV traveling at 55 mph
    - 92 passes before the installation of CRSs

  - 99 passes after the installation of CRSs
- DRV traveling at 60 mph
  - 106 passes before the installation of CRSs
  - 110 passes after the installation of CRSs
- DRV traveling at 65 mph
  - 25 passes before the installation of CRSs
  - 47 passes after the installation of CRSs
- Data collapsed regardless of speed
  - 223 passes before the installation of CRSs
  - 256 passes after the installation of CRSs

Table 5 contains a detailed count of the number of observations recorded to video. The values presented in bold were analyzed with respect to the MOEs for this thesis.

TABLE 5 Number of Observed Vehicles

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Total**	
Period	*Before*	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
No Pass[1]	13	15	31	39	13	30	57	84
Pass[1]	**92**	**99**	**106**	**110**	**25**	**47**	223	256
Platooned Pass[1]	19	15	11	9	1	2	31	26
Multiple Pass[1]	9	10	9	12	4	2	22	24
Total	133	139	157	170	43	81	333	390

1 No Pass = vehicle did not pass DRV, Pass = vehicle passed DRV, Platooned Pass = vehicle passed the DRV in a platoon, Multiple Pass = a vehicle passed the DRV and at least one other vehicle simultaneously.

Error

Two types of error affect any data collection effort. There is random/experimental error that is assumed inherent in all data, and then there is systematic error associated with equipment, personnel, or the experimental design. The only way to reduce random error is by increasing the sample size taken from a population in an experiment. It is believed that the random error was minimized for the data collected at the speeds of 55 and 60 mph, because the original goal of 50 passes for each speed in each direction for the before and the after periods was almost met for each case. Unfortunately, the average number of passes collected at 65 mph was only 36 with the extreme values of 25 and 57 for the northbound before and the northbound after periods, respectively. Consequently, it is expected that there will be greater random error associated with any analysis of the 65 mph data.

The research discussed in this thesis also contained systematic error. The two primary issues were related to: (1) the quantity of study sites, and (2) the differences between the before-and-after periods. The low number of study sites and the exact differences between the before-and-after periods were shown previously in Table 4.

DATA REDUCTION

All of the data from the videos were transcribed into a computer spreadsheet, and these data were then “cleaned” for analysis. Gap distance, DRV speed, and the distance traveled by the DRV were recorded each time that a passing vehicle encroached the centerline behind the DRV. These measures were also recorded when a passing vehicle had completely crossed the centerline into the opposing traffic lane at the start of a pass. Each line of data was then condensed into a single vehicle record for analysis. Approximately one hour was required for each passing vehicle to transcribe the data from video and convert it to a single vehicle record for analysis.

A detailed discussion of the procedure for reducing the data from the video is discussed in Appendix B.

ANALYSIS APPROACH

The data collected from the before-and-after periods were analyzed using Microsoft Excel™ and Statistical Package for the Social Sciences (SPSS™). The analysis approach detailed in Table 6 was selected after consulting various texts on statistical analysis (*27*,*28*,*29*,*30*).

TABLE 6 Statistical Analysis Approach

Method	Purpose
Descriptive Statistics	Mean, standard deviation, variance, range, percentiles
Graphical Analysis	Cumulative distribution, box plot, histogram, normal Q-Q plot
Statistical Tests	Test of Proportions, Wilcoxin Rank Sum, Chi-Square

Variables

Multiple spreadsheets were generated to organize the data and to analyze the data in steps. The first two spreadsheets were created containing all of the raw data for each recorded passing vehicle, and each passing vehicle recorded could have anywhere from 4 to 100 or more lines of data. Hence, summary worksheets were produced to reduce all of the lines of data for each vehicle to one line of data for each represented vehicle. The summary data were the only data analyzed for this thesis. The variables that were analyzed included:

- Number of Erratic Movements by Type
- Number of and Time between Centerline Encroachments
- Gap Distance Prior to Pass
- Crossing Centerline Time

Descriptive Statistics

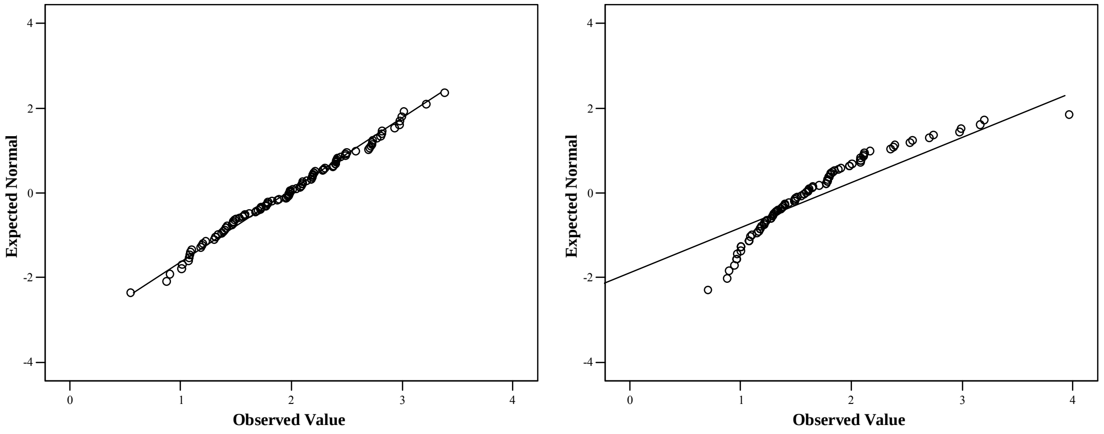
The statistics formulated for each MOE included: quantity of data, mean, median (50th percentile), standard deviation, sample variance, range, minimum, maximum, skewness, kurtosis, and percentiles (10th, 15th, 25th, 50th, 75th, 85, and 90th). These values were grouped by the before-and-after periods, DRV speed (55, 60 and 65 mph), and direction of travel. The before period denoted the data collected prior to the installation of CRSs, and the after period defined the data collected after CRSs were installed. These statistics were used in conjunction with various different methods for plotting the data to graphically analyze the data for each MOE.

Graphical Statistics

Cumulative distributions, box plots, histograms and Q-Q plots were used to analyze the MOEs when applicable. The cumulative distributions and the box plots were two ways of comparing the distribution of the data. While the calculation of the fences in the box plots do not always exactly represent the 25th and 75th percentiles in

SPSS, it was believed that the box plots provided a better way to compare the spread and the location of the center of each data set (*31*). The comparison provided an early insight into probable differences between various data sets.

Histograms and normal Q-Q plots were generated to analyze the distribution of the data. The histograms and the calculated values of skewness and kurtosis provided an early indication of the type of distribution associated with the data. The normal Q-Q plots were used to confirm whether data sets were normally distributed. The quantiles of the data sets with respect to the MOEs were plotted against a line that represented the expected path of a particular distribution, such as a normal distribution in the case of this thesis (*32*). Figure 15 contains a picture of a data set that is normally distributed on the left and a data set that is not normally distributed on the right.



Normally Distributed

Not Normally Distributed

FIGURE 15 Normal Q-Q Plot

Statistical Tests for Significance

The Chi-Square test, test of proportions, and Wilcoxin Rank Sum test were used to examine statistical significance. The Chi-Square test was used to determine whether any dependent variables (i.e., gap distance and centerline crossing time) were associated with each other. This was a concern because, if they were associated, a multivariate analysis would need to be conducted to test for statistical significance.

The test of proportions was used to investigate differences in MOEs based on counted values, such as the number of erratic movements by type and the number of centerline encroachments. The test of proportions is not affected by the distribution of the data. The equation for the test of proportions is:

$$t = \frac{p_1 - p_2}{\sqrt{p_0(1 - p_0)\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}}$$

$$p_0 = \frac{p_1 N_1 + p_2 N_2}{N_1 + N_2}$$

t = statistic of the t distribution

p_i = proportion observed in sample i

N_i = number of observations in sample i

The Wilcoxin Rank Sum test was used to determine whether there was a difference in MOEs based on measured values, such as time between encroachments, gap distance and centerline crossing time. This specific test allowed for the following: (1) the data did not need to be normally distributed; (2) the data needed to be continuous, but not paired; and (3) the number of data points did not need to be equal between the before-and-after periods.

All tests for significance were conducted assuming a two-tailed, 95 percent confidence interval. A two-tailed test was chosen to statistically test whether the population of the data associated with each MOE after installing CRSs shifted to the right or the left of the data collected prior to installing CRSs. If the test statistic (i.e., t-statistic for the t-test or z-statistic for the z-test) is less than the lower (negative) critical value (i.e., t_{crit} or z_{crit}) for a given level of confidence, the first population (before period) is shifted to the right of the second population (after period), and vice-versa if the test statistic is greater than the upper (positive) critical value. If the first population is shifted to the left of the second population, the overall values of the first population are less than the overall values of the second population. Again, this finding is switched when the test statistic indicates that the first population is shifted to the right.

RESULTS

This section contains the results of the analysis of the data collected for each of the MOEs. Descriptive statistics that are addressed in detail below and the results of the Wilcoxin Rank Sum tests are discussed in this chapter. The descriptive statistics that are presented are the quantity of data points, the mean, and the 15th, 50th, and the 85th percentile values. The mean values are presented for a comparison with the percentile values, but the focus of the results are on the percentile values. This decision is based on two reasons: (1) the data with respect to each MOE were found to be skewed and so the median (50th percentile) is a better indicator of the center of the data, and (2) the 15th and the 85th percentile values are commonly used in transportation design. The histograms and normal Q-Q plots verified that the data were not normally distributed, which was one of the reasons for using the Wilcoxin Rank Sum test (*28*).

The Chi-Square Test was used to test for association between the MOE variables. There was not a sufficient quantity of data to analyze the MOEs for erratic movements, or centerline encroachments. Therefore, only centerline crossing time and gap distance were tested for association. No association was found. Consequently, a multivariate analysis was not necessary, and the Wilcoxin Rank Sum test was used to test the data for significant changes between the before-and-after periods.

The MOEs for gap distance and centerline crossing time were studied with respect to the direction of travel (i.e., northbound and southbound), speed of the DRV (i.e. 55, 60, and 65 mph), and period (i.e., before and after). It was found that the data were not statistically different with respect to direction. It was also found that the majority of the data were statistically different with respect to speed of the DRV; however, there did not appear to be any explainable trends. The above findings are documented in Appendix C in Tables 15 through 18. Subsequently, direction was not considered a factor and the analysis discussed in this thesis was categorized by speed of the DRV and study period. The material in this chapter was organized by the analysis of each of the following MOEs:

1. Erratic movements;
2. Centerline encroachments;
3. Gap distance; and
4. Centerline crossing time.

ERRATIC MOVEMENTS

While it was originally intended to count the number of erratic movements by type that occurred before and after the installation of CRSs, no erratic movements were recorded after observing a total of 479 passing vehicles during the before and after periods. Furthermore, no drivers were recorded initially shifting left when contacting CRSs prior to returning the original travel lane. Thus, the installation of CRSs along US 67 in Comanche County did not induce erratic movements

CENTERLINE ENCROACHMENTS

The intent of this analysis was to compare differences in the number of and time between centerline encroachments before and after the installation of CRSs; however, the frequency of multiple centerline encroachments was less than expected. Out of 479 observed passing vehicles, only 41 centerline encroachments were recorded in addition to the centerline encroachment required at the start of a pass. Not enough data were available to conduct a Wilcoxin Rank Sum test on the time between encroachments.

A test of proportions was conducted on the number of encroachments. None of the t-statistics fell outside the t_{crit} values of -1.960 and 1.960 (see Table 7). Table 19 in Appendix D contains all of the factors that went into calculating the t-statistics shown in Table 7. The results indicate there was no statistically significant change in driver behavior with respect to the number of times that a driver encroached the centerline prior to passing. Subsequently, the installation of CRSs along US 67 in Comanche County did not change driver behavior with respect to encroaching the centerline prior to initiating a passing maneuver.

TABLE 7 Test of Proportions for Number of Centerline Encroachments

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size	**191**	**216**	**72**	**479**
t-statistic	-0.678	-0.102	1.129	-0.026

*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval.

GAP DISTANCE

Gap distance was determined by measuring the distance between the front bumper of a passing vehicle and the back bumper of the DRV at the point in which the left tires of a passing vehicle encounter the centerline pavement markings at the start of a successful pass. The results are documented in Table 8 (see also Table 19 in Appendix E). Graphs that were generated to evaluate the spread of and distribution of the gap distance data are located in Appendix E (see Figures 21 through 36). The tests for significance associated with gap distance are presented in Tables 9 and 10 (see Tables 21 and 22 in Appendix E).

TABLE 8 Descriptive Statistics for Gap Distance

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean (ft)	47.8	47.8	46.1	46.4	68.6	43.5	49.3	46.4
15th Percentile (ft)	26	23	28	26	40	29	28	26
50th Percentile (ft)	42	40	44	42	67	41	45	41
85th Percentile (ft)	73	72	67	65	86	63	72	65

Initial statistical tests indicated that the gap distance data were not normally distributed. Therefore, it was inappropriate to make comparisons of the means between the before and after conditions. Thus, the Wilcoxin Rank Sum Test was used to test whether the probability distributions associated with the before and after conditions were equivalent.. The null hypothesis that gap distances after the installation of CRSs were the same as the gap distances before the installation of CRSs was rejected for the data collected with the DRV traveling at 65 mph, but was not rejected at DRV speeds of 55 and 60 mph (see Table 9). Again, the findings are based on a two-tailed, 95 percent confidence interval. An analysis of the data when the DRV was traveling at 65 mph indicated that overall the gap distances decreased after the CRSs were installed. The statistically significant decrease indicates that the drivers overall accepted smaller gap distances between the passing and passed vehicles when initiating a passing maneuver around a vehicle traveling at 65 mph on US 67 in Comanche County after the installation of CRSs.

TABLE 9 Wilcoxin Rank Sum Test for Gap Distance

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size	**191**	**216**	**72**	**479**
z-statistic	0.807	0.590	3.822*	2.007*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

While the Wilcoxin Rank Sum test could not be used to state whether a specific change in mean gap distance was significant, the results presented in Table 8 appear to support the findings of the statistical tests. For instance, 85 percent of the drivers that passed the DRV while it was traveling at 65 mph after the installation of CRSs had a gap distance of 63 feet or less prior to passing versus 86 feet before the installation of CRSs. This was a reduction of approximately 23 feet. There were also reductions in gap distance after the installation of CRSs for the data collected while the DRV was traveling at 55 and 60 mph. These changes were not considered contradictory to the results of the statistical tests (null hypothesis rejected) because these changes were small relative to the data collected before the installation of CRSs. For example, the 23-foot reduction was approximately a 27 percent decrease in the gap distance used by drivers passing a vehicle traveling at 65 mph. In the case of drivers passing the DRV traveling at 60 mph, there was a reduction of 3 feet, or 3 percent of the gap distance used before the installation of CRSs.

The gap distance data were collapsed and a Wilcoxin Rank Sum test was conducted on the entire data set irrespective of DRV speed. The results indicated that the overall gap distances decreased after the installation of the CRSs. Passing drivers along US 67 in Comanche County initiated their passes closer to the DRV after the installation of CRSs. It is believed that this suggests drivers are conducting more of the acceleration in the original lane of travel prior to contacting the CRSs and the centerline pavement markings. If drivers accelerate more in the original lane of travel before crossing into the opposing lane of travel to complete a passing maneuver, drivers should theoretically increase their overall average passing speed and decrease the amount of time that they occupy the opposing lane of travel.

As stated earlier, possible systematic errors related to the study design may have impacted the results of the data collection efforts described in this thesis. Therefore, additional tests were conducted to investigate discrepancies. Gap distance data in the after period collected over the weekend were compared to the weekday data for 60 and 65 mph. The specific days of the week and the associated timeframes were the same as discussed previously for the Wilcoxin Rank Sum tests conducted on the centerline crossing time. However, it was found that there was not a statistically significant difference between weekend and weekday data collected at 60 and 65 mph in the after period (see Table 10).

TABLE 10 Wilcoxin Rank Sum Test for Gap Distance (Weekday vs. Weekend)

DRV Speed	**60 mph**	**65 mph**
Sample Size	**55**	**29**
z-statistic	0.81	-0.97

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The null hypothesis is not rejected for either DRV speed. Both z-statistics did not exceed the lower or upper 95 percent confidence interval z-values of -1.960 and 1.960, respectively. Hence, there was not a significant difference in the gap distance data collected on the weekend or on a weekday. This finding does not dispel the possibility that there may have been an effect on the results in relation to the weather; however, no data were collected before the installation of CRSs to test if there was a statistically significant difference between data collected under dry and wet conditions. Consequently, the decrease in gap distance may be a combination of the variation in the weather, and the installation of the CRSs.

CENTERLINE CROSSING TIME

Centerline crossing time was investigated by analyzing the amount of time that was taken by each driver that passed the DRV to cross the centerline pavement marking. Table 11 contains the general results, and a complete list of the descriptive statistics is in Table 23 in Appendix F. In addition, the plots that were generated to graphically analyze the data are contained in Appendix F (see Figures 37 through 52). The graphical analysis is not discussed in this chapter because its sole purpose was to choose the proper tests for significance. Initial analysis indicated that the data for centerline crossing time could not be represented by Normal distributions. Therefore, Wilcoxin Rank Sum tests were used to evaluate differences between the before and after period.

TABLE 11 Descriptive Statistics for Centerline Crossing Time

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean (sec)	1.77	2.25	1.97	1.96	2.02	1.77	1.90	2.04
15th Percentile (sec)	1.10	1.51	1.20	1.33	1.34	1.30	1.17	1.39
50th Percentile (sec)	1.58	2.11	1.88	1.98	2.09	1.67	1.79	1.99
85th Percentile (sec)	2.23	2.93	2.72	2.65	2.56	2.32	2.52	2.72

The results of the Wilcoxin Rank Sum tests are shown in Tables 12 and 13. Table 12 contains the z-statistics for verifying any statistically significant changes in centerline crossing times after the installation of CRSs along the RTLTW highway used in this study. The parameters that were used to develop Table 12 are presented in Table 24 in Appendix F.

TABLE 12 Wilcoxin Rank Sum Test for Centerline Crossing Time

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size	**191**	**216**	**72**	**479**
z-statistic	-5.697*	-1.029	1.722	-3.665*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

According to the z-statistics, assuming a two-tailed, 95 percent confidence interval, only drivers passing the DRV while it was traveling at 55 mph changed their driving behavior with respect to centerline crossing time at the start of a passing maneuver. The null hypothesis that the centerline crossing times in the after period was the same as the before period was rejected for the data collected while the DRV was traveling at 55 mph, because the z-statistic (-5.697) is less than the z-value (-1.960) for the lower end of the 95 percent confidence interval. Analysis of the data indicated that crossing times were longer after the CRSs were installed. The z-statistics for data collected while the DRV was traveling at 60 and 65 mph were within the 95 percent confidence interval, and they cannot be used to reject the null hypothesis. Therefore, while the DRV was traveling at 60 and 65 mph crossing times were the same after the installation of CRSs.

The results of the descriptive statistics that were shown in Table 11 appear to support the results of the statistical testing. The largest change was for the 85th percentile data collected at 55 mph. Before the installation of CRSs, drivers traversed the centerline in 2.23 seconds, and after the installation of CRSs, they crossed the centerline in 2.73 seconds. This was a 0.70-second increase (31 percent). This result supports the earlier statement that the population of the data collected at 55 mph after the installation of CRSs shifted to the right, or increased. Centerline crossing time data collected at 60 and 65 mph decreased for the 85th percentile, and these decreases were 3 and 9 percent, respectively. These changes were smaller than for data collected at 55 mph, which did not appear to contradict the statement that the installation of CRSs did not appear to shift the population of the data. Again, the Wilcoxin Rank Sum test does not allow it to be stated that a particular change of the values presented in Table 11 above was statistically significant.

A Wilcoxin Rank Sum test was also conducted on centerline crossing time data without regard to the speed of the DRV. The test statistic was -3.665, which was outside the two-tailed, 95 percent confidence interval. The overall population of centerline crossing time after the installation of CRSs shifted to the right an indication that the crossing times were longer after the CRSs were installed. Subsequently, it is believed that drivers are being more cautious when crossing CRSs by taking more time to ensure a smooth and controlled crossing event during a passing maneuver.

Additional tests were conducted to investigate the possibility of systematic error associated with the differences between the before-and-after periods other than the installation of the CRSs. The difference in the weather or pavement conditions cannot be fully addressed in this thesis, because no data were collected in the before period under wet roadway conditions. However, an analysis of after data was completed to determine whether there was a difference between data collected on a weekday versus a weekend.

In particular, centerline crossing time data collected in the after period when the DRV was traveling at 60 mph and 65 mph were analyzed. All of the after data recorded when the DRV was traveling at 55 mph were collected on the weekend, and so, a weekend to weekday statistical comparison was not possible. The weekday 60 mph data were collected on a Friday morning from around 7:30 am to 12:00 pm, and the weekend data were collected the following Saturday, during the same timeframe. The weekday 65 mph after data were gathered from approximately 2:00 pm to 6:00 pm on Monday, and the weekend data were gathered the previous day on Sunday, during the same timeframe. A Wilcoxin Rank Sum test was completed on the reduced data sets and results are listed in Table 13 below (see Table 25 in Appendix F).

TABLE 13 Wilcoxin Rank Sum Test for Transition Time (Weekday vs. Weekend)

DRV Speed	**60 mph**	**65 mph**
Sample Size	**55**	**29**
z-statistic	-4.76*	3.62*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The null hypothesis that the centerline crossing times were the same during the weekday and weekend was rejected at both 60 mph and 65 mph. This result is of particular interest because it was presented earlier that the centerline crossing time data collected when the DRV was traveling at 60 and 65 mph did not change significantly after the installation of CRSs (see Table 10). Hence, it is the believed that the significant differences in the centerline crossing times between the before-and-after periods cannot be said to be solely attributed to the installation of CRSs, but the variations may be a combination of the differences in the weather, the part of the week that the data was collected, and the installation of the CRSs.

SUMMARY OF FINDINGS

Centerline rumble strips (CRSs) were installed along US 67, a rural, two-lane, two-way (RTLTW) highway between the cities of Comanche and Dublin in north-central Texas. The CRSs were milled continuously along the marked centerline of the roadway in no-passing and passing zones. The Texas Department of Transportation (TxDOT) was concerned about how CRSs in passing zones would affect passing maneuvers, and so a study of passing maneuvers was conducted by the Texas Transportation Institute (TTI). A portion of the project was specifically developed for this thesis, and the following measures of effectiveness (MOEs) were analyzed:

1. Number of and type of erratic driving behavior during the initial stages of passing maneuvers;
2. Number of and time between centerline encroachments prior to starting a passing maneuver;
3. Gap distance between a passing vehicle and a passed vehicle at the start of a passing maneuver; and
4. Centerline crossing time at the start of a passing maneuver.

Passing maneuvers were recorded using a four-door sedan that was instrumented with concealed video cameras and a distance-measuring instrument (DMI). This instrumented vehicle was developed by the author and is referred to as the data-recording vehicle (DRV).

The site conditions during data collection were not identical between the before-and-after periods. The data gathered prior to the installation of CRSs were collected under ideal conditions (i.e., daytime, clear skies, dry pavement) over three weekdays. Data for the after period was collected over a four-day period that included the weekend, and the conditions were daytime, intermittent rain, and wet pavement. When reading the findings in this thesis, it should be noted that these differences may have impacted the results.

GENERAL FINDINGS

Measures of Effectiveness

The general findings are listed below:

- No erratic movements were seen either before or after the installation of CRSs;
- The number of centerline encroachments by a passing vehicle prior to starting a pass did not increase after the installation of CRSs;
- There were not enough data with respect to time between centerline encroachments to analyze if there was a change after the installation of CRSs;
- Gap distances prior to passing the DRV traveling at 55 and 60 mph did not change after the installation CRSs;
- Gap distances prior to passing the DRV traveling at 65 mph were statistically significantly shorter after the installation of CRSs;
- Gap distances, irrespective of the speed of the DRV, were statistically significantly shorter after the installation of CRSs;

- Centerline crossing times were statistically significantly longer for drivers passing the DRV traveling at 55 mph, but not when the DRV traveled at 60 and 65 mph; and
- Centerline crossing times, irrespective of the speed of the DRV, were statistically significantly higher after the installation of CRSs.

Table 14 contains a tabulated summary of the findings. Based on the results, driver behavior was not negatively impacted with respect to all but one of the MOEs at one speed after the installation of the centerline rumble strips (CRSs) on US 67. The decrease in the allowed gap distances was not a desired result, because passing drivers will have less time to react if the passed vehicle begins to decelerate during the initial stage of a passing maneuver. However, since there has not been any documented increases in rear-ending or same direction sideswipe crashes along RTLTW highways with CRSs, the author believes that the decrease in gap distance after the installation of CRSs does not negate the use of CRSs along US 67 in Comanche County.

TABLE 14 Comparison of MOEs Before and After Installation of CRSs

Measure of Effectiveness	Statistical Change	Practical Change
Number of Erratic Movements	No	No
Number of Centerline Encroachments	No	No
Time between Centerline Encroachments	N/A	N/A
Gap Distances	Decrease	No
Centerline Crossing Times	Increase	No

Data Collection System

It is believed that the data collection system used in the DRV is an innovative piece of technology that can be used in future research looking at collecting driver behavior, and in particular, driver behavior under passing conditions. The device is relatively small and inexpensive to construct. The system is extremely easy to use, and almost all of the concepts associated with its use are easy to understand.

The hardest concept to comprehend is the angle geometry involved with the gap distance calculations. The problem is that a three-dimensional environment is difficult to accurately measure in the two-dimensional environment presented on the surface of a reviewing television monitor. This problem is further compound by the shape and orientation of the video camera lens. For instance, vehicles that are below the horizontal axis of the lens and offset from the vertical axis of the lens will appear closer than they actually are.

It is thought that the empirical formulas, and the manner in which they were derived, were good approximations of the real world environment they were trying to emulate, but it is hoped that it may be possible to resolve this problem through computer software and photogrammetry.

Another possible benefit of the data collection system is in gathering speeds of observed vehicles from the DRV. Researchers at the TTI are currently conducting a controlled study design that will validate whether accurate speeds of observed vehicles can be derived using: (1) the empirical formula method for gap distance, and (2) the known travel speed and (3) distance traveled by the DRV.

Benefits to Future Research

The other major benefit of the research discussed in this thesis is that the originally proposed research methodology and the actual results can serve as a foundation for future research efforts. For instance, all previously documented research did not explain how the researchers had arrived at their original goal for population size (*9*,*20*,*21*,*22*,*23*,*24*,*25*). The original research that serves as a foundation for defining passing maneuvers did not appear to contain a reason the amount of data that was collected. Also, the type of data that were collected for the study discussed in this paper were not reported in any of the previous research, so it was not possible to back calculate the required population size. The final sample size was based on the minimum number of data points collected for each site in the more recent research efforts related to passing sight distance (*24*,*25*).

Furthermore, previous researchers did not accurately document the time involved in collecting the data, nor reducing it. It took approximately 3, 5, and 8 hours to collect 50 passing observations at 15, 10 and 5 mph under the posted speed limit, respectively. The time required to reduce the data is a lot less accurate, but it would take between 2 and 3 hours per passing vehicle to transcribe the data from videotape to paper, into a spreadsheet computer program, and reduce the extraneous data points prior to analysis. Until new techniques are developed, the most time consuming portion is the data reduction.

RECOMMENDATIONS

There are no findings from the research in this thesis to suggest that CRSs negatively impact the initial stage of passing maneuvers, and it is recommended that CRSs not be removed from US 67 in Comanche County in Texas.

It is also recommended that further evaluation of the effects of CRSs on passing maneuver behavior be conducted. This effort should include:

1. A survey of the states that have installed CRSs should be conducted to document the specifically why and where CRSs are installed, and why or why were not installed in passing zones;
2. Another analysis of available crash data from RTLTW highways with CRSs to continue to document the benefits of CRSs;
3. An analysis of various MOEs available to study changes in driver behavior associated with safety improvements from the installation of CRSs, in particular, a validation of the MOEs used in this thesis;
4. An additional study in a similar manner as documented in this thesis of at least three more similar sites that have CRSs installed; and
5. A simulator study that specifically focuses on passing behavior.

There are two additional recommendations for future research that do not directly relate to CRS and they are:

1. Investigate the use of photogrammetry and computer software to refine the distance calculation methodology used with the DRV; and
2. Investigate the benefits of CRSs on undivided highways other than RTLTW highways, such as rural, four-lane, two-way highways.

REFERENCES

1. NHTSA. Fatality Analysis Reporting System (FARS) Web-Based Encyclopedia. http://www-fars.nhtsa.dot.gov. Accessed April 2, 2003.
2. Slack, K., T. Neuman, and R. Pfefer. A Guide for Addressing Head-On Collisions. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*. NCHRP, CH2M Hill, Maron Engineering, Vol. 4, 2003.
3. Elango, V. V., and D. A. Noyce. *Safety Evaluation of Centerline Rumble Strips*. University of Massachusetts Transportation Center, Amherst, Massachusetts. November 2003.
4. FHWA. *Manual of Traffic Control Devices* (MUTCD). FHWA, Washington, D.C., 2002.
5. Harwood, D. W. *NCHRP Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*. Transportation Research Board, National Research Council, FHWA, Washington, D.C., 1993.
6. Centerline Rumble Strips. The Delaware Experience. Delaware Department of Transportation. http://www.deldot.net/static/projects/rumblestrip/handout.pdf. Accessed February 21, 2002.
7. Monsere, C. Centerline Rumble Strip Policy in Oregon. Oregon DOT. Personal interview. monsere@pdx.edu. June 25, 2003.

8. Smith, K., and R. Martindale. Centerline Rumble Strip Policy in Alaska. Alaska DOT. Personal interview. kurt_smith@dot.state.ak.us. July 1, 2004.

9. *Traffic Safety Facts 2001*. National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, D.C., 2002.

10. Safety: Rumble Strips. FHWA. http://safety.fhwa.dot.gov/programs/rumble.htm. Accessed April 12, 2003.

11. Hickey, J. J., Jr. Shoulder Rumble Strip Effectiveness: Drift-Off-Road Accident Reductions on Pennsylvania Turnpike. Pennsylvania Turnpike Commission, Harrisburg, January 1997.

12. Rumble Strip Survey. California Department of Transportation. http://www.dot.ca.gov/hq/traffops/survey. Accessed April 12, 2003.

13. Anderson, I., K. Balke, K. Fitzpatrick, D. Harwood. *NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways*. TRB, National Research Council, Washington, D.C., 2000.

14. Outcalt, W. *Centerline Rumble Strips*. Report No. CDOT-DTD-R-2001-8. Colorado Department of Transportation, Denver, Colorado. August 2001.

15. Mahoney, K. M., R. J. Porter, E. T. Donnell, D. Lee, and M. T. Pietrucha. *Evaluation of Centerline Rumble Strips on Lateral Vehicle Placement and Speed on Two-Lane Highways* (Final Report). PENNDOT, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, March 2003.

16. Thompson, H. T., and D. D. Perkins. Surrogate Measures for Accident Experience at Rural Isolated Horizontal Curves. In *Transportation Research Record 905*, TRB, National Research Council, Washington, D.C., 2000, pp. 142-147.

17. Idaho Department of Transportation. *The Transporter*. http://www.itd.idaho.gov/transporter/2004/043004_Trans/043004_Rumblestrips.html. July 1, 2004.

18. Nebraska Department of Transportation. Centerline Rumble Strips Installed. *Roadrunner*. December 2002/January 2003. http://www.nebraskatransportation.org/roadrunner/docs/archives/DecJan-02-03.pdf. July 5, 2004.

19. Prisk, C. W. Passing Practices on Rural Highways. In *Proceedings HRB*, Vol. 21, Highway Research Board, 1941, pp. 366-378.

20. Holmes, E. H. Procedure Employed in Analyzing Passing Practices of Motor Vehicles. *Public Roads*, No.19:11, 1939, pp. 209-212, 221.

21. Normann, O. K. Progress in Study of Motor-Vehicle Passing Practices. *Public Roads*, No. 20:12, 1940, pg. 221.

22. Farber, E. Passing Behavior on Public Highways Under Daytime and Nighttime Conditions. In *Highway Research Record 292*, Highway Research Board, National Research Council, Washington, D.C., 1969, pp. 11-23.

23. Polus, A., and Andrej Tomecki. Passing Experiment on Two-Lane Rural Highways. In *Transportation Research Record 1112*, TRB, National Research Council, Washington, D.C., 1987, pp. 115-123.

24. Glennon, J. C., and G. D. Weaver. *Passing Performance Measurements Related to Sight Distance Design*. Research Report 134-6. Texas Transportation Institute, College Station, Texas. June 1971.

25. Polus, A., M. Livneh, and B. Frischer. Evaluation of the Passing Process on Two-Lane Rural Highways. In *Transportation Research Record 1701*, TRB, National Research Council, Washington, D.C., 2000, pp. 53-60.

26. AASHTO. *A Policy on Geometric Design on Highways and Streets*. AASHTO, Washington, D.C., 2001.

27. Montgomery, D. C., and G. C. Runger. *Applied Statistics and Probability for Engineers*, Third Edition. John Wiley & Sons, Inc.: New York, 2003.

28. Ott, R.L. *An Introduction to Statistical Methods and Data Analysis*, Fourth Ed. Duxbury Press: Belmont, California, 1993.

29. Agresti, A. *An Introduction to Categorical Data Analysis*. John Wiley & Sons, Inc.: New York, 1996.

30. Conover, W. J. *Practical Nonparametric Statistics*. John Wiley & Sons, Inc.: New York, 1999.

31. SPSS. Resolution Detail: 26015. http://support.spss.com. Accessed August 14, 2002.

32. SPSS. Topics: Q-Q Plots. In *SPSS 12.0.1 for Windows and SmartViewer*. CD-ROM. SPSS Inc., Chicago, Illinois, 2003.

APPENDIX A

DATA COLLECTION SYSTEM CALIBRATION

The data collection system developed for this thesis was calibrated to obtain accurate data. One instrument on the DRV that needed calibration was the DMI. This device was calibrated using the manufacturer's recommended calibration method. The other instruments calibrated for this thesis were the data reduction reviewing monitors (see Figure 16).

The calibration of the reviewing monitors consisted of developing a distance relationship between objects presented on the monitors and the objects in the field. The purpose of this calibration was to allow researchers to estimate distances between objects videotaped in the field (i.e., passing vehicles) by measuring distances off of a reviewing monitor. The estimated gap distance measurements were essential to studying gap distance prior to a vehicle passing the DRV. It is important to note that the distance relationship is not linear and it was developed from meticulous data collection in a controlled environment at a gated research facility.

FIGURE 16 Reviewing Television Monitor

The data for the calibration were recorded at the Riverside Campus at Texas A&M University. The DRV was driven north and south on runway 35R. The Erosion and Sediment Control Laboratory Rainfall Simulator located at the south end of runway 35R was used as a fixed reference point. Video footage was collected as the DRV was driven away from and towards the facility along a perpendicular trajectory from the north-facing wall of the building (see Figures 17 and 18).

FIGURE 17 Lab Facility

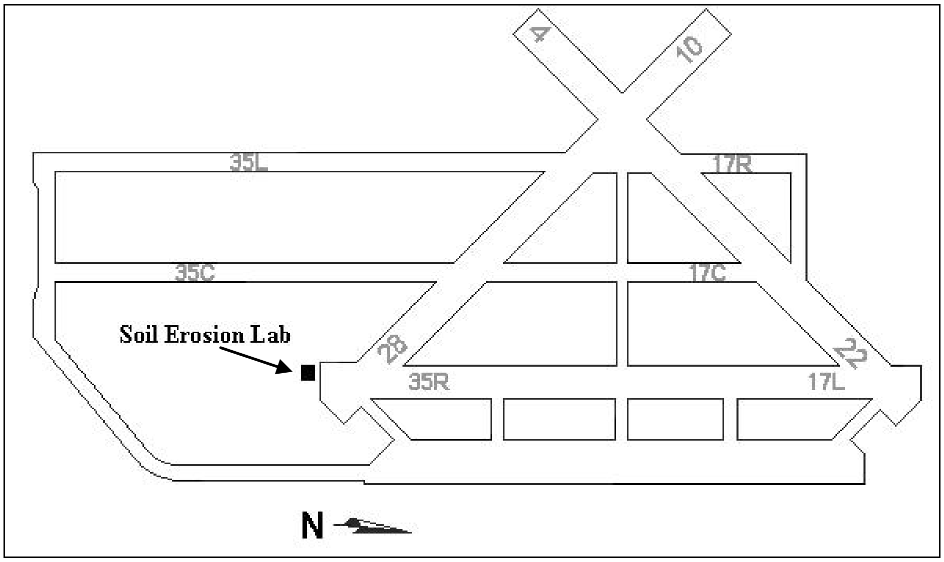


FIGURE 18 Riverside Campus Layout

The location of the base (bottom) of the facility was used in conjunction with the distance measures collected from the DMI to establish the gap distance of the front and rear bumpers of the DRV from the north face of the facility. The vertical distance on a reviewing monitor (see Figure 16) between the base of the lab building and the projected horizon of each video camera was measured. The measurements on the reviewing monitor were based on an engineers SAE scale of 50 (1/50th of an inch). This measure was correlated with the in-field physical distance recorded from the DMI.

Calibration video was taken for the before period and the after period. From this data, empirical formulas were developed for the R1 and F1 cameras (see Figure 19). The formulas in Figure 20 were developed using Microsoft Excel's regression analysis. Power functions were used because the trend lines appeared to fit the data the best with R^2 values greater than 0.99. The differences in the two curves presented in Figure 18 are that the data were reduced on more than one monitor. Consequently, calibration curves were generated for each reviewing monitor to minimize the possibility of systematic data reduction errors. While the formulas generated in the before-and-after periods could generate non-integer values, only the rounded integer values were used because the distance measures recorded with the DMI were only accurate to whole numbers.

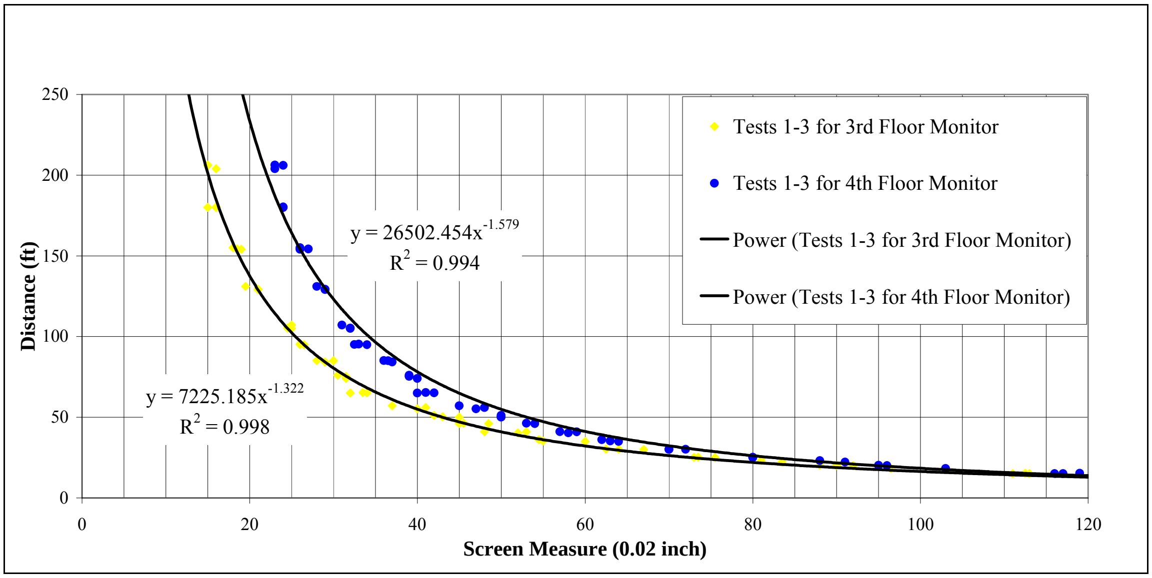


FIGURE 19 R1 Camera Gap Distance Calibration Curve (After Period)

APPENDIX B

DATA REDUCTION PROCEDURE

This section of the report contains a detailed discussion of the method used to reduce the data from the videotape for the analysis of the MOEs, and it is subdivided into the following topics:

- Prior to Passing Maneuver
- Initial Stage of a Passing Maneuver

PRIOR TO PASSING MANEUVER

The MOEs for erratic movements and time between encroachments were investigated from data collected on a tracked vehicle prior to a driver initiating a successful pass. A successful pass was considered any completed pass around the DRV that did not require the driver of the DRV or of an opposing vehicle to leave his/her respective lane of travel to allow the passing vehicle to complete its pass. The reviewer of the video data focused on the tracked vehicle's proximity to the centerline pavement markings to determine whether to collect any data prior to passing on either of the two MOEs mentioned above.

All of these data were reduced from the R1 camera view (see Figure 16 in Appendix A). The MOE for erratic movements was a count value, and the MOE for time between encroachments was a calculated value from time measurements.

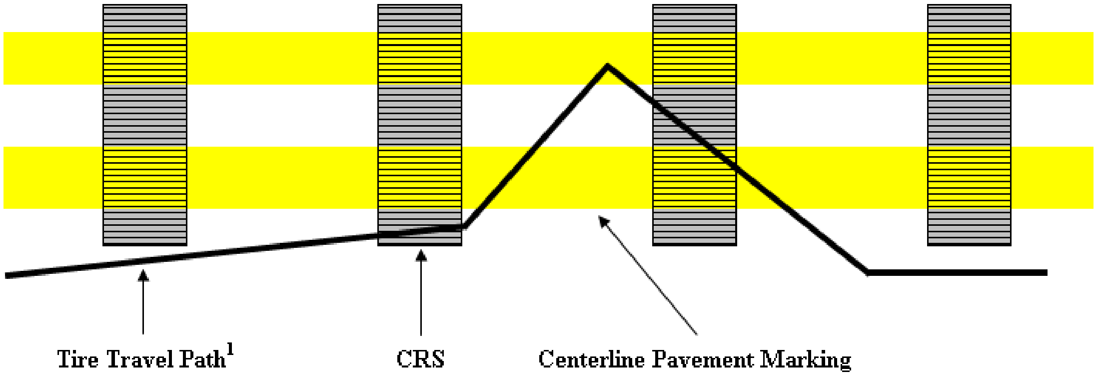
Erratic movement

With regard to erratic movements, the reviewer specifically looked for rapid lane shifts or wrong corrective action by the tracked driver. It was believed that a rapid lane shift would be denoted by a downward shift of the front headlight on the side of a tracked vehicle opposite of the directional change. This vehicle lean would be caused by the acceleration. It was also presumed that drivers that conducted rapid lane shifts would need to make corrective action to stabilize their respective vehicles in their intended lane of travel.

When a tracked driver inadvertently contacts CRSs and corrects to the left instead of the right, a wrong corrective action was recorded. This specific action was documented by Elango and Noyce (*3*). However, it was decided to further investigate this responsive action, because it was believed that drivers would not continue to respond in this manner with increased exposure. It was thought that a wrong corrective action would appear to be an increase in a tracked vehicle's leftward movement when contacting the CRSs, and then, followed by a rightward shift back into the initial lane of travel. Figure 20 depicts the travel path of the front, driver-side tire of a tracked vehicle with respect to a proposed wrong corrective action. The travel path was not based on field data, and may be more or less conservative than a real-world corrective action.

While it was possible that erratic movements could occur throughout a passing maneuver, it was not believed that the reason for the erratic movement could be solely attributed to the installation of CRSs. For instance, an erratic movement that occurs when a tracked vehicle is in the opposing direction of travel would not be contacting

CRSs. Furthermore, a driver that passes would have already made the active decision to cross CRSs, and it was assumed that erratic movements by drivers would occur because of a driver's discomfort with contacting CRSs or the result of inadvertently contacting CRSs. A driver that actively decided to cross CRSs did not inadvertently contact them. It was also not considered likely that a driver who feels such level of discomfort that he or she would respond in an erratic manner each time when crossing CRSs would have completed a pass.



1 The travel path was not based on field data, and may be more or less conservative than a real-world corrective action.

FIGURE 20 Front, Driver-Side Tire Travel Path for Wrong Correction Action

Time between Encroachments

Time between encroachments was the second MOE studied from the data collected prior to a tracked vehicle completing a successful pass. Data were recorded each time that a tracked vehicle encroached on the centerline markings. This particular MOE was the measure of time between two consecutive encroachments. The starting reference point occurred when the tracked vehicle's front, driver-side tire last touches the centerline pavement marking when the vehicle is returning from an encroachment. The next consecutive encroachment, when the front, driver-side tire contacts the centerline, is the ending reference point. The difference between these values was calculated in a computer spreadsheet that the transcribed video data were input.

INITIAL STAGE OF A PASSING MANEUVER

Centerline crossing time and gap distance were the two MOEs investigated using the data reduced from successful passing maneuvers. All of the data for both of these MOEs were collected from the R1 camera view. While the initial passing maneuver was normally started prior to crossing the centerline, it was assumed that the start of a pass occurred when the front, driver-side tire first contacted the centerline pavement marking. This was assumed because it was not possible to know the point at which a driver first decided to pass, but it was possible to assume that contacting the centerline at the beginning of a successful pass indicated the intent to pass.

It was thought that the first initial shift towards the centerline may be an indicator of the intent to pass. This was not chosen because early system testing prior to collecting field data indicated that drivers had a tendency to shift in the lane. Consequently, it was believed that it was not possible to clearly differentiate between natural lane shifting within the lane and natural lane shifting into the opposing lane of travel prior to passing.

Centerline Crossing Time

Data were collected at two different points to evaluate centerline crossing time. Data were first transcribed from video when the front, driver-side tire first contacted the centerline. The next set of data was collected when the front, passenger-side tire last contacted the centerline. The elapsed time between these two events was the centerline crossing time value. This value was not calculated during the video data reduction process. These values were input into a computer, and the differences were calculated in a summary spreadsheet.

Gap Distance

The gap distance was recorded at the start of each successful pass. Data were reduced from the video when the front, driver-side tire first contacted the centerline pavement marking. The actual transcribed value was the physical distance from the bottom of the front of a tracked vehicle in the R1 camera view to the marked horizon line. This value was then input into a power function, and a relative distance was computed. These calculations were also conducted internal to a computer spreadsheet based off of the original transcribed video measurement.

APPENDIX C

STATISTICAL TESTING ON DIRECTION AND SPEED

STATISTICAL SIGNIFICANCE OF DIRECTION

This section of the appendix contains all of the tabulated results of the statistical tests on the data with respect to direction (see Tables 15 and 16). The Wilcoxin Rank Sum test was used. These tests were categorized by speed and period. The general hypothesis and the associated assumptions for significance were:

- H_0: There is not a difference between data collected at speed *i* in northbound direction from the southbound direction at speed *i* in period *j*;
- H_1: There is a statistical difference between data collected at speed *i* in northbound direction from the southbound direction at speed *i* in period *j*;
- 95% Confidence Interval;
- Two-Tailed test with z-value = 1.960; and
- Reject H_0 if -1.960 > z-stat or if z-stat > 1.960.

TABLE 15 Gap Distance with Respect to Direction

DRV Speed	55 mph		60 mph		65 mph	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	1212	684	1608	1056	24	186
T	2034.5	2817.5	2781.0	3760.0	95.5	683.0
Count (Northbound)	40	52	53	63	9	29
Count (Southbound)	52	47	53	47	16	18
μ_T	1860.0	2600.0	2835.5	3496.5	117.0	696.0
σ_T^2	16094.9	20352.3	25013.1	27367.5	311.5	2084.3
σ_T	126.9	142.7	158.2	165.4	17.6	45.7
z-stat	1.375	1.525	-0.345	1.593	-1.218	-0.285

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The null hypothesis was not rejected for any of the tested categories in Table 15, above.

TABLE 16 Centerline Crossing Time with Respect to Direction

DRV Speed	55 mph		60 mph		65 mph	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	1062	768	1476	1338	18	204
T	2058.5	2561.0	3052.0	3775.0	99.0	743.0
Count (Northbound)	40	52	53	63	9	29
Count (Southbound)	52	47	53	47	16	18
μ_T	1860.0	2600.0	2835.5	3496.5	117.0	696.0
σ_T^2	16098.0	20350.5	25015.9	27361.7	311.6	2083.9
σ_T	126.9	142.7	158.2	165.4	17.7	45.6
z-stat	1.564	-0.273	1.369	1.684	-1.020	1.030

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The null hypothesis was not rejected for any of the tested categories in Table 16, above.

STATISTICAL SIGNIFICANCE OF SPEED

This section of the appendix contains all of the tabulated results of the statistical tests on the data with respect to speed (see Tables 17 and 18). The Wilcoxin Rank Sum test was used. These tests were categorized by speed and period. The general hypothesis and the associated assumptions for significance were:

- H_0: There is not a difference between data collected at speed i_1 from the data at speed i_2 in period j;
- H_1: There is a statistical difference between data collected at speed i_1 from the data at speed i_2 in period j;
- 95% Confidence Interval;
- Two-Tailed test with z-value = 1.960; and
- Reject H_0 if $-1.960 >$ z-stat or if z-stat > 1.960.

TABLE 17 Gap Distance with Respect to Speed

DRV Speed	**55 and 60 mph**		**60 and 65 mph**		**55 and 65 mph**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	8796	4674	2220	3348	1644	1944
T	9180.5	10253.0	6374.0	8713.0	4940.0	7213.0
Count (Speed i_1)	92	99	106	110	92	99
Count (Speed i_2)	106	110	25	47	25	47
μ_T	9154.0	10395.0	6996.0	8690.0	5428.0	7276.5
σ_T^2	161537.4	190477.4	29121.2	68012.8	22593.4	56963.6
σ_T	401.9	436.4	170.6	260.8	150.3	238.7
z-stat	0.066	-0.325	-3.645*	0.088	-3.247*	-0.266

The i_1 speed indicates the first speed listed in the speed category and i_2 denotes the second speed. For the first two columns of values, the i_1 equals 55 mph and the i_2 equals 60 mph.

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

TABLE 18 Centerline Crossing Time with Respect to Speed

DRV Speed	**55 and 60 mph**		**60 and 65 mph**		**55 and 65 mph**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	8556	5400	2250	2694	1686	2862
T	8107.0	11603.5	6828.0	9235.0	5064.0	8271.5
Count (Speed i_1)	92	99	106	110	92	99
Count (Speed i_2)	106	110	25	47	25	47
μ_T	9154.0	10395.0	6996.0	8690.0	5428.0	7276.5
σ_T^2	161542.4	190462.3	29120.8	68024.3	22592.9	56946.8
σ_T	401.9	436.4	170.6	260.8	150.3	238.6
z-stat	-2.605	2.769	-0.984	2.090	-2.422	4.170

The i_1 speed indicates the first speed listed in the speed category and i_2 denotes the second speed. For the first two columns of values, the i_1 equals 55 mph and the i_2 equals 60 mph.

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

APPENDIX D

NUMBER OF CENTERLINE ENCROACHMENTS

TABLE 19 Test of Proportions for the Number of Centerline Encroachments

DRV Speed	55 mph	60 mph	65 mph	Combined
P_1	0.052	0.102	0.074	0.079
P_2	0.075	0.106	0.021	0.079
P_0	0.064	0.104	0.040	0.079
N_1	97	118	27	242
N_2	107	123	48	278
t-statistic	-0.678	-0.102	1.129	-0.026

P_1 is the proportion of multiple passes that occurred prior to installing CRSs and P_2 is the proportion after the installation of CRSs. P_0 is a combination of P_1 and P_2. N_1 is the number of observed centerline encroachments prior to installing CRSs and N_2 is the number observed after installing CRSs.
*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval.

APPENDIX E

GAP DISTANCE

DESCRIPTIVE STATISTICS

TABLE 20 Descriptive Statistics for Gap Distance

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	Before	After	Before	After	Before	After	Before	After
Sample Size	92	99	106	110	25	47	223	256
Mean (ft)	47.79	47.81	46.08	46.38	68.55	43.48	49.30	46.40
Std. Error (Mean)	2.320	2.837	1.749	2.441	7.055	2.181	1.554	0.040
C.I. Lower Bound[1] (mean)	43.18	42.18	42.61	41.55	53.99	39.09	46.24	43.32
C.I. Upper Bound[1] (mean)	52.40	53.44	49.55	51.22	83.11	47.87	52.37	49.49
5% Trimmed Mean	46.09	44.86	44.73	43.78	64.99	42.96	47.39	43.74
Median	42.41	39.94	44.04	41.82	66.78	41.27	45.21	41.00
Variance	495.117	796.621	324.180	655.199	1,244.211	223.491	538.400	628.877
Std. Deviation	22.251	28.224	18.005	25.597	35.273	14.950	23.203	25.077
Minimum	19	12	17	16	17	21	17	12
Maximum	134	164	106	224	199	78	199	224
Range	116	152	89	208	182	58	182	212
Interquartile Range	33	27	21	25	40	23	32	25
10th Percentile	24	21	26	24	36	26	26	23
15th Percentile	26	23	28	26	40	29	28	26
25th Percentile	31	29	32	30	44	32	32	30
50th Percentile	42	40	44	42	67	41	45	41
75th Percentile	64	55	54	55	82	54	63	55
85th Percentile	73	72	67	65	86	63	72	65
90th Percentile	74	87	71	71	96	64	74	73
Skewness	1.262	1.711	1.070	3.451	2.076	0.502	1.912	2.555
Std. Error (skewness)	0.251	0.243	0.235	0.230	0.464	0.347	0.163	0.152
Kurtosis	2.301	3.284	1.091	20.578	7.070	-0.621	7.674	11.656
Std. Error (Kurtosis)	0.498	0.481	0.465	0.457	0.902	0.681	0.324	0.303

1 A 95% confidence interval (CI) for the mean

PLOTS

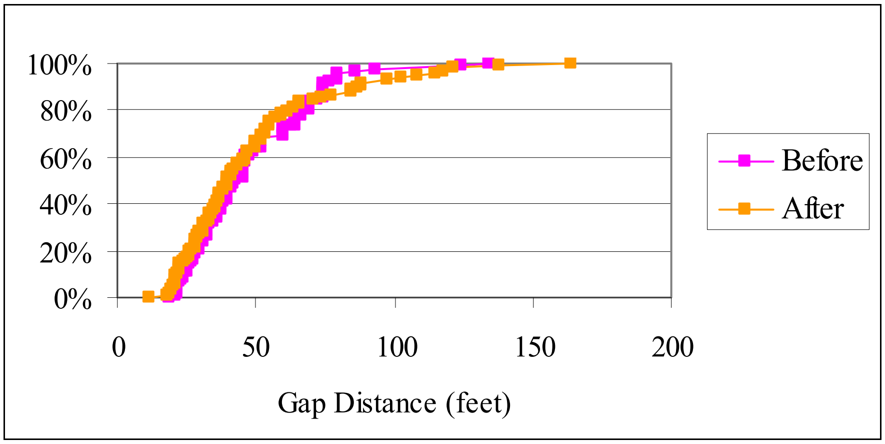


FIGURE 21 Cumulative Distribution of Gap Distance (55 mph)

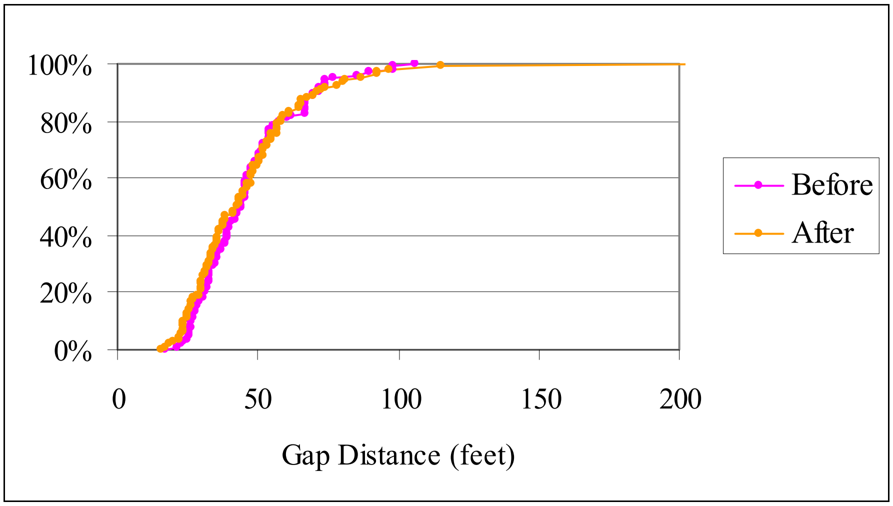


FIGURE 22 Cumulative Distribution of Gap Distance (60 mph)

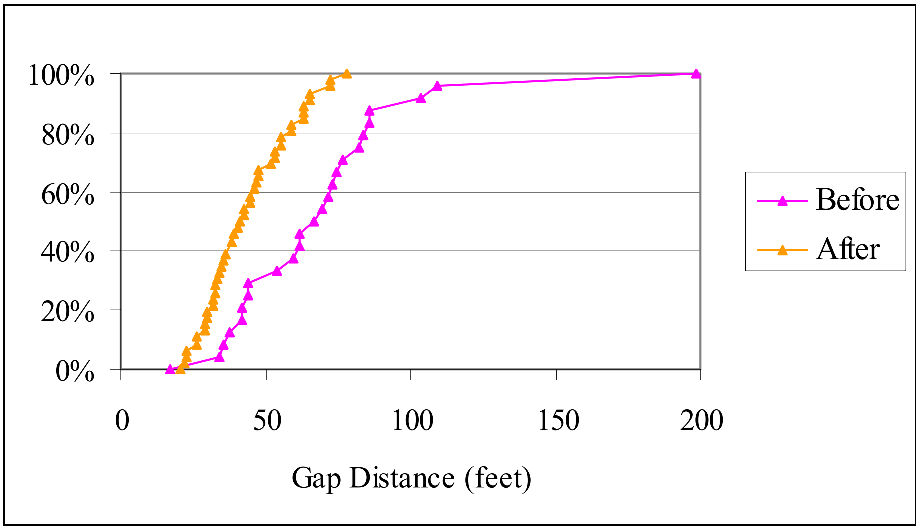


FIGURE 23 Cumulative Distribution of Gap Distance (65 mph)

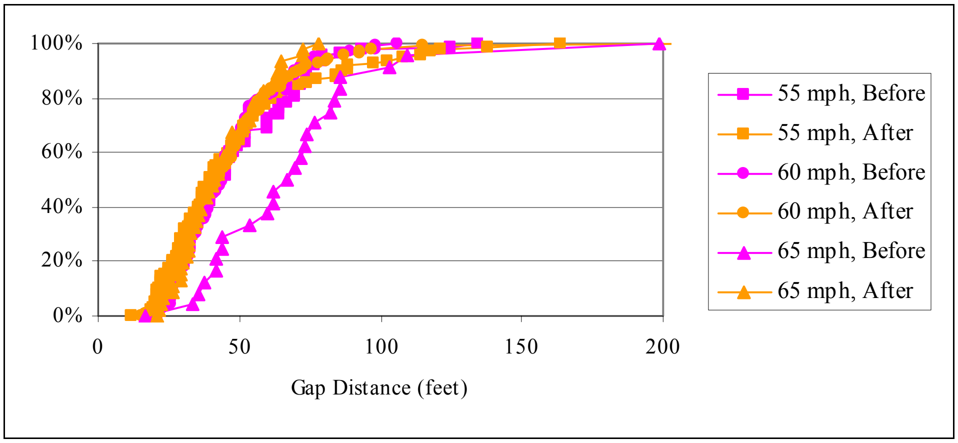


FIGURE 24 Cumulative Distribution of Gap Distance

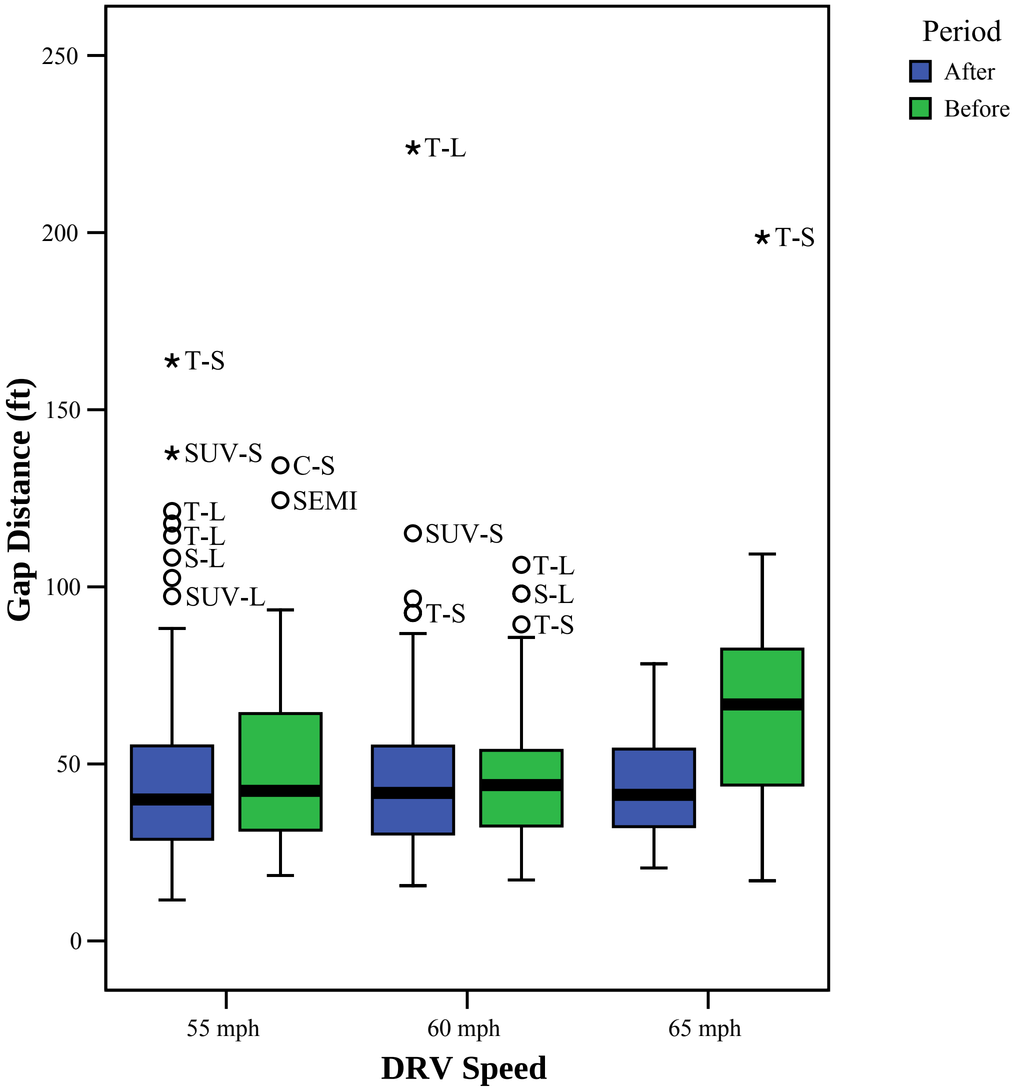


FIGURE 25 Box Plot of Gap Distance with Respect to Speed

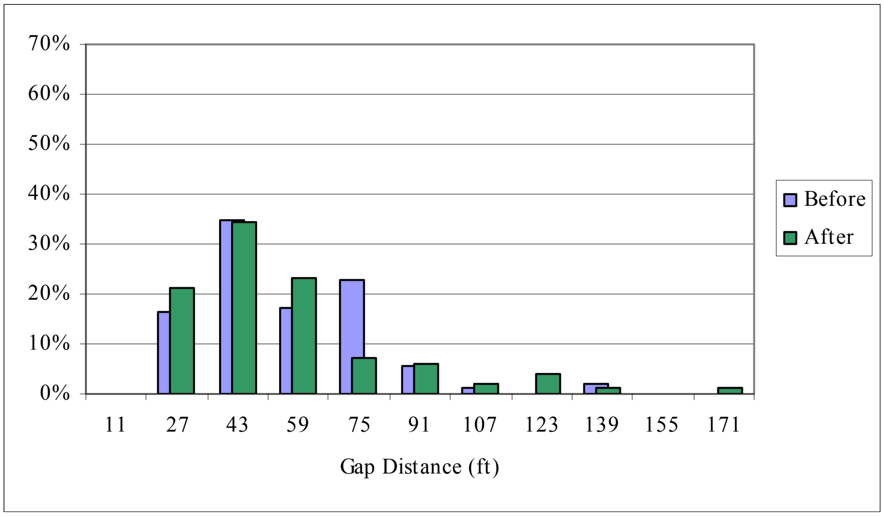


FIGURE 26 Distribution of Gap Distance (55 mph)

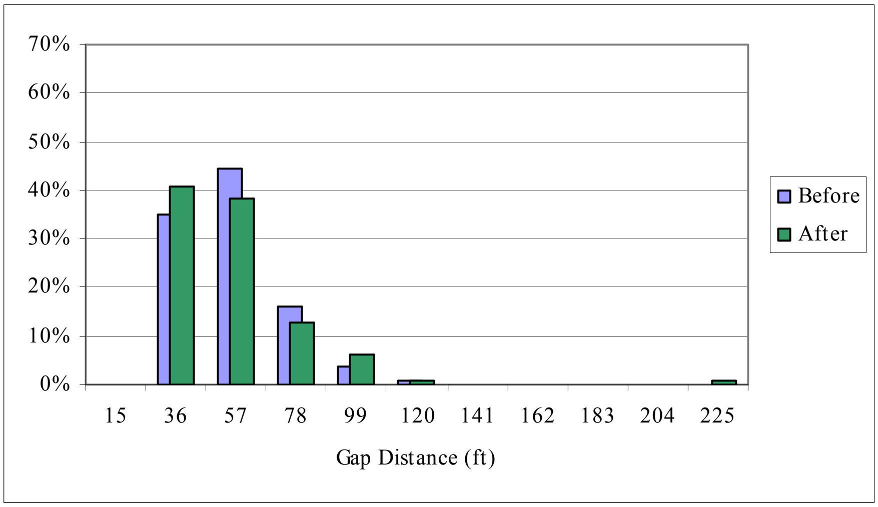


FIGURE 27 Distribution of Gap Distance (60 mph)

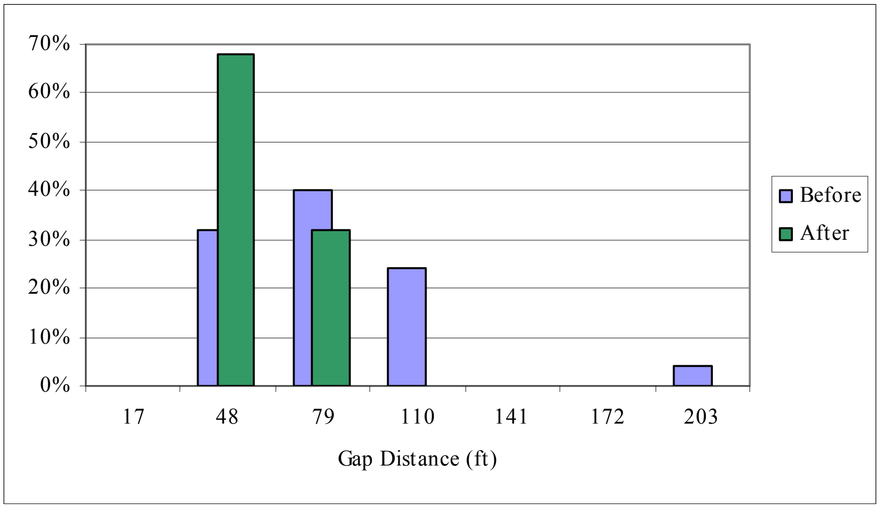


FIGURE 28 Distribution of Gap Distance Time (65 mph)

NORMALITY TESTING

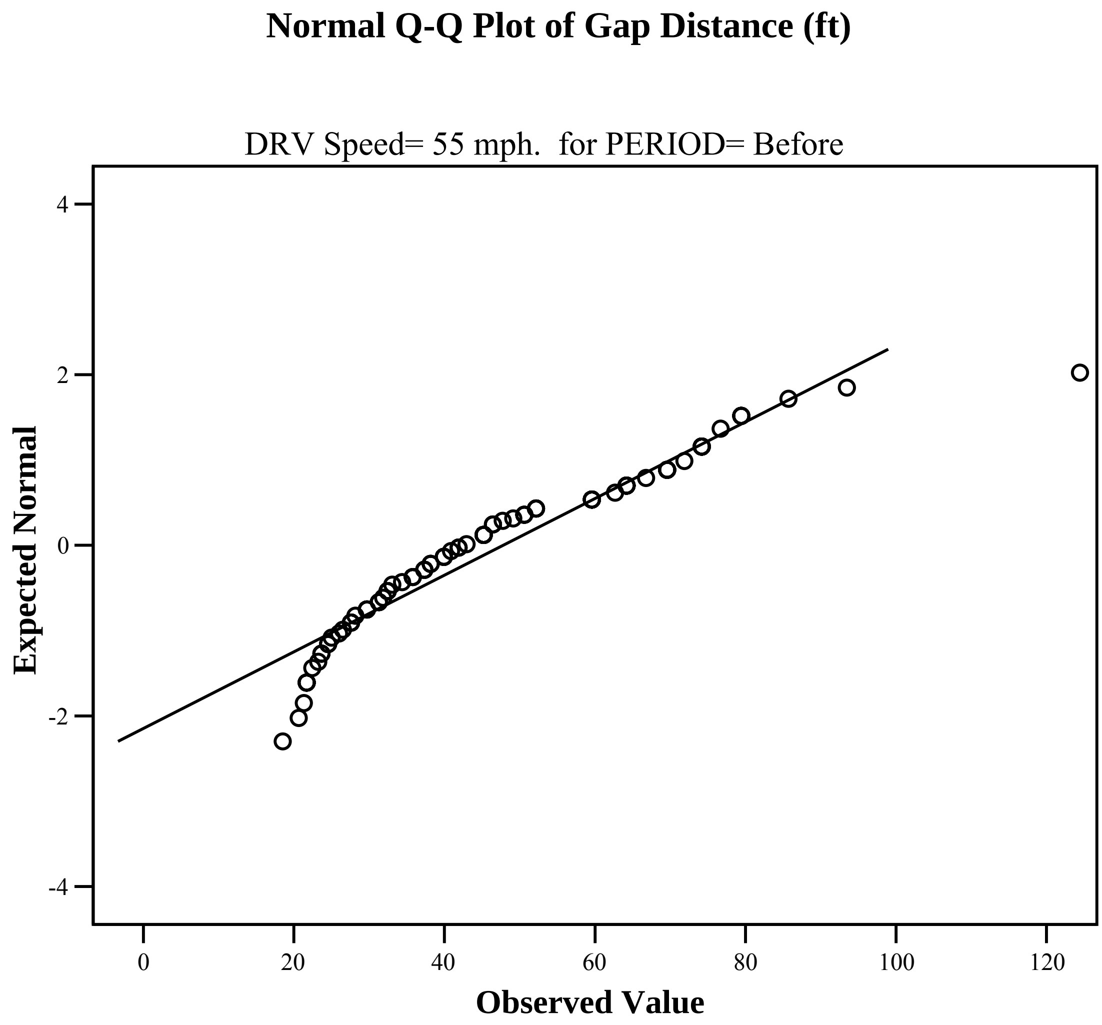


FIGURE 29 Normal Q-Q Plot of Gap Distance (Before/55 mph)

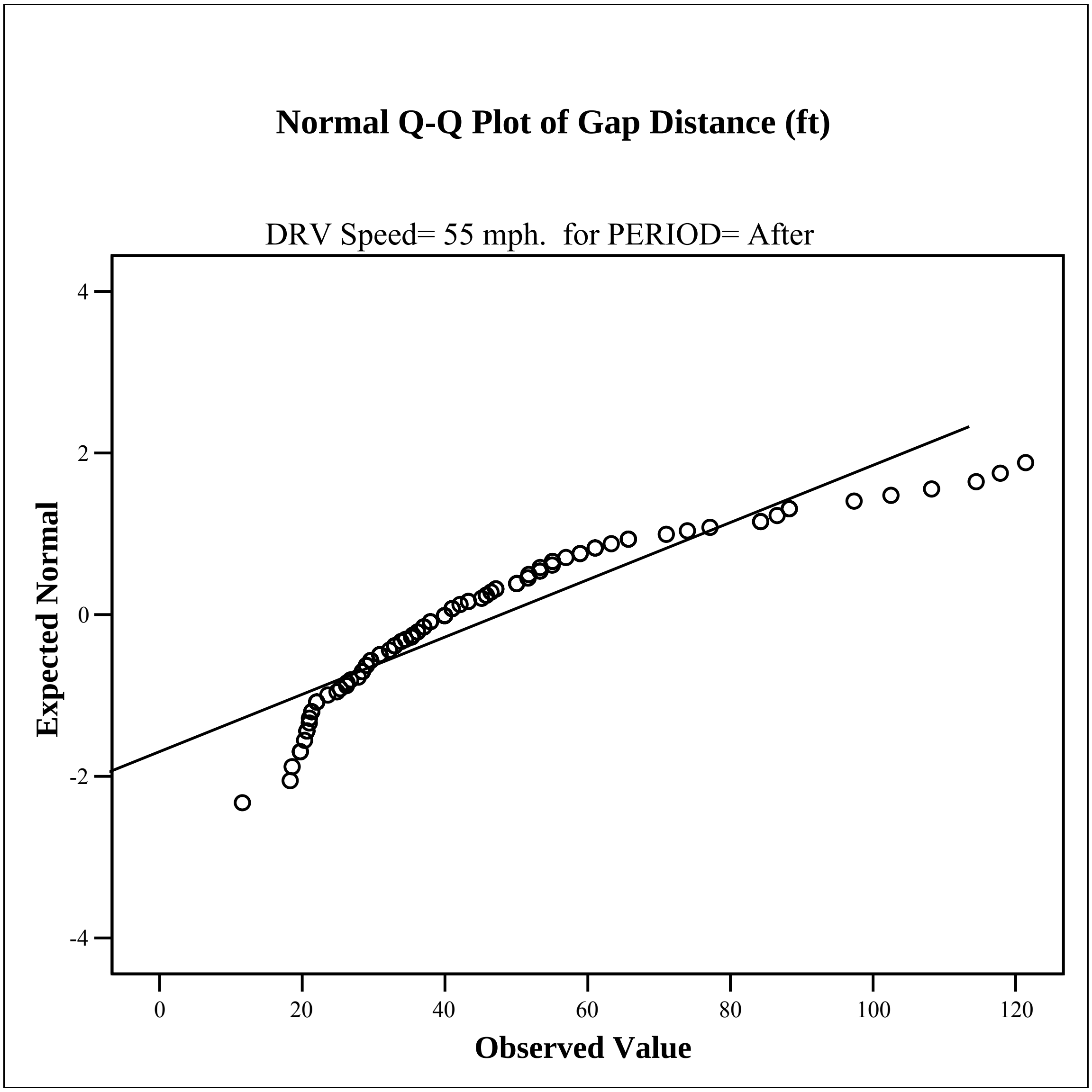


FIGURE 30 Normal Q-Q Plot of Gap Distance (After/55 mph)

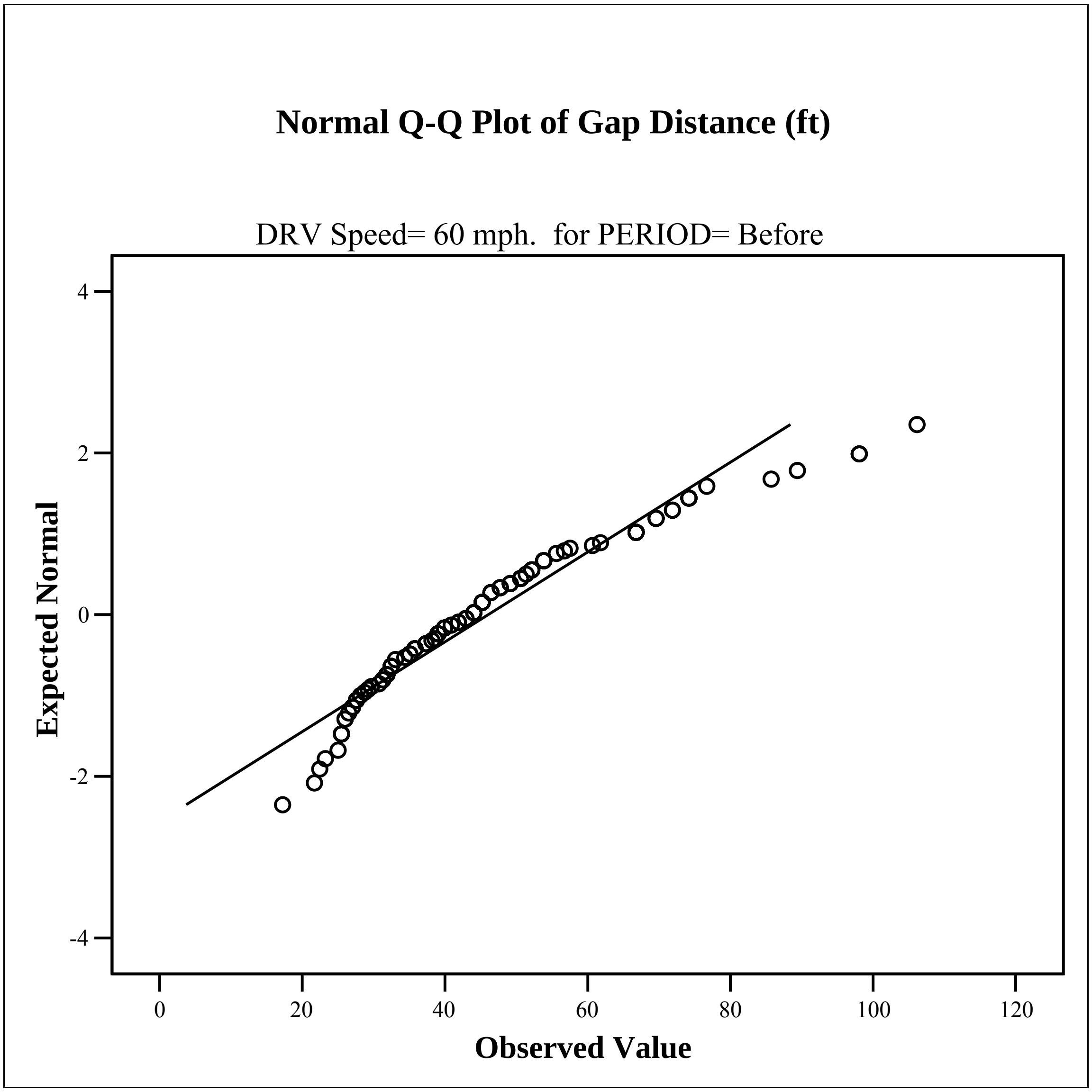


FIGURE 31 Normal Q-Q Plot of Gap Distance (Before/60 mph)

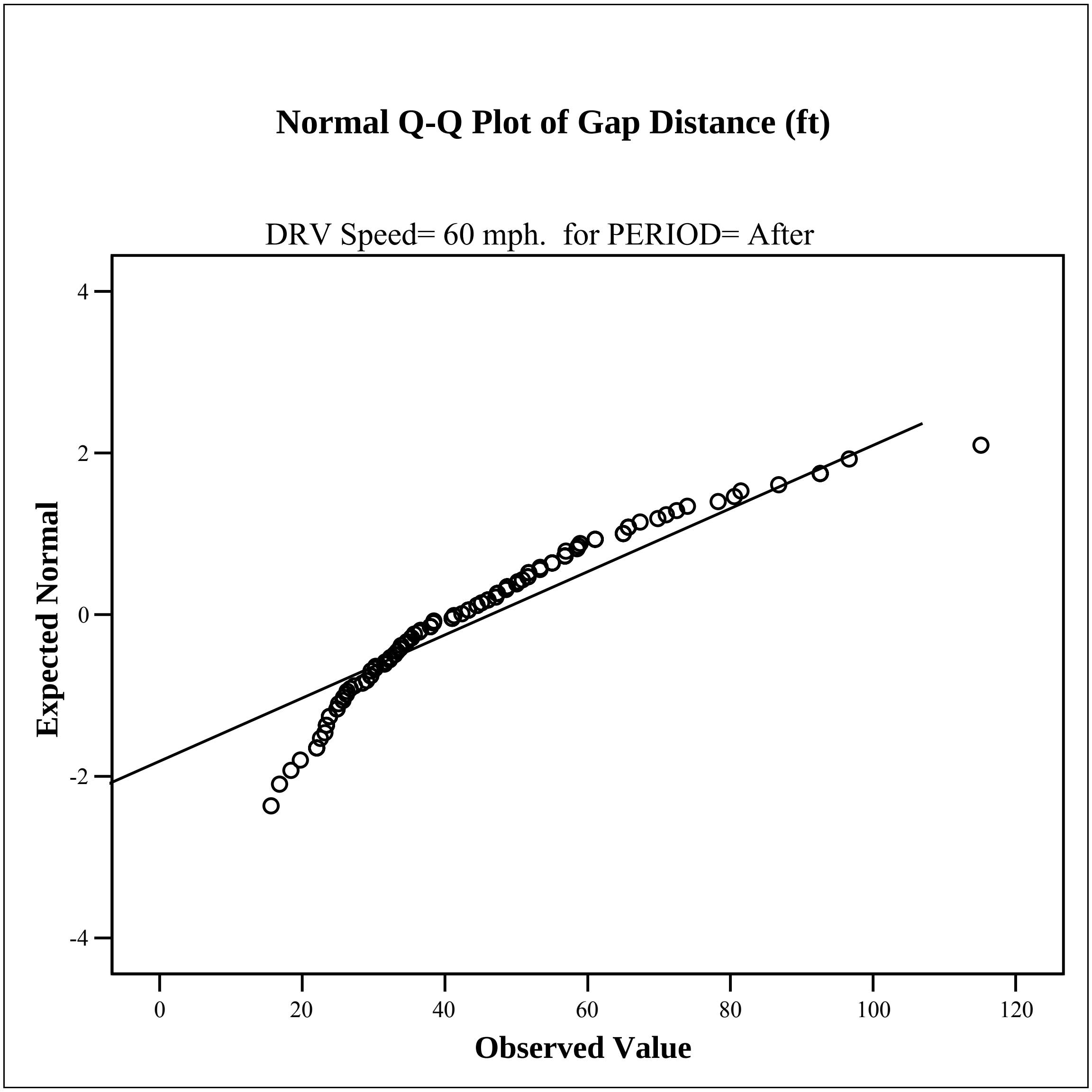


FIGURE 32 Normal Q-Q Plot of Gap Distance (After/60 mph)

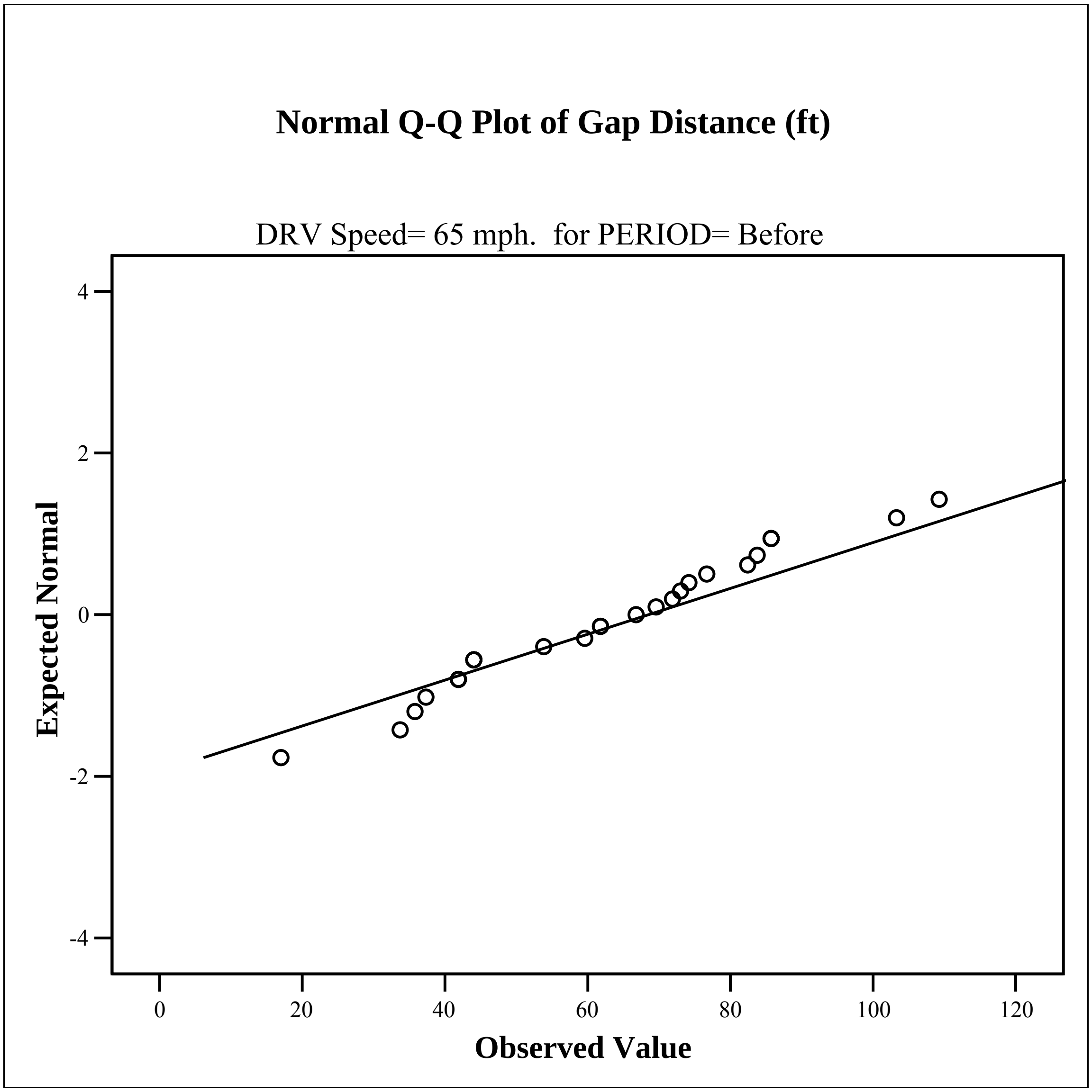


FIGURE 33 Normal Q-Q Plot of Gap Distance (Before/65 mph)

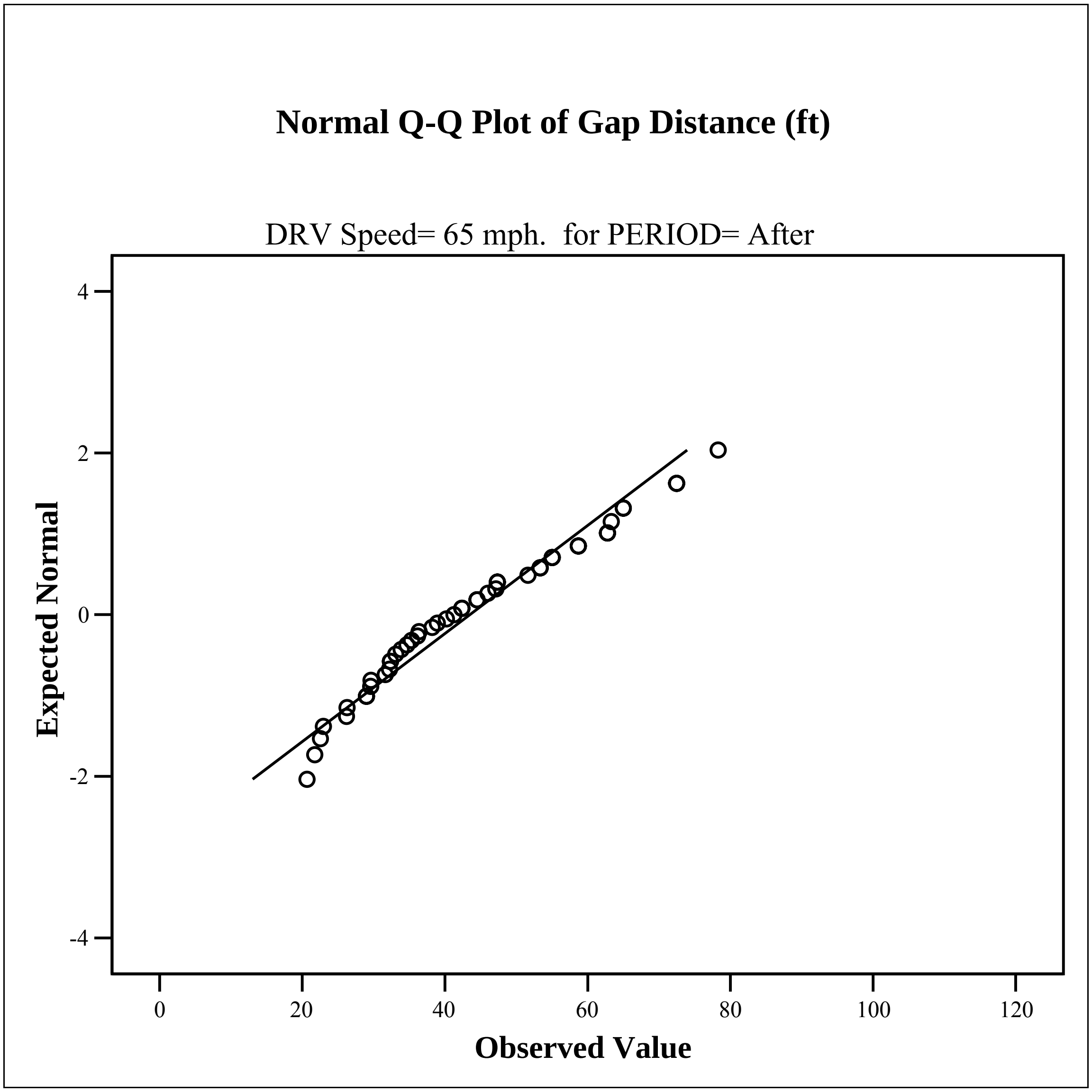


FIGURE 34 Normal Q-Q Plot of Gap Distance (After/65 mph)

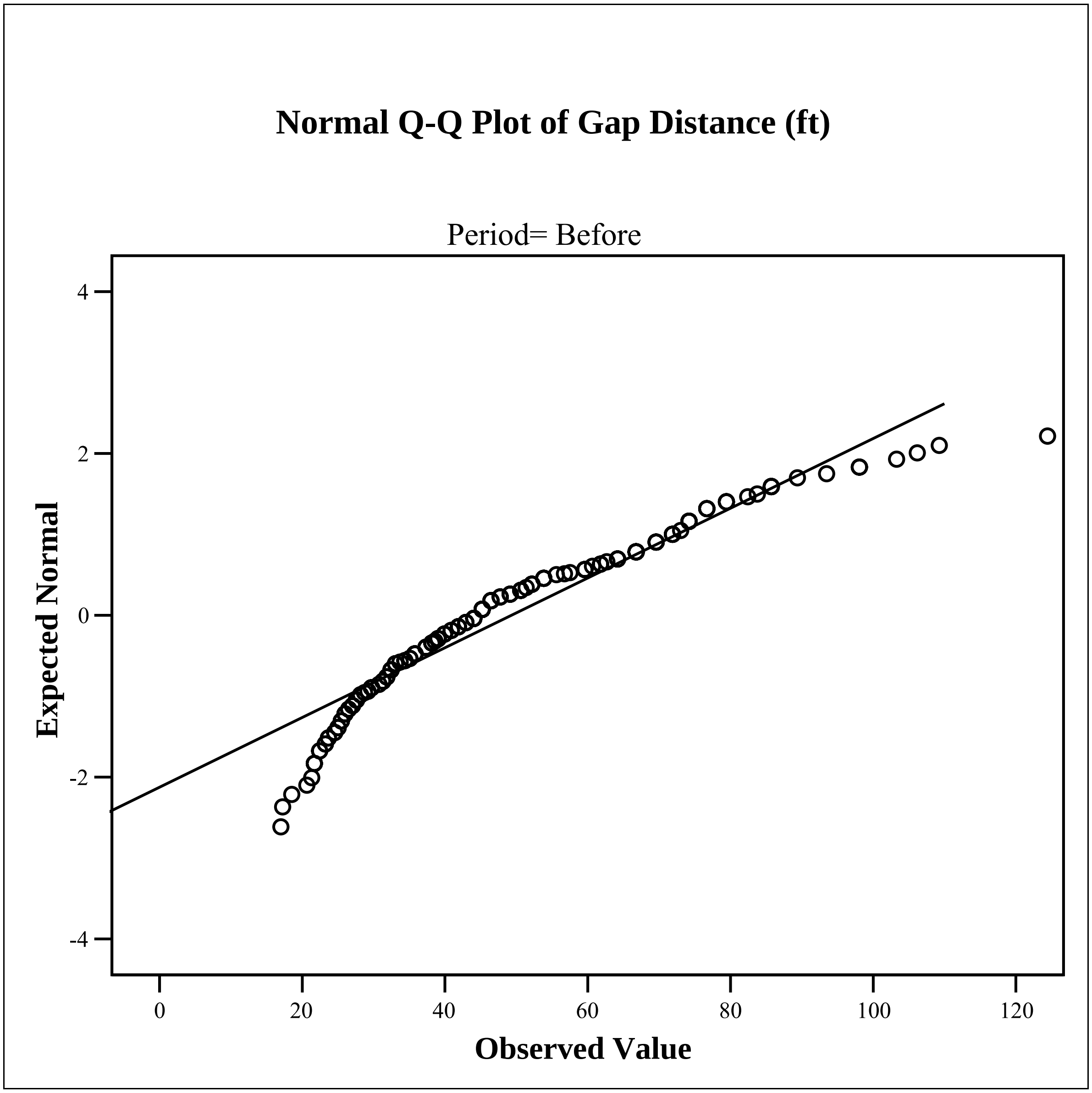


FIGURE 35 Normal Q-Q Plot of Gap Distance (Before/All Speeds)

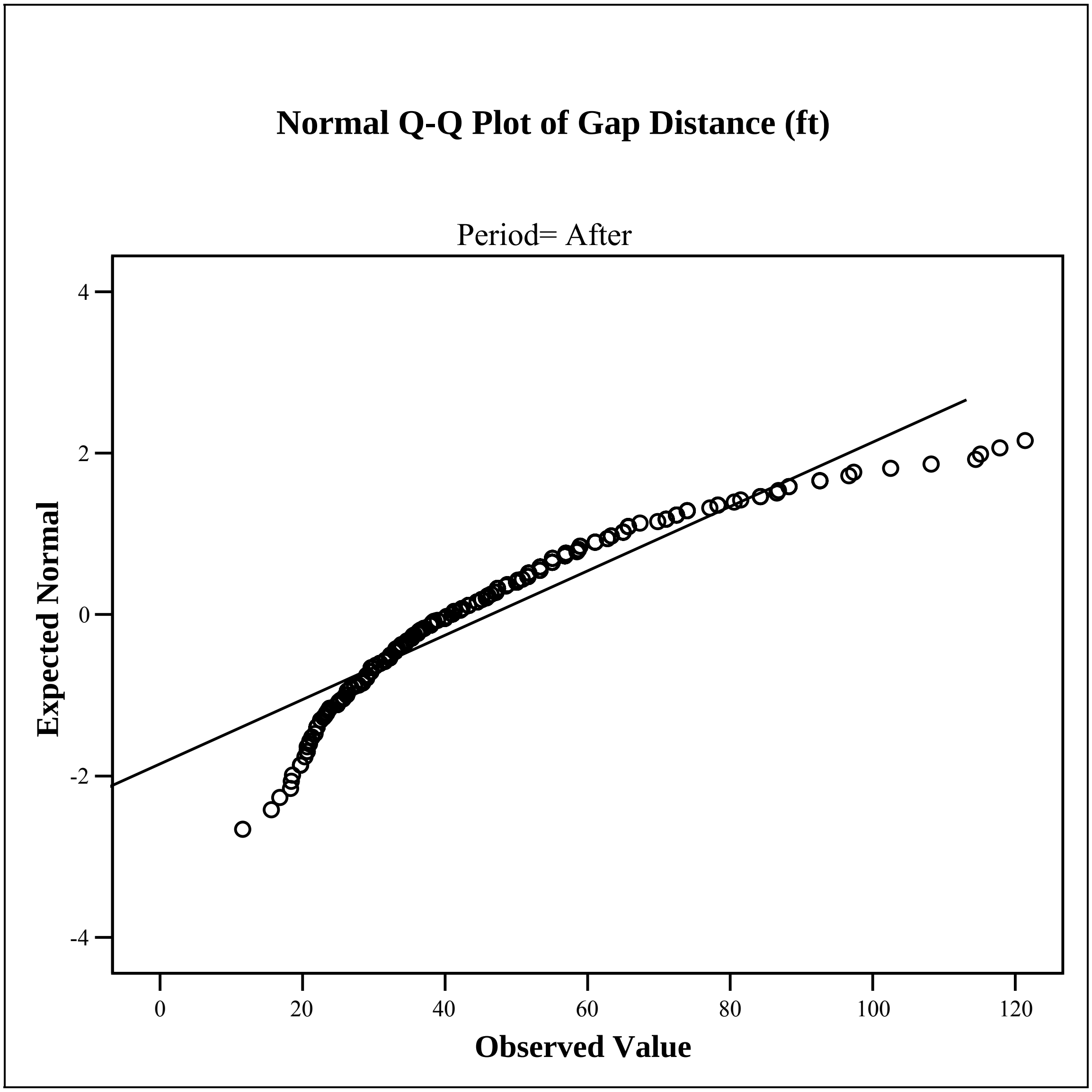


FIGURE 36 Normal Q-Q Plot of Gap Distance (After/All Speeds)

WILCOXIN RANK SUM TESTS

Table 21 contains the complete Wilcoxin Rank Sum test results conducted on the gap distance data. The general hypothesis and the associated assumptions for significance were:

- H_0: There is not a difference between gap distance data collected at speed *i* between the before-and-after period;
- H_1: There is a statistical difference between gap distance data collected at speed *i* between the before-and-after period;
- 95% Confidence Interval;
- Two-Tailed test with z-value = 1.960;
- Reject H_0 if -1.960 > z-stat or if z-stat > 1.960;

TABLE 21 Gap Distance with Respect to Period

DRV Speed	55 mph	60 mph	65 mph	Combined
Sum	4596.0	6138.0	342.0	48666.0
T	9140.0	11772.0	1235.5	56552.5
Before	92	106	25	223
After	99	110	47	256
μ_T	8832.0	11501.0	912.5	53520.0
σ_T^2	145631.9	210723.2	7141.4	2282508.8
σ_T	381.6	459.0	84.5	1510.8
z-stat	0.807	0.590	3.822	2.007

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The test results detailed in Table 22 were only from the after period and they did not include all of the data points. Data collected over identical sections of the time on a weekday and a weekend were tested to verify if there was any difference between weekend and weekday data in the after period. No tests were needed for the before data, because the data were collected on weekdays only.

TABLE 22 Gap Distance with Respect to Weekday and Weekend

DRV Speed	**60 mph**	**65 mph**
Sum	270.0	60.0
T	719.5	173
Weekday	24	13
Weekend	31	16
μ_T	672	195
σ_T^2	3466.4	518.7
σ_T	58.9	22.8
z-stat	0.807	-0.966

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

APPENDIX F

CENTERLINE CROSSING TIME

DESCRIPTIVE STATISTICS

TABLE 23 Descriptive Statistics for Centerline Crossing Time

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	Before	After	Before	After	Before	After	Before	After
Sample Size	92	99	106	110	25	47	223	256
Mean (sec)	1.7706	2.2458	1.9724	1.9612	2.0245	1.7714	1.8950	2.0364
Std. Error (Mean)	0.09784	0.06813	0.08068	0.05594	0.13380	0.07473	0.05787	0.03970
C.I. Lower Bound[1] (mean)	1.5762	2.1106	1.8124	1.8503	1.7484	1.6210	1.7809	1.9582
C.I. Upper Bound[1] (mean)	1.9649	2.3810	2.1324	2.0720	2.3007	1.9218	2.0090	2.1146
5% Trimmed Mean	1.6548	2.2165	1.8879	1.9571	2.0119	1.7459	1.8056	2.0137
Median	1.5826	2.1125	1.8821	1.9830	2.0881	1.6678	1.7851	1.9891
Variance	0.881	0.459	0.690	0.344	0.448	0.262	0.747	0.403
Std. Deviation	0.93843	0.67784	0.83070	0.58674	0.66901	0.51230	0.86425	0.63521
Minimum	0.71	0.88	0.81	0.55	0.80	0.99	0.71	0.55
Maximum	7.93	4.39	6.06	3.39	3.45	3.38	7.93	4.39
Range	7.22	3.51	5.25	2.84	2.65	2.39	7.22	3.84
Interquartile Range	0.77	0.94	0.84	0.92	0.85	0.64	0.82	0.94
10th Percentile	1.01	1.47	1.12	1.19	1.18	1.20	1.09	1.31
15th Percentile	1.10	1.51	1.20	1.33	1.34	1.30	1.17	1.39
25th Percentile	1.23	1.78	1.40	1.48	1.52	1.41	1.32	1.52
50th Percentile	1.58	2.11	1.88	1.98	2.09	1.67	1.79	1.99
75th Percentile	1.99	2.71	2.22	2.39	2.32	2.03	2.12	2.45
85th Percentile	2.23	2.93	2.72	2.65	2.56	2.32	2.52	2.72
90th Percentile	2.55	3.10	2.91	2.74	2.87	2.52	2.81	2.82
Skewness	3.757	0.606	2.030	0.073	0.295	0.892	2.741	0.543
Std. Error (skewness)	0.251	0.243	0.235	0.230	0.464	0.347	0.163	0.152
Kurtosis	20.803	0.258	6.652	-0.546	-0.131	0.885	13.245	0.303
Std. Error (Kurtosis)	0.498	0.481	0.465	0.457	0.902	0.681	0.324	0.303

[1] A 95% confidence interval (CI) for the mean

PLOTS

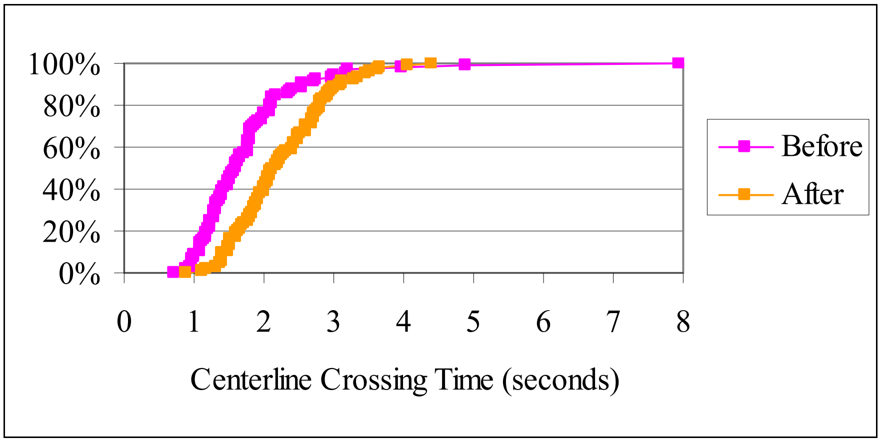


FIGURE 37 Cumulative Distribution of Centerline Crossing Time (55 mph)

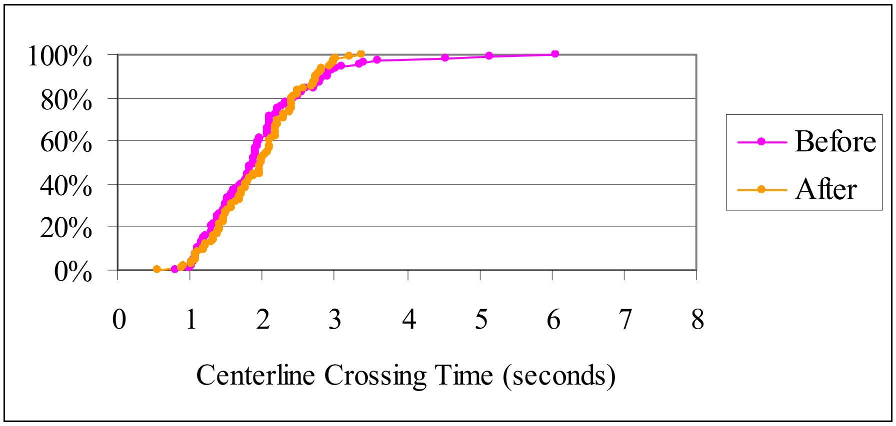


FIGURE 38 Cumulative Distribution of Centerline Crossing Time (60 mph)

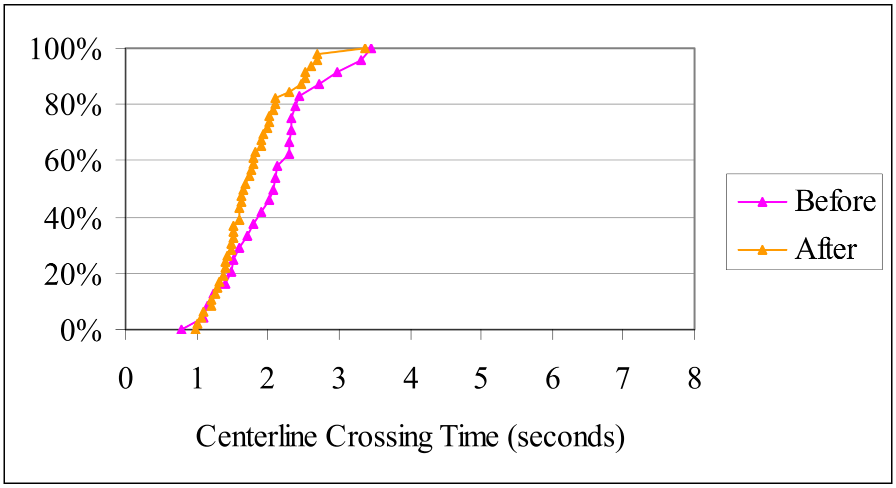


FIGURE 39 Cumulative Distribution of Centerline Crossing Time (65 mph)

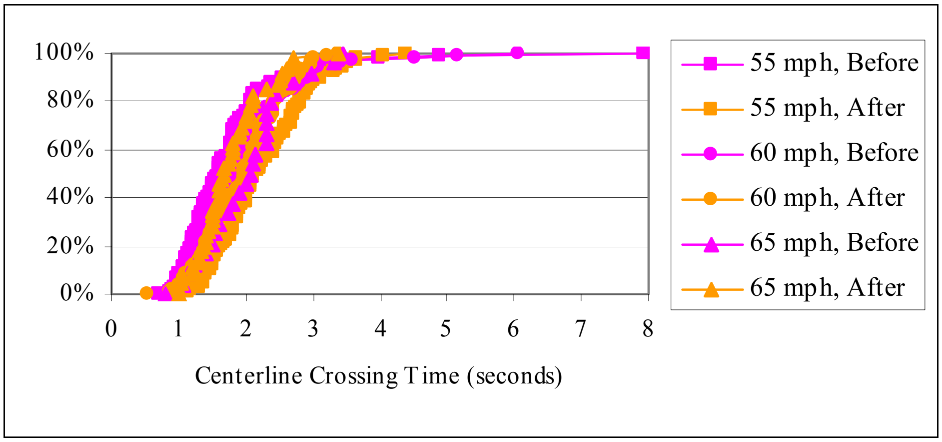


FIGURE 40 Cumulative Distribution of Centerline Crossing Time

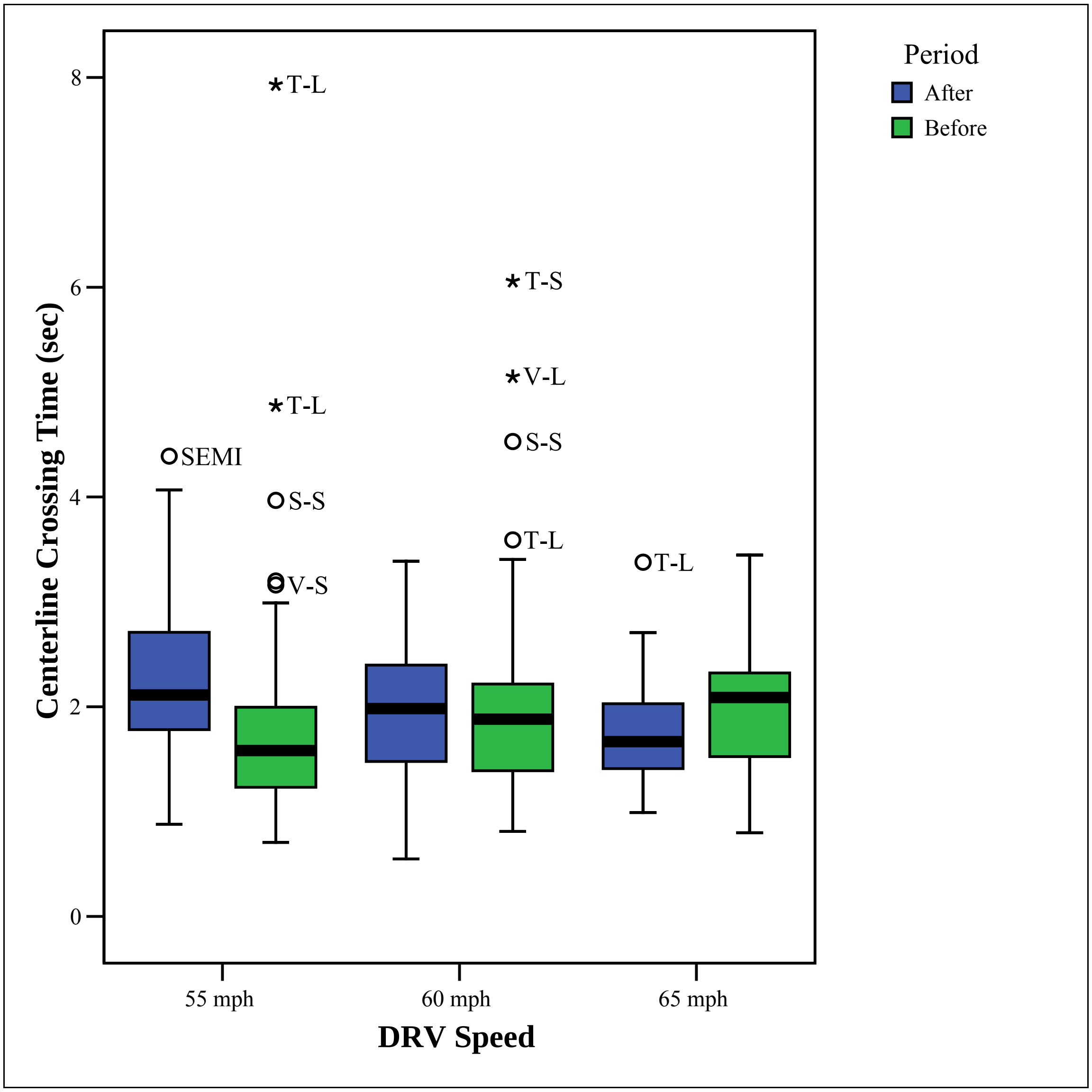


FIGURE 41 Box Plot of Centerline Crossing Time with Respect to Speed

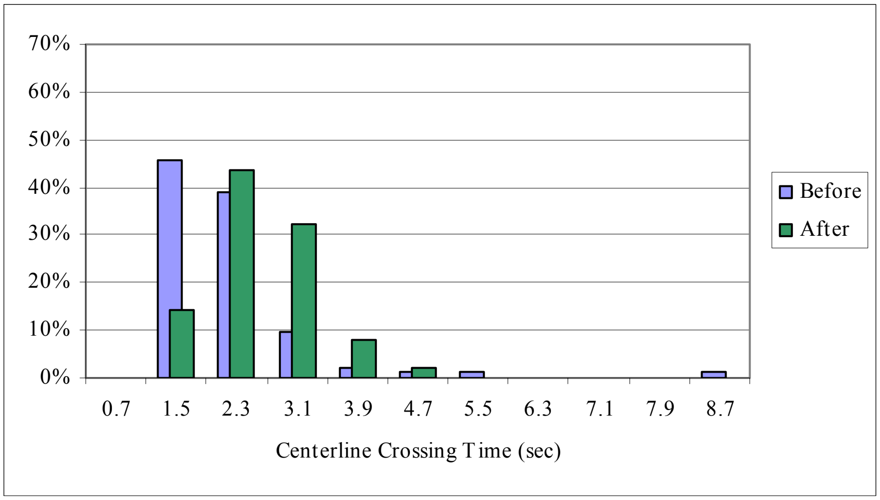


FIGURE 42 Distribution of Centerline Crossing Time (55 mph)

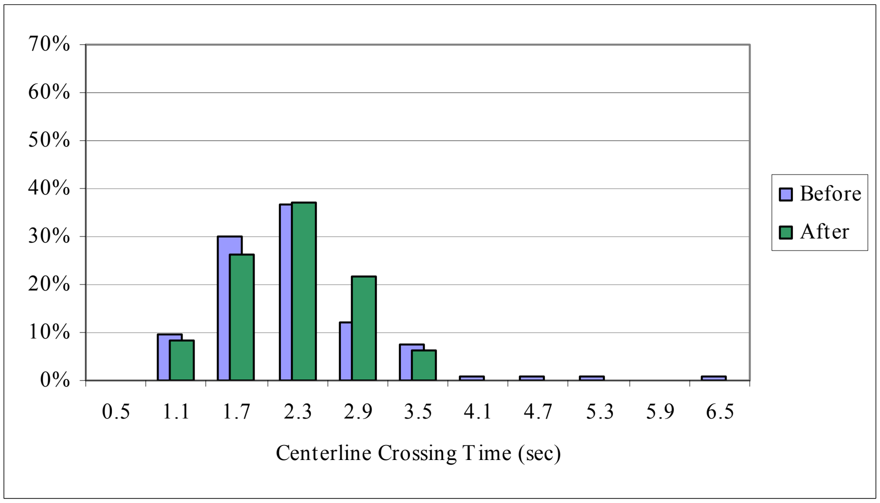


FIGURE 43 Distribution of Centerline Crossing Time (60 mph)

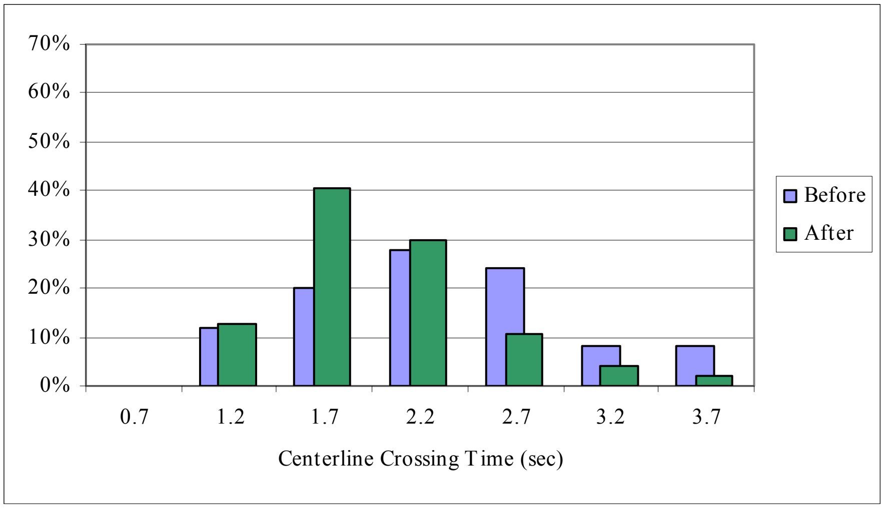


FIGURE 44 Distribution of Centerline Crossing Time (65 mph)

NORMALITY TESTING

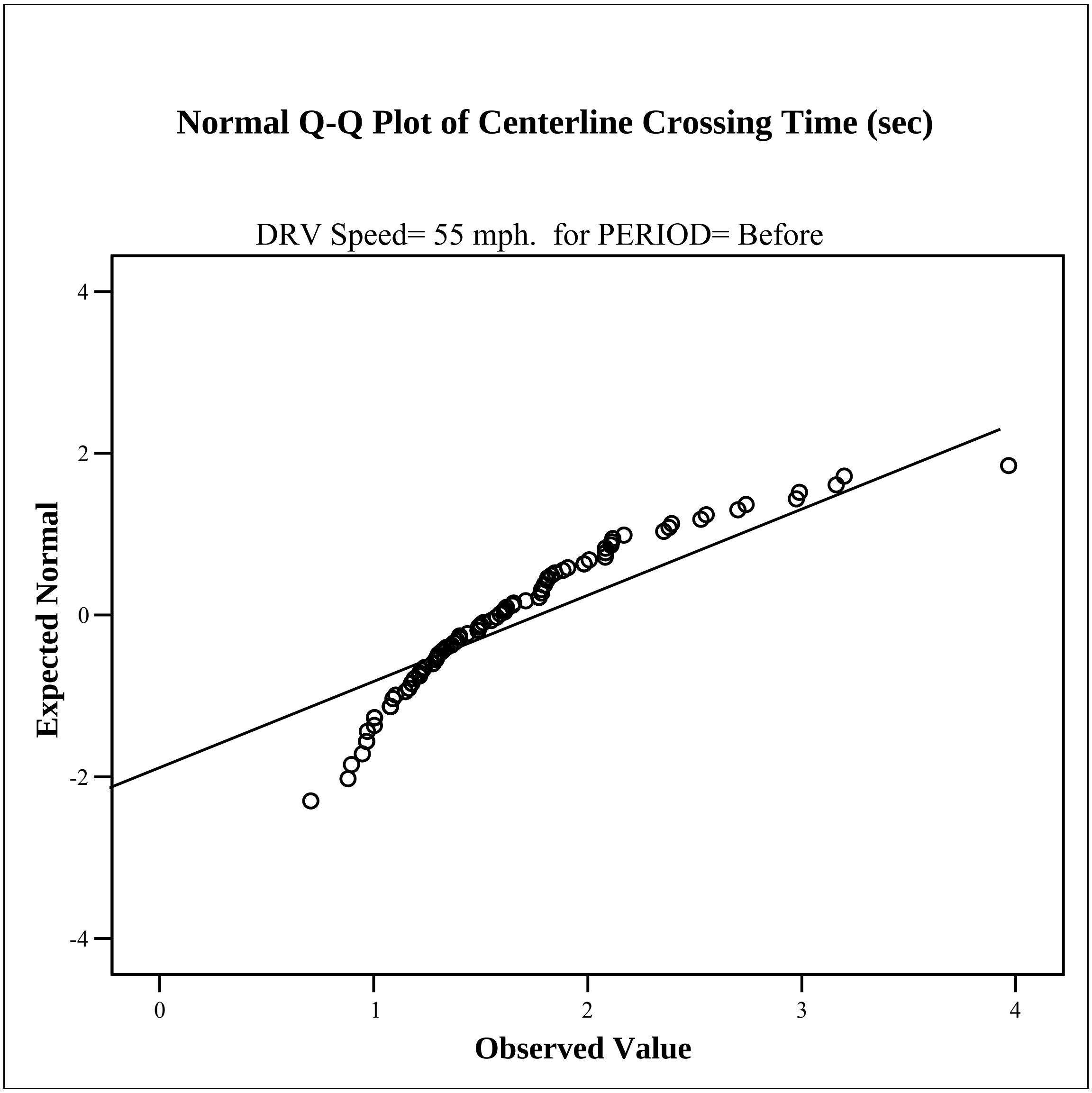


FIGURE 45 Normal Q-Q Plot of Centerline Crossing Time (Before/55 mph)

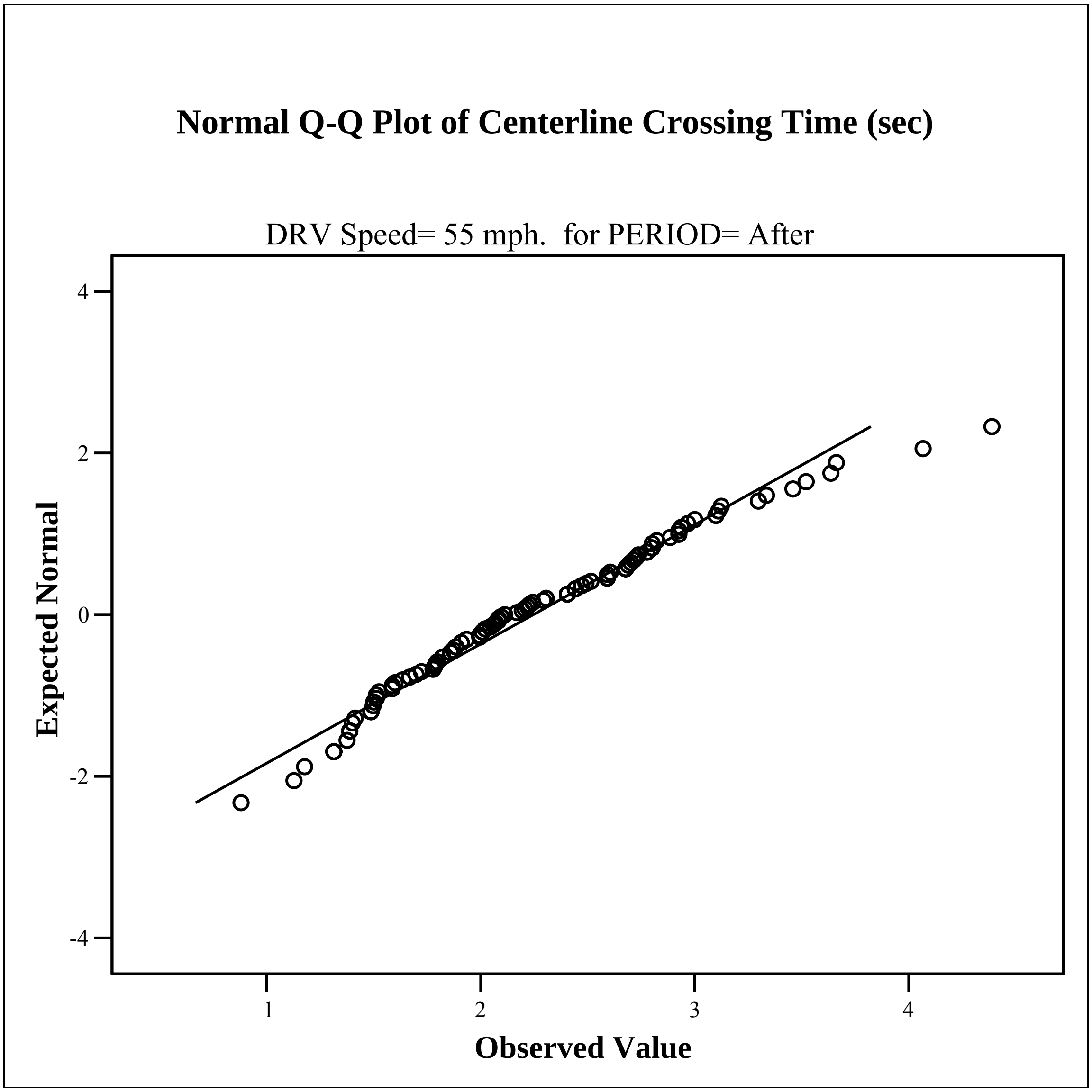


FIGURE 46 Normal Q-Q Plot of Centerline Crossing Time (After/55 mph)

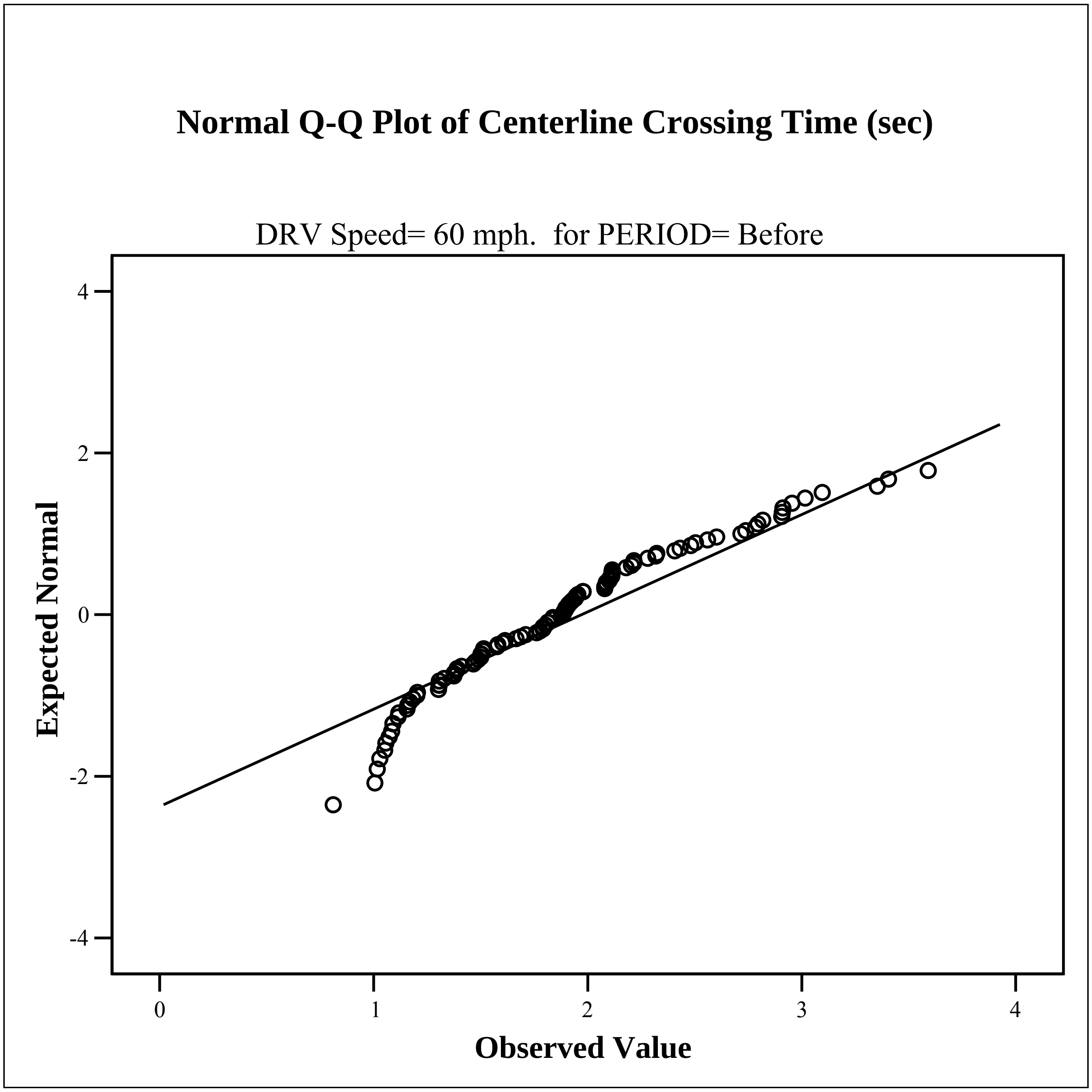


FIGURE 47 Normal Q-Q Plot of Centerline Crossing Time (Before/60 mph)

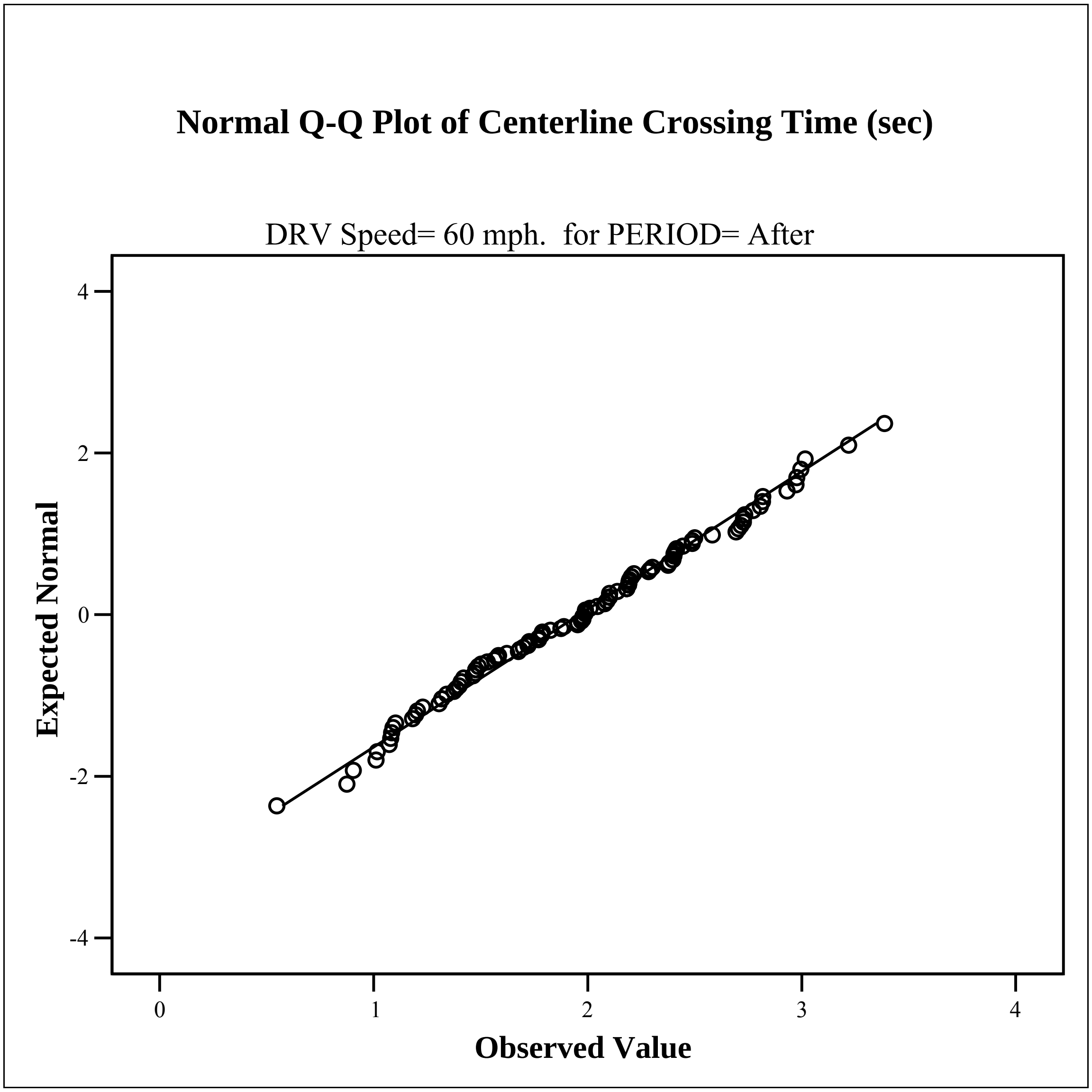


FIGURE 48 Normal Q-Q Plot of Centerline Crossing Time (After/60 mph)

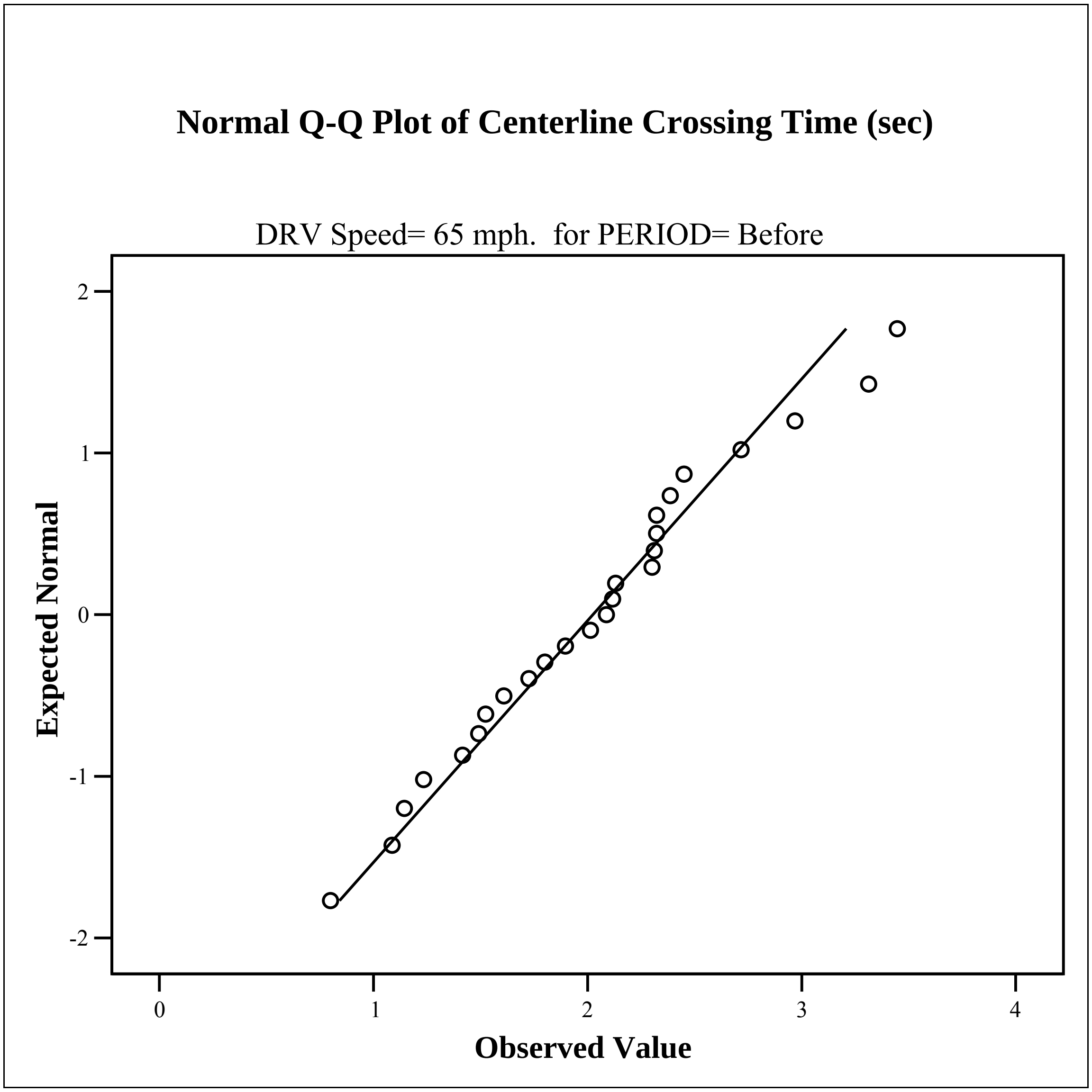


FIGURE 49 Normal Q-Q Plot of Centerline Crossing Time (Before/65 mph)

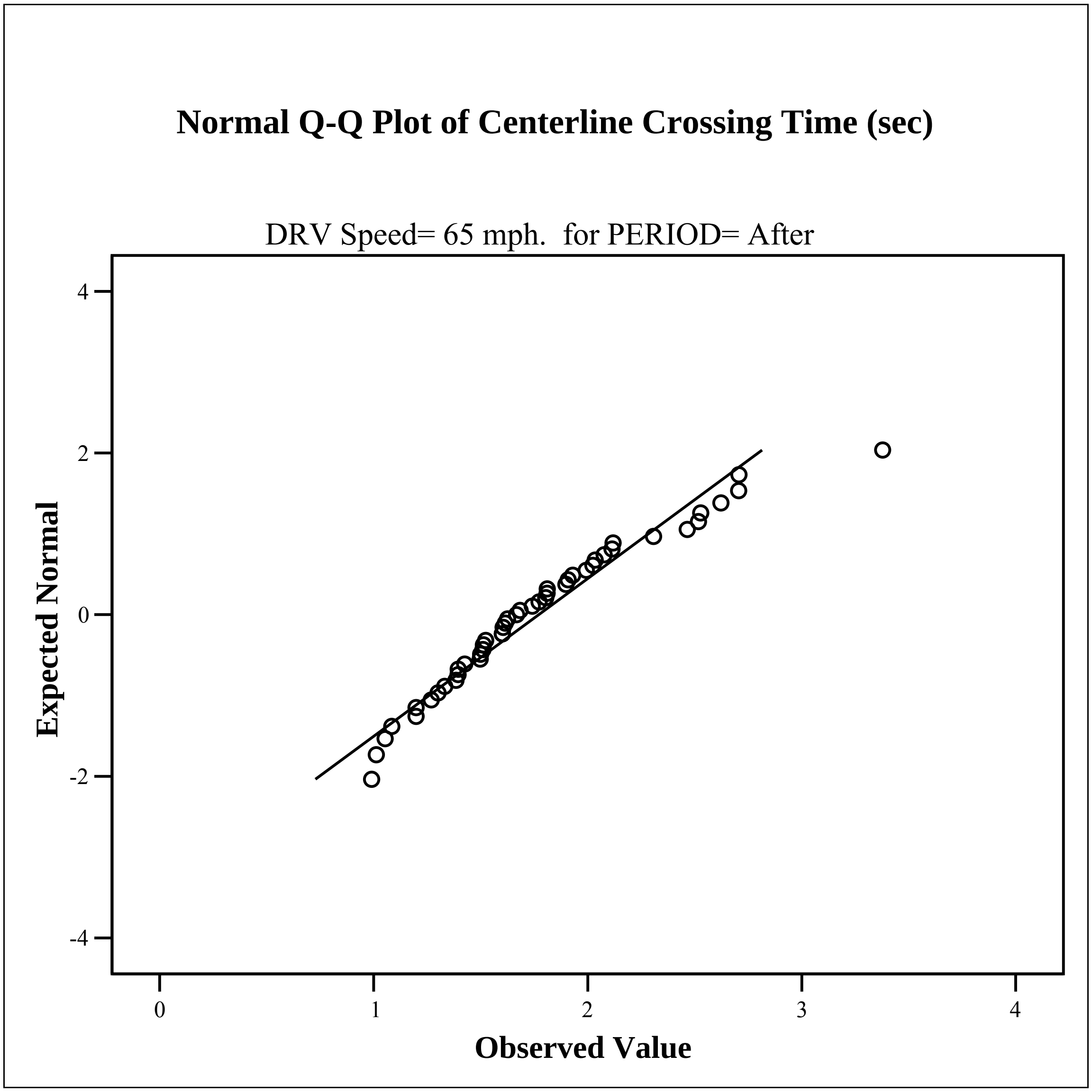


FIGURE 50 Normal Q-Q Plot of Centerline Crossing Time (After/65 mph)

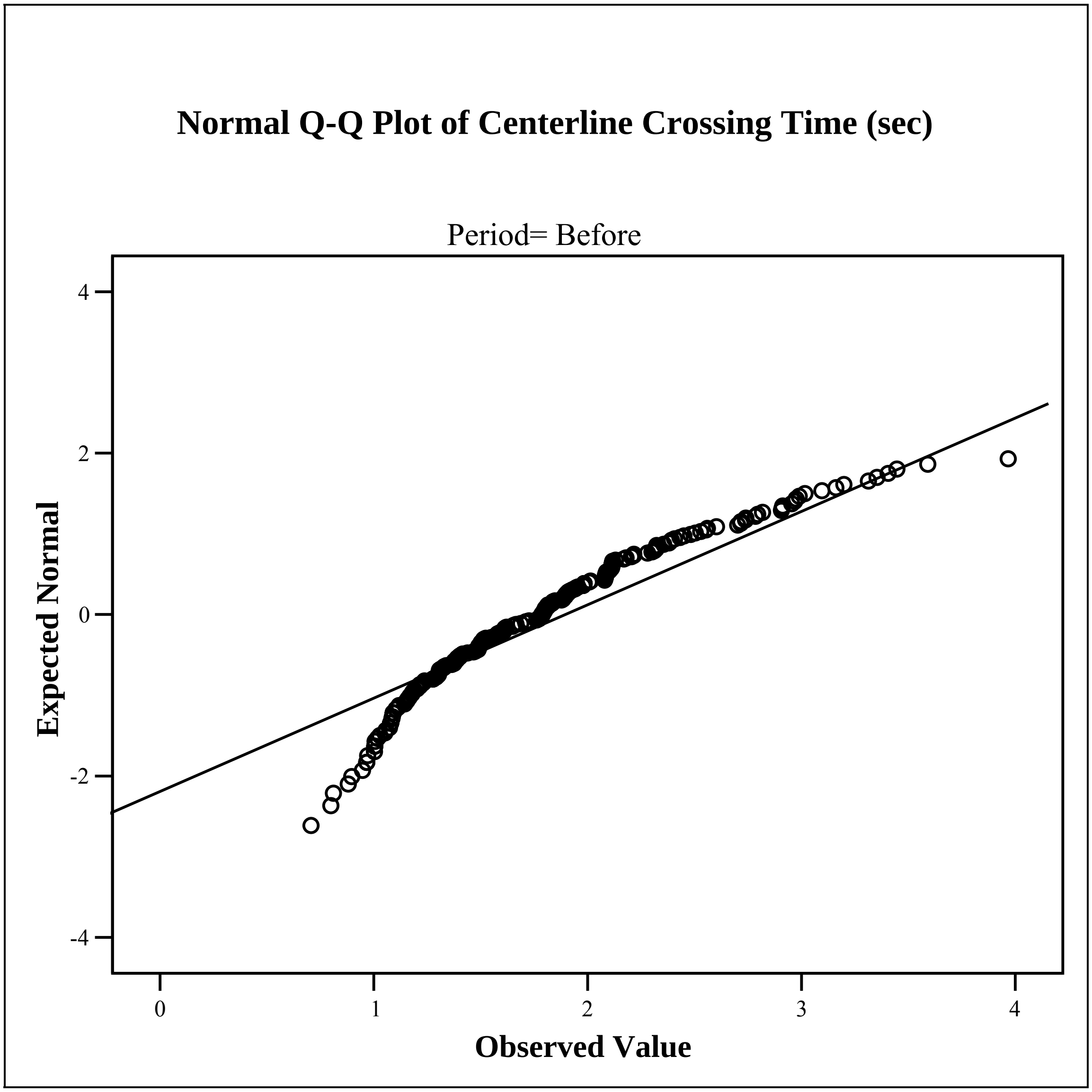


FIGURE 51 Normal Q-Q Plot of Centerline Crossing Time (Before/All Speeds)

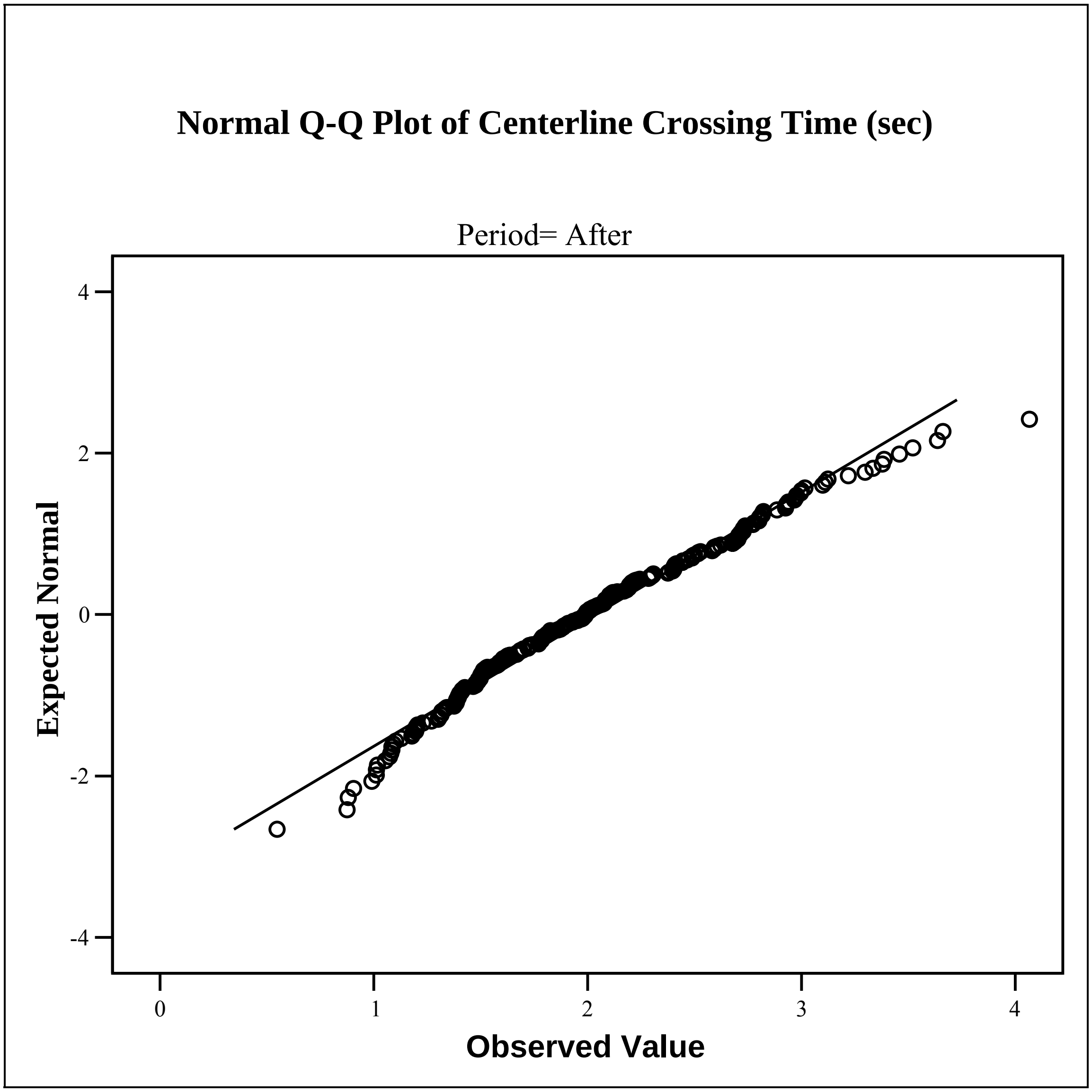


FIGURE 52 Normal Q-Q Plot of Centerline Crossing Time (After/All Speeds)

WILCOXIN RANK SUM TESTS

Table 24 contains the complete Wilcoxin Rank Sum test results conducted on the centerline crossing time data. The general hypothesis and the associated assumptions for significance were:

- H_0: There is not a difference between centerline crossing time data collected at speed *i* between the before-and-after period;
- H_1: There is a statistical difference between centerline crossing time data collected at speed *i* between the before-and-after period;
- 95% Confidence Interval;
- Two-Tailed test with z-value = 1.960;
- Reject H_0 if -1.960 > z-stat or if z-stat > 1.960;

TABLE 24 Centerline Crossing Time with Respect to Period

DRV Speed	55 mph	60 mph	65 mph	Combined
Sum	5154.0	7836.0	522.0	68934.0
T	6658.0	11028.5	1058.0	47998.5
Before	92	106	25	223
After	99	110	47	256
μ_T	8832.0	11501.0	912.5	53520.0
σ_T^2	145620.2	210687.7	7137.9	2282087.7
σ_T	381.6	459.0	84.5	1510.7
z-stat	-5.697*	-1.029	1.722	-3.655*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The test results detailed in Table 25 were only from the after period and they did not include all of the data points. Data collected over identical sections of the time on a weekday and a weekend were tested to verify if there was any difference between weekend and weekday data in the after period. No tests were needed for the before data, because the data were collected on weekdays only.

TABLE 25 Centerline Crossing Time with Respect to Weekday and Weekend

DRV Speed	**60 mph**	**65 mph**
Sum	240.0	48.0
T	391.5	277.5
Weekday	24	13
Weekend	31	16
μ_T	672	195
σ_T^2	3467.0	519.0
σ_T	58.9	22.8
z-stat	-4.764*	3.621*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

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