Field Testing of Cantilevered Traffic Signal Structures under Truck-Induced Gust Loads

by

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Dedication

To Jessica for all her love, support, and understanding throughout the past two years.

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May 2006

Abstract

Field Testing of Cantilevered Traffic Signal Structures under Truck-Induced Gust Loads

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The University of Texas at Austin, 2006

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Changes in the AASHTO fatigue design equations for truck-induced gust loads have been made in recent years. However, there has not been any long-term field testing of cantilevered traffic signal structures to verify the design equations. In this study, two cantilevered traffic signal structures were monitored in field testing to determine the effects of truck-induced gust loads. Over 400 truck events were observed in the field, but only 18 trucks produced a detectable effect on the cantilevered traffic signal structure. Interestingly, the truck-induced gusts caused a greater effect in the out-of-plane direction (same direction as traffic flow) instead of the in-plane direction that is included in the AASHTO Specifications. It was determined that overall natural wind gusts produce a larger response in cantilevered traffic signal structures than gusts produced by trucks passing beneath the signals.

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Chapter One: Introduction

1.1 Background

Cantilevered traffic signal structures are located at intersections throughout the United States as an economical solution for traffic control. A major advantage of using a single support structure for traffic control is the reduced probability of a vehicle collision. However, as the spans of the horizontal mast arms continue to increase, the flexibility of these structures also significantly increases. The high flexibility, combined with low mass and damping, causes cantilevered traffic signal structures to be susceptible to large amplitude oscillations and in some cases fatigue cracking due to cyclic loading. The four sources of wind-induced cyclic loading are galloping, natural wind gusts, truck-induced gusts, and vortex shedding.

1.2 Research Motivation

Since cantilevered traffic signal structures are so widely used, any problematic issue could lead to enormous problems for Departments of Transportations (DOTs) across the nation. Failures of cantilevered traffic signal structures in several states including Texas, illustrated in Figures 1.1 and 1.2, led to stricter provisions for fatigue design in the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals in 2001. These new provisions, which were developed without wind tunnel or field testing, made it much more difficult for several states including Texas to design economical AASHTO-compliant cantilevered traffic signal structures. Thus, following a previous study summarized in the National Cooperative Highway Research Program (NCHRP) Report 412, Fatigue-Resistant Design of Cantilevered Signal, Sign and Light Supports (Kaczinski et al., 1998) and the 2001

AASHTO Specifications, Report 469, Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports (Dexter and Ricker, 2002) recommended that long-term field testing be performed to verify the new truck-induced gust equivalent static pressure ranges recommended in the fatigue design section of the Specifications.

Figure 1.1: Failure of Cantilevered Traffic Signal Structure in Pflugerville, Texas in December 2003

Figure 1.2: Fatigue Crack Initiated by Cyclic Loading

1.3 TRUCK-INDUCED GUST LOADS

This research study was concerned with field tests and the recommended design provisions for truck-induced gust loads on cantilevered traffic signal structures. Every time a truck passes beneath a cantilevered traffic signal structure, it generates both a horizontal and vertical force on the structure. According to the Specifications, only the vibrations caused by the vertical component of the truck-induced gust need to be considered because in the horizontal direction the vibrations resulting from the natural wind are more dominant than those produced by truck-induced gusts (AASHTO, 2003). For this reason, truck-induced gust pressures are only applied to the exposed horizontal surfaces of the mast arm and attachments (traffic signals and dampening plates). Texas is one of a few states that have their traffic signals positioned horizontally on the mast arm, as can be seen in Figure 1.3. For the other states that mount their traffic signals vertically on the mast arm, the vertical orientation reduces the exposed area over which the vertical truck-induced gust pressure is applied. Therefore, truck-induced gusts are a greater concern for design engineers at the Texas Department of Transportation (TxDOT).

Figure 1.3: Typical Cantilevered Traffic Signal Structure in Texas

The current design equations for truck-induced gust loads are thought by many design engineers across the country to be overly conservative. This might be particularly true in the case of cantilevered traffic signal structures because there have not been much field testing to determine truck-induced gust loads. Of the field tests that have been completed, the majority were studies of variable-message sign (VMS) structures and a few on cantilevered highway sign structures. The reason for this is that VMS structures have large horizontal areas making them the most susceptible type of cantilevered support structure to truck-induced gusts. In fact, the AASHTO design equations were likely adopted following the study of a single VMS failure (as is discussed in Chapter 2), although it has not been shown that the design pressures for a VMS structure are applicable to cantilevered traffic signal structures.

1.4 PROJECT SCOPE AND OBJECTIVES

This thesis presents results from a series of field tests of cantilevered traffic signal structures under truck-induced gust loading conducted by the University of Texas at Austin. It is part of the TxDOT-sponsored research Project No. 0-4586, “Revision of AASHTO Fatigue Design Loadings for Signs, Luminaires, and Traffic Signal Structures, for Use in Texas.” TxDOT Project No. 0-4586 is a joint effort between the University of Texas at Austin and Texas Tech University to re-evaluate the AASHTO design equations for galloping loads and truck-induced gust loads based on a series of controlled tests and field tests. The University of Texas at Austin was responsible for the field testing associated with the project while Texas Tech conducted the controlled tests at their Reese Technology Center site. Details related to the field testing of galloping loads can be found in the Master’s thesis titled “Field Tests and Analytical Studies of the Dynamic Behavior and the Onset of Galloping in Traffic Signal Structures” (Florea, 2005).

The primary objective of this research project is to conduct field testing of cantilevered traffic signal structures under truck-induced gust loads in order to improve or validate the current fatigue design specifications. Chapter 2 contains a literature review of the pertinent articles related to truck-induced gusts. It also discusses the design philosophy of the AASHTO Specifications. Chapter 3 describes the equipment used during the field testing and the field setup procedures. Chapter 4 summarizes field test data and Chapter 5 discusses the results and provides the recommendations.

Chapter Two: Literature Review

2.1 OVERVIEW

The first portion of this research project consisted of an extensive literature search to review earlier studies that discussed not only truck-induced gust loads but cantilevered traffic signal structure behavior in general. The complete list of references compiled during this search is presented in Appendix A. Although not all of these references will be discussed in this chapter, each one was invaluable in gaining knowledge about the behavior of cantilevered traffic signal structures as well as methods used by researchers across the country to study these structures. In the following sections, the results and findings from various research projects related to truck-induced gust loads are summarized.

2.2 PREVIOUS RESEARCH ON TRUCK-INDUCED GUST LOADS

2.2.1 Creamer et al. (1979)

The foremost study of truck-induced gust loading was performed by Bruce M. Creamer, Karl H. Frank, and Richard E. Klingner at the University of Texas at Austin in 1979. Their research report, titled “Fatigue Loading of Cantilever Sign Structures from Truck Wind Gusts,” describes an experimental and analytical study where three cantilevered highway sign structures were instrumented in the field to determine how they would respond when trucks passed beneath them. Because of the low inherent damping of cantilevered highway sign structures, there were concerns that an impulse load from a single truck could produce a large number of cycles of motion and ultimately cause a fatigue failure. During the development of the field tests, the researchers realized that measuring the actual truck-induced gust using pressure gages on the sign face was not practical due to the highly turbulent flow of the gust. By measuring strains during the field tests, it was observed that the magnitude of the member response varied depending upon the truck speed, truck shape, and time interval between trucks. Trucks with a large projected flat area, such as box-type trucks and gravel trucks, produced the greatest sign movement. Based on the largest recorded event, the researchers were able to develop a pressure distribution, shown in Figure 2.1, that when applied to an analytical model of a cantilevered highway sign support structure, resulted in member stresses that matched the stresses observed during the field tests. The pressure distribution consisted of a uniform maximum pressure of 1.23 psf (58.9 Pa) applied vertically to the lighting fixtures while horizontally the pressure varied linearly from 0 psf (0 Pa) at the top of the sign face to the maximum pressure of 1.23 psf (58.9 Pa) at the bottom of the sign face. The researchers understood that this pressure distribution did not accurately represent the actual loading that was observed in the field, but rather it was one that simulated measured member stresses. For this reason and for convenience, it was recommended that a maximum pressure of 1.25 psf (60 Pa) be used for design. The anchor bolts were determined to be critical elements governing the design of the cantilevered highway sign structures for truck-induced gusts.

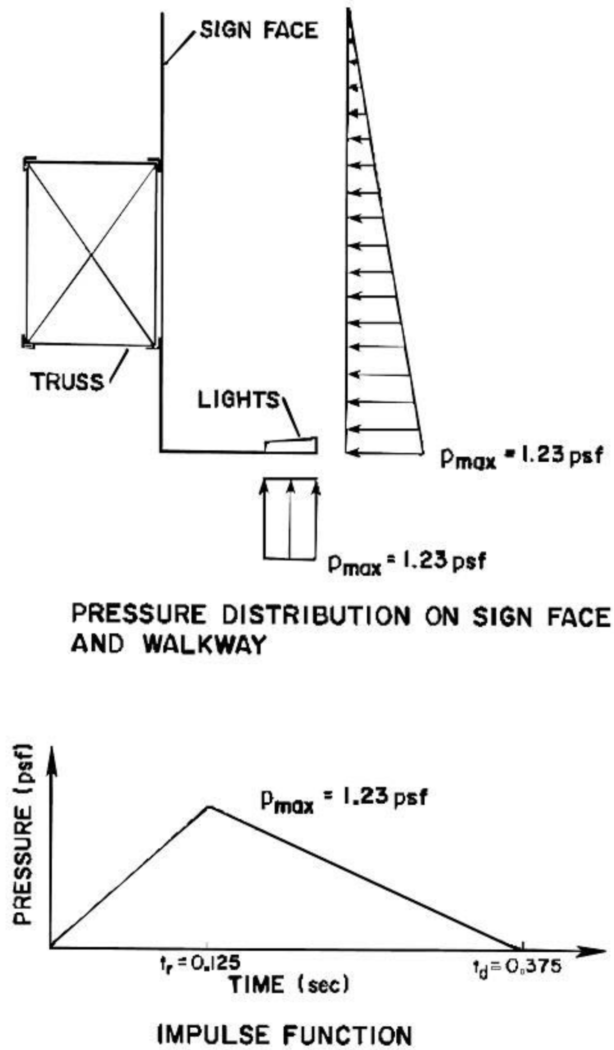


Figure 2.1: Pressure Distribution and Impulse Function To Simulate a Truck-Induced Gust (Creamer et al., 1979)

2.2.2 Edwards and Bingham (1984)

In 1984, Professors J. A. Edwards and W. L. Bingham of North Carolina State University in Raleigh studied vibrations of four cantilevered highway sign structures in the field. One of these cantilevered highway sign structures was implemented with hot film anemometer patches to investigate truck-induced gust loading. Assuming

Bernoulli's equation to calculate pressure from velocity, the researchers determined that the maximum pressure recorded on the sign due to truck-induced gusts was 1.41 psf (67.5 Pa). It was concluded that both box-type medium duty trucks and large semi/tractor-trailer trucks produced a similar response on the cantilevered highway sign structure. The report concluded from both the experimental testing and analytical modeling that the vibrations of the cantilevered highway sign structure due to truck-induced gusts did not result in stress levels that would damage the structure.

2.2.3 Cook et al. (1996)

In 1996, Ronald A. Cook, David Bloomquist, Angelica M. Agosta, and Katherine F. Taylor at the University of Florida, Gainesville, conducted the most extensive experiments to date to determine the magnitude, direction, and frequency of truck-induced gust pressure distributions. In order to obtain the data, pressure transducers and pitot tubes were instrumented on an existing bridge over an interstate highway. Wind pressures were recorded simultaneously at a rate of 714 readings per second from instruments mounted at 15 degree increments between 0 degrees and 90 degrees to the traffic flow as trucks passed beneath the apparatus. The setup can be seen in Figure 2.2. It required four people to complete the field data collection: one controlled the computer, another used the radar gun, another recorded the speeds of the trucks, and the fourth took a picture of each truck and signaled when a truck was approaching.

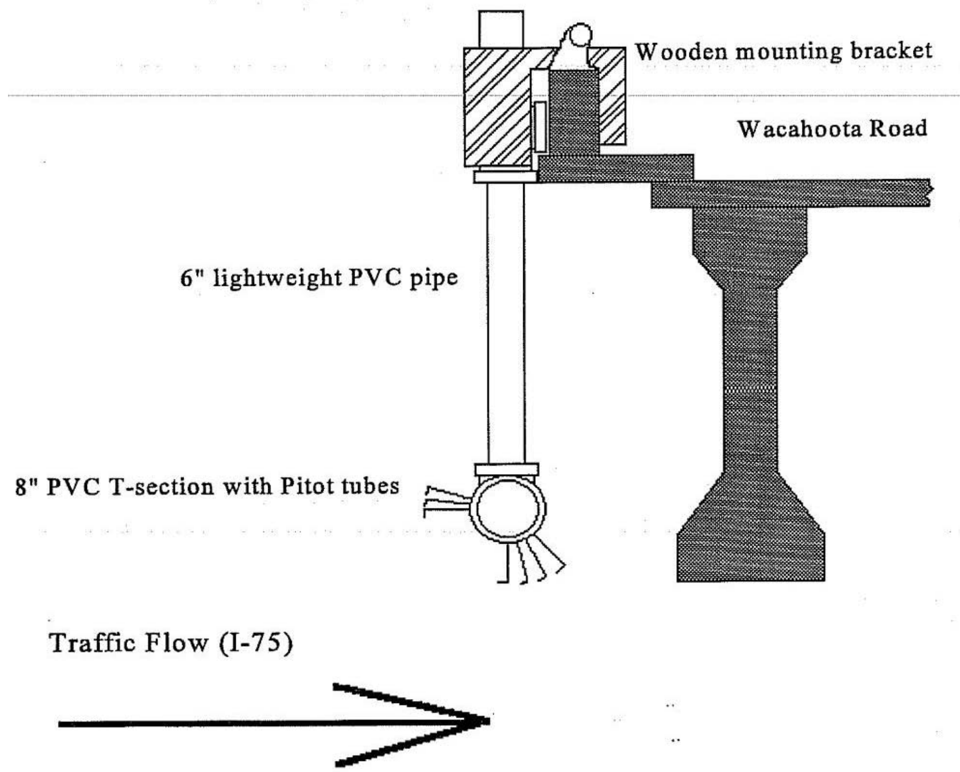


Figure 2.2: Bridge Mounted Apparatus (Cook et al., 1996)

The researchers collected readings from 23 random trucks with the apparatus at an elevation of 17 ft (5.2 m) above the road surface. A typical pressure versus time plot is shown in Figure 2.3 with the corresponding truck in Figure 2.4. In order to determine the vertical profile of the pressure variation, three readings were recorded at 17, 18, 19, and 20 feet (5.2, 5.5, 5.8, and 6.1 m) using a rented control truck at a constant speed of 65 mph (29 m/s) for each test. Using this relatively simple setup, the researchers made several important conclusions. First, as a truck passed under the sign, it produced a positive pressure pulse followed by a negative pressure as the end of the truck passed. The maximum positive and negative pressure magnitudes were 1-2 psf (47.9-95.8 Pa), with a mean pressure magnitude of one psf (47.9 Pa). Second, for every foot increase in elevation from 17 feet (5.2 m) above the road surface, the design pressure pulse could be decreased by 10%. Finally, the significant frequencies of truck-induced gust pressure pulses were observed to range from 0.5 to 2 Hz. These frequencies are close to the natural frequencies of VMS structures and could lead to resonance of such structures.

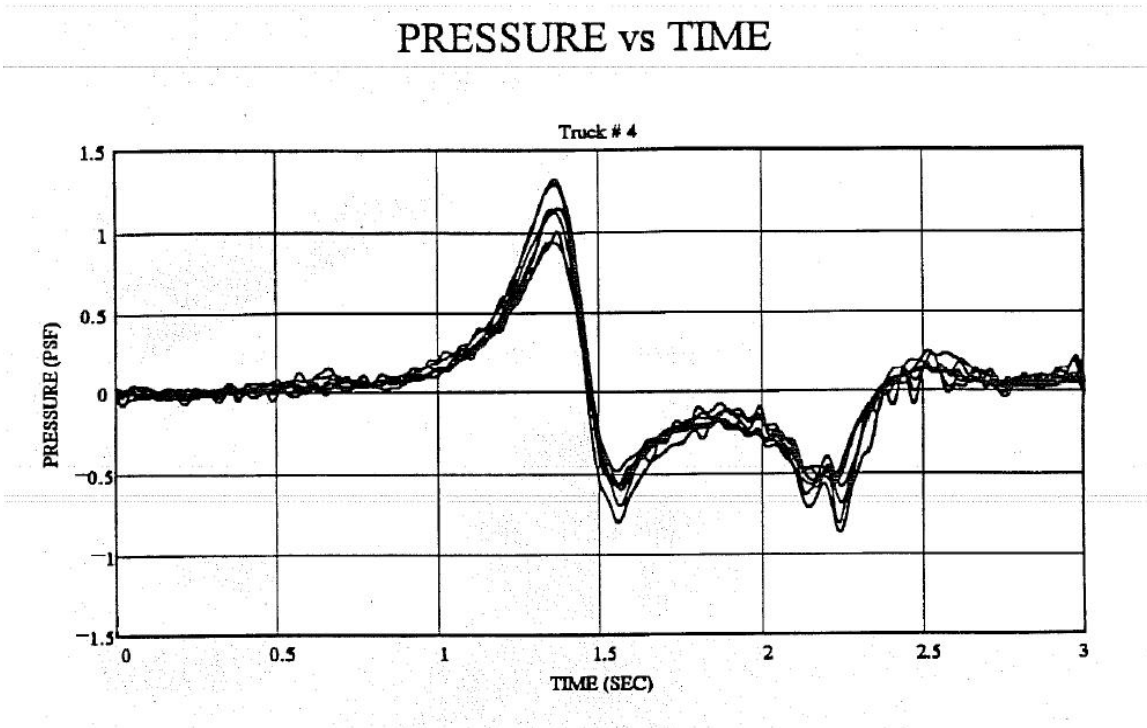


Figure 2.3: Typical Truck-Induced Gust Pressure (Cook et al., 1996)

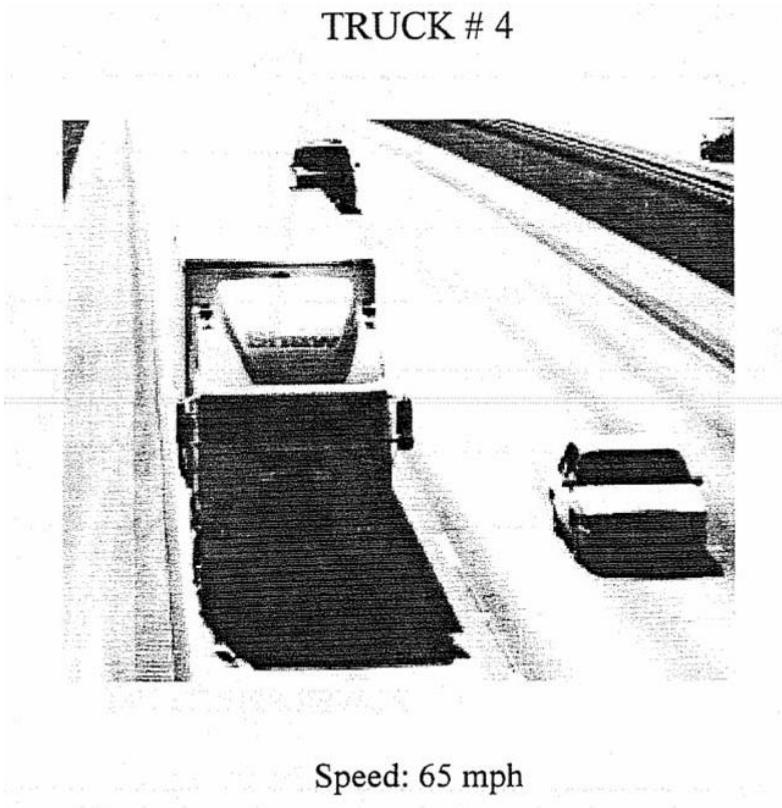


Figure 2.4: Typical Truck (Cook et al., 1996)

2.2.4 DeSantis and Haig (1996)

In 1996, Philip V. DeSantis and Paul E. Haig used the static and dynamic analysis capabilities of ANSYS to investigate the failure of a variable message sign (VMS) structure in Virginia. The paper reports that the failure surface indeed revealed a fatigue crack even though the structure was less than a year old and had not been exposed to any recorded severe loads during its service life. During the investigation, it was concluded that "the only loads that would explain the fatigue failure were vertical oscillations of the arm" (DeSantis and Haig, 1996). The researchers reasoned that because VMS structures are thicker than typical highway signs, they are more susceptible to a vertical force produced by semi/tractor-trailer trucks with wind deflectors and decided truck-induced gusts caused the failure. DeSantis and Haig believed that the wind deflectors on trucks forced the air upward causing the VMS structure to move upward and subsequently gravity would pull it back down causing the sign to oscillate. To model the truck-induced gust load, it was assumed that the velocity of the wind being pushed upward by the trucks was equal to the truck speed. DeSantis and Haig used a truck speed of 65 mph (29 m/s) and decided to account for a potentially larger effective wind speed due to head winds by including a gust factor of 1.3. Using the equation for wind pressure shown in Equation 2.1 below, the upward pressure on the sign caused by trucks is 18.28 psf (875 Pa) multiplied by the drag coefficient. DeSantis and Haig used a drag coefficient of 1.45 for the variable message sign. However, after the truck passes, there is a negative cycle as gravity pulls the arm back down; this was conservatively assumed to be equal to the initial upward cycle. Therefore, the calculated equivalent static pressure should be doubled to account for the entire stress range. Using this philosophy, an equivalent static pressure range of 36.6 psf (1760 Pa) multiplied by the drag coefficient can be obtained as shown below.

Equation 2.1: $P = 0.00256 * V_c^2 * C_d * C_h$ (psf)

where: P = Wind Pressure

V_c = Velocity of Wind (Gust Factor * Truck Speed [mph])

C_d = Drag Coefficient

C_h = Height Coefficient (Use 1.0)

Calculation: $P = 0.00256 * V_c^2 * C_d * C_h$

$P = 0.00256 * [1.3 * 65 \text{ (mph)}]^2 * C_d * 1.0$

$P = 18.28 \text{ psf} * C_d$ (double for complete cycle)

$P = 36.6 \text{ psf} * C_d$ or $1760 \text{ Pa} * C_d$

To confirm their assumptions, DeSantis and Haig back-calculated a pressure from deflections observed in the field. However, these deflections were never measured and were obtained from highway field crews that observed the arm moving up and down "about a foot" total when trucks would pass under the sign. DeSantis and Haig calculated the force using their ANSYS model that would produce the same "about a foot" displacement at the tip of the arm. Using the calculated force, the researchers were able to determine the equivalent pressure and finally back-calculate the truck speed. It was reported that "with a significant number of assumptions, the calculated truck speed was 60 mph (26.8 m/s)" (DeSantis and Haig, 1996). Since this back-calculated truck speed of 60 mph (26.8 m/s) was similar to the original assumed truck speed of 65 mph (29 m/s), DeSantis and Haig concluded that their failure theory must be correct.

2.2.5 Cali and Covert (1997)

Philip M. Cali and Eugene E. Covert studied the horizontal loading of highway sign structures due to truck-induced gusts at Massachusetts Institute of Technology in 1997. The researchers chose to study the effects of sign height, truck length, truck speed, and truck shape by creating a 1:30 scale model of a truck and sign, and then running different tests, which are summarized in Table 2.1. Each test case consisted of 14 to 18 different runs for the model. An example of the pressure measured on the front of the sign face is shown in Figure 2.5. Cali and Covert concluded that the height of the sign above the roadway and how aerodynamic the truck was both were inversely proportional to the size of the truck-induced gust. In addition, they found that there are at most five pressure pulses applied on the highway sign as the truck passes.

Table 2.1: Test Matrix (Cali and Covert, 1997)

Test Case	Truck Shape	Truck Length (in)	Sign Height (in)	Speeds (mph)	Load Cell Capacity (gms)
A	Box	24.0	7.25	24.6, 19.0, 13.4	1000
B	Box	24.0	7.25	21.6, 17.6, 14.3	50
C	Source	35.7	7.25	21.5, 18.2, 15.6	50
D	Box	35.7	7.25	20.4, 17.5, 16.0	50
E	Box	35.7	6.32	20.5, 17.6, 15.9	50
F	Box	35.7	7.25	20.4, 17.5, 16.0	50

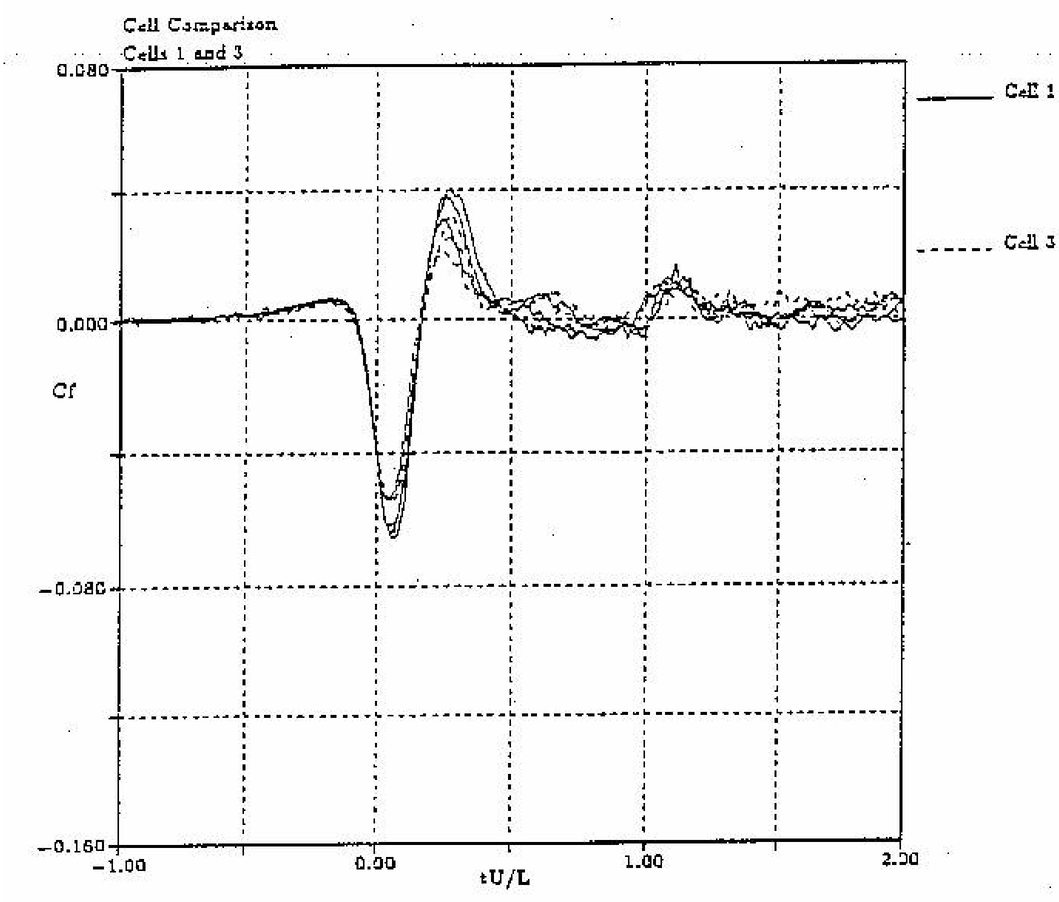


Figure 2.5: Pressure on Front of Highway Signs (Cali and Covert, 1997)

2.2.6 NCHRP Report 412 (Kaczinski et al., 1998)

The objectives of the National Cooperative Highway Research Program (NCHRP) Project 10-38, "Fatigue-Resistant Design of Cantilevered Signal, Sign and Light Supports," were to develop design procedures for wind-induced cyclic stresses for the AASHTO Specifications. The results of this research project conducted by M. R. Kaczinski, R. J. Dexter, and J. P. Van Dien at Lehigh University were published as <u>NCHRP Report 412: Fatigue-Resistant Design of Cantilevered Signal, Sign and Light Supports</u>. While performing a dynamic analysis, the authors considered both Creamer's pressure distribution model (Creamer et al., 1979), discussed in Section 2.2.1, as well as the DeSantis model (DeSantis and Haig, 1996), discussed in Section 2.2.4. It was determined that Creamer's model did not accurately represent truck-induced gust pressure distributions. Also, after analyzing two variable message sign structures that had not long before experienced fatigue failures using the simple DeSantis model, it was found that the life prediction calculations were consistent with the structure's service life prior to failure. Thus, the researchers concluded that the simple static load model described by DeSantis should be used for design. The final design recommendation for truck-induced gust loading was the procedure added in the AASHTO Specifications in 2001, which is presented in Section 2.3.1.

2.2.7 Johns and Dexter (1998)

Kevin W. Johns and Robert J. Dexter monitored a cantilevered variable message sign structure in the field for three months for the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University in 1998. The VMS structure was instrumented with strain gauges, pressure transducers, and a wind sentry in order to determine the equivalent static pressures. The structure had been reported as having experienced large-amplitude vertical displacements. However, by the time it was monitored in the field, several aspects of the VMS structure had been changed since the large-amplitude displacements had been reported. These changes included moving the sign to a different location, using a taller column, experiencing potentially different anchor bolt tightness, and removing a walkway that used to be located in front of the sign and 18 inches (0.457 m) below the bottom of the sign. These changes might explain why the VMS structure did not experience the same large-amplitude displacements during monitoring that were observed before.

The pressure transducers with pitot tubes were placed at different elevations on the face of the sign in order to obtain the gradient of truck-induced gust pressures. However, the data from the pressure transducers appeared to be unpredictable even from rented control trucks. Therefore, the researchers calculated truck-induced gust pressures using the strain gauge data. See Figure 2.6 for the strain magnitudes measured in the column from the control tests. Truck Tests 1 and 2 consisted of a conventional cab followed by a cabover truck both in the first lane. Truck Test 3 consisted of both trucks passing under the VMS at the same time side by side and traveling at 51 mph (22.8 m/s).

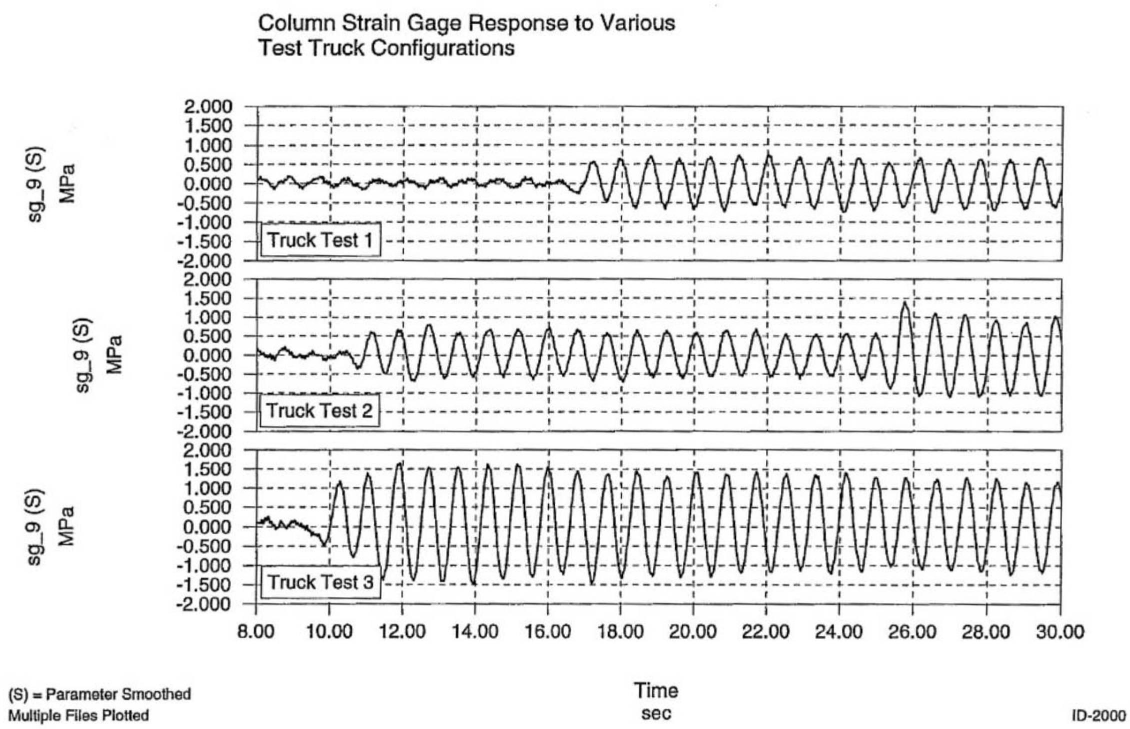


Figure 2.6: Column Response Due to Truck-Induced Gust (Johns and Dexter, 1998)

After monitoring the structure for three months, the researchers back-calculated an equivalent static pressure of 11 psf (525 Pa) based on the largest stress recorded. In the recommendations and conclusions, the authors stated that even though the measured truck-induced gusts were significantly lower than DeSantis' recommendation of 36.6 psf (1760 Pa) times the drag coefficient, it did not seem unreasonable to use the design value of 36.6 psf (1760 Pa) times C_d. Therefore, the only design changes recommended by Johns and Dexter to the earlier proposals of NCHRP Report 412 were that the truck-induced gust pressure should vary with height as shown in Table 2.2.

Table 2.2: Truck-Induced Gust Pressure Variation with Height (Johns and Dexter, 1998)

Elevation Above Road Surface (m)	Truck-Gust Pressure (Pa)
0 – 6	1760
6.1 – 7	1530
7.1 – 8	1150
8.1 – 9	690
9.1 – 10	380
10.1 and above	0

Johns and Dexter also looked into the effects of wind deflectors, used to improve fuel efficiency, on the cabs of trucks. However, in order to achieve this, the air flow must be kept laminar as it flows along the trailer instead of being pushed turbulently upward towards the VMS. The presence of laminar flow over trucks with wind deflectors was confirmed by researchers at Mack Trucking where wind tunnel tests were performed on trucks with and without wind deflectors. The research findings showed that wind deflectors keep the flow laminar; thus, wind deflectors are not expected to increase truck-induced gust pressures applied to the cantilevered signs.

2.2.8 NCHRP Report 469 (Dexter and Ricker, 2002)

NCHRP Project 10-38(2), "Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports," addressed the areas of suggested future research defined in NCHRP Report 412. This research conducted by R. J. Dexter and M. J. Ricker at the University of Minnesota was published as <u>NCHRP Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports</u>. One change in the truck-induced gust section from Report 412 dealt with drag coefficients. In the 1994 Specifications, the accepted wind drag coefficient for a variable message sign was 1.45; however, the 2001 Specifications recommended a drag coefficient of 1.7 for variable message signs. This would change the accepted design pressure value of 36.6 psf (1760 Pa) recommended by

DeSantis and Haig (1996). DeSantis and Haig used a drag coefficient of 1.45 with the design pressure of 36.6 psf (1760 Pa) to obtain a factored pressure of 53.3 psf (2,550 Pa). Since the 2001 Specifications used a drag coefficient of 1.7 for a VMS, the design pressure in the code would need to be changed to 31.3 psf (1,500 Pa) in order to obtain the same factored pressure of 53.3 psf (2,550 Pa).

NCHRP Report 469 states that the recommended pressure in NCHRP 412 was probably too conservative since the equivalent static pressure from Johns and Dexter (1998) was only about one-fifth of the recommended factored pressure (11 psf [525 Pa] compared to 53.3 psf [2,550 Pa]). However, Dexter and Ricker (2002) did not believe that the design pressure could be lowered to the value reported by Johns and Dexter (1998). Therefore, NCHRP Report 469 recommended a design value of 18.8 psf (900 Pa), which when factored for a VMS, led to an equivalent static pressure of 32 psf (1,530 Pa), which is still approximately three times the value measured in the field by Johns and Dexter. NCHRP Report 469 also concluded that wind deflectors on trucks would not increase the truck-induced gust pressure, and cited the Johns and Dexter (1998) study to justify this.

NCHRP 469 suggested further research on three different areas, one of which was wind load testing:

"Although little uncertainty exists about the magnitudes of the vortex-shedding and galloping equivalent static pressure ranges, long-term field testing to verify the natural wind-gust and, particularly, truck-induced gust pressures is still needed. Testing should base equivalent static pressures on stresses induced in support members, rather than on actual pressure measurements. Pinpoint pressure readings, on the one hand, only cover small areas and poorly describe the effects of an entire gust on a structure. Support member stresses, on the other hand, average the effects of the entire air mass applied to the structure. Equivalent static pressure ranges can then be back-calculated from the measured stresses" (Dexter and Ricker, 2002).

All of the design recommendations of NCHRP Report 469 for truck-induced gusts were added to the AASHTO Specifications through the 2002 Interim Report, which is discussed in Section 2.3.2.

2.3 AASHTO FATIGUE DESIGN

It is important to understand where the information in the AASHTO specifications comes from in order to appreciate potential problems with the design code provisions.

2.3.1 The 2001 AASHTO Specifications

In 2001, the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals were updated to include "Section 11 – Fatigue Design." This new section of the design code was based on NCHRP Report 412 (Kaczinski et al. 1998) and, under Article 11.4, required that cantilevered traffic signal structures be designed for fatigue due to galloping, natural wind gusts, and truck-induced gusts. The AASHTO Specifications takes an infinite-life fatigue design approach by requiring that cantilevered traffic signal structures be designed to resist different equivalent static wind loads modified by appropriate importance factors. The importance factors adjust the level of structural reliability by accounting for the degree of hazard to traffic in the event of failure, as seen in Table 2.3. The AASHTO Specifications' Commentary recommends that cantilevered traffic signal structures with long mast arms be classified as a Fatigue Category I.

Table 2.3: Importance Factors for Truck-Induced Gusts (AASHTO, 2001)

Fatigue Category	Importance Factor, I_F	Category Description
I	1	Critical cantilevered support structures installed on major highways
II	0.84	Other cantilevered support structures installed on major highways and all cantilevered support structures installed on secondary highways
III	0.68	Cantilevered support structures installed at all other locations

The equivalent static pressure range for truck-induced gusts is given in Equation 2.3 where C_d is the appropriate wind drag coefficient, given in Table 2.4, and I_F is the importance factor, previously shown in Table 2.3.

Equation 2.3: $P_{TG} = 36.6 * C_d * I_F$ (psf)

$P_{TG} = 1760 * C_d * I_F$ (Pa)

where: P_{TG} = Truck-Induced Gust Pressure Range

C_d = Drag Coefficient

I_F = Fatigue Importance Factor

Table 2.4: Wind Drag Coefficients (AASHTO, 2001)

Traffic Signal	1.2
Mast Arm	1.1
Dampening Plate (by ratio of length to width)	
L/W = 1.0	1.12
2.0	1.19
5.0	1.20
10.0	1.23
15.0	1.30

The equivalent static design pressure range is then applied in a vertical direction to the mast arm as well as to all attachments projected on a horizontal plane. It is applied along the entire length of any sign panels/enclosures or along the outer 12 ft (3.7 m) length of the mast arm, whichever is greater, but this length can be reduced for locations where vehicle speeds are lower than 65 mph (30 m/s). The reduced pressure is given by Equation 2.4.

Equation 2.4: $P_{TG} = 36.6 * C_d * [V / 65 \text{ (mph)}]^2 * I_F$ (psf)

$P_{TG} = 1760 * C_d * [V / 30 \text{ (m/s)}]^2 * I_F$ (Pa)

where: V = Truck Speed in mph or m/s

The code does note that truck-induced gust loading might not apply to every cantilevered traffic signal structure with the following statement in the commentary:

"The given truck-induced gust loading may be excluded for the fatigue design of overhead cantilevered traffic signal structures, as allowed by the owner. Many traffic signal structures are installed on roadways with negligible truck traffic. In addition, the typical response of cantilevered traffic signal structures from truck-induced gusts can be significantly overestimated by the design pressures prescribed in this article" (AASHTO, 2001).

2.3.2 The 2002 Interim Edition to AASHTO Specifications

When the 2002 Interim Edition to the 2001 AASHTO Specifications was released, it contained drastic changes to the truck-induced gust section. These changes were all recommended in NCHRP Report 469. As previously discussed in Section 2.2.7, the most significant change in the Specifications was the reduction of the design pressure, which can be seen in Equation 2.5.

Equation 2.5: $P_{TG} = 18.8 * C_d * I_F$ (psf)

$P_{TG} = 900 * C_d * I_F$ (Pa)

where: P_{TG} = Truck-Induced Gust Pressure Range

C_d = Drag Coefficient

I_F = Fatigue Importance Factor

Additional changes include stating that the equivalent static pressure only needs to be applied to the 12 ft (3.7 m) length that produces the maximum stress range and never has to be applied to any portion of the structure that is not directly above the roadway. A linear variation of the pressure was also added depending on the height of the structure above the roadway. The Specifications also state that the full design pressure needs to be applied for heights up to and including 19.7 ft (6 m). Above 19.7 ft (6 m) the pressure may be linearly reduced to a value of zero at 32.8 ft (10 m). The reduction due to lower truck speeds still applies; only, it uses the updated design pressure values.

Both the 2001 AASHTO Specifications as well as the 2002 Interim Edition, very likely contain an incorrect statement in the Commentary where it is stated that “a drag coefficient value of 1.20 was used by DeSantis and Haig (1996) to determine an equivalent static truck pressure range on VMS” (AASHTO, 2001 and 2002). As discussed in Sections 2.2.4 and 2.2.7, DeSantis and Haig (1996), in fact, used a drag coefficient of 1.45.

2.3.3 The 2003 Interim Edition to AASHTO Specifications

The 2003 Interim Edition to the AASHTO Specifications did not propose any changes to the truck-induced gust section. An extended fatigue design calculation example for a cantilevered traffic signal structure based on the 2003 Interim Edition of the AASHTO Specifications is presented in Appendix B.

Chapter Three: Preparations for Field Tests

3.1 SELECTION OF FIELD SITES

The first step in performing field tests on cantilevered traffic signal structures was to identify potential sites and then choose the best sites to conduct the experiments based on the following factors: posted speed limit, amount of truck traffic, types of trucks, length of the mast arm, traffic signal configuration, safety during testing, and accessibility for field testing personnel. TxDOT supplied a list of traffic signal structures in four counties (Bastrop, Hays, Travis, and Williamson) surrounding Austin, Texas that were located on roads where the posted speed limit exceeded 60 mph (26.82 m/s). After discussions with TxDOT employees in the signal shop, several other potential sites were added to the list, which is included in Appendix C. Using this preliminary list, all the sites were visited and it was discovered that the majority of the sites on the list were strain pole wire-supported traffic signal structures instead of cantilevered mast arms. Eliminating these wire-supported structures, the list was reduced to the one shown in Table 3.1. For the location of these sites around Austin, see Figure 3.1.

Table 3.1: Potential Sites for the Field Tests

#	Intersection	City	County
1	US290 AT CONVICT HILL RD	AUSTIN	TRAVIS
2	RM620 AT HOME DEPOT BLVD	BEE CAVE	TRAVIS
3	RM620 AT FALCON HEAD BLVD	BEE CAVE	TRAVIS
4	RM620 AT LAKE TRAVIS HIGH SCHOOL	BEE CAVE	TRAVIS
5	RM620 AT LOHMANS SPUR	BEE CAVE	TRAVIS
6	RM620 AT LAKEWAY BLVD	BEE CAVE	TRAVIS
7	RM2222 AT RIVER PLACE BLVD	AUSTIN	TRAVIS
8	RM2222 AT MCNEIL DR	AUSTIN	TRAVIS
9	US183 AT NEW HOPE DR (CR-181)	CEDAR PARK	WILLIAMSON
10	SH29 AT DB WOOD DR	GEORGETOWN	WILLIAMSON
11	SH29 AT INNER LOOP	GEORGETOWN	WILLIAMSON
12	FM685 AT ROWE LN	PFLUGERVILLE	TRAVIS
13	US290 AT SH95	ELGIN	BASTROP
14	US290 AT SH95S	ELGIN	BASTROP
15	FM973 AT PEARCE LN	AUSTIN	TRAVIS

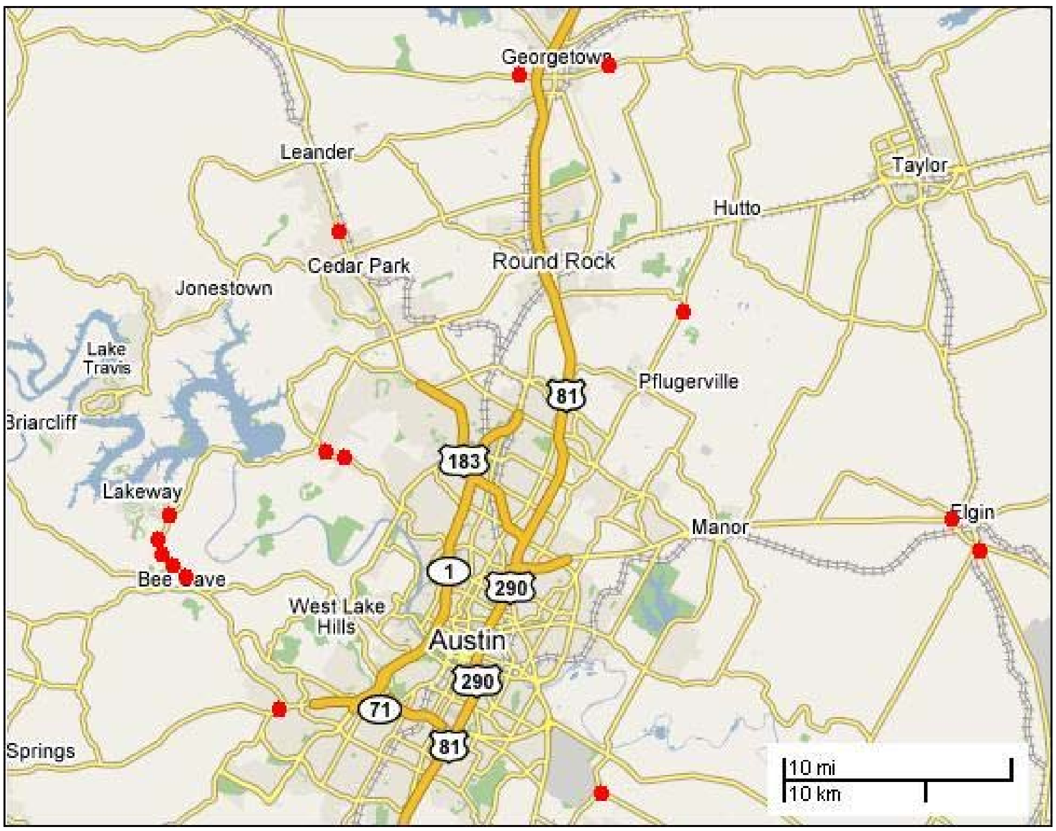


Figure 3.1: Location of Potential Sites for Field Tests (Google Maps, 2006)

The next step was to choose at least two of the potential sites to conduct the field tests. Some of the sites were eliminated because of lack of truck traffic, insufficient space on the shoulder to safely park a vehicle during testing, or proximity to road construction, which would increase truck traffic but at a cost of lower vehicle speeds. Sufficient space on the should for a vehicle was necessary because of the amount of equipment needed at the site which included a datalogger, laptop computer, and other related testing apparatuses discussed in Section 3.2. It should be noted that even though the initial list provided by TxDOT included sites with posted speed limits greater than 60 mph (26.82 m/s), the range of actual speeds for the sites on the list varied from 45 to 60 mph (20.12 to 26.82 m/s), with all but two sites involving vehicle speeds below 60 mph (26.82 m/s). After careful consideration, RM620 at Home Depot Blvd in Bee Cave, Texas and US290 at SH95 in Elgin, Texas were chosen as the two field sites that best satisfied all of the criteria.

3.1.1 The Field Test Site on RM620 at Home Depot Blvd

The cantilevered traffic signal structure on RM620 at Home Depot Blvd in Bee Cave, Texas, shown in Figure 3.2, was located at a tee-intersection, shown in Figure 3.3. Home Depot Blvd only provided access to a Home Depot store and a few smaller stores. The structure that was monitored served the northbound traffic on RM620. This site was chosen because the majority of the box-type trucks and dump trucks that use RM620 would likely not be affected by the traffic lights in the northbound lanes of the intersection since this was not a very busy tee-intersection. The structure consisted of a 40-foot mast arm with three traffic signals, two signs, a dampening plate, a camera, and a luminarie on top of the column. There were two northbound lanes of traffic that passed beneath the mast arm, and the posted speed limit was 55 mph. The dimensions of the cantilevered traffic signal structure and the TxDOT drawings for the intersection are shown in Appendix D.

Figure 3.2: The Field Test Site on RM620 at Home Depot Blvd

Figure 3.3: Aerial View of the Field Test Site on RM620 at Home Depot Blvd (Google Maps, 2006)

3.1.2 The Field Test Site on US290 at SH95

The cantilevered traffic signal structure on US290 at SH95 in Elgin, Texas, shown in Figure 3.4, was located at a tee-intersection, shown in Figures 3.5 and 3.6. At the intersection, SH95 bends in such a manner as to join with US290 through Elgin; however, there is a small road that services a gas station on the other side of the tee-intersection. The structure that was monitored served the eastbound traffic on the divided US290. This site was chosen because of the potential for a significant volume of truck traffic between Austin and Houston that used this section of US290, especially semi/tractor-trailer trucks that were not very common at the RM620 field test site. The structure consisted of a dual mast arm assembly (two arms orthogonal to each other) with a 40-foot mast arm with three traffic signals, one sign, and a dampening plate. There were two lanes of traffic that passed beneath the mast arm, and the posted speed limit was 50 mph (22.35 m/s). The dimensions of the cantilevered traffic signal structure and the TxDOT drawings for the intersection are shown in Appendix D.

Figure 3.4: The Field Test Site on US290 at SH95

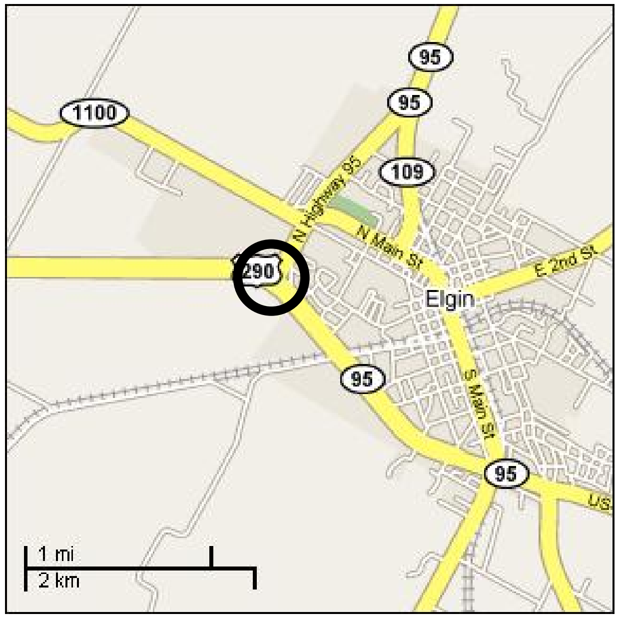


Figure 3.5: Site Location in Elgin (Google Maps, 2006)

Figure 3.6: Aerial View of the Field Site on US290 at SH95 (Google Maps, 2006)

3.2 EQUIPMENT

The following summarizes various details regarding the equipment used for the field tests, along with suggestions for improvement of such testing that might help future researchers engaged in similar studies.

3.2.1 Strain Gauges

Waterproof strain gauges type WFLA-6-11-1L made by TML Tokyo Sokki Kenkyujo Co., Ltd. of Tokyo, Japan were utilized to eliminate the need to provide a waterproof covering for the strain gauge in the field. The entire gauge and lead wire connection was covered with a transparent and flexible epoxy resin. Complete waterproofing was achieved by bonding the gauge with adhesive. Every gauge was 6 millimeters in length, had a resistance of 120 Ohms, and had a gauge factor of 2.11. Using the procedure described below, the strain gauges were attached to the mast arm sufficiently far enough from the weld to avoid being affected by the stress concentration at the weld toe. All strains discussed in this report have been extrapolated to estimate the nominal strain at the weld toe. However, none of these stresses or strains takes into account the stress concentration at the weld toe.

The procedure for attaching the strain gauges included the following steps:

1) Remove galvanization by grinding a small area of mast arm where the strain gauge is to be located
2) Sand mast arm to ensure a smooth surface
3) Clean thoroughly with acetone using gauze sponges
4) Attach strain gauge to mast arm in correct location using cellophane tape
5) Peel back tape just enough so strain gauge is no longer touching mast arm
6) Lightly coat strain gauge with a catalyst

7) Add adhesive to mast arm
8) Push down strain gauge and tape over adhesive
9) Apply pressure
10) Carefully peel off tape
11) Measure distance from fillet weld to the strain gauge
12) Paint over strain gauge with an air-drying acrylic coating
13) Cover strain gauge with foil tape.

This method had remarkable success in the field. The only suggested change for future tests is to use strain gauges of type WFLA-6-11-3LT because the additional third wire allows for the benefit of temperature-compensation along its entire length. This difference did not present any problems for the field tests because each strain gauge's wires were cut to approximately five inches and soldered to a 22 AWG (American Wire Gauge) three conductor shielded control cable made by Belden CDT making them temperature-compensating gauges. Each shielded control cable was approximately 22 feet long allowing the strain gauges located on the mast arm to be plugged into the datalogger located at the base of the traffic signal, as seen in Figure 3.7.

Figure 3.7: Strain Gauges Attached to Mast Arm and Shielded Cables

3.2.2 Data Acquisition Unit and Software

A Campbell Scientific CR23X Micrologger data acquisition unit was used to collect the short-term data in the field. This unit was selected because of its positive performance in earlier field tests for galloping of cantilevered traffic signal structures (Florea, 2005). The CR23X, shown in Figure 3.8, is a compact, self-contained datalogger that was easily attached to the traffic signal base. The unit was able to record up to twelve channels; however, at the field test site on RM620 at Home Depot Blvd, only three channels were used, one for each of the strain gauges. At the field test site on US290 at SH95, nine channels were used – six for strain gauges and three for the anemometer (discussed in Section 3.2.4). To communicate with the CR23X datalogger, the Campbell Scientific PC208W software was used and the program used at the second site (US290 at SH95) is presented in Appendix E. The only difference between the programs used at the two sites was that at the site on RM620 at Home Depot Blvd, the data from the three strain gauges was recorded every 0.04 seconds or at a sampling rate of 25 Hz, while at the site on US290 at SH95, the data was recorded from six strain gauges and the anemometer (wind speed in three directions) every 0.07 seconds or at a sampling rate of 14.286 Hz. At each site, these data sampling rates were the fastest that could be obtained across all the channels. During the field tests, it was powered by its own batteries and then recharged at night. The CR23X datalogger performed exceptionally well in the field.

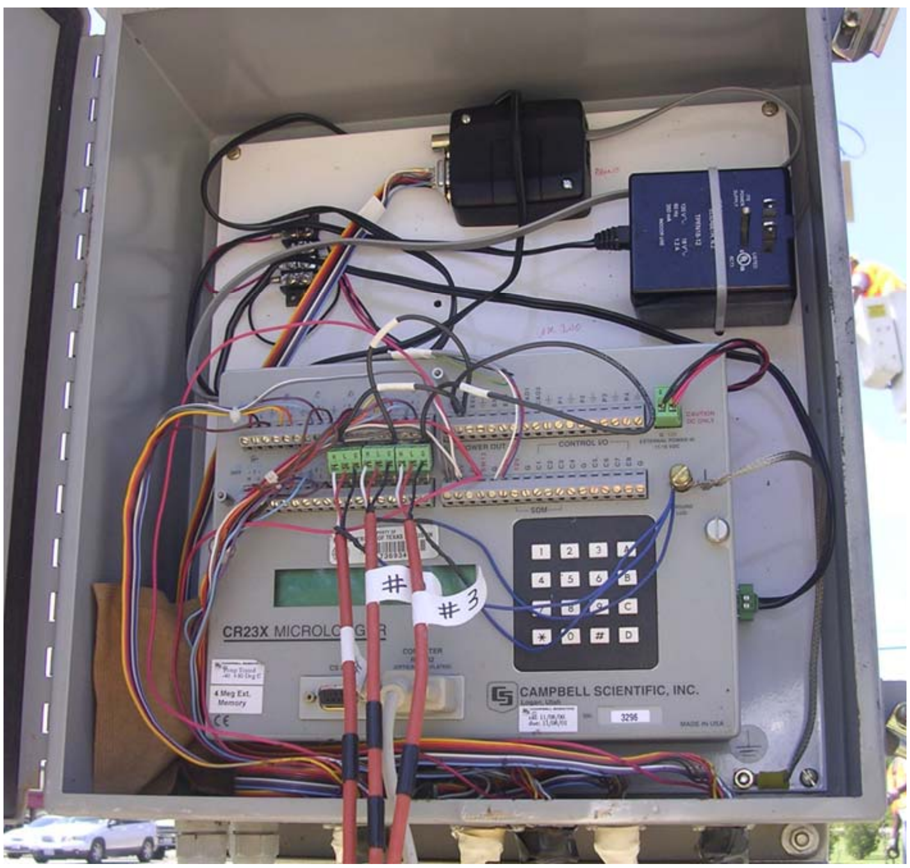


Figure 3.8: CR23X Datalogger

3.2.3 Radar Gun

A Marksman model of the LTI 20-20 laser speed detection system from TxDOT, shown in Figure 3.9, was used to record the speed of trucks that passed beneath the instrumented structure. The Marksman model was different from the more conventional radar guns in that it uses a laser light beam instead of microwaves to detect the speed of a vehicle. This Marksman model was able to measure speeds up to 200 mph (89.41 m/s) from as far away as 2,500 ft (762 m). However, for this project, the speeds were recorded as close to the mast arm as possible in order to obtain the speed as the truck passed beneath the arm. The Marksman model was very easy to use and the only concern for future researchers is that it required a vehicle's cigarette lighter socket for power. A battery-powered radar gun would work just as well and would allow for a wider range of movement for the test personnel involved in recording the truck speeds.

Figure 3.9: Radar Gun

3.2.4 Anemometer

A RM Young Model 81000 Ultrasonic Anemometer was used to determine wind speed and direction at the field site. The three-axis ultrasonic anemometer is able to measure wind speeds of 0-90 mph (0-40.23 m/s) in any direction. The anemometer was attached to the column so that it was at the same height as the mast arm, as can be seen in Figure 3.10. This anemometer was only used at the field test site on US290 at SH95. It is recommended that future researchers always record wind speed and direction even if truck-induced gusts are the primary focus as was the case in this study. The anemometer was instrumented so that "north" was pointing in the direction of the oncoming traffic.

Figure 3.10: Anemometer

3.2.5 MicroSAFE Units

The Micro-Miniature Stress Analysis and Forecasted Endurance (MicroSAFE) unit is a miniature smart sensor that measures strain data and records either raw data or rainflow data in a histogram by using an ASTM Rainflow Cycle Counting Algorithm. It was determined that using the MicroSAFE units connected to a strain gauge and attached to the mast arm, as shown in Figure 3.11, was the easiest way to record long-term strain data on the mast arms of the cantilevered traffic signal structures. The MicroSAFE units recorded all strain data at 32 Hz but since the data were aggregated, it was not possible to distinguish between strains caused by galloping, natural wind gusts, truck-induced gusts, or vortex shedding. Most importantly, the MicroSAFE units were able to capture the greatest strain cycles that each mast arm experienced during the period of the field tests. These units were used for long-term monitoring for periods up to approximately 40 days, limited by the unit's battery life. Alternatively, raw data could have been recorded but then the longest period for which data could be recorded would have been two hours. Therefore, all the results from the MicroSAFE units consisted of aggregated long-term rainflow-counted strain cycle histograms.

In order to record rainflow histogram data, the units had to be programmed with a desired bin size. There were exactly 32 available bins for the rainflow analysis. Therefore, care had to be taken to select an appropriate bin size so that all the data would fall within the 32 bins. Any cycles that exceeded the largest bin were placed in the last bin, emphasizing the need to choose a correct bin size. Previous research had shown that a good starting point would be to have a bin size that would be able to record a value of 240 microstrain (Brisko, 2002), while others recommended a bin size of 17.2 microstrain (Connor et al., 2004). Therefore, at the field site on RM620 at Home Depot Blvd, a bin size of 20 microstrain was used. This proved to be too large, and hence, a bin size of eight microstrain was used at the second field site on US290 at SH95. The MicroSAFE units were programmed to collect data for one hour and 59 minutes and to then take the next minute to record this data. This was done mainly to eliminate a problem the MicroSAFE units have due to temperature changes throughout the day. In addition, this method provided an added unforeseen benefit of comparing the rainflow data over two-hour intervals instead of daily intervals.

Extensive testing was completed prior to the field testing to ensure that the MicroSAFE units used were operating correctly. During this testing, several of the available MicroSAFE units were found to be unreliable. Due to this low reliability, if future researchers intend to use these MicroSAFE units, similar testing is recommended and ample time should be set aside to verify to accuracy of the units prior to their use in the field.

Figure 3.11: MicroSAFE Unit with Battery

3.2.6 Additional Equipment

In addition to the equipment discussed, a digital camera, a laptop computer, and a stopwatch were also used in the field testing. One of the Ferguson Structural Engineering Laboratory's Nikon Coolpix 3100 digital cameras was used to take a picture of each truck as it approached the traffic signal structure. This was an important piece of information obtained from the field as it was used to identify exactly the shape of trucks that produced displacements of the mast arm. The only difficulty with the digital camera was that the battery life was very low and recharging was necessary throughout the day. Thus, it is imperative that the testing personnel have several sets of batteries available. Another inconvenience was that if consecutive trucks were very close together, the camera was unable to take two pictures directly back to back, making it impossible to take a picture of the second truck in the series. A Dell Inspiron 2600 laptop computer was used in the field to connect to the CR23X datalogger and download the data obtained from the testing. An extra computer battery was also very useful. A stopwatch was used to determine exactly when a truck passed beneath the mast arm.

3.3 DATA RECORDING PROCEDURE

The data recording procedure required two people to collect all of the necessary information during the field tests. Summarized below is the resulting data recording procedure:

1) Attach CR23X datalogger to column.
2) Connect the strain gauges, anemometer, and computer to the datalogger.
3) Turn on datalogger and computer and start PC208W software.
4) Start recording data and at the same time start the stopwatch.

5) When a truck is approaching, one person takes a picture while the other person records the truck speed with the radar gun.
6) As the truck passes beneath the mast arm, the time on the stopwatch is recorded along with truck speed, traffic lane, and truck type on a field data sheet, examples of which are shown in Appendix F.
7) Steps 5 and 6 are repeated for each truck.
8) After 40 to 60 minutes depending on the sampling rate, the data is downloaded to the computer. This is done to ensure that the data set will not be larger than what would fit in a Microsoft Excel file.
9) Repeat Steps 4-8 for additional data sets or disconnect the equipment.
10) Make sure to protect the ends of the strain gauges' shielded cables and of the anemometer cord by placing them in a Ziploc bag and zip-tying them to the column.

3.4 TYPES OF TRUCKS

The different types of trucks that were observed during the field testing were categorized into six major groups: Box-Type Trucks, Concrete Trucks, Dump Trucks, Garbage Trucks, School Buses, and Semi/Tractor-Trailer Trucks. Not all trucks fell into one of these groups, so some trucks were classified on an individual basis. For both the box-type trucks and the semi/tractor-trailer trucks, additional classification was necessary. Box-type trucks were separated into Box-Tall and Box-Small groups; while semi/tractor-trailer trucks were divided into Semi-Tall, Semi, and Semi-Low groups. A Box-Tall was a large box-type truck while a Box-Small was a small box-type truck. A Semi-Tall was a semi/tractor-trailer truck where the trailer was taller than the cab; a Semi was a semi/tractor-trailer truck with a trailer the same height as the cab; and a Semi-Low was a semi/tractor-trailer truck with a trailer shorter than the cab. Examples of the different types of trucks can be seen in Figures 3.12 to 3.17. In Appendix F, a complete list of all the trucks observed during the field testing is presented.

Figure 3.12: Box-Type Trucks (Box-Small and Box-Tall)

Figure 3.13: Concrete Truck

Figure 3.14: Dump Truck

Figure 3.15: Garbage Truck

Figure 3.16: School Bus

Figure 3.17: Semi/Tractor-Trailer Truck (Semi-Low, Semi, Semi-Tall)

Chapter Four: Field Testing

4.1 OVERVIEW

This chapter presents details regarding several of the field tests that were performed including static load tests, pluck tests, and recording of truck-induced gust events. The chapter also discusses results from these tests and describes the influence of natural wind gusts on the response of cantilevered traffic signal structures in contrast with that due to truck-induced gust loads.

4.2 CONTROLLED FIELD TESTS

The two controlled field tests that were performed at each test site were a static load test and a pluck test.

4.2.1 Static Load Test

A static load test has numerous valuable benefits including verification that the equipment is working properly, confirmation (or calibration) of structural analysis models, and enhanced insight into the behavior of the cantilevered traffic signal structure being studied. At each field test site, a static load test was performed by hanging weights from the tip of the mast arm while recording strain data, as shown in Figure 4.1. The weights were hung from a chain that weighed 31.00 lbs (14.06 kg). The five weights that were added to the chain weighed 22.62, 21.90, 25.70, 28.58, and 32.14 lbs (10.26, 9.93, 11.66, 12.94, and 14.58 kg). This resulted in a total of 161.94 lbs (73.455 kg) when all five weights were attached to the chain. Applying different weights incrementally verified that the structures responded in a linear elastic manner. Since this was a static test, the results from both field test sites are very similar; therefore, the data are only shown in Figure 4.2 for the site on US290 at SH95. The plot shows the data from two strain gauges – one located on the top of the mast arm and the other located on the bottom of the mast arm. As expected, the strain values from the two strain gauges are equal and opposite. Also, the strain readings increase linearly with each incremental change in applied weight at the tip of the mast arm.

Figure 4.1: Static Load Test

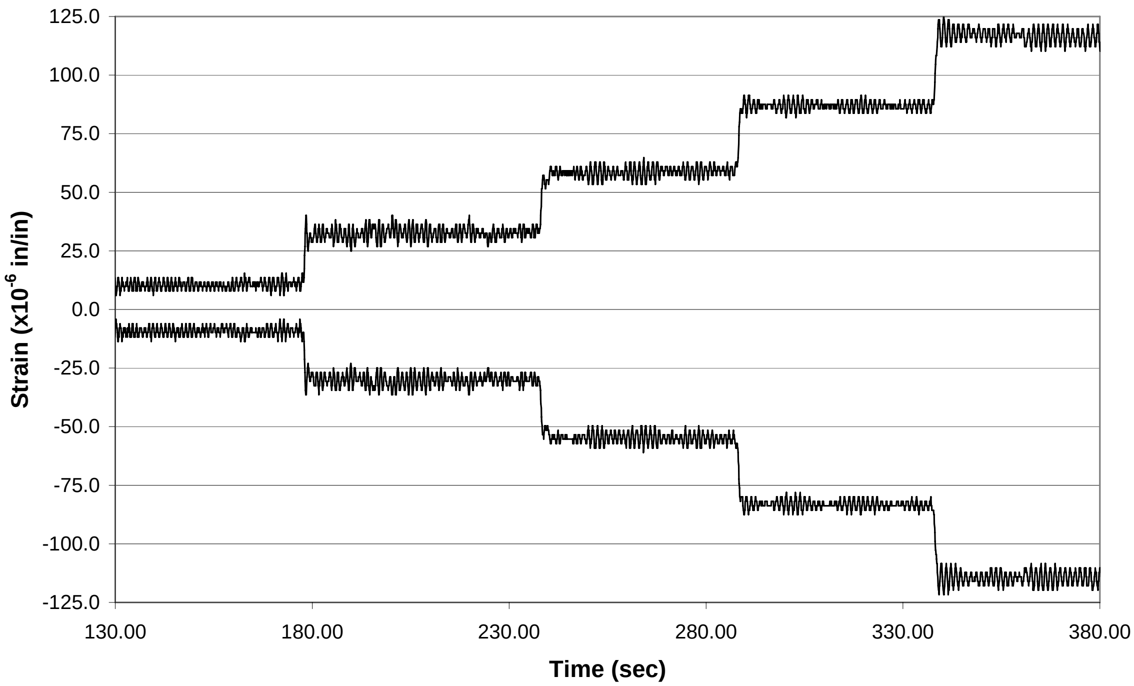


Figure 4.2: Static Load Test Data (Strain Data at the Top and Bottom of the Mast Arm) for the Field Test Site on US290 at SH95

4.2.2 Pluck Test

It is not easy to estimate the dynamic properties of cantilevered traffic signal structures. For this reason, a free vibration experiment, called a pluck test here, was performed at each field test site in order to determine the damping ratio, ζ, of the structure for in-plane vibrations. To perform the pluck test, a weight was hung from the mast arm near the tip. Once the movement from adding the weight had ceased and the tip had experienced an initial downward displacement, the weight was suddenly cut and allowed to fall to the ground. This allowed the cantilevered traffic signal structure to experience in-plane free vibration. The time history of this free vibration response was recorded using the datalogger, as can be seen in Figures 4.3 and 4.4 for the two sites. It is easy to see the appearance of a "beating" response in the free vibration test for the cantilevered traffic signal structure at the field site on US290 at SH95. This is likely due to the additional mast arm in an out-of-plane (orthogonal) direction that makes up the dual mast arm assembly at this site (see Figure 3.4). Using Equation 4.1, the damping ratio for in-plane vibration of each cantilevered traffic signal structure can be estimated.

Equation 4.1: $\zeta = 1 / (2 * \pi * j) * \ln(u_i / u_{i+j})$

where: ζ = Damping Ratio (fraction of critical damping)

j = Number of cycles separating two points in the displacement time history where the amplitudes are u_i and u_{i+j}, respectively

Figures 4.5 and 4.6 show smoothed power spectra of the strain data from the pluck tests at the two field sites. It is easy to pick out the fundamental natural frequencies (of 0.822 Hz and 1.036 Hz) for the cantilevered traffic signal structures at the two sites. Other higher mode frequencies are also indicated on the plots.

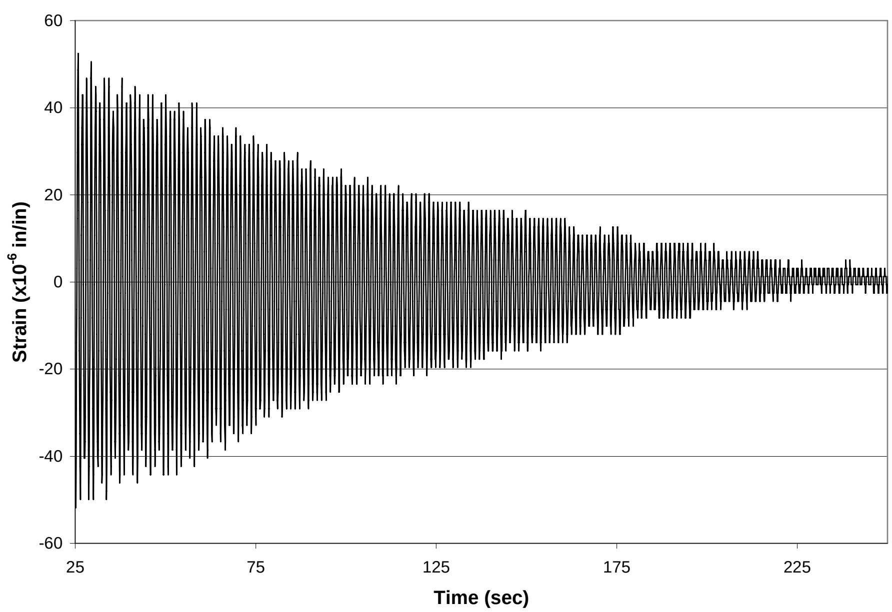


Figure 4.3: Free Vibration Response of the Instrumented Structure at the Field Site on RM620 at Home Depot Blvd

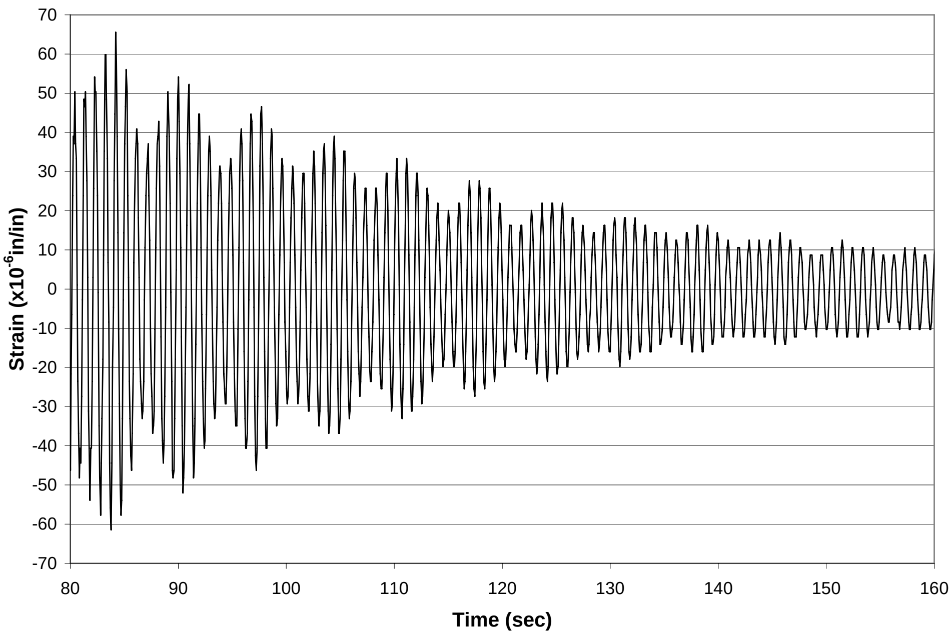


Figure 4.4: Free Vibration Response of the Instrumented Structure at the Field Site on US290 at SH95

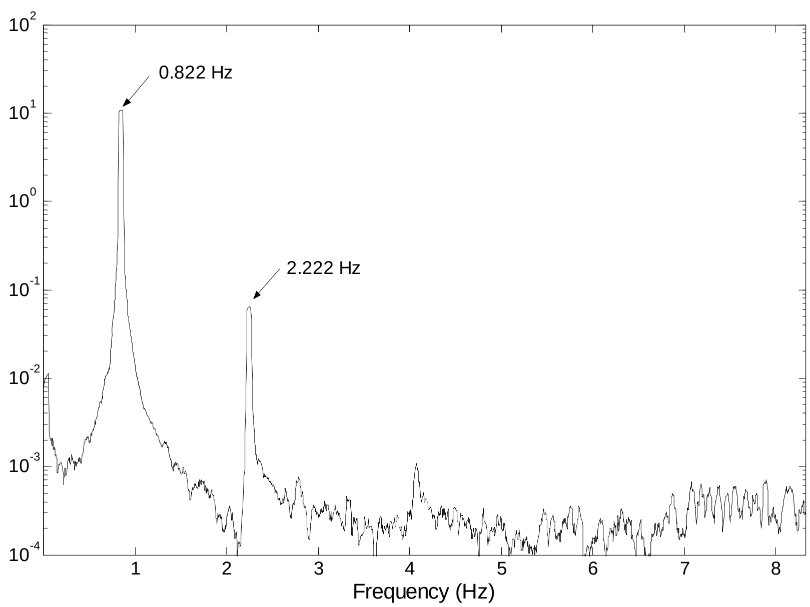


Figure 4.5: Smoothed Power Spectra of the Strain Data from the Top of the Mast Arm as Obtained from the Pluck Test at the Field Site on RM620 at Home Depot Blvd

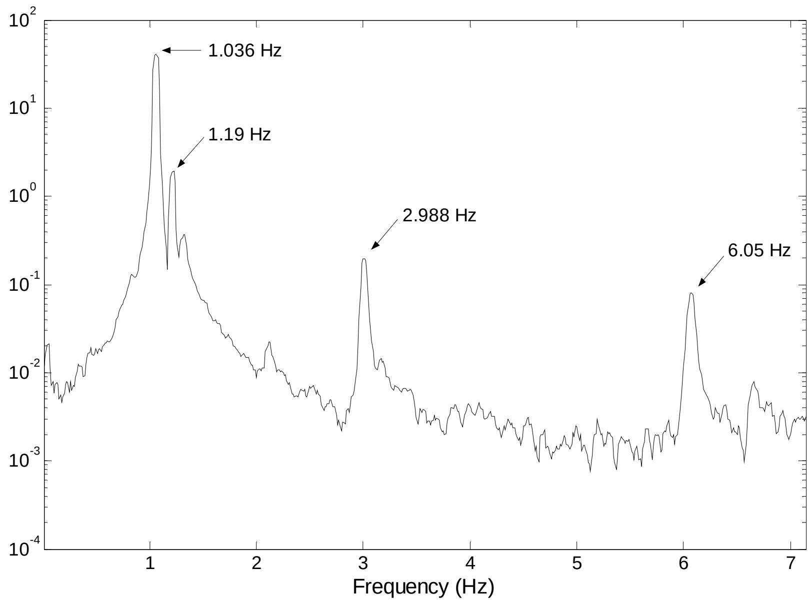


Figure 4.6: Smoothed Power Spectra of the Strain Data from the Top of the Mast Arm as Obtained from the Pluck Test at the Field Test Site on US290 at SH95

4.3 AVAILABLE DATA ON TRUCK-INDUCED GUSTS

During the field testing, there were over 400 recorded truck events at the two test sites, as summarized in Appendix F. To be included as a recorded truck event, the truck needed to make it through the traffic light without stopping or without having to slow down to a speed of approximately 25 mph (11.18 m/s) or less. Thus, trucks that were stopped or slowed down by the traffic light were not included. At the field site on RM620 at Home Depot Blvd, most of the trucks were box-type trucks, dump trucks, and concrete trucks traveling close to the posted speed limit of 55 mph (24.59 m/s). The distribution of truck speeds at this site is summarized by the histogram shown in Figure 4.7. On the other hand, the trucks at the field test site on US290 at SH95 were mostly semi/tractor-trailer trucks traveling at speeds below the speed limit of 50 mph (22.35 m/s), as summarized in the histogram shown in Figure 4.8. The reason for this difference observed at the two sites is that the RM620 at Home Depot Blvd site had a very long light cycle allowing most vehicles to make it through the intersection without being stopped or slowed down by the traffic light. However, the US290 at SH95 site had a very short light cycle causing most of the vehicles to be slowed down by the traffic light. Figures 4.9 and 4.10 show the distribution of trucks according to the lane in which they were traveling for the aggregated date from both field test sites. Lane 1 represents the right lane while Lane 2 is the left lane or the "passing lane." As expected, the majority of trucks traveled in Lane 1, the right lane.

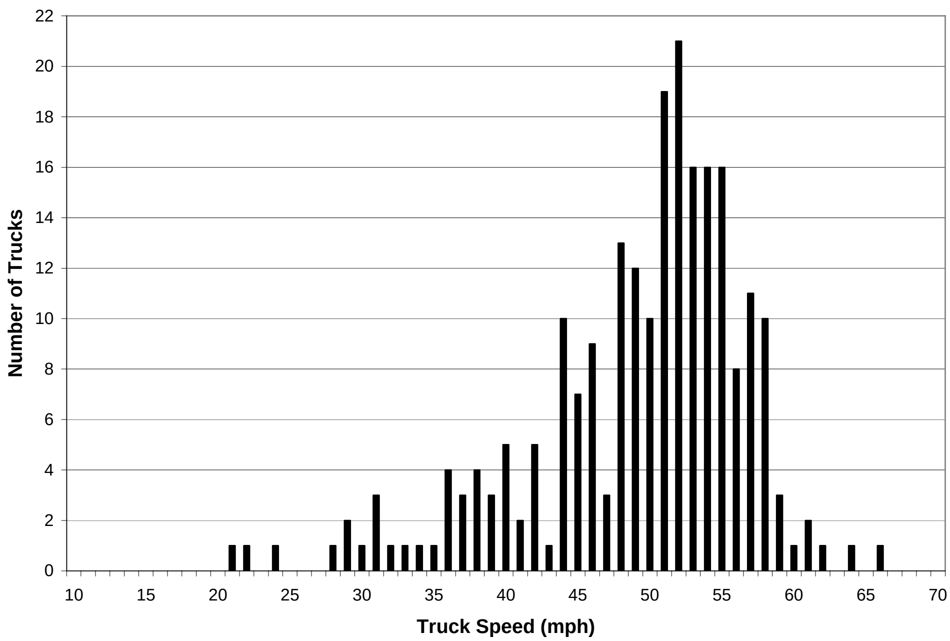


Figure 4.7: Histogram of Truck Speeds at the Field Test Site on RM620 at Home Depot Blvd

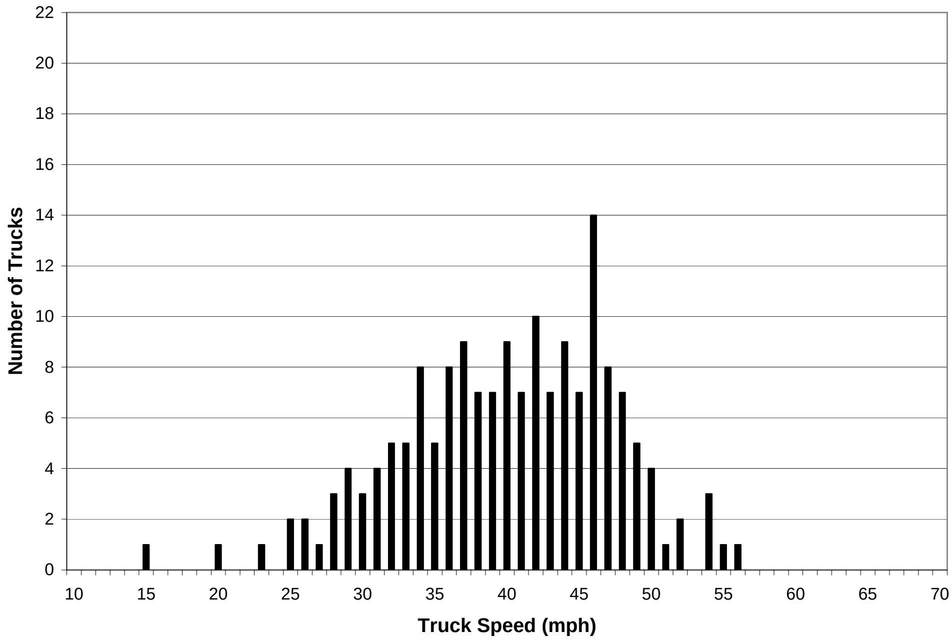


Figure 4.8: Histogram of Truck Speeds at the Field Test Site on US290 at SH95

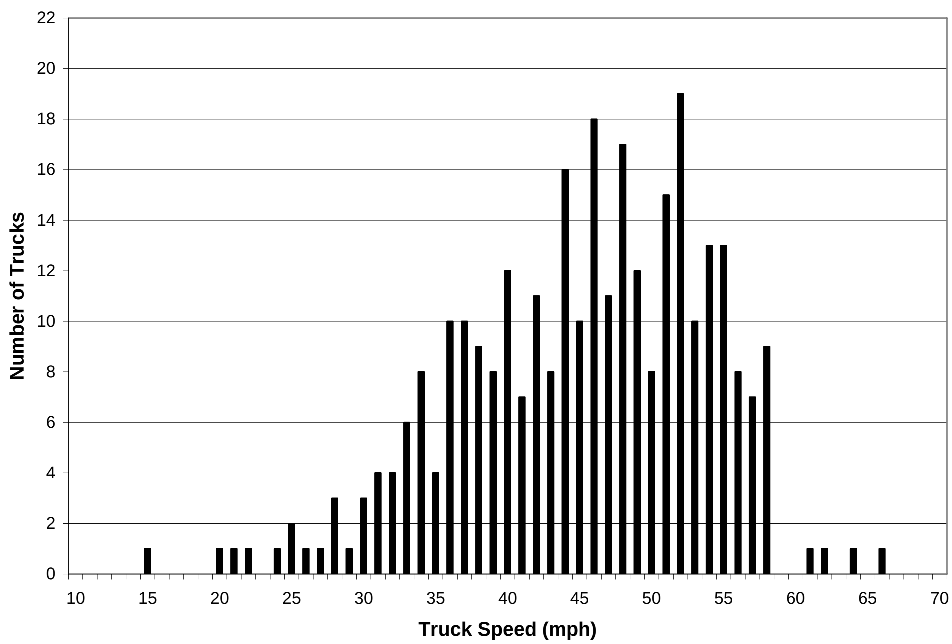


Figure 4.9: Histogram of Speeds for Trucks Traveling in Lane 1 Based on Data from Both Field Test Sites

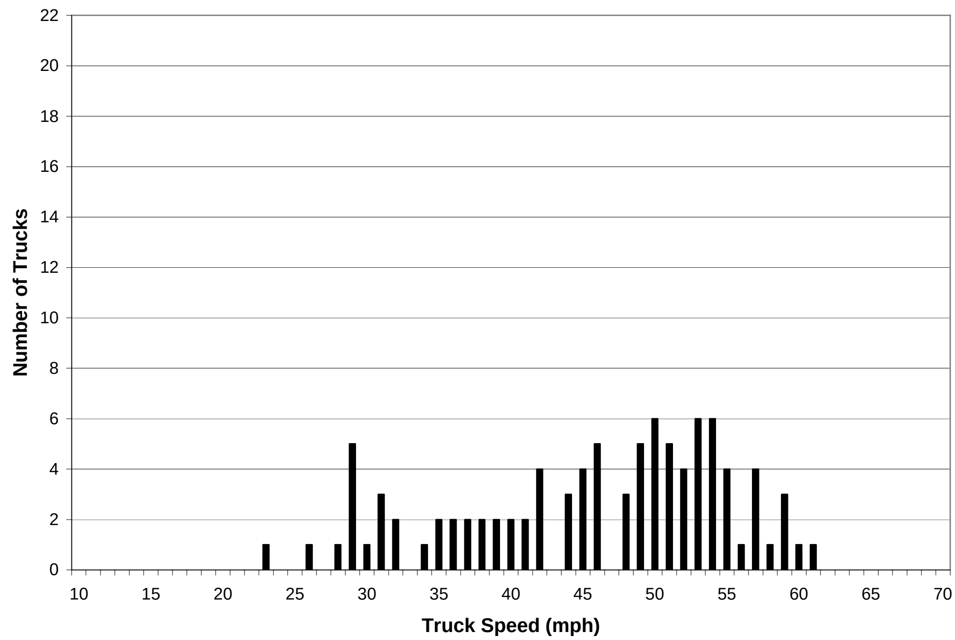


Figure 4.10: Histogram of Speeds for Trucks Traveling in Lane 2 Based on Data from Both Field Test Sites

4.4 ANALYSIS OF TRUCK EVENTS

After analyzing the recorded strain time histories from all the trucks, it appeared that at both field test sites, the majority of trucks did not produce significant strains in the mast arms. Some examples of field data gathered are described to illustrate the level of response measured in the field. Figures 4.11 and 4.12 show truck events (indicated by vertical dotted lines on the plots) recorded at the field test site on RM620 at Home Depot Blvd where there was a significant change in the strain readings either from the strain gauges located at the top of the mast arm (in-plane), the strain gauges located on the side of the mast arm (out-of-plane), or both. The information on these truck events is given in Tables 4.1 and 4.2. More details regarding the events can also be found in Appendix F. In Figure 4.11, the first truck (Truck No. 15) produced an obvious increase in the side strain data when it passed beneath the mast arm. However, this truck did not produce a similar effect on the in-plane strain. Also, note that the other three trucks (Truck Nos. 16, 17, and 18) did not have an appreciable effect on either strain measurement. It is important to note that the resolution of the datalogger was 0.001 mV/V (millivolt/volt) which corresponds to 1.9×10^{-6} in/in when converted to strain units for strain gauges that have a 2.11 strain gauge factor. Thus, the smallest incremental change in strains that could be recorded or resolved in the field was 1.9 microstrain. Therefore, as a quick screening to ensure that the change in strain measurements was in fact due to the truck and not due to noise or wind, a strain range of at least 7.6 microstrain (4 x 1.9 microstrain) when a truck event occurred was considered to be significant. As shown in Figure 4.12, not all truck events were as obvious to pick out as the one (Truck No. 15) in Figure 4.11. The truck event (Truck No. 9) shown in Figure 4.12 was still considered as one that caused a change in the strain data. However, of the over 400 trucks that were analyzed at the two field sites most did not produce any appreciable change in the strain data as is illustrated in Figure 4.13 with data from the field test site on US290 at SH95. None of the seven truck events (Truck Nos. 2-8) presented in Figure 4.13 caused any change in the strain data. To verify that the trucks in Figure 4.13 were not the slowest or smallest trucks observed, information on these trucks is presented in Table 4.3.

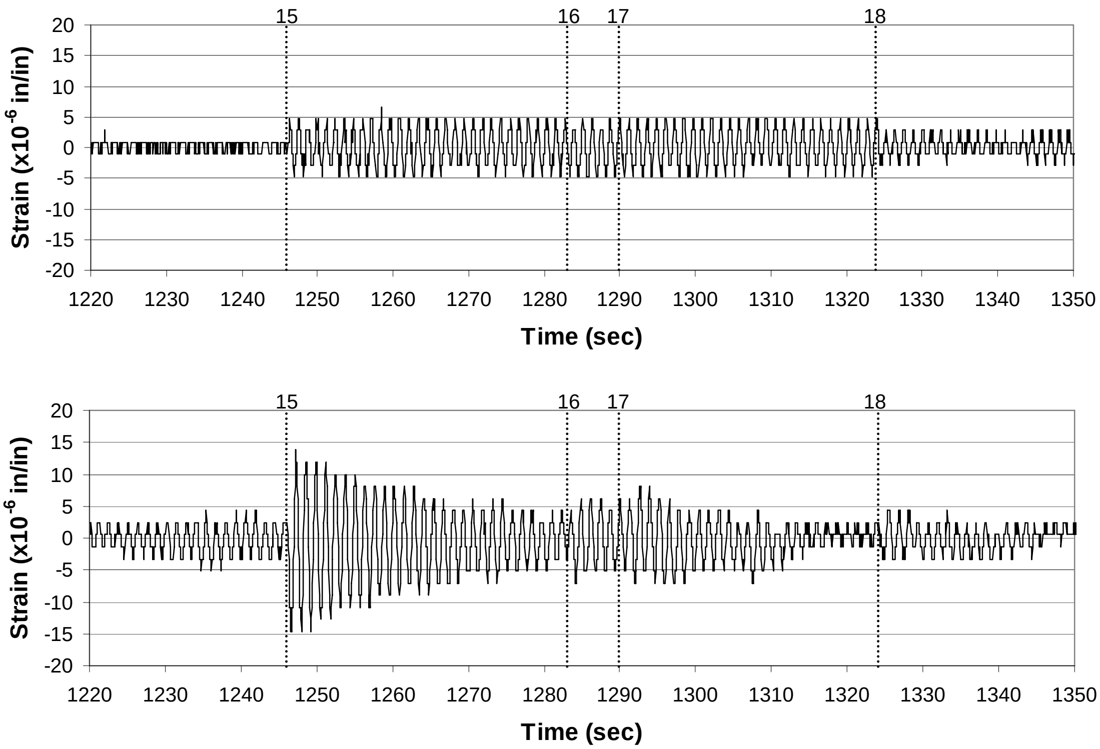


Figure 4.11: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.1: Truck Information for Figure 4.11 (from the Field Test Site on RM620 at Home Depot Blvd – 09-20-2005, Part 1)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
15	1246	59	2	Box-Small (Dump Truck)
16	1283	54	1	Semi
17	1290	44	1	Dump Truck
18	1324	52	1	Box-Small (Dump Truck)

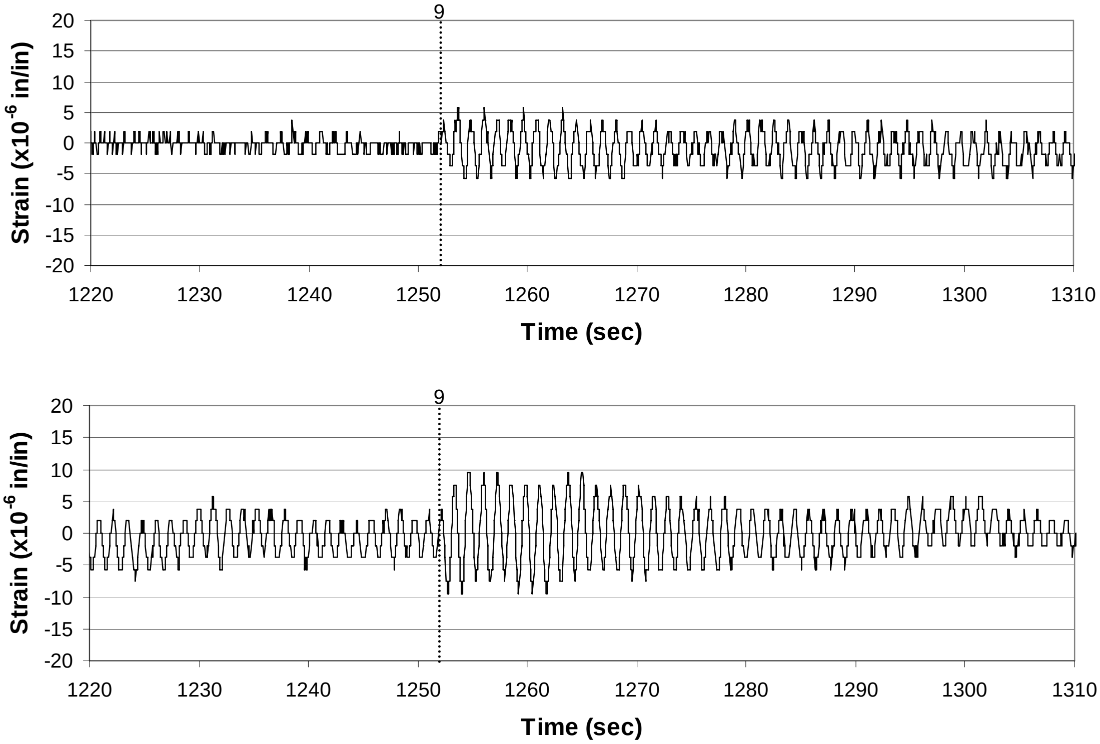


Figure 4.12: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.2: Truck Information for Figure 4.12 (from the Field Test Site on RM620 at Home Depot Blvd – 08-24-2005, Part2)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
9	1252	49	2	Box-Small (Dump Truck)

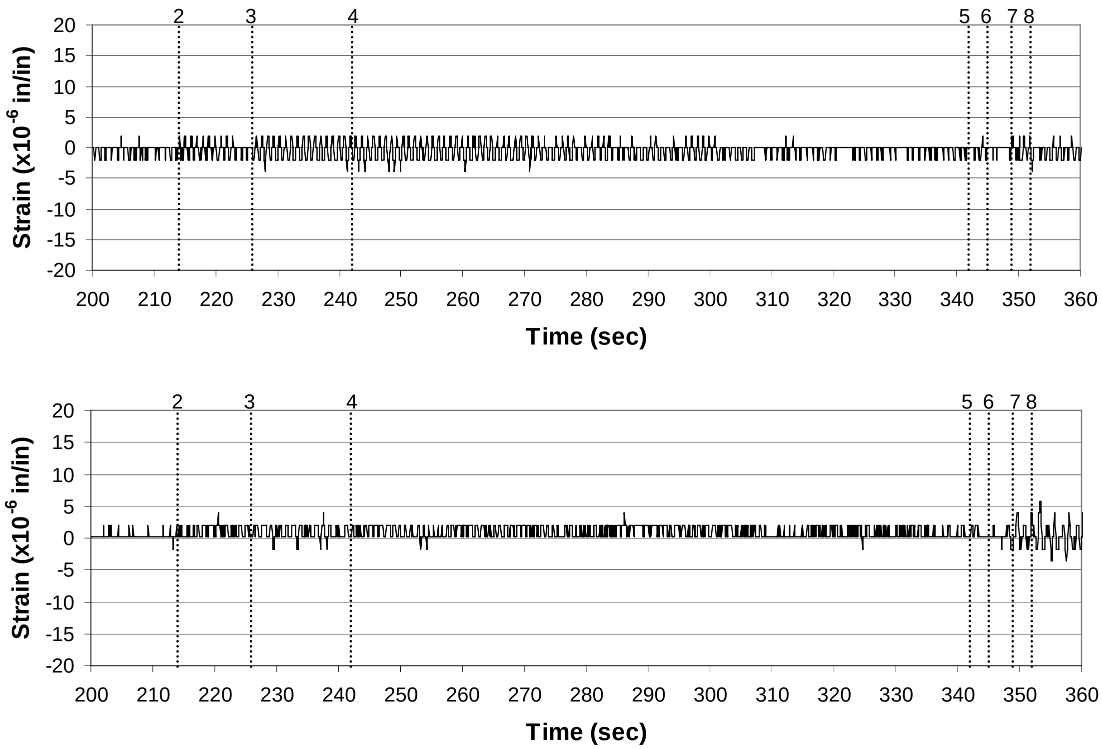


Figure 4.13: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on US290 at SH95

Table 4.3: Truck Information for Figure 4.13 (from the Field Test Site on US290 at SH95 – 03-27-2006, Part1)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
2	214	36	1	Camper
3	226	43	1	Semi
4	242	48	1	Pickup w/Trailer
5	342	45	1	Semi-Tall
6	345	48	1	Semi-Tall
7	349	48	2	Semi-Tall
8	352	50	2	Semi-Tall

Once the trucks that appeared to have caused a change in the strain data were identified, their raw strain data were converted into rainflow cycle counts using the program Crunch. Crunch is a program developed at the National Wind Technology Center to analyze wind turbine fatigue loads (Buhl, Jr., 2003); however, it is a general-purpose program and can be used to perform rainflow cycle calculations on most tabular data. The rainflow cycle counts were converted into effective strain levels (using a fatigue exponent of three corresponding to steel). An effective strain level of ten microstrain was used as a cutoff for determining which trucks truly affected the response of the cantilevered traffic signal structure. Of the over 400 truck events that were recorded, only 18 trucks were determined to produce an appreciable change in the strain data in the in-plane direction, out-of-plane direction, or both (16 trucks in the out-of-plane direction only and two trucks in both directions for a total of 20 events). These trucks are summarized in Table 4.4. All of these truck events were from the field test site on RM620 at Home Depot Blvd. None of the trucks at the site on US290 at SH95 caused an appreciable change in the strain data. The information provided in Table 4.4 includes the data set that contained the truck event, the truck number from that data set, the time the truck passed beneath the mast arm, the speed of the truck, the lane in which the truck was traveling, the truck type, the component of mast arm strain that was affected, the effective strain, and the maximum strain range recorded for the 20 events. Additional details regarding these and all the other truck events at both field test sites may be found in Appendix F. As can be seen from Table 4.4, the trucks that caused appreciable strains were mostly box-type trucks and were traveling close to or slightly above the posted speed limit. Interestingly, the truck events generally showed a greater influence on out-of-plane strains than in-plane strains, which is an interesting finding since in the AASHTO design code, the design for truck-induced gusts is based on application of a vertical pressure which would produce in-plane motions (AASHTO, 2003). Some of the truck events exhibiting this behavior are discussed in the following sections.

Table 4.4: Summary of Trucks that Affected the Strain Data

Event #	Data Set	Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type	Plane Affected	Effective Strain ($x10^{-6}$ in/in)	Max Strain Range ($x10^{-6}$ in/in)
1	8-24-05 Part 1	9	1142	51	2	Dump Truck	Out-of-Plane	14.97	25
2	8-24-05 Part 1	13	1479	58	2	Box-Small	In-Plane	17.84	27
3	8-24-05 Part 1	13	1479	58	2	Box-Small	Out-of-Plane	16.62	37
4	8-24-05 Part 2	1	129	54	2	Box-Tall	In-Plane	14.79	21
5	8-24-05 Part 2	1	129	54	2	Box-Tall	Out-of-Plane	10.12	21
6	8-24-05 Part 2	9	1252	49	2	Box-Small (Dump Truck)	Out-of-Plane	10.83	19
7	9-20-05 Part 1	15	1246	59	2	Box-Small (Dump Truck)	Out-of-Plane	16.28	29
8	9-20-05 Part 1	24	1804	57	1	Semi	Out-of-Plane	10.24	25
9	9-20-05 Part 1	31	2469	54	2	Box-Tall	Out-of-Plane	14.48	29
10	9-20-05 Part 2	18	1933	57	1	Box-Tall	Out-of-Plane	10.34	17
11	9-20-05 Part 2	19	2033	59	2	Box-Small	Out-of-Plane	17.52	27
12	9-27-05 Part 1	7	396	52	1	Box-Small	Out-of-Plane	11.60	21
13	9-27-05 Part 1	14	1278	58	1	Box-Small	Out-of-Plane	9.91	17
14	9-27-05 Part 2	7	426	60	2	Semi-Tall	Out-of-Plane	9.97	15
15	9-27-05 Part 3	8	951	49	1	Box-Small	Out-of-Plane	10.27	17
16	9-29-05 Part 1	2	486	45	2	Delivery Truck	Out-of-Plane	24.85	39
17	9-29-05 Part 1	27	2068	44	2	Box-Small (Dump Truck)	Out-of-Plane	24.97	51
18	9-29-05 Part 1	34	2330	55	2	Box-Small (Dump Truck)	Out-of-Plane	9.70	15
19	9-29-05 Part 2	8	698	58	1	Box-Tall	Out-of-Plane	17.87	25
20	9-29-05 Part 2	9	713	54	1	Box-Tall	Out-of-Plane	18.84	31

4.4.1 "Ideal" Truck Event

Consider Event No. 7 in Table 4.4. This is an example of an "ideal" truck event where the truck produced a large increase in strain and then the motion damped out. As shown in Figure 4.14, before the Box-Small (Dump Truck) (Truck No. 15) passed beneath the mast arm, the in-plane strain range was only two microstrain (practically zero microstrain) and the out-of-plane strain range was six microstrain. Even though the in-plane strain range only increased to about ten microstrain (an insignificant change), the out-of-plane strain range increased to just under 30 microstrain. This out-of-plane strain amplitude then proceeded to damp out in free vibration over the next 35-40 seconds (i.e., very slowly due to the very light damping). This is an important finding because the AASHTO Specifications states that "although loads are applied in both the horizontal and vertical direction, horizontal support vibrations caused by forces in the vertical direction are most critical" (AASHTO, 2003). As shown in Table 4.5 and Figure 4.15, the first truck and the fourth truck were the same Box-Small (Dump Truck) type of truck. However, the fourth truck (Truck No. 18) did not produce the same strain response as the first truck (Truck No. 15). The reasons for this might include the different speeds (59 mph vs. 52 mph), different lanes (Lane 2 vs. Lane 1), and different heights (from the picture in Figure 4.15, the first truck appears to be a little taller than the fourth truck).

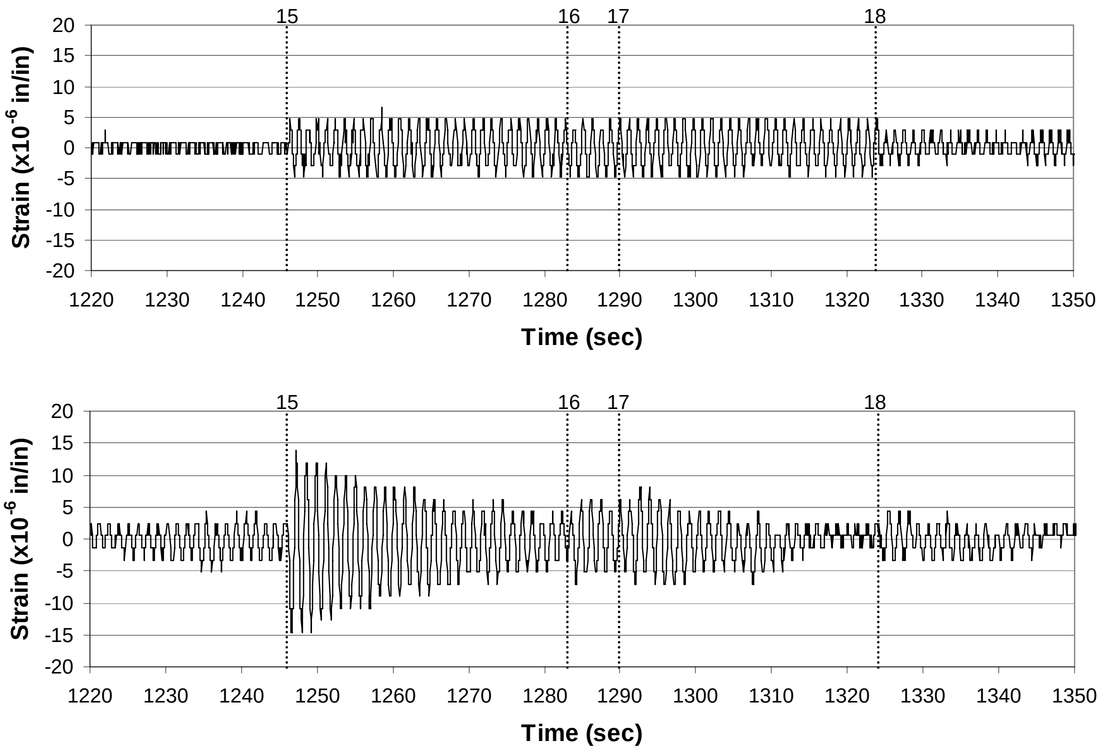


Figure 4.14: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.5: Truck Information for Figures 4.14 and 4.15 (from the Field Test Site on RM620 at Home Depot Blvd – 09-20-2005, Part 1)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
15	1246	59	2	Box-Small (Dump Truck)
16	1283	54	1	Semi
17	1290	44	1	Dump Truck
18	1324	52	1	Box-Small (Dump Truck)

Figure 4.15: Trucks that Produced the Strain Data Shown in Figure 4.14

4.4.2 Three Consecutive Semi/Tractor-Trailer Trucks in Lane 1

Next, consider Event No. 8 in Table 4.4. One of the potential worst load case scenarios for truck-induced gust loads on a cantilevered traffic signal structure might be when a single traffic lane has consecutive trucks traveling at the speed limit. In this particular truck event, three semi/tractor-trailer trucks passed beneath the cantilevered traffic signal structure one right after the other, all in Lane 1. As shown in Figure 4.16, none of the trucks (Truck Nos. 23, 24, and 25) caused any appreciable strains in the in-plane direction. However, changes in the out-of-plane direction were again noticeable larger. As shown in Table 4.6, all three of the trucks were traveling only slightly above the speed limit. A picture of the first truck is shown in Figure 4.17; unfortunately, the next two trucks passed too quickly, before another picture could be taken.

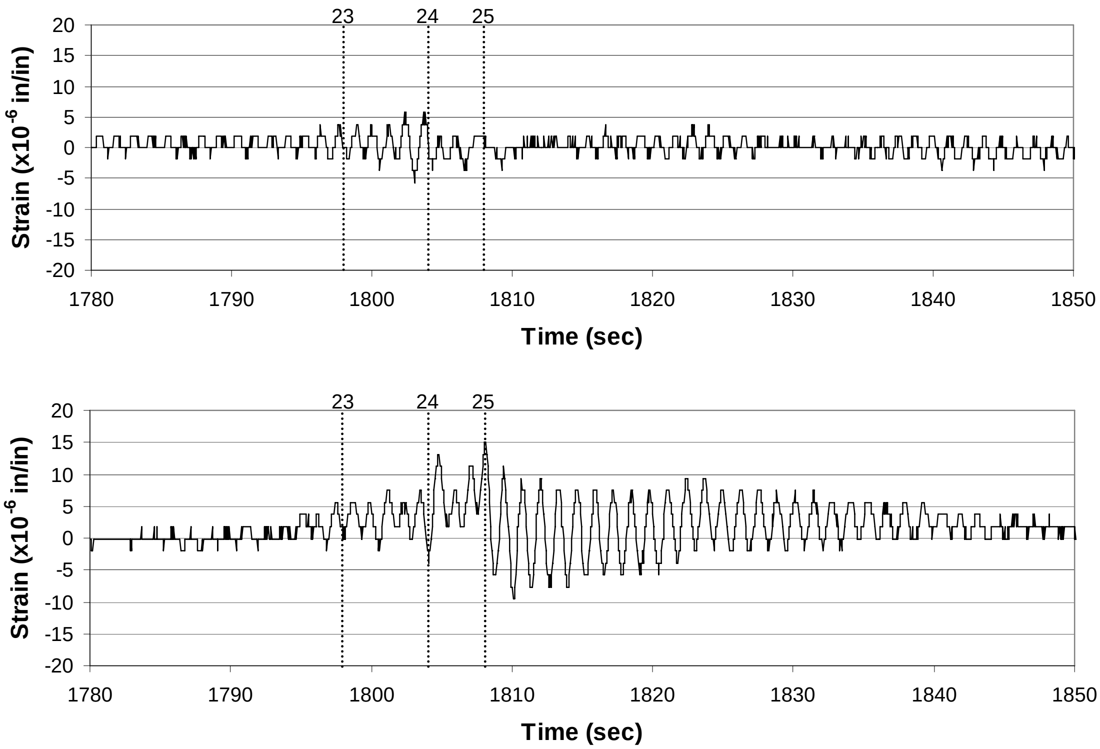


Figure 4.16: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.6: Truck Information for Figures 4.16 and 4.17 (from the Field Test Site on RM620 at Home Depot Blvd – 09-20-2005, Part 1)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
23	1798	56	1	Semi
24	1804	57	1	Semi
25	1808	56	1	Semi

Figure 4.17: Truck that Produced the Strain Data Shown in Figure 4.16

4.4.3 Box-Tall Type Truck

As previously discussed, the box-type trucks seemed to have the greatest effect on cantilevered traffic signal structures. The following is another example of a truck (Event No. 9 in Table 4.4) that produced a noticeable change only in the out-of-plane strain data as can be confirmed by studying Figure 4.18. It is interesting to note that, for this truck, the motions of the mast arm do not decay as quickly as in the previous examples discussed. It appears to take between 60-70 seconds for the motion to damp out completely. As stated in Table 4.7, the second truck (Truck No. 31) shown in Figure 4.19 was a Box-Tall type truck traveling at 54 mph (24.14 m/s) in Lane 2.

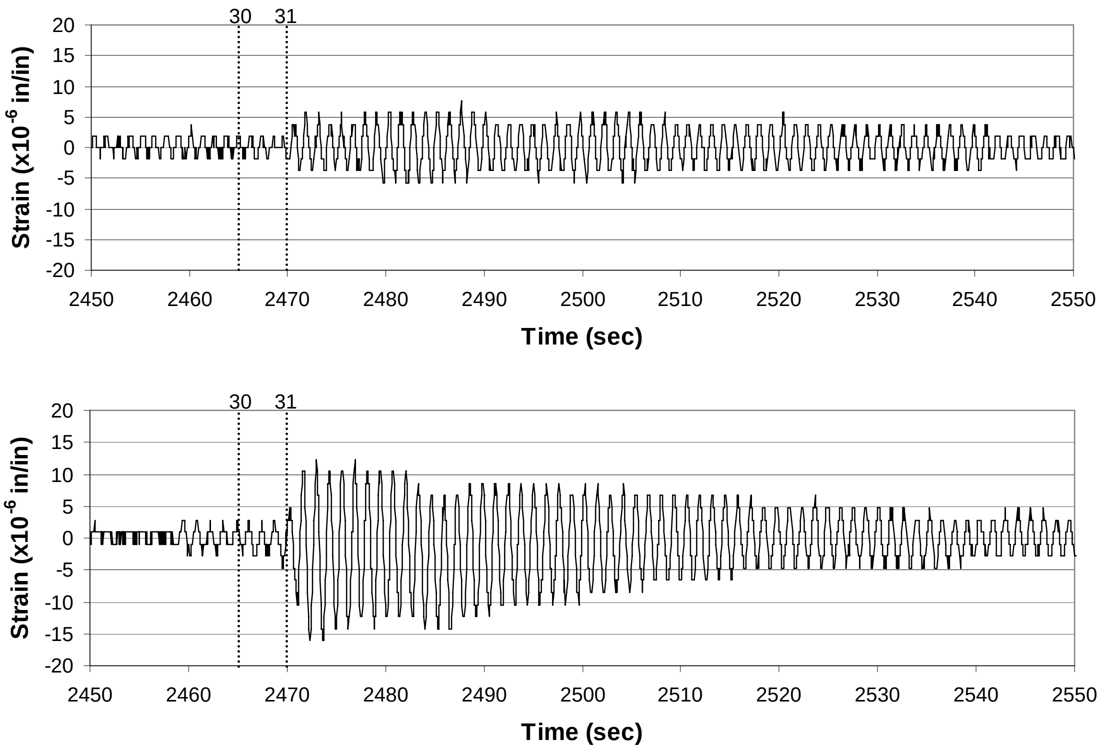


Figure 4.18: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.7: Truck Information for Figures 4.18 and 4.19 (from the Field Test Site on RM620 at Home Depot Blvd – 09-20-2005, Part 1)

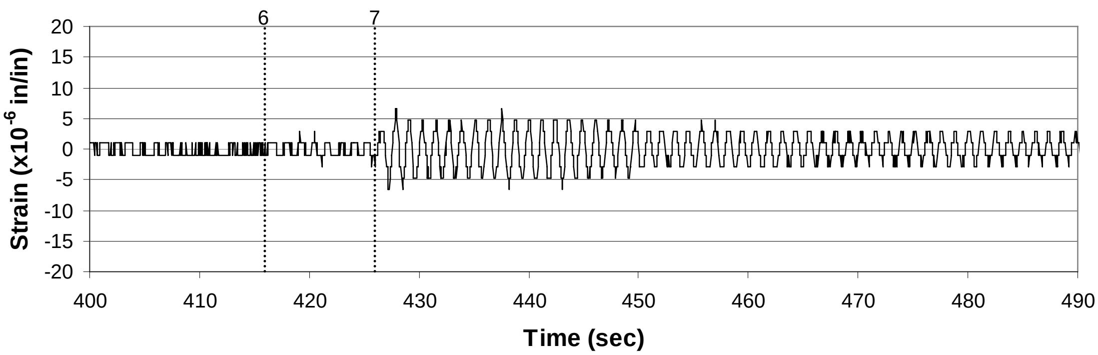
Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
30	2465	N/A	1	Semi
31	2469	54	2	Box-Tall

Figure 4.19: Trucks that Produced the Strain Data Shown in Figure 4.18

4.4.4 Semi-Tall Truck in Lane 2

It is sometimes thought that semi/tractor-trailer trucks are the worst type of trucks for truck-induced gust loading. Event No. 14 in Table 4.4 is an example of such an extreme semi/tractor-trailer truck event. The strain time history for this event in the two components is shown in Figure 4.20. As Table 4.8 shows, the truck involved (Truck No. 7), shown in Figure 4.21, is a semi with a tall trailer traveling at 60 mph (26.82 m/s) in Lane 2. As illustrated in Figure 4.20, this truck did have a slight influence on the top strain; however, it was not enough to produce an effective strain over ten microstrain.

Likewise, in the out-of-plane direction there were not any significantly large strain cycles recorded, but the strain cycles did stay relatively constant and were rather slow in damping out.



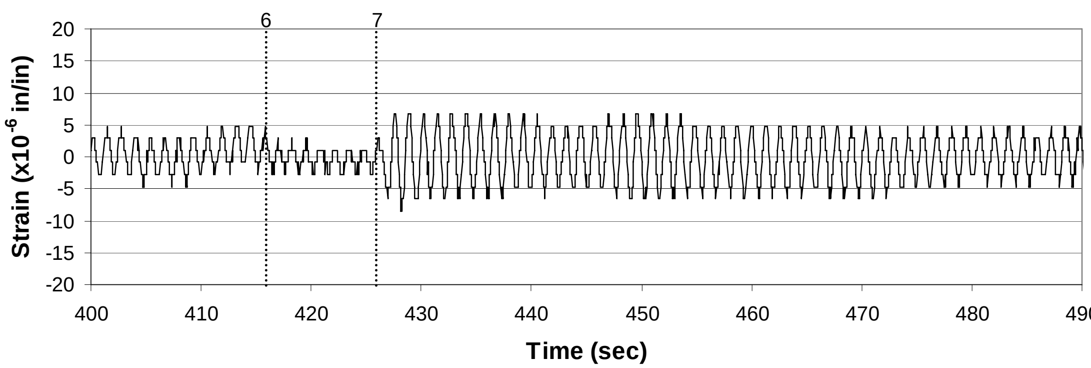


Figure 4.20: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

Table 4.8: Truck Information for Figures 4.20 and 4.21 (from the Field Test Site on RM620 at Home Depot Blvd – 09-27-2005, Part 2)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
6	416	47	1	Concrete Truck
7	426	60	2	Semi-Tall

Figure 4.21: Trucks that Produced the Strain Data Shown in Figure 4.20

4.4.5 Delivery Truck's Unexpected Response

In one of the more unusual truck events (Event No. 16 in Table 4.4), a delivery truck, shown in Figure 4.22, produced an unexpectedly large strain response in the out-of-plane direction, as seen in Figure 4.23. As Table 4.9 states, the delivery truck (Truck No. 2) was only traveling at 45 mph (20.12 m/s) in Lane 2. The truck produced almost no vertical movement of the mast arm but it caused a strain cycle of 39 microstrain in the out-of-plane horizontal direction. It appears from Figure 4.23 that roughly six seconds before the truck passed beneath the mast arm, the side strain was influenced by something. This could perhaps have been a wind gust but because no wind data were recorded at the field test site on RM620 at Home Depot Blvd, this cannot be verified. However, additional field notes did indicate that the day of the test in question – September 29, 2005 – was indeed a windier day than the previous days when data were recorded at this site.

Figure 4.22: Trucks that Produced the Strain Data Shown in Figure 4.23

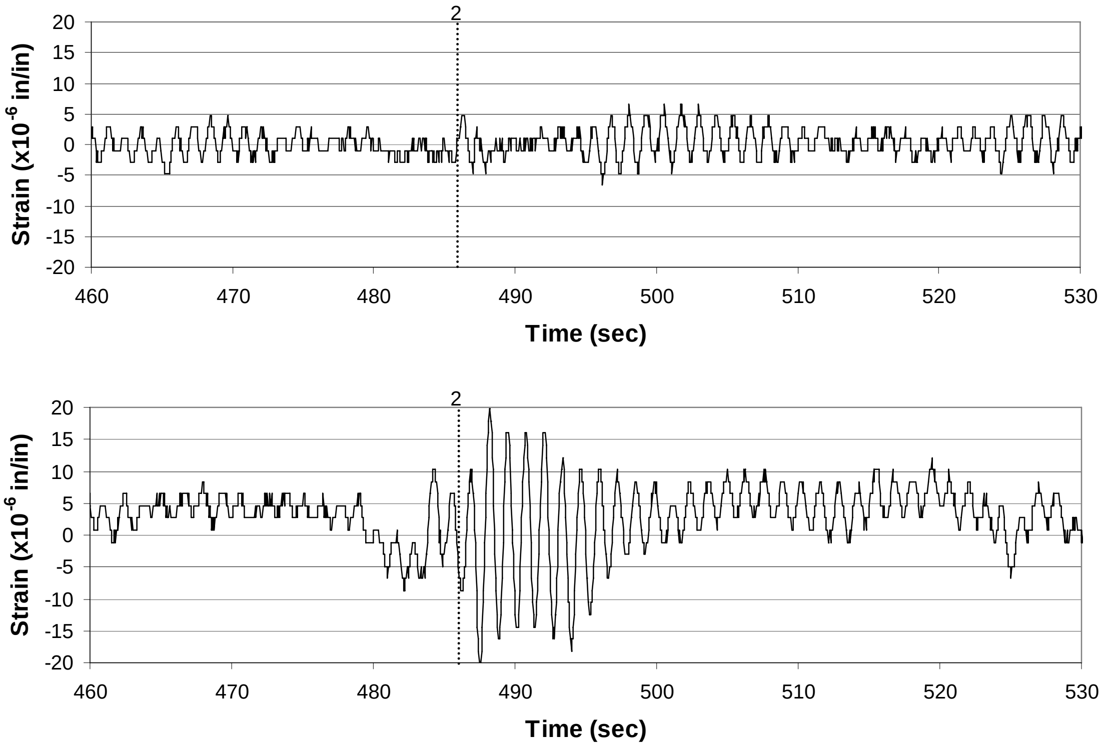


Figure 4.23: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on RM620 at Home Depot Blvd

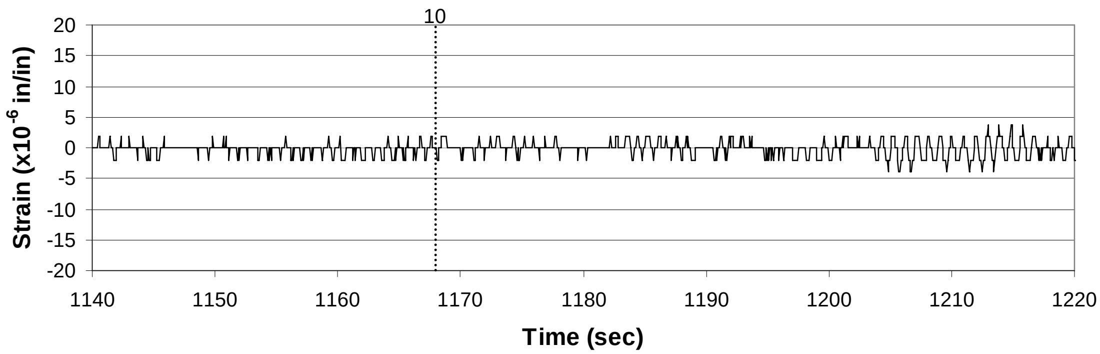
Table 4.9: Truck Information for Figures 4.22 and 4.23 (from the Field Test Site on RM620 at Home Depot Blvd – 09-29-2005, Part 1)

Truck #	Time (Sec)	Speed (mph)	Lane	Truck Type
2	486	45	2	Delivery Truck

4.4.6 Trucks in Lanes 1 and 2 at the Same Time

The overall worst case truck-induced gust loading scenario for a cantilevered traffic signal structure is believed by some to be one where two trucks pass simultaneously beneath the mast arm. The following is an example of a Semi-Tall truck in Lane 1 and a Semi-Low truck in Lane 2, as shown in Figure 4.24, both traveling simultaneously at 49 mph (21.9 m/s) beneath the cantilevered traffic signal structure at the field test site on US290 at SH95 (see Truck No. 10 in the data from March 27, 2006, Part 3 in Appendix F). As seen in the strain response of the structure in Figure 4.25, the two semi/tractor-trailer trucks together produced virtually no change in the in-plane response and only limited change in the out-of-plane response. This is an important finding since it is generally believed that this scenario might cause large truck-induced gust response for such structures; yet, the response was barely noticeable. This demonstrates that even though this field test site on US290 at SH95 should have been an ideal location for truck-induced gust loads because of the significant truck traffic and the relatively high posted speed limit (50 mph) there, the instrumented cantilevered traffic signal structure at that site was not affected by truck-induced gusts.

Figure 4.24: Trucks that Produced the Strain Data Shown in Figure 4.25



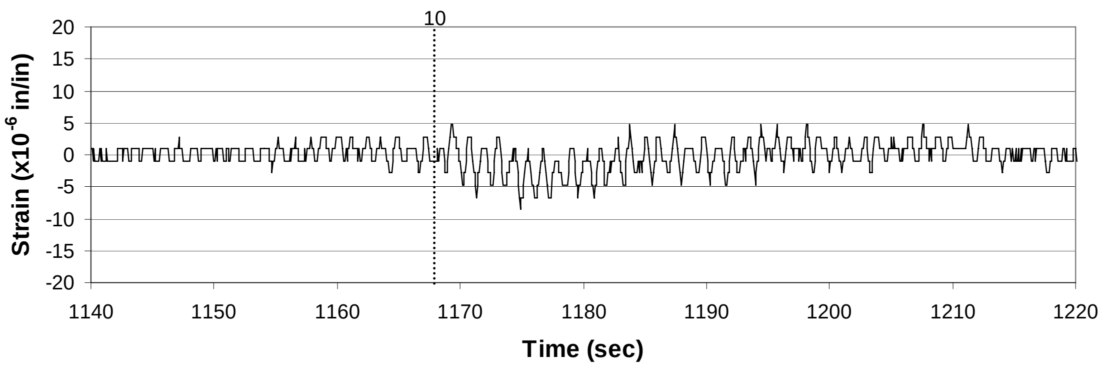
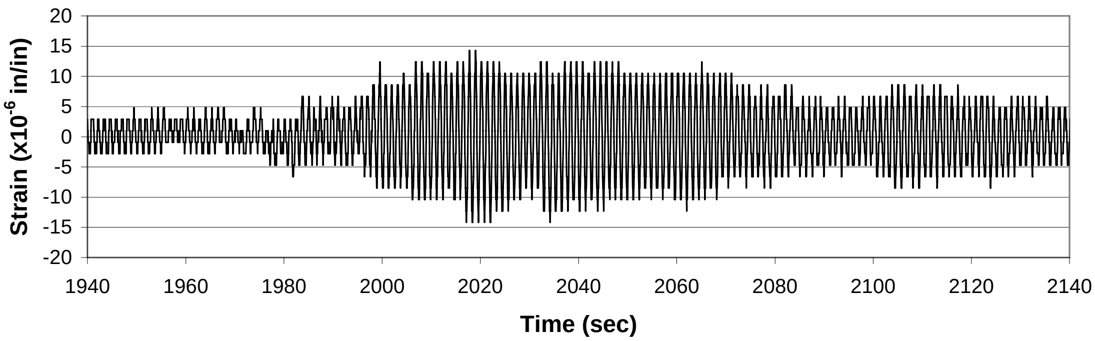


Figure 4.25: Strain Data from the Top of the Mast Arm (top) and the Side of the Mast Arm (bottom) Recorded at the Field Test Site on US290 at SH95

4.5 EFFECT OF NATURAL WIND

While analyzing the strain data due to truck events at the field test site on RM620 at Home Depot Blvd, it was discovered that on numerous occasions the strain data would increase significantly even though no trucks were present at the time. Sometimes these strain recordings were even larger than those induced by any of the trucks. An example of such a situation is shown in Figure 4.26. It was assumed that this strain variation was due to the natural wind; however, since an anemometer was not installed at the field test site on RM620 at Home Depot Blvd, there was no way to verify this. For this reason, an anemometer was added to the test equipment used at the second test site, US290 at SH95.



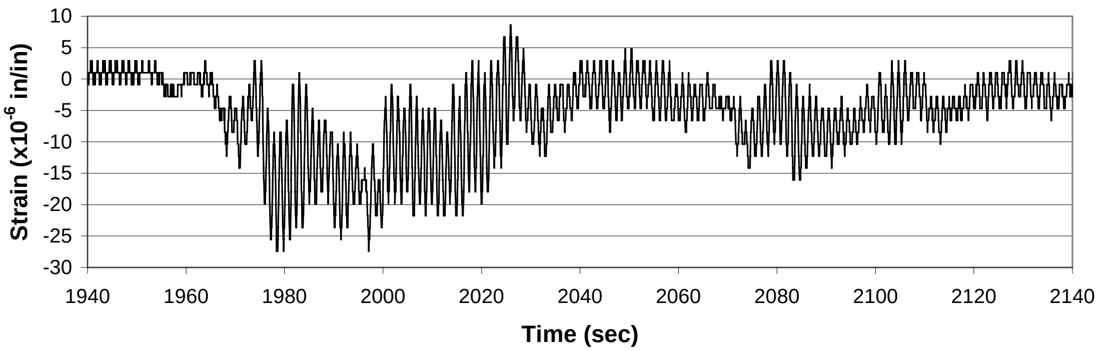


Figure 4.26: Large Strain Cycles not Caused by Trucks at the Field Test Site on RM620 at Home Depot Blvd

4.5.1 Short-Term Wind Data

Throughout the field testing program that was part of this study, a difference in the response of the cantilevered traffic signal structures on windy days versus that on days with little or no wind was apparent. On relatively calm days, the tip of the mast arm would sometimes not even appear to move; however, on windy days, there were noticeable tip displacements. To reinforce this observation below is an example of a windy day, Wednesday, March 15, 2006, compared to a calm day, Thursday, March 16, 2006. The strain data were recorded at the field test site located at US290 at SH95 in Elgin. Information regarding the time of the tests and the wind data can be found in Table 4.10. Figures 4.27 to 4.30 show the top strain, side strain, and recorded wind speed during the field testing. As can be seen, there was far greater movement of the cantilevered traffic signal structure on March 15, 2006 (when the wind speed were higher) than on March 16, 2006. By monitoring short-term field data, it is clear that there is a correlation between large strain cycles and higher wind speeds.

Table 4.10: Wind Information at the Field Test Site on US290 at SH95 for March 15 and 16, 2006

Data Set Name	Start Time	End Time	Average Wind Speed (mph)	Max Wind Gust (mph)
3-15-2006 Part1	10:58:09	12:03:32	6.94	14.42
3-15-2006 Part2	13:13:20	14:21:58	8.23	17.99
3-16-2006 Part1	9:50:28	10:57:30	2.82	7.43
3-16-2006 Part2	11:06:29	11:37:54	2.63	5.66

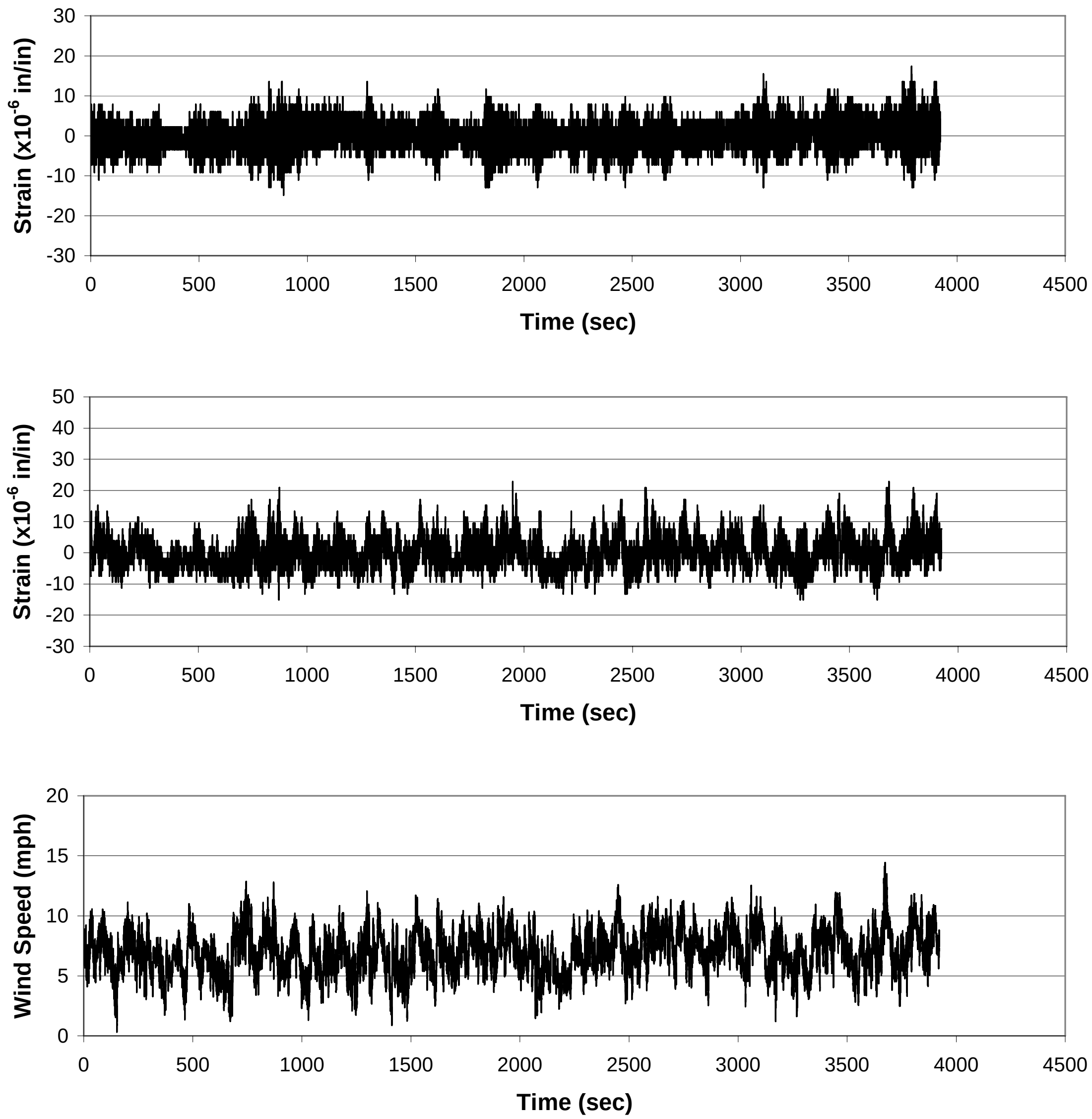


Figure 4.27: Strain and Wind Data Recorded at the Field Test Site on US290 at SH95 – 03-15-06, Part 1: Top Strain (top), Side Strain (middle), Wind Speed (bottom)

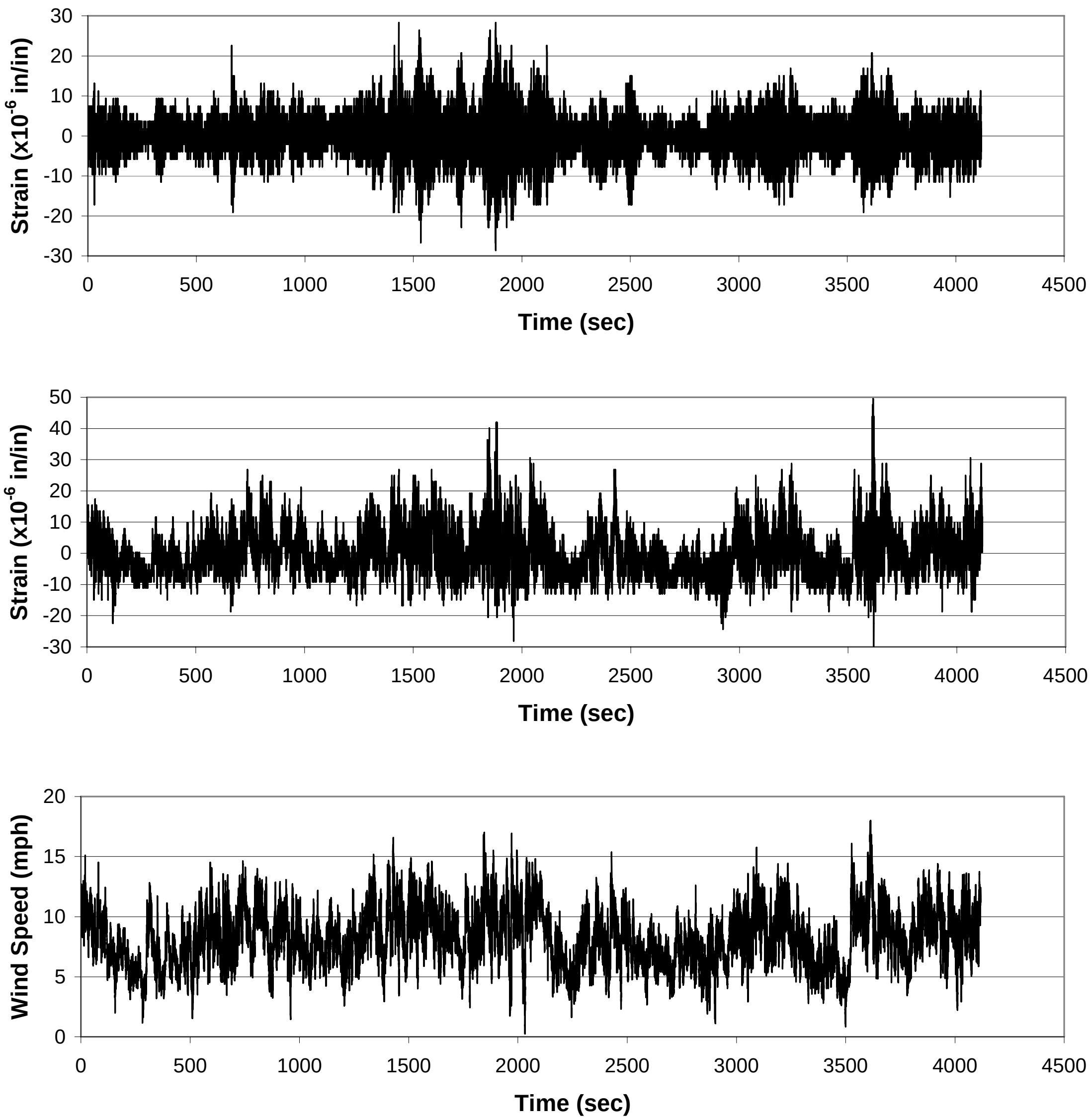


Figure 4.28: Strain and Wind Data Recorded at the Field Test Site on US290 at SH95 – 03-15-06, Part 2: Top Strain (top), Side Strain (middle), Wind Speed (bottom)

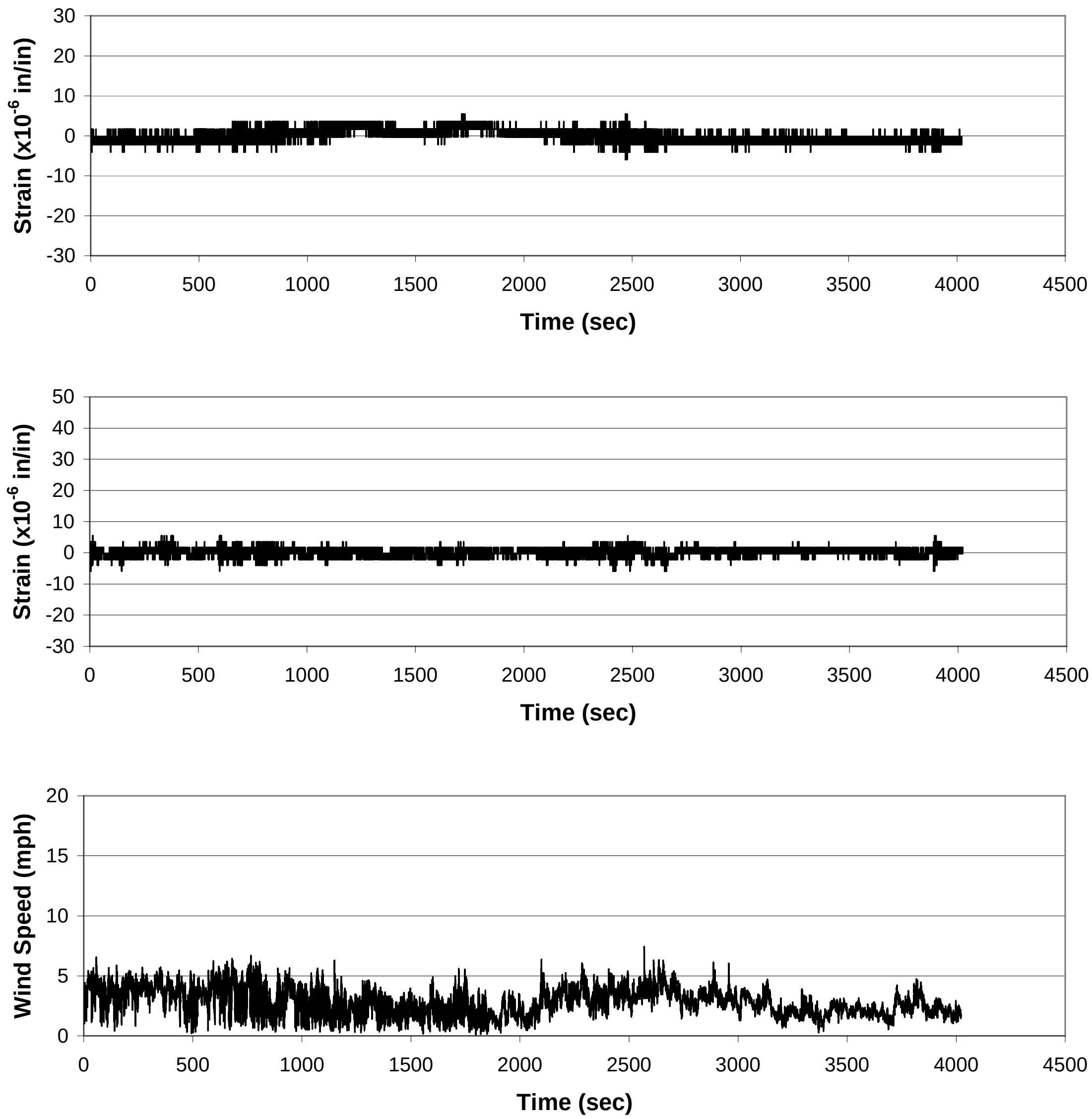


Figure 4.29: Strain and Wind Data Recorded at the Field Test Site on US290 at SH95 – 03-16-06, Part 1: Top Strain (top), Side Strain (middle), Wind Speed (bottom)

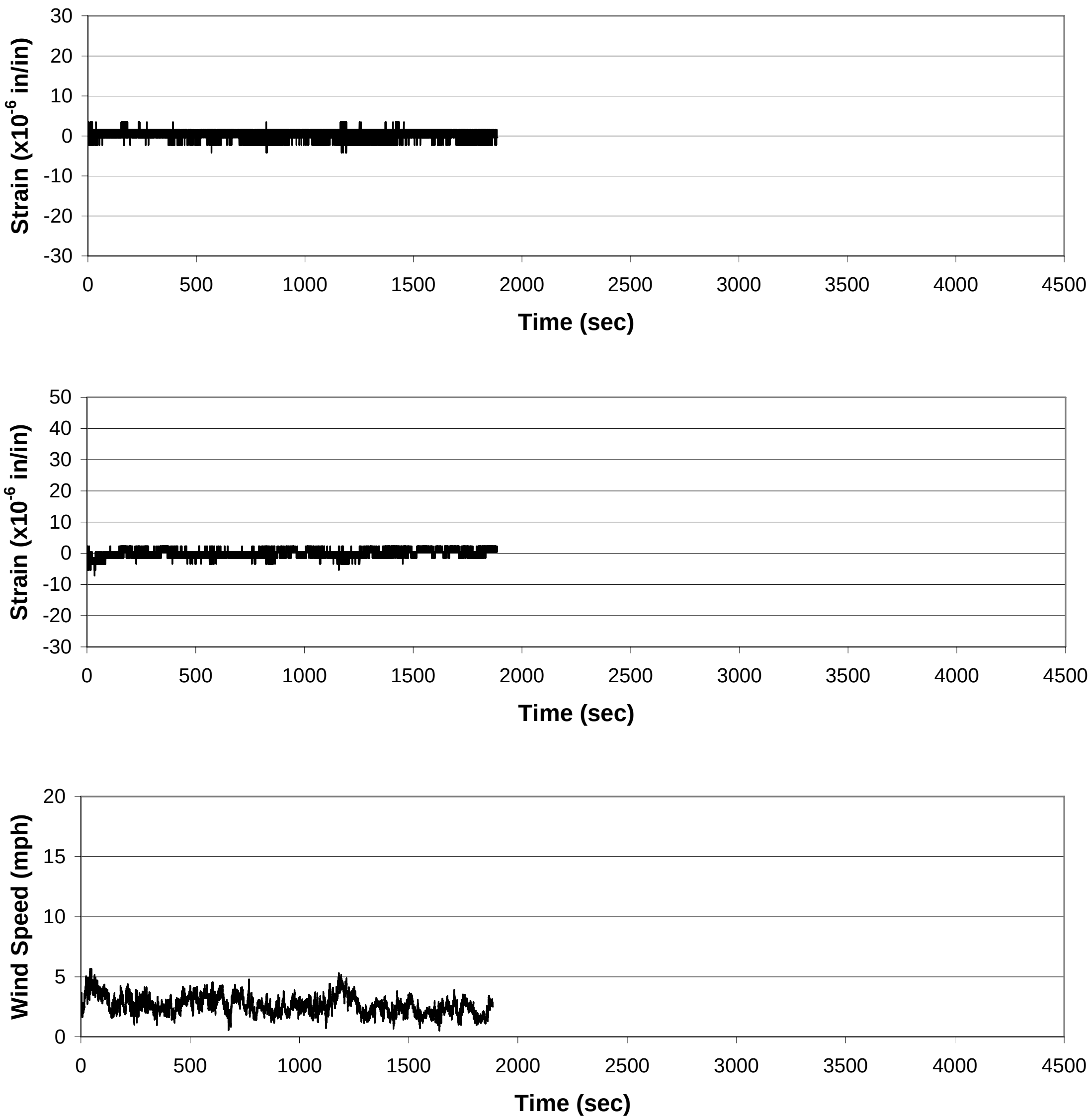


Figure 4.30: Strain and Wind Data Recorded at the Field Test Site on US290 at SH95 – 03-16-06, Part 2: Top Strain (top), Side Strain (middle), Wind Speed (bottom)

4.5.2 Long-Term Wind Data

Since the anemometer only collected wind data while the field tests were being conducted and strains recorded, there were no continuous 24-hour wind speed data available for either of the two field test sites. However, using the Weather Underground website, 24-hour wind data for each day were recorded from the Arbors at Dogwood Creek Weather Station (Weather Underground, 2006). This weather station is located at 30°17'17" North Latitude and 97°19'49" West Longitude, approximately five miles from the field test site in Elgin which is located at 30°21'03" North Latitude and 97°23'12" West Longitude. As shown in Figures 4.31 and 4.32, it was indeed much windier on March 15, 2006 (except for very early in the morning when there were very light winds) than on March 16, 2006.

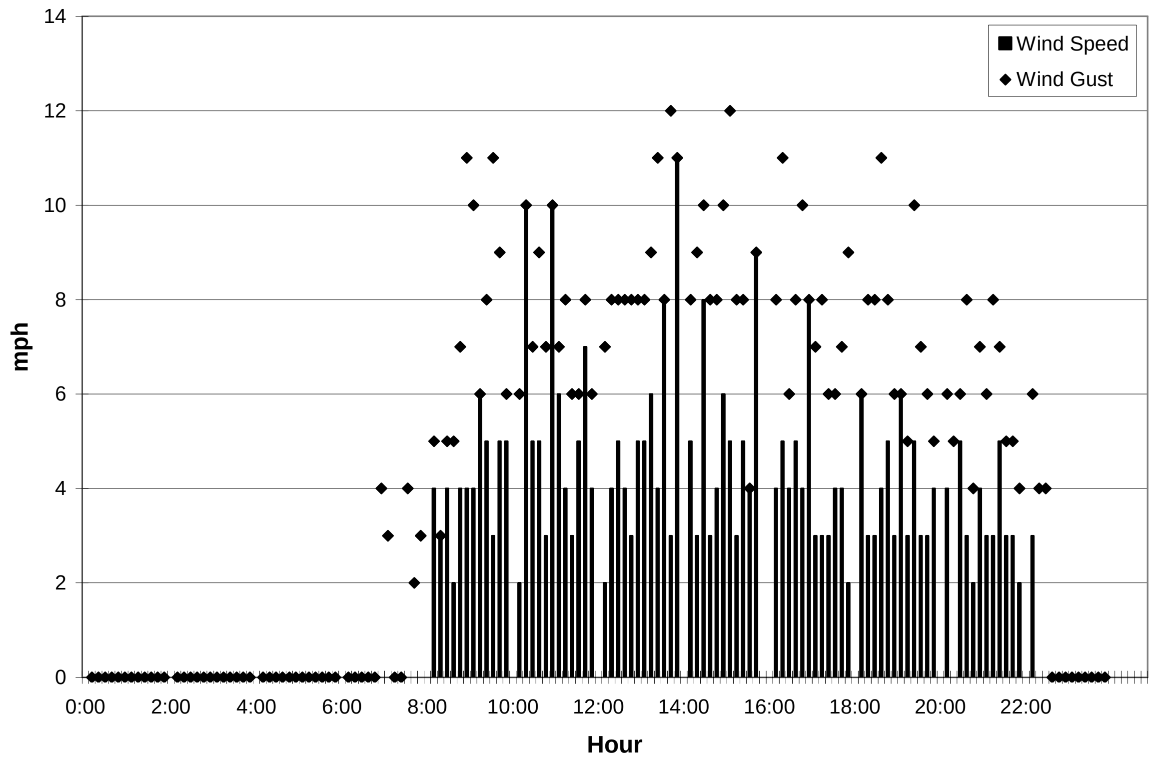


Figure 4.31: Wind Data for March 15, 2006 at the Field Test Site on US290 at SH95

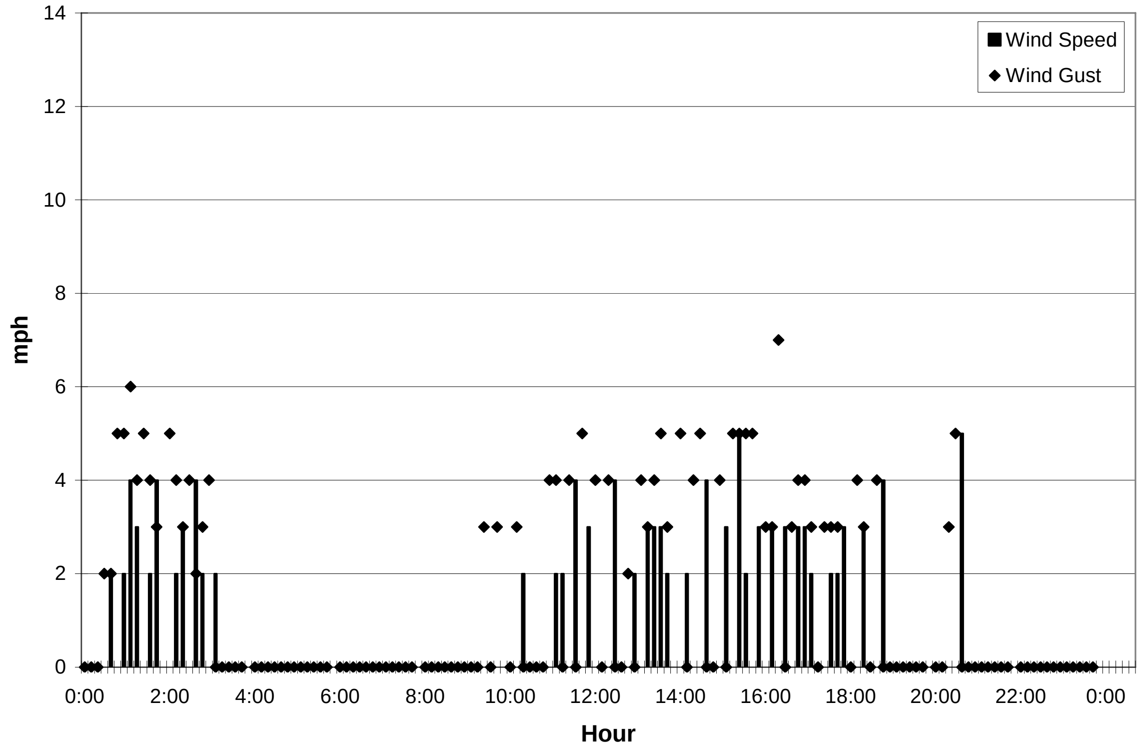


Figure 4.32: Wind Data for March 16, 2006 at the Field Test Site on US290 at SH95

Since the MicroSAFE units captured the long-term strain data for the site in two-hour intervals, it was interesting to compare the MicroSAFE rainflow cycle counts data to the 24-hour wind data on March 15 and 16, 2006. The MicroSAFE rainflow cycle counts data are presented in Tables 4.11 and 4.12 and shown as 3-D histograms in Figures 4.33 and 4.34. The rainflow cycle counts data correlate very well with the wind data shown in Figures 4.31 and 4.32. On March 15, 2006, there was very little wind in the early morning before 8:00am, and there were also only a very small number of rainflow cycles during that time period. However, later in the day when it became windier, the rainflow cycle counts clearly picked up. Conversely, March 16, 2006 was a relatively calm day, and there were basically no significant rainflow cycle counts throughout the day. From the various illustrations presented, it appears that cantilevered traffic signal structures are more susceptible to the natural wind gusts than to truck-induced gusts.

Table 4.11: MicroSAFE Rainflow Cycle Counts Data for March 15, 2006 at the Field Test Site on US290 at SH95

	Bin Median (με)					
Time	**20**	**28**	**36**	**44**	**52**	**60**
3/15/2006 1:00	0	0	0	0	0	0
3/15/2006 3:00	0	0	0	0	0	0
3/15/2006 5:00	2	2	0	0	0	0
3/15/2006 7:00	23	3	1	0	0	0
3/15/2006 9:00	640	96	9	1	0	0
3/15/2006 11:00	764	51	2	1	0	0
3/15/2006 13:00	1064	301	84	24	4	2
3/15/2006 15:00	1539	387	97	19	3	1
3/15/2006 17:00	1109	209	45	4	0	1
3/15/2006 19:00	536	66	8	0	0	0
3/15/2006 21:00	800	197	36	5	4	0
3/15/2006 23:00	10	0	0	0	0	0

Table 4.12: MicroSAFE Rainflow Cycle Counts Data for March 16, 2006 at the Field Test Site on US290 at SH95

	Bin Median (με)					
Time	**20**	**28**	**36**	**44**	**52**	**60**
3/16/2006 1:00	32	0	0	0	0	0
3/16/2006 3:00	0	0	0	0	0	0
3/16/2006 5:00	0	0	0	0	0	0
3/16/2006 7:00	0	0	0	0	0	0
3/16/2006 9:00	2	0	0	0	0	0
3/16/2006 11:00	0	0	0	0	0	0
3/16/2006 13:00	2	0	0	0	0	0
3/16/2006 15:00	2	2	0	0	0	0
3/16/2006 17:00	5	1	0	0	0	0
3/16/2006 19:00	1	0	0	0	0	0
3/16/2006 21:00	0	0	0	0	0	0
3/16/2006 23:00	0	0	0	0	0	0

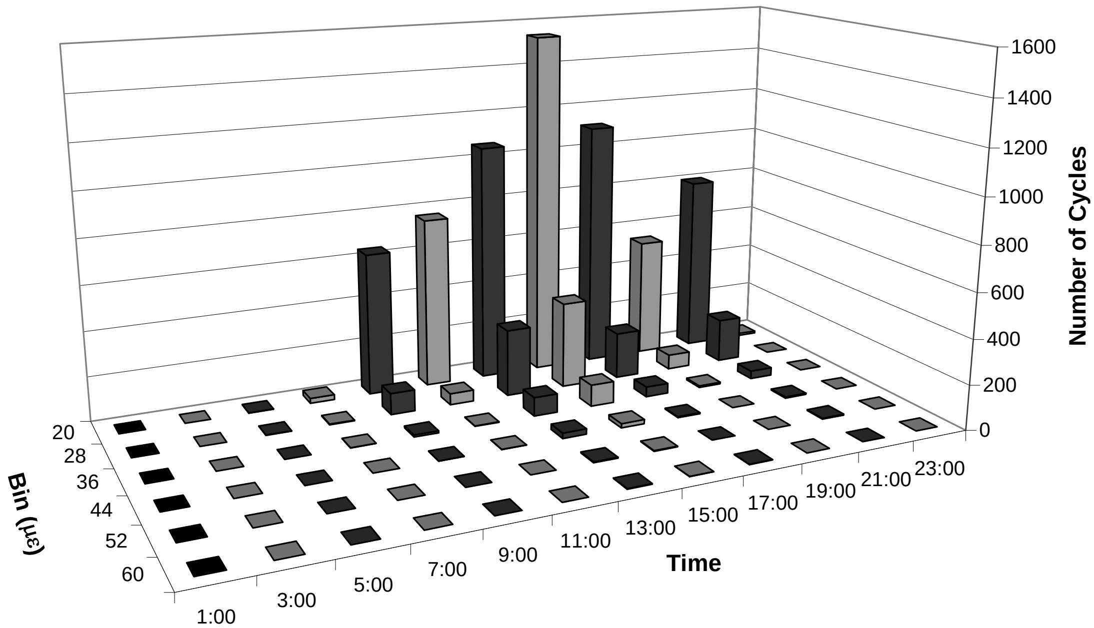


Figure 4.33: 3-D Rainflow Cycle Counts Histogram for March 15, 2006 at the Field Test Site on US290 at SH95

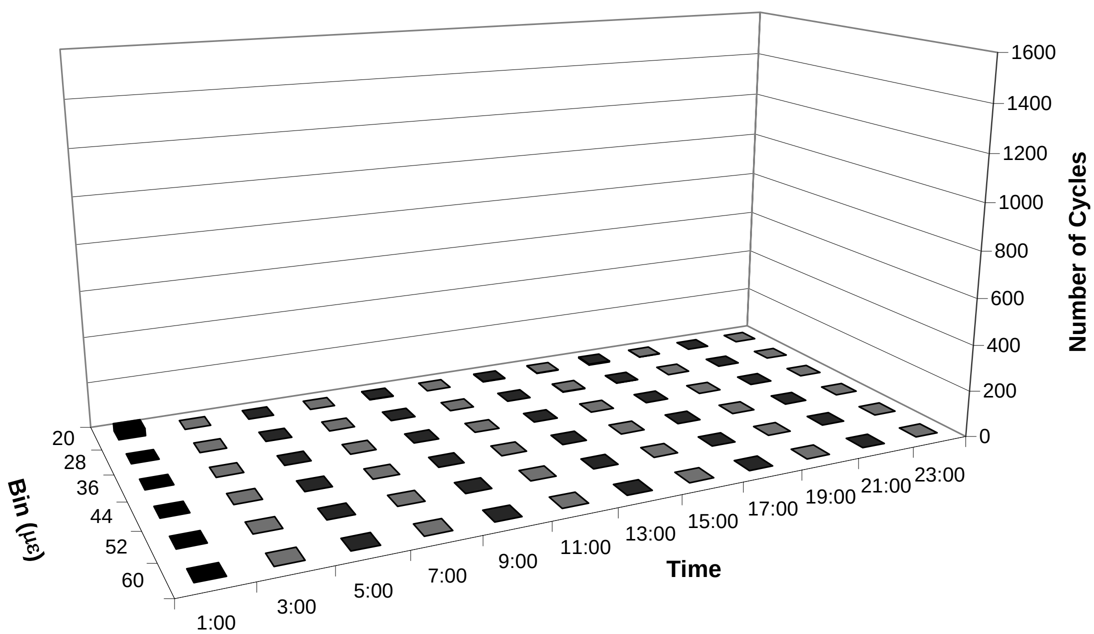


Figure 4.34: 3-D Rainflow Cycle Counts Histogram for March 16, 2006 at the Field Test Site on US290 at SH95

Chapter Five: Conclusions

5.1 Discussion of Results

5.1.1 Exposure of Cantilevered Traffic Signal Structures to High Speed Truck Traffic

Prior to performing the field tests, it was known that many cantilevered traffic signal structures are located on roadways with negligible truck traffic or where vehicle speeds are generally low. In addition to this, most traffic signal structures at locations with a lot of truck traffic and where vehicle speeds are higher (usually outside cities) are often wire-supported traffic signal structures instead of cantilevered traffic signal structures. Thus, it is rare (and difficult) to find a cantilevered traffic signal structure that is influenced by truck-induced gusts as was found during this study when only fifteen potential sites were identified in four counties surrounding Austin, Texas. Even among these fifteen sites, some either do not have sufficient truck traffic or see high vehicle speeds as was the case for the field test site on US290 at SH95, which registered very low strain levels during the field tests, as was discussed in Section 4.4.

5.1.2 Cantilevered Traffic Signal Structures versus Cantilevered Highway Sign Structures

Cantilevered highway sign structures have been the focus of several studies on truck-induced gust loads. However, cantilevered traffic signal structures and cantilevered highway sign structures have many key differences. Cantilevered highway sign structures (either variable message sign structures or the more common flat, green highway signs) are located on major roadways such as highways and interstates where vehicle speeds are high. These types of roadways are usually designed to keep the traffic moving so vehicles are usually able to maintain a constant speed and rarely slow down. On the other hand, the purpose of cantilevered traffic signal structures is to sometimes stop traffic as part of traffic control for an intersection. It is reasonable to assume that trucks traveling on a major highway with a posted speed limit of 55-65 mph (24.59-29.06 m/s) will, in fact, be traveling close to the posted speed limit as they pass beneath the cantilevered highway sign structures. Thus, if the effects of trucks on the structure can be determined and the daily truck traffic is known, then any such cantilevered highway sign structure can be designed to meet a certain fatigue life. However, this philosophy is not applicable for cantilevered traffic signal structures. First, cantilevered traffic signal structures are located on roads where vehicle speeds are lower (there are not any traffic lights on interstate highways, for example); therefore, trucks may be expected to cause less damage to cantilevered traffic signal structures than to cantilevered highway sign structures. Secondly, cantilevered traffic signal structures are generally used to stop traffic. Even though the daily truck traffic for a particular roadway might be known, the cantilevered traffic signal structures located on such a roadway will not experience the entire daily truck traffic at the speed limit because some of the trucks may be stopped or slowed down by the traffic light.

In this study, even though no actual traffic statistics were gathered, this fact was observed at both sites. The field test site on RM620 at Home Depot Blvd was relatively unaffected by these constraints because the site was located at a tee-intersection that only served a couple of retail stores and consequently, had an infrequent and short stop time. Even with a long light cycle, it was still estimated that approximately 20% of the truck traffic was affected by the traffic light (trucks either came to a complete stop or had to slow down to speeds lower than 25 mph because vehicles ahead had stopped) and another 20% of the trucks slowed down a bit simply on nearing the intersection. The field test site on US290 at SH95 had a more realistic light cycle length because even though it was also located at a tee-intersection, the intersecting road was a highway with considerably greater traffic volume than on Home Depot Blvd at the other field test site. Because of the shorter light cycle, about 60% of the truck traffic was directly affected by the traffic light and only about 10% of the truck traffic made it completely through the intersection without having to slow down at all.

5.1.3 Influence of Truck Type

From the contours of the cab to the height of the trailer, all trucks are shaped differently. Thus, it is a reasonable assumption that each type of truck has a different effect on a cantilevered traffic signal structure. This was noted in the literature review in Chapter 2 – for instance, previous researchers stated that box-type trucks, gravel trucks, and semi/tractor-trailer trucks caused some structural motions (Creamer et al., 1979 and Edwards and Bingham, 1984). The influence of truck shape and height were also noted by Cali and Covert (1997). In Section 4.4, it was shown that very few of the trucks analyzed during the field tests caused any significant movement in the mast arm at all. Of all the trucks, the box-type trucks appear to have the greatest influence on the response of the cantilevered traffic signal structure as seen in Figure 5.1. Interestingly, a specific box-type truck carrying a dumpster (called a Box-Small Dump Truck in this study) seemed to affect structural motions to the greatest extent (four of eight such trucks influenced structural motions). A picture of a Box-Small Dump Truck is shown in Figure 2.2. One possible solution is that the top front edge of the dumpster is not rounded at all, as is the case with most other trucks, making the truck less aerodynamic producing a greater pressure pulse.

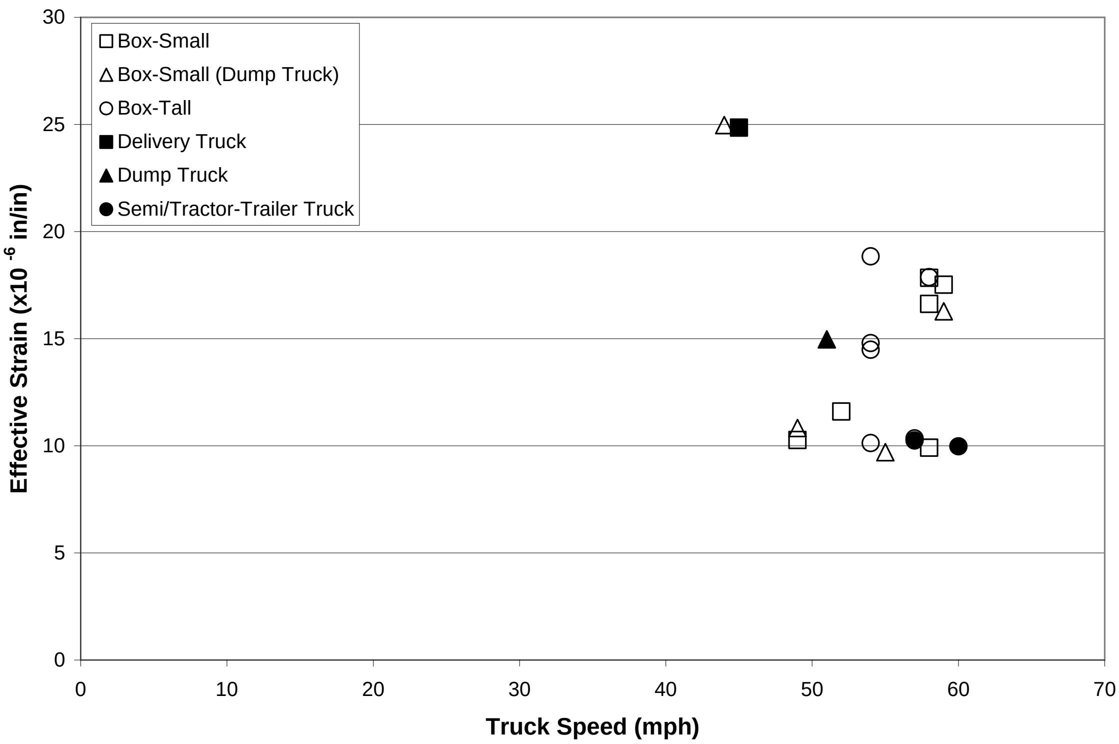


Figure 5.1: Influence of Truck Type on Mast Arm Structural Response (Strain)

Figure 5.2: Box-Type Dump Truck

5.1.4 Influence of Traffic Lane

As was discussed in Section 2.3.2, the AASHTO Specifications state that the equivalent static pressure range needs to be applied along a 12-foot (3.7-meter) length of the mast arm directly above a traffic lane that produces the maximum stress range (AASHTO, 2002). This section that produces the maximum stress range is usually the outermost 12 feet (3.7 meters) of the mast arm. The actual section, though, might vary a little depending on the location of traffic signals and any dampening plates since those are the attachments to mast arms that can increase the exposed horizontal surfaces where the equivalent static pressure is to be applied. Most cantilevered traffic signal structures have the column located on the right shoulder with the mast arm extending left over the roadway as was the case at the field test site on RM620 at Home Depot Blvd. For such a typical setup, the outermost 12-foot section of the mast arm is located directly above Lane 2 (left lane). However, as was seen in Section 4.3, the majority of trucks travel in Lane 1 (right lane). Thus, it is relatively unlikely (or rare) for the structure to experience the design equivalent static pressure from truck-induced gust loads applied on the outermost 12-foot section of the mast arm.

On the other hand, a cantilevered traffic signal structure might have its column located on the left shoulder with its mast arm extending right over the roadway comparable to what was seen at the field test site on US290 at SH95. This setup is only practical on divided highways (i.e., with a median) or on one-way streets since the mast arm will then not have to cross traffic from another direction. In such a setup, the outermost 12-foot section would be located directly over Lane 1; however, as was seen at the site on US290 at SH95, there is no need for the mast arm to extend across the entire length of Lane 1. The traffic signals need to be located close to the centers of relevant traffic lanes; therefore, the mast arm need only extend to the middle of Lane 1. Thus, even with this setup, it is unlikely that trucks in Lane 1 could bring about pressures similar to the levels of AASHTO's design equivalent static pressure because they would only influence a portion of the outermost 12-foot section of the mast arm that is directly above that lane. Moreover, trucks in Lane 2 would cause pressures closer to the column which would not lead to maximum stress ranges. This fact combined with the lower truck speeds and the different types of trucks (more semi/tractor-trailer and fewer box-type trucks) is most likely why none of the trucks at the field test site on US290 at SH95 registered any significant mast arm motions or response.

Figure 5.3 shows that most of the trucks that caused any appreciable structural response (greater than ten microstrain) were traveling in Lane 2 (thirteen, compared to seven in Lane 1) even though, overall, the majority of all trucks traveled in Lane 1. Earlier, it was noted that none of the trucks in Lane 1 caused appreciable in-plane structural response. The dampening plate on the mast arm was located directly over Lane 2 which would increase the horizontal area that the truck's vertical pressure could affect. It is not known whether the trucks in Lane 2 would still cause in-plane structural response if the dampening plate were removed.

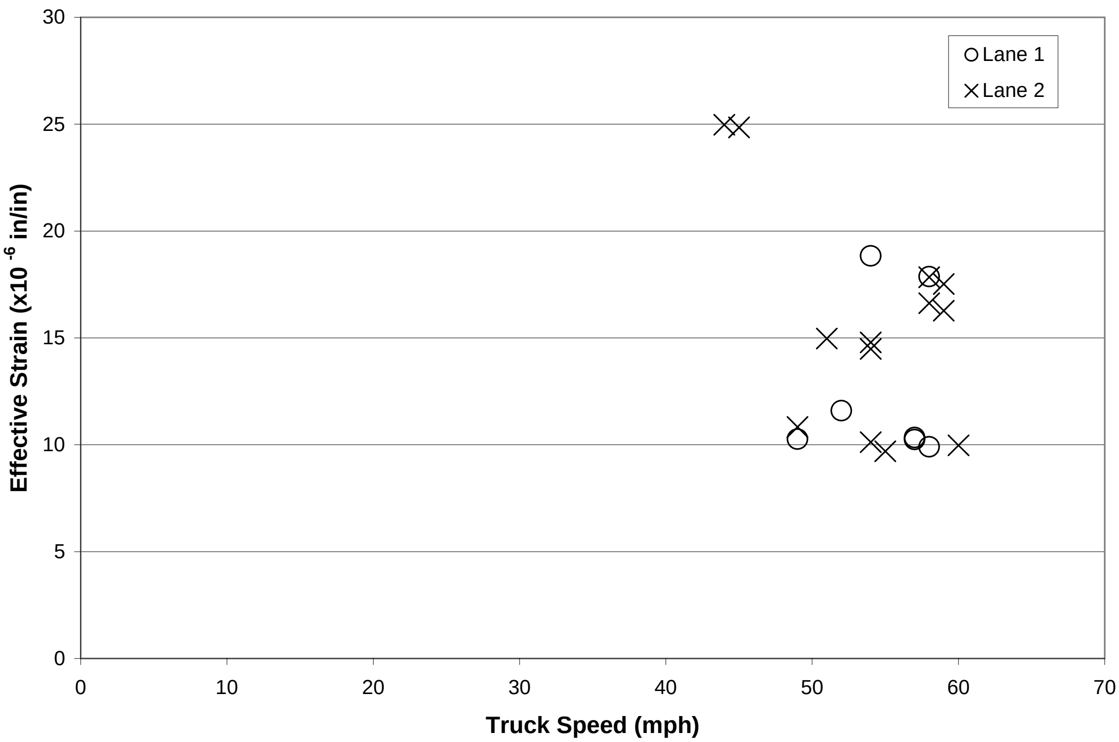


Figure 5.3: Influence of Traffic Lane on Mast Arm Structural Response (Strain)

5.1.5 Influence of Truck Speed

The AASHTO Specifications allow a reduction in the design equivalent static pressure by a factor of $(V / 65 \text{ mph})^2$ where V is the truck speed in mph or, equivalently, a reduction by a factor of $(V / 30 \text{ m/s})^2$ if the truck speed is in m/s (AASHTO, 2002). Thus, for a location with a speed limit of 55 mph (24.59 m/s), such as the test site on RM620 at Home Depot Blvd, the reduction factor would be 0.716, while for a location with a speed limit of 50 mph (22.35 m/s), such as the test site on US290 at SH95, it would be 0.592. However, as noted in Section 4.3, the majority of the trucks that were not affected by the traffic signal were still traveling at speeds below the posted speed limit, especially at the site on US290 at SH95.

By studying Figure 5.4, it is apparent that most of the trucks that caused any appreciable strains were traveling at speeds above 50 mph (22.35 m/s). Interestingly, there are a few cases such as the delivery truck, discussed in Section 4.4.5, which caused one of the largest out-of-plane strain ranges, even though that truck was only traveling at 45 mph (20.12 m/s). In Figure 5.4, the two truck events with effective strains of approximately 25 microstrain both occurred on September 26, 2005 which was a relatively windy day. Therefore, it should be noted that these two data points probably reflect the combined effects of both truck-induced gusts as well as natural wind gusts.

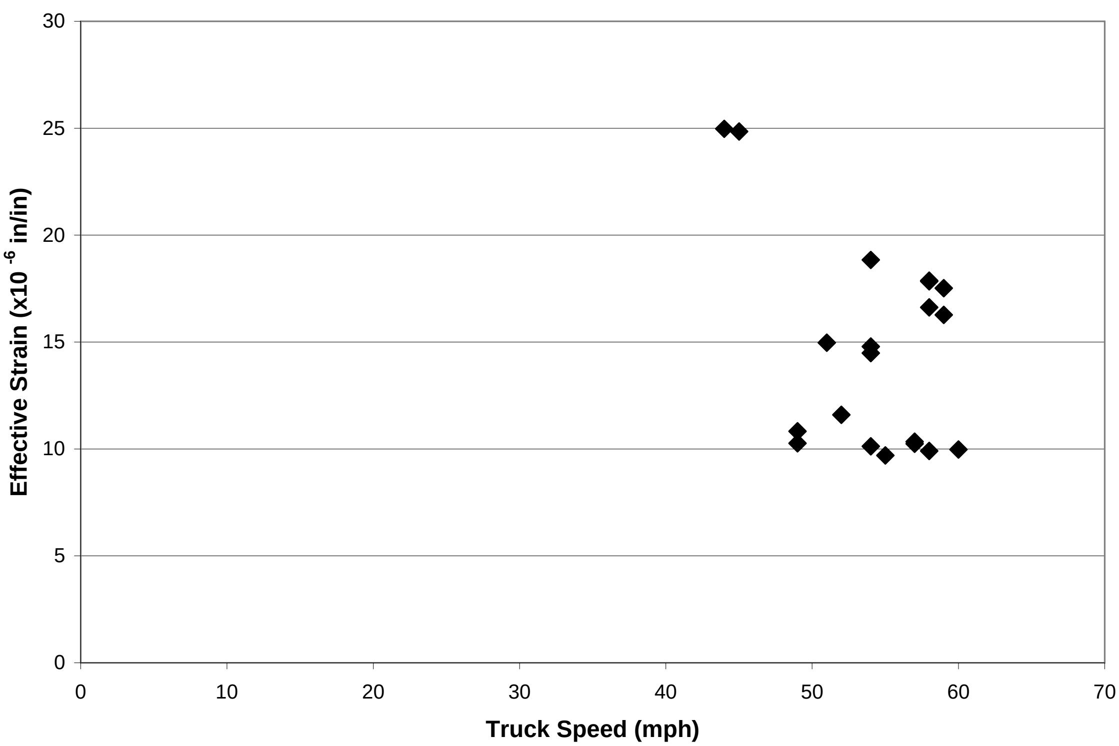


Figure 5.4: Influence of Truck Speed on Mast Arm Structural Response (Strain)

5.1.6 In-Plane versus Out-of-Plane Structural Response

One of the most unexpected results from this study was that truck-induced gusts appear to have a significant, and often greater, effect in the out-of-plane direction than was the case in the in-plane direction as shown in Figure 5.5. According to the AASHTO design code, only vibrations caused by the vertical force of the truck-induced gust need to be considered because in the horizontal direction, vibrations resulting from the natural wind are more dominant than those produced by truck-induced gusts (AASHTO, 2003). The code does not state where the information that led to these conclusions came from. However, there are some important things to note. First, as already discussed in the literature review in Chapter 2, most of the previous research on truck-induced gusts was performed on variable message sign structures. Previous research has shown that the damping of motions due to truck-induced gusts for a VMS structure is much greater in the out-of-plane direction than the in-plane direction. This can be confirmed by studying Figure 5.6. The greater damping for out-of-plane motions was stated to be due to the large amount of wind resistance as the sign moves through the air (Johns and Dexter, 1998). Johns and Dexter state that “this proves that it is not necessary to apply the truck-induced gust loads to the front of the structure because a natural wind gust will undoubtedly govern in this direction” (Johns and Dexter, 1998). Cantilevered traffic signal structures, though, are very different from VMS structures and generally exhibit similar damping characteristics and natural frequencies in in-plane and out-of-plane directions of motion (Florea, 2005). In this study, it was found that trucks often caused greater response levels in the horizontal (out-of-plane) direction than in the vertical (in-plane) direction for the cantilevered signal structures studied.

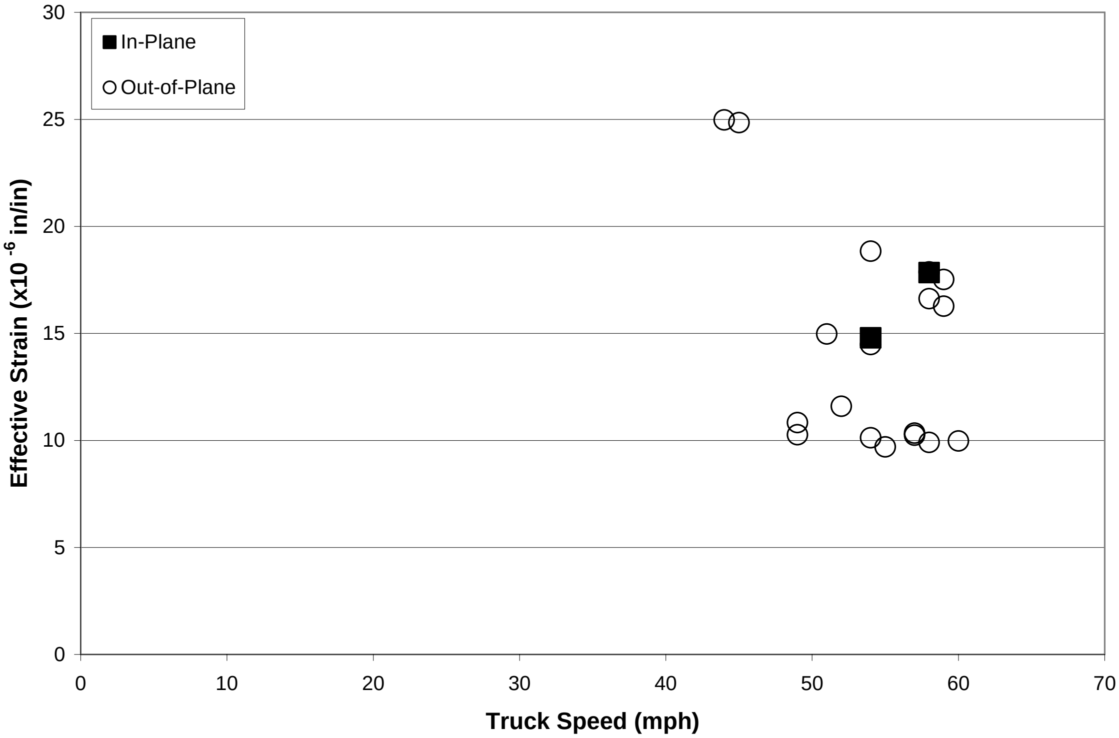


Figure 5.5: In-Plane versus Out-of-Plane Mast Arm Strains

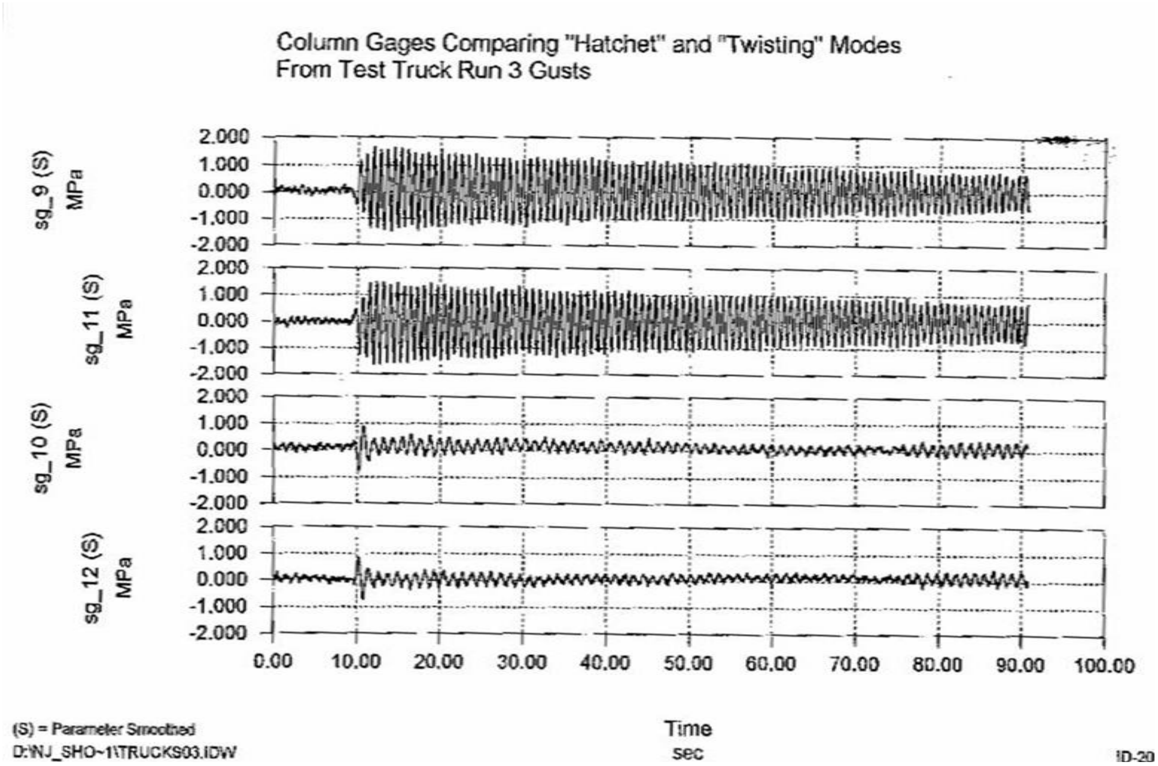


Figure 5.6: In-Plane versus Out-of-Plane Stresses for a VMS Structure (Johns and Dexter, 1998)

5.1.7 Structural Response Due to Truck-Induced Gusts versus Natural Wind

Throughout the field testing program, it was clear that the majority of the trucks caused no significant movement of the mast arms studied. However, the natural wind would sometimes cause noticeable tip displacements. As discussed in Section 4.5, there were virtually negligible strains in the mast arm on days without wind; yet, on windy days there were sometimes significant recordings of strains in both directions. In Figure 5.7, the twenty most important truck events are compared with some natural wind events. As seen in the figure, the natural wind is more critical for both in-plane and out-of-plane directions of motion. While comparing the influence of truck-induced gusts with that of natural wind gusts, it is assumed that the maximum truck-induced gusts at the sites were captured in the short-term monitoring of the structures because of the variety of different truck types that were recorded in each lane at speeds above the posted speed limit. However, it is known that the wind speed at a particular site can vary throughout the year. Thus, it cannot be assumed that the maximum natural wind loading was actually observed during the limited duration of field testing in this study. Therefore, the natural wind has the potential to have an even greater influence on the response of a cantilevered traffic signal structures over its service life than was found here. As previously discussed, truck-induced gust loads will only affect a small percentage of cantilevered traffic signal structures, but natural wind, on the other hand, affects every structure. Thus, it is imperative to correctly design cantilevered traffic signal structures for the more critical loading case of natural wind gusts, and if this is done correctly, the design will effectively account for truck-induced gusts.

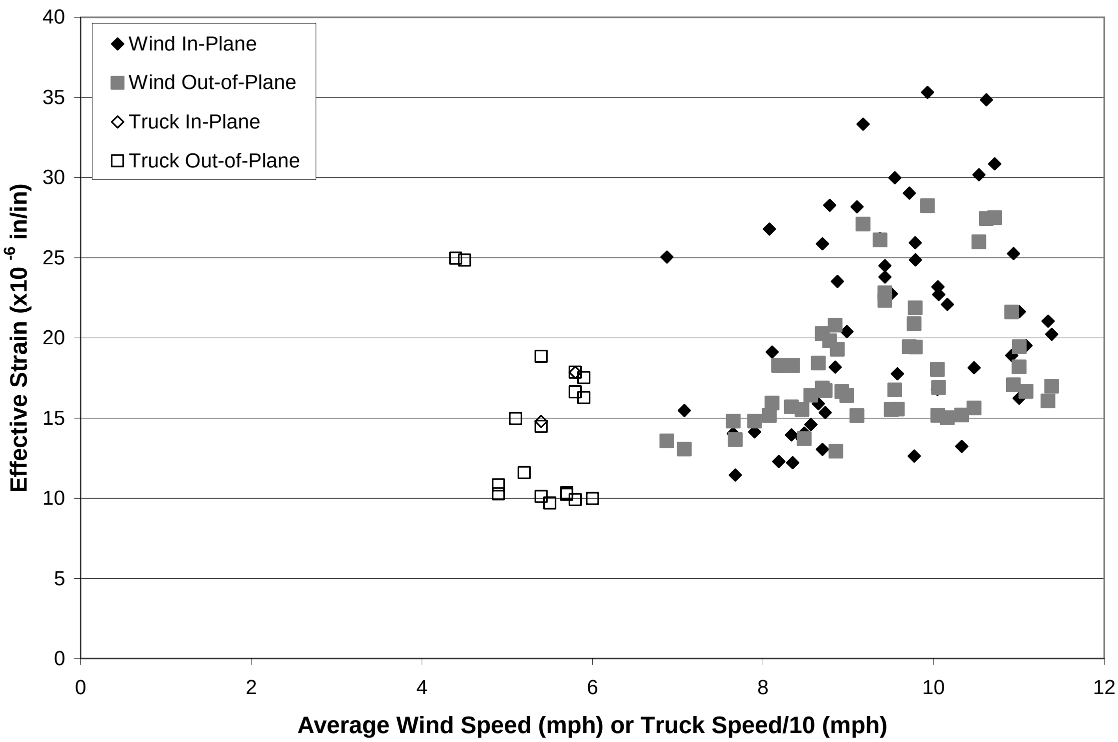


Figure 5.7: Influence of Truck-Induced Gust versus Natural Wind on In-Plane and Out-of-Plane Mast Arm Strains

5.2 COMPARISON OF RESULTS FROM FIELD DATA TO AASHTO DESIGN CODE

The strain data collected during the field tests can be directly compared with the strain levels consistent with the current AASHTO design code provisions. As shown in Table 5.1, the current AASHTO equivalent static pressure design equations for truck-induced gust loads on cantilevered traffic signal structures greatly overestimate the maximum strain range. Using the maximum strain range observed and the AASHTO design philosophy, new equivalent static pressure equations can be back-calculated. The AASHTO design equations would need to be reduced as much as 90% in order to accurately predict the maximum observed response of the cantilevered traffic signal structures due to truck-induced gusts in this study.

Table 5.1: Comparison of Observed Strain Range Levels to AASHTO Design Strain Ranges

Observed Max Strain Range (In-Plane)	Predicted Max Strain Range by AASHTO					
	Without Speed Reduction			With 55 mph Speed Reduction		
	I_F = 1.00	I_F = 0.84	I_F = 0.68	I_F = 1.00	I_F = 0.84	I_F = 0.68
27 $\mu\varepsilon$	339 $\mu\varepsilon$	285 $\mu\varepsilon$	231 $\mu\varepsilon$	243 $\mu\varepsilon$	204 $\mu\varepsilon$	165 $\mu\varepsilon$

5.3 CONCLUSIONS

5.3.1 Summary of Work

The research documented here was based upon a study of the effects of truck-induced gusts on cantilevered traffic signal structures in the field. Initially, an extensive literature review was completed through which valuable knowledge of cantilevered traffic signal structures was obtained. This provided a useful starting point for the design of a field testing setup. It was decided to complete short-term monitoring of the structures by measuring strain data in both the in-plane and out-of-plane directions. When a truck would pass beneath the mast arm, the time was recorded as were the speed of the truck and the traveling lane; additionally, a picture of the truck was taken. The method employed offered a rather simple and inexpensive way to obtain strain data as well as other pertinent information about the trucks. The only disadvantage was that the field testing was time-consuming since there was typically idle time between truck events. Long-term monitoring was also completed by recording rainflow cycle counts data using MicroSAFE devices.

Structures at two sites were instrumented as part of this study. One field test site was located on RM620 at Home Depot Blvd in Bee Cave, Texas; the other was located on US290 at SH95 in Elgin, Texas. Structures at both sites consisted of 40-foot mast arms; however, the site on RM620 at Home Depot Blvd was a single mast arm, while the site on US290 at SH95 was a dual mast arm assembly. Over 400 truck events (trucks not slowed down or stopped by the traffic signal) were observed at the two sites. Of these 400 truck events, only 18 trucks caused any significant or appreciable movement in the mast arm. Sixteen of these trucks only influenced the out-of-plane direction and two trucks influenced the mast arm in both the in-plane and out-of-plane directions. Thus, for this study, trucks were more likely to move the mast arm in the out-of-plane direction than in the in-plane direction. This contradicts the AASHTO design provisions which suggest that only truck-induced gusts in the vertical direction need to be considered (AASHTO, 2001).

Even though trucks potentially pose a greater problem in the out-of-plane direction than in the in-plane direction, the natural wind produced even greater response in both directions during the field tests. The natural wind produced greater strain amplitude cycles on the mast arm than any of the trucks. For this reason, the natural wind loads are concluded to be more critical than truck-induced gust loads for cantilevered traffic signal structures. Natural wind gusts can affect all cantilevered traffic signal structures whereas truck-induced gusts can only potentially affect a limited number of structures.

5.3.2 Recommendations

Based upon results from the field test studies carried out, it has been determined that truck-induced gusts are not a critical design loading consideration for cantilevered traffic signal structures. As previously discussed, natural wind has a far greater influence on the overall behavior of cantilevered traffic signal structures. Therefore, it is believed that if engineers design cantilevered traffic signal structures correctly for natural wind, then any possible influence of truck-induced gusts will automatically be accounted for. It is important to point out that this study did not include the effects of truck-induced gusts on cantilevered highway signs (VMS or regular) structures, so these conclusions should only be applied to cantilevered traffic signal structures. Also, this study was limited to only two cantilevered traffic signal structures in Texas, where there is a minimum clearance of 18 ft (5.5 m) above the roadway to the lowest point on the mast arm or attachments. It is believed that the most extreme truck-induced gust for each structure was observed and recorded, but the most extreme natural wind gust likely did not occur during the field testing. For this reason, the natural wind has the potential to be an even larger controlling factor in the design of cantilevered traffic signal structures than what was initially believed. This study did not check the validity of the AASHTO design equations for natural wind gusts on cantilevered traffic signal structures, but on the basis of back-calculated strains associated with the AASHTO-specified equivalent static pressure ranges for design against truck-induced gusts, it was found that the design pressure ranges are extremely conservative compared to the measured strains in the field for the two structures.

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Appendix B: AASHTO Design Example

AASHTO Design of Traffic Signal Due to Truck Gusts

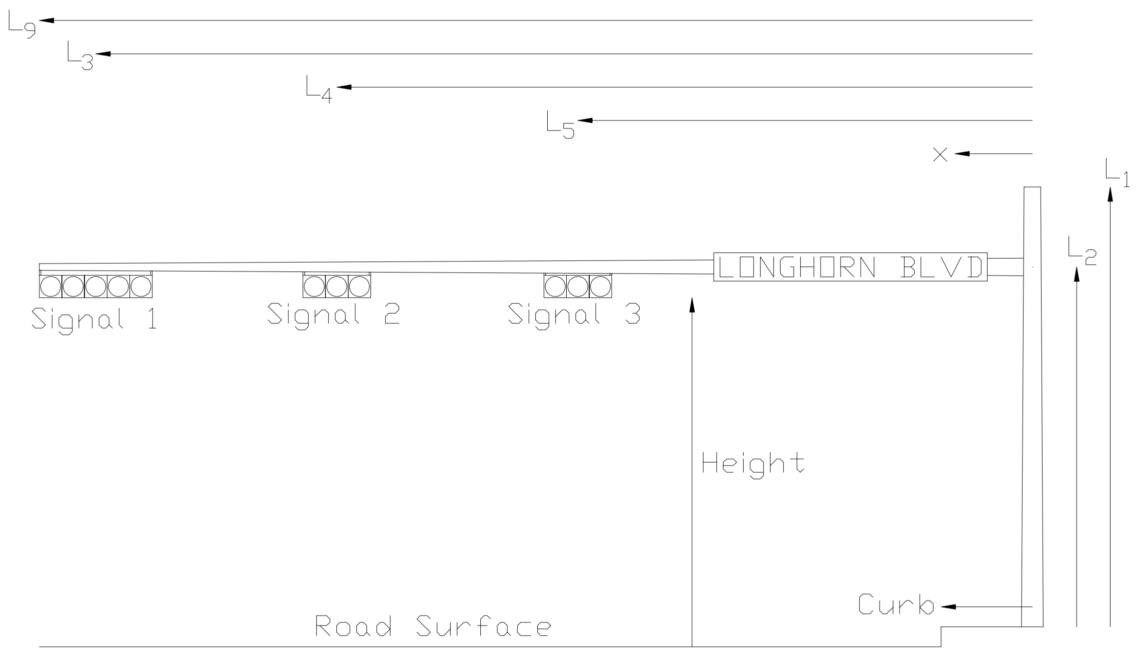
This program is written to do the 2003 AASHTO Fatigue Design of Traffic Signal Structures due to Truck-Induced Loading only. It assumes that the maximum number of attachments to the Traffic Signal Structure is five traffic signals and one dampening plate. It also assumes that signs in the vertical plane as well as signal back plates can be neglected.

Units and Definitions

$psf := \frac{lbf}{ft^2}$ $\quad$ $kip := 1000lbf$ $\quad$ $ksi := \frac{kip}{in^2}$ $\quad$ ORIGIN:= 1 $\quad$ $n := 1..5$

USER INPUTS

The user can change any of the values that are shaded.



Column Dimensions:

Column height = $L_1 := 22ft$

Height to mast arm = $L_2 := 18ft$

Outer diameter at base = $d_{bc} := 13in$

Outer diameter at tip = $d_{tc} := 10in$

Thickness = $t_c := 0.2391in$

Mast Arm Dimensions:

If there is not a signal or dampening plate, enter 0. Lengths are measured from the center of the column to the center of the signal or dampening plate. Signals are ordered starting with the one closest to the tip and continuing towards the column.

Length to signal 1 = $L_3 := 49ft$

Length to signal 2 = $L_4 := 37ft$

Length to signal 3 = $L_5 := 25ft$

Length to signal 4 = $L_6 := 0ft$

Length to signal 5 = $L_7 := 0ft$

Length to dampening plate = $L_8 := 0ft$

Length of mast arm = $L_9 := 52ft$

Outer diameter at base = $d_{bma} := 10.5in$

Outer diameter at tip = $d_{tma} := 4in$

Thickness = $t_{ma} := 0.2391in$

Dampening Plate Dimensions:

If there is not a dampening plate, enter 0 for L_8 under Mast Arm Dimensions. If $L_8 = 0$, then the following dimensions do not matter. **Note**: Do not enter 0 for W_{DP} or an error will occur.

Length of dampening plate: $L_{DP} := 24in$

Width of dampening plate: $W_{DP} := 4.8in$ $\qquad LW_{ratio} := \frac{L_{DP}}{W_{DP}} \qquad LW_{ratio} = 5$

Traffic Signal Dimensions:

Enter the number of section heads per signal. Remember that signals are ordered starting with the one closest to the tip and continuing towards the column.

$$NumSigHeads := \begin{pmatrix} 5 \\ 3 \\ 3 \\ 0 \\ 0 \end{pmatrix} \begin{matrix} \text{Signal 1} \\ \text{Signal 2} \\ \text{Signal 3} \\ \text{Signal 4} \\ \text{Signal 5} \end{matrix}$$

Effective Projected Area (EPA) for a single signal head = $EPA := 1.472ft^2$

Width of single signal head = $SigHead_{width} := 13.5in$

Height:

Height of horizontal support and attachments above traffic lane = $height := 18ft$

Speed Limit:

Posted speed limit at location of traffic signal = $V := 65mph$

Fatigue Category:

There are three fatigue categories of cantilevered support structures. Enter 1, 2, or 3.
Category Descriptions

1 - Critical cantilevered support structures installed on major highways.
2 - Other cantilevered support structures installed on major highways and all cantilevered support structures installed on secondary highways.
3 - Cantilevered support structures installed at all other locations.

Note: According to the AASHTO Commentary, traffic signal structures with long mast arms should be classified as category 1.

Fatigue category = $FC := 2$

Location of Applied Truck Gust Pressure:

The truck gust pressure range shall be applied along any 3.7 m (12 ft) length to create the maximum stress range, excluding any portion of the structure not located directly above a traffic lane. The distance to the curb is measured from the center of the column at the base to the curb.

Distance to curb = $curb := 3ft$

Distance Where You Wish To Know The Stress:

Note: You will want to be away from the stress concentration of the weld toe. However, this does mean that the weld toe sees a higher stress range than the one calculated by this program. The variable "xx" is the distance from the center of the column to the outer edge of the column based on the mast arm height. Thus, "x" (the stress location) must be at least the value of "xx" but not more than the length of the mast arm. It is recommended that you move 2 ft away from the weld toe to avoid the stress concentration.

$$xx := \frac{(d_{bc} - d_{tc})}{2 \cdot L_1} \cdot \left(L_1 - L_2 - \frac{d_{bma}}{2}\right) + \frac{d_{tc}}{2} \qquad xx = 5.243in$$

Distance from weld toe = $Distance_{weld} := 2ft$

$$x := xx + Distance_{weld}$$

$$Location := \begin{cases} error(\text{"x is too small"}) & \text{if } x < xx \\ (error(\text{"x is too large"})) & \text{if } x > L_9 \\ x & \text{otherwise} \end{cases}$$

$$Location = 2.437ft$$

<u>**STOP**</u>**: Make sure that the above calculation is not red before moving on.**

<u>**NOTE:**</u> This concludes the user inputs section.

CALCULATIONS

Truck Gusts Calculations:

Fatigue Importance Factor

$$I_F := \begin{cases} 1.0 & \text{if } FC = 1 \\ 0.84 & \text{if } FC = 2 \\ 0.68 & \text{if } FC = 3 \end{cases}$$ (AASHTO Table 11-1)

$I_F = 0.84$

Wind Drag Coefficients

$C_{dMA} := 1.1$ (C_d for Mast Arm = 1.1 (AASHTO Table 3-6))

$C_{dTS} := 1.2$ (C_d for Traffic Signal = 1.2 (AASHTO Table 3-6))

$$C_{dDP} := \begin{cases} 1.12 & \text{if } LW_{ratio} \le 1.0 \\ 1.19 & \text{if } 1.0 < LW_{ratio} \le 2.0 \\ 1.20 & \text{if } 2.0 < LW_{ratio} \le 5.0 \\ 1.23 & \text{if } 5.0 < LW_{ratio} \le 10.0 \\ 1.30 & \text{if } LW_{ratio} > 10.0 \end{cases}$$

(C_d for Dampening Plate depends on the length to width ratio of the plate, this command assumes that the L/W ratio is rounded up to the next interval given in the table (AASHTO Table 3-6))

$$C_d := \begin{pmatrix} C_{dMA} \\ C_{dTS} \\ C_{dDP} \end{pmatrix} \qquad C_d = \begin{pmatrix} 1.1 \\ 1.2 \\ 1.2 \end{pmatrix} \begin{matrix} \text{Mast Arm} \\ \text{Traffic Signal} \\ \text{Dampening Plate} \end{matrix}$$

Equivalent Static Pressure

Description: The passage of trucks beneath cantilevered support structures may induce gust loads on the attachments mounted to the horizontal support of these structures. Although loads are applied in both the horizontal and vertical directions, horizontal support vibrations caused by forces in the vertical direction are most critical. Therefore, truck gust pressures are applied only to the exposed horizontal surface of the attachment and horizontal support. Overhead sign and traffic signal support structures shall be designed to resist an equivalent static truck gust pressure range.

$$P_{TG} = 900 \cdot C_d \cdot I_F$$ (Pa) (AASHTO Eq. 11-6)

$$P_{TG} = 18.8 \cdot C_d \cdot I_F$$ (psf)

Reduction due to speeds less than 30 m/s (65 mph)

Description: The equivalent static truck pressure range may be reduced for locations where vehicle speeds are less than 30 m/s (65 mph).

$$P_{TG} = 900 \cdot C_d \cdot \left(\frac{V}{30 \frac{m}{s}} \right)^2 \cdot I_F$$ (Pa) (AASHTO Eq. C 11-6)

$$P_{TG} = 18.8 \cdot C_d \cdot \left(\frac{V}{65mph}\right)^2 \cdot I_F \qquad \text{(psf)}$$

Reduction due to height above traffic lane

Description: Full pressure shall be applied for heights up to and including 6 m (19.7 ft), and then the pressure may be linearly reduced for heights above 6 m (19.7 ft) to a value of zero at 10 m (32.8 ft).

$$P_{TG} = \left| \begin{array}{l} P_{TG} \ \text{ if height} \le 6m \\ P_{TG} - \frac{\text{height} - 6m}{10m - 6m} \cdot (P_{TG} - 0psf) \\ 0psf \ \text{ if height} \ge 10m \end{array} \right.$$

Equivalent Static Pressure Calculations:

Pressure from Truck Gust with Reductions

$$P := 18.8 psf \cdot \left(\frac{V}{65mph}\right)^2 \cdot I_F$$

$$P := \left[\left| \begin{array}{l} P \ \text{ if height} \le 6m \\ \left[P - \frac{\text{height} - 6m}{10m - 6m} \cdot (P - 0psf) \right] \ \text{ if height} > 6m \\ 0psf \ \text{ if height} \ge 10m \end{array} \right. \right]$$

$$P_{TG} := P \cdot C_d$$

$$P_{TG} = \begin{pmatrix} 17.371 \\ 18.95 \\ 18.95 \end{pmatrix} psf \quad \begin{array}{l} \text{Mast Arm} \\ \text{Traffic Signal} \\ \text{Dampening Plate} \end{array}$$

Equivalent Static Force Calculations:

The equivalent static force is the pressure times the area on which the pressure is applied. The pressure is applied over the 3.7 m (12 ft) length that creates the maximum stress range. Thus, the forces are functions of location.

Force from Truck Gust on Mast Arm

Diameter of mast arm at beginning of 12 ft section:

$$d_1(loc) := \frac{(d_{tma} - d_{bma}) \cdot (loc - xx)}{L_9 - xx} + d_{bma}$$

Diameter of mast arm at end of 12 ft section:

$$d_2(loc) := \frac{(d_{tma} - d_{bma}) \cdot (loc + 12ft - xx)}{L_9 - xx} + d_{bma}$$

Projected area of the mast arm:

$$A_{armhor}(loc) := 12ft \cdot \frac{(d_1(loc) + d_2(loc))}{2}$$

Force from truck gust on mast arm:

$$F_{TGma}(loc) := P_{TG_{1,1}} \cdot A_{armhor}(loc)$$

Note: It is conservatively assumed that F_{TGma} acts at the midpoint of the 12 ft.

Moment arm for the force acting on the mast arm:

$$MomentArm_{ma}(loc) := loc + 6ft - x$$

<u>Force from Truck Gust on Traffic Signals</u>

Projected Area for the traffic signal:

$$A_{sighor} := Num_{SigHeads} \cdot \frac{EPA}{ft^2} \qquad A_{sighor} = \begin{pmatrix} 7.36 \\ 4.416 \\ 4.416 \\ 0 \\ 0 \end{pmatrix} \begin{array}{l} \text{Signal 1} \\ \text{Signal 2} \\ \text{Signal 3} \\ \text{Signal 4} \\ \text{Signal 5} \end{array}$$

For design purposes the Projected Area will be rounded up.

$$Area_{sighor_{n,1}} := \left| \begin{array}{ll} 0 \cdot ft^2 & \text{if } A_{sighor_{n,1}} = 0 \\ \left(\text{trunc}\left(A_{sighor_{n,1}}\right) + 1\right) \cdot ft^2 & \text{otherwise} \end{array} \right.$$

$$Area_{sighor} = \begin{pmatrix} 8 \\ 5 \\ 5 \\ 0 \\ 0 \end{pmatrix} ft^2 \begin{array}{l} \text{Signal 1} \\ \text{Signal 2} \\ \text{Signal 3} \\ \text{Signal 4} \\ \text{Signal 5} \end{array}$$

Starting location for traffic signals:

$$TS_{start} := \begin{pmatrix} L_3 - Num_{SigHeads_{1,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_4 - Num_{SigHeads_{2,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_5 - Num_{SigHeads_{3,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_6 - Num_{SigHeads_{4,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_7 - Num_{SigHeads_{5,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \end{pmatrix} \qquad TS_{start} = \begin{pmatrix} 46.187 \\ 35.313 \\ 23.312 \\ 0 \\ 0 \end{pmatrix} ft$$

Ending location for traffic signals:

$$TS_{end} := \begin{pmatrix} L_3 + Num_{SigHeads_{1,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_4 + Num_{SigHeads_{2,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_5 + Num_{SigHeads_{3,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_6 + Num_{SigHeads_{4,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \\ L_7 + Num_{SigHeads_{5,1}} \cdot \frac{1}{2} \cdot SigHead_{width} \end{pmatrix} \qquad TS_{end} = \begin{pmatrix} 51.813 \\ 38.688 \\ 26.687 \\ 0 \\ 0 \end{pmatrix} ft$$

Length of traffic signals:

$$TS_{length_{n,1}} := TS_{end_{n,1}} - TS_{start_{n,1}} \qquad TS_{length} = \begin{pmatrix} 5.625 \\ 3.375 \\ 3.375 \\ 0 \\ 0 \end{pmatrix} ft$$

Length of traffic signals in 12 ft section of applied pressure:

$$Length_{TS1}(loc) := \begin{cases} TS_{end_{1,1}} - loc & \text{if } 0ft \le TS_{end_{1,1}} - loc \le TS_{length_{1,1}} \\ loc + 12ft - TS_{start_{1,1}} & \text{if } 0ft \le loc + 12ft - TS_{start_{1,1}} \le TS_{length_{1,1}} \\ 0ft & \text{if } TS_{end_{1,1}} \le loc \\ 0ft & \text{if } TS_{start_{1,1}} \ge loc + 12ft \\ TS_{length_{1,1}} & \text{otherwise} \end{cases}$$

$$Length_{TS2}(loc) := \begin{cases} TS_{end_{2,1}} - loc & \text{if } 0ft \le TS_{end_{2,1}} - loc \le TS_{length_{2,1}} \\ loc + 12ft - TS_{start_{2,1}} & \text{if } 0ft \le loc + 12ft - TS_{start_{2,1}} \le TS_{length_{2,1}} \\ 0ft & \text{if } TS_{end_{2,1}} \le loc \\ 0ft & \text{if } TS_{start_{2,1}} \ge loc + 12ft \\ TS_{length_{2,1}} & \text{otherwise} \end{cases}$$

$$Length_{TS3}(loc) := \begin{cases} TS_{end_{3,1}} - loc & \text{if } 0ft \le TS_{end_{3,1}} - loc \le TS_{length_{3,1}} \\ loc + 12ft - TS_{start_{3,1}} & \text{if } 0ft \le loc + 12ft - TS_{start_{3,1}} \le TS_{length_{3,1}} \\ 0ft & \text{if } TS_{end_{3,1}} \le loc \\ 0ft & \text{if } TS_{start_{3,1}} \ge loc + 12ft \\ TS_{length_{3,1}} & \text{otherwise} \end{cases}$$

$$\mathrm{Length}_{TS4}(loc) := \left| \begin{array}{l} TS_{end_{4,1}} - loc \ \text{ if } \ 0ft \le TS_{end_{4,1}} - loc \le TS_{length_{4,1}} \\ loc + 12ft - TS_{start_{4,1}} \ \text{ if } \ 0ft \le loc + 12ft - TS_{start_{4,1}} \le TS_{length_{4,1}} \\ 0ft \ \text{ if } \ TS_{end_{4,1}} \le loc \\ 0ft \ \text{ if } \ TS_{start_{4,1}} \ge loc + 12ft \\ TS_{length_{4,1}} \ \text{ otherwise} \end{array} \right.$$

$$\mathrm{Length}_{TS5}(loc) := \left| \begin{array}{l} TS_{end_{5,1}} - loc \ \text{ if } \ 0ft \le TS_{end_{5,1}} - loc \le TS_{length_{5,1}} \\ loc + 12ft - TS_{start_{5,1}} \ \text{ if } \ 0ft \le loc + 12ft - TS_{start_{5,1}} \le TS_{length_{5,1}} \\ 0ft \ \text{ if } \ TS_{end_{5,1}} \le loc \\ 0ft \ \text{ if } \ TS_{start_{5,1}} \ge loc + 12ft \\ TS_{length_{5,1}} \ \text{ otherwise} \end{array} \right.$$

$$\mathrm{AreaFractionApplied}(loc) := \begin{pmatrix} \dfrac{\mathrm{Length}_{TS1}(loc)}{TS_{length_{1,1}}} \\ \dfrac{\mathrm{Length}_{TS2}(loc)}{TS_{length_{2,1}}} \\ \dfrac{\mathrm{Length}_{TS3}(loc)}{TS_{length_{3,1}}} \\ \dfrac{\mathrm{Length}_{TS4}(loc)}{TS_{length_{4,1}}} \\ \dfrac{\mathrm{Length}_{TS5}(loc)}{TS_{length_{5,1}}} \end{pmatrix}$$

Force from truck gust on traffic signals:

$$F_{TGts}(loc) := \begin{pmatrix} P_{TG_{2,1}} \cdot \mathrm{Area}_{sighor_{1,1}} \cdot \mathrm{AreaFractionApplied}(loc)_{1,1} \\ P_{TG_{2,1}} \cdot \mathrm{Area}_{sighor_{2,1}} \cdot \mathrm{AreaFractionApplied}(loc)_{2,1} \\ P_{TG_{2,1}} \cdot \mathrm{Area}_{sighor_{3,1}} \cdot \mathrm{AreaFractionApplied}(loc)_{3,1} \\ P_{TG_{2,1}} \cdot \mathrm{Area}_{sighor_{4,1}} \cdot \mathrm{AreaFractionApplied}(loc)_{4,1} \\ P_{TG_{2,1}} \cdot \mathrm{Area}_{sighor_{5,1}} \cdot \mathrm{AreaFractionApplied}(loc)_{5,1} \end{pmatrix}$$

Moment arm for the force acting on the traffic signals:

$$\mathrm{MomentArm}_{ts1}(loc) := \begin{vmatrix} TS_{start_{1,1}} + \dfrac{\mathrm{Length}_{TS1}(loc)}{2} - x & \text{if } loc + 6ft \le L_3 \\ TS_{end_{1,1}} - \dfrac{\mathrm{Length}_{TS1}(loc)}{2} - x & \text{if } loc + 6ft > L_3 \end{vmatrix}$$

$$\mathrm{MomentArm}_{ts2}(loc) := \begin{vmatrix} TS_{start_{2,1}} + \dfrac{\mathrm{Length}_{TS2}(loc)}{2} - x & \text{if } loc + 6ft \le L_4 \\ TS_{end_{2,1}} - \dfrac{\mathrm{Length}_{TS2}(loc)}{2} - x & \text{if } loc + 6ft > L_4 \end{vmatrix}$$

$$\mathrm{MomentArm}_{ts3}(loc) := \begin{vmatrix} TS_{start_{3,1}} + \dfrac{\mathrm{Length}_{TS3}(loc)}{2} - x & \text{if } loc + 6ft \le L_5 \\ TS_{end_{3,1}} - \dfrac{\mathrm{Length}_{TS3}(loc)}{2} - x & \text{if } loc + 6ft > L_5 \end{vmatrix}$$

$$\mathrm{MomentArm}_{ts4}(loc) := \begin{vmatrix} TS_{start_{4,1}} + \dfrac{\mathrm{Length}_{TS4}(loc)}{2} - x & \text{if } loc + 6ft \le L_6 \\ TS_{end_{4,1}} - \dfrac{\mathrm{Length}_{TS4}(loc)}{2} - x & \text{if } loc + 6ft > L_6 \end{vmatrix}$$

$$\mathrm{MomentArm}_{ts5}(loc) := \begin{vmatrix} TS_{start_{5,1}} + \dfrac{\mathrm{Length}_{TS5}(loc)}{2} - x & \text{if } loc + 6ft \le L_7 \\ TS_{end_{5,1}} - \dfrac{\mathrm{Length}_{TS5}(loc)}{2} - x & \text{if } loc + 6ft > L_7 \end{vmatrix}$$

$$\mathrm{MomentArm}_{ts}(loc) := \begin{pmatrix} \mathrm{MomentArm}_{ts1}(loc) \\ \mathrm{MomentArm}_{ts2}(loc) \\ \mathrm{MomentArm}_{ts3}(loc) \\ \mathrm{MomentArm}_{ts4}(loc) \\ \mathrm{MomentArm}_{ts5}(loc) \end{pmatrix}$$

Force from Truck Gust on Dampening Plate

Start of dampening plate: $DP_{start} := \begin{vmatrix} 0ft & \text{if } L_8 = 0ft \\ L_8 - \dfrac{L_{DP}}{2} & \text{otherwise} \end{vmatrix}$ $\quad DP_{start} = 0\,ft$

End of dampening plate: $DP_{end} := \begin{vmatrix} 0ft & \text{if } L_8 = 0ft \\ L_8 + \dfrac{L_{DP}}{2} & \text{otherwise} \end{vmatrix}$ $\quad DP_{end} = 0\,ft$

Length of dampening plate:

$$\text{Length}_{DP}(\text{loc}) := \begin{cases} DP_{end} - \text{loc} & \text{if } 0ft \le DP_{end} - \text{loc} \le L_{DP} \\ \text{loc} + 12ft - DP_{start} & \text{if } 0ft \le \text{loc} + 12ft - DP_{start} \le L_{DP} \\ 0ft & \text{if } DP_{end} \le \text{loc} \\ 0ft & \text{if } DP_{start} \ge \text{loc} + 12ft \\ L_{DP} & \text{otherwise} \end{cases}$$

Force from truck gust on dampening plate:

$$F_{TGdp}(\text{loc}) := P_{TG_{3,1}} \cdot W_{DP} \cdot \text{Length}_{DP}(\text{loc})$$

Moment arm for the force acting on the dampening plate:

$$\text{MomentArm}_{dp}(\text{loc}) := \begin{cases} DP_{start} + \dfrac{\text{Length}_{DP}(\text{loc})}{2} - x & \text{if } \text{loc} + 6ft \le L_8 \\ DP_{end} - \dfrac{\text{Length}_{DP}(\text{loc})}{2} - x & \text{if } \text{loc} + 6ft > L_8 \end{cases}$$

Calculation of Maximum Bending Moment

Determine "loc" that produces the maximum bending moment:

$$\begin{aligned} M_{TG}(\text{loc}) := {} & F_{TGma}(\text{loc}) \cdot \text{MomentArm}_{ma}(\text{loc}) + F_{TGts}(\text{loc})_{1,1} \cdot \text{MomentArm}_{ts}(\text{loc})_{1,1} \ldots \\ & + F_{TGts}(\text{loc})_{2,1} \cdot \text{MomentArm}_{ts}(\text{loc})_{2,1} + F_{TGts}(\text{loc})_{3,1} \cdot \text{MomentArm}_{ts}(\text{loc})_{3,1} \ldots \\ & + F_{TGts}(\text{loc})_{4,1} \cdot \text{MomentArm}_{ts}(\text{loc})_{4,1} + F_{TGts}(\text{loc})_{5,1} \cdot \text{MomentArm}_{ts}(\text{loc})_{5,1} \ldots \\ & + F_{TGdp}(\text{loc}) \cdot \text{MomentArm}_{dp}(\text{loc}) \end{aligned}$$

$$\text{loc} := L_9 - 12ft$$

Given

$$\text{loc} \le L_9 - 12ft \qquad \text{loc} \ge \text{curb}$$

$$\text{Loc}_{start} := \text{Maximize}(M_{TG}, \text{loc}) \qquad \text{Loc}_{end} := \text{Loc}_{start} + 12ft \qquad \text{Loc}_{start} = 39.813ft$$

$$M_{TG} := M_{TG}(\text{Loc}_{start}) \qquad M_{TG} = 127.929 kip \cdot in$$ Moment due to Truck Gust at location "x".

Stress at location "x"

Diameter of mast arm at location "x":

$$d_{xma} := \frac{(d_{tma} - d_{bma}) \cdot (x - xx)}{L_9 - xx} + d_{bma}$$

Moment of Inertia at location "x":

$$I_{xma} := \frac{\pi}{64} \cdot \left[d_{xma}^{\ 4} - (d_{xma} - 2 \cdot t_{ma})^4 \right]$$

Stress at location "x":

$$c_x := \frac{d_{xma}}{2}$$

$$\text{Stress} := \frac{M_{TG} \cdot c_x}{I_{xma}} \qquad \text{Stress} = 6.959ksi$$ Stress due to Truck Gust at location "x".

SUMMARY OF IMPORTANT VALUES

Note: It is OK if the moment arm values are negative.

Fatigue Importance Factor = $I_F = 0.84$

Wind Drag Coefficients = $C_d = \begin{pmatrix} 1.1 \\ 1.2 \\ 1.2 \end{pmatrix}$ $\begin{matrix} \text{Mast Arm} \\ \text{Traffic Signal} \\ \text{Dampening Plate} \end{matrix}$

Pressure from Truck Gust with Reductions = $P_{TG} = \begin{pmatrix} 17.371 \\ 18.95 \\ 18.95 \end{pmatrix} \text{psf}$ $\begin{matrix} \text{Mast Arm} \\ \text{Traffic Signal} \\ \text{Dampening Plate} \end{matrix}$

Starting Location for Applied Truck Gust = $Loc_{start} = 39.813\text{ft}$

Ending Location for Applied Truck Gust = $Loc_{end} = 51.813\text{ft}$

Force from Truck Gust on Mast Arm = $F_{TGma}(Loc_{start}) = 83.034\text{lbf}$

Moment Arm for Force Acting on Mast Arm = $MomentArm_{ma}(Loc_{start}) = 43.376\text{ft}$

Force from Truck Gust on Traffic Signals = $F_{TGts}(Loc_{start}) = \begin{pmatrix} 151.603 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{lbf}$ $\begin{matrix} \text{Signal 1} \\ \text{Signal 2} \\ \text{Signal 3} \\ \text{Signal 4} \\ \text{Signal 5} \end{matrix}$

Moment Arm for Force Acting on Traffic Signals = $MomentArm_{ts}(Loc_{start}) = \begin{pmatrix} 46.563 \\ 36.251 \\ 24.251 \\ -2.437 \\ -2.437 \end{pmatrix} \text{ft}$

Force from Truck Gust on Dampening Plate = $F_{TGdp}(Loc_{start}) = 0\,\text{lbf}$

Moment Arm for Force Acting on Dampening Plate = $MomentArm_{dp}(Loc_{start}) = -2.437\text{ft}$

Location to Determine Stress ("x") = $x = 2.437\text{ft}$

Maximum Bending Moment at "x" = $M_{TG} = 127.929\text{kip}\cdot\text{in}$

Stress at "x" = $Stress = 6.959\text{ksi}$

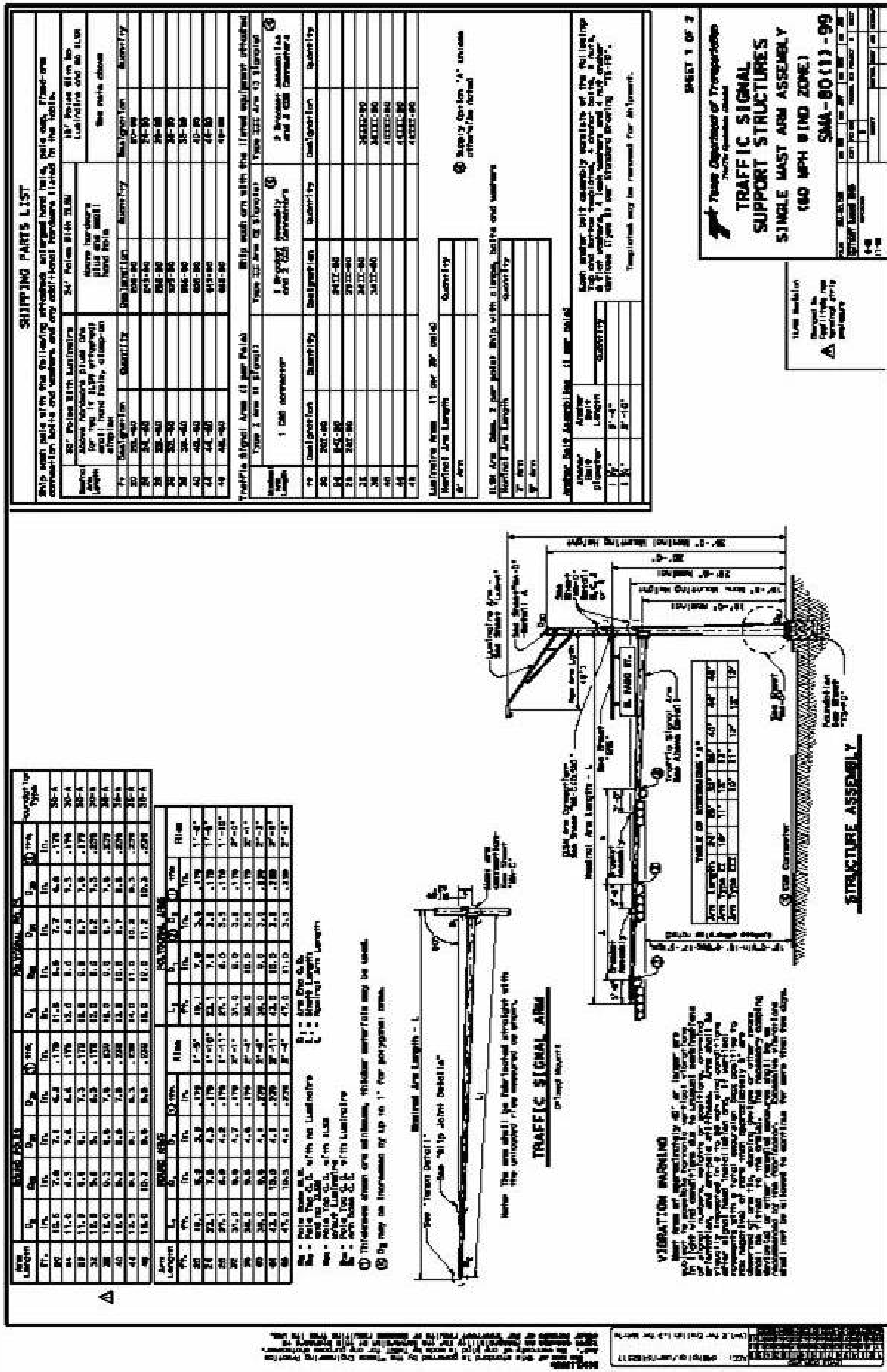
Note: This is the stress at location "x". However, the stress at the weld toe is larger due to a stress concentration.

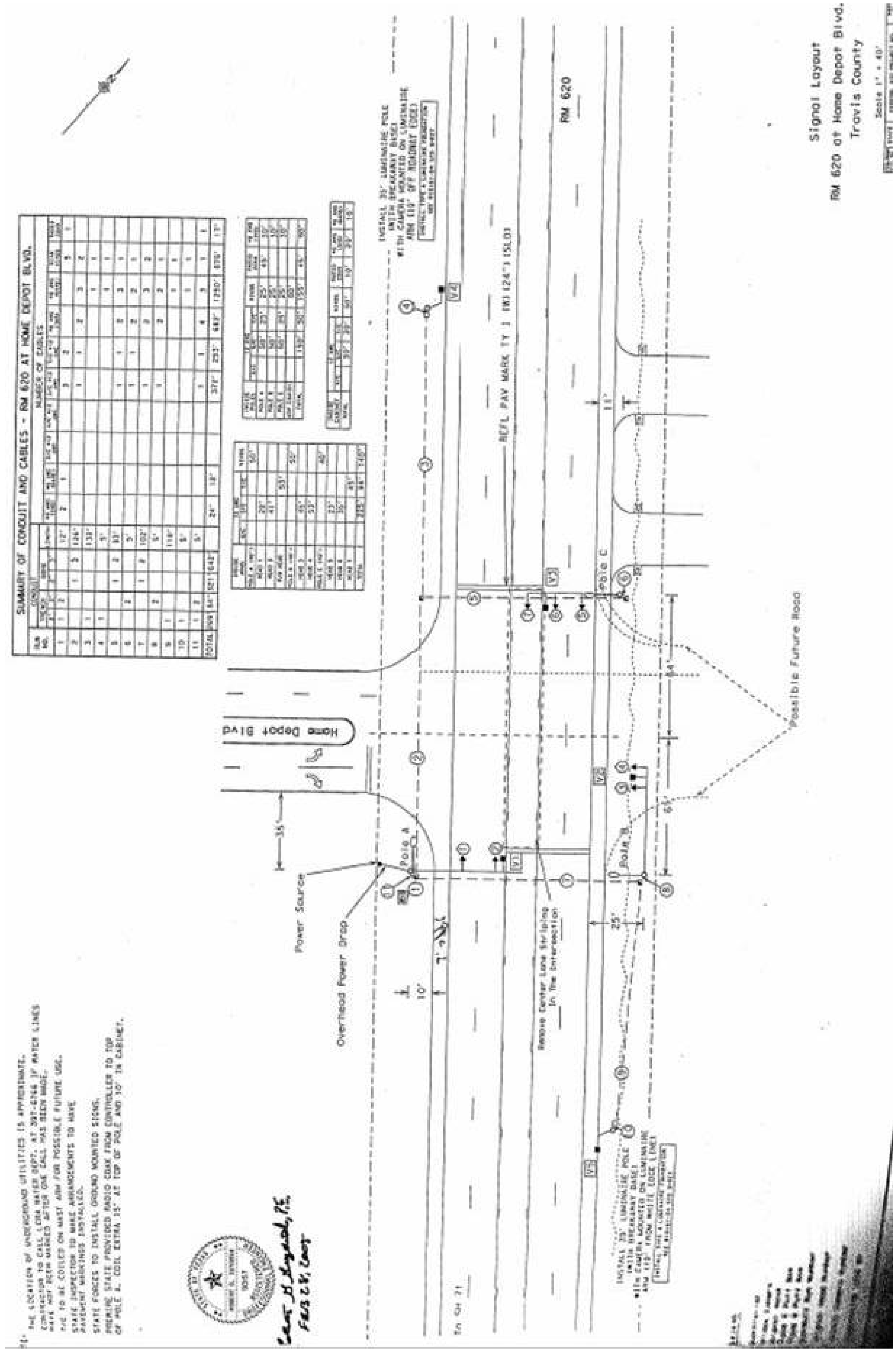
Appendix C: Potential Sites for Field Tests

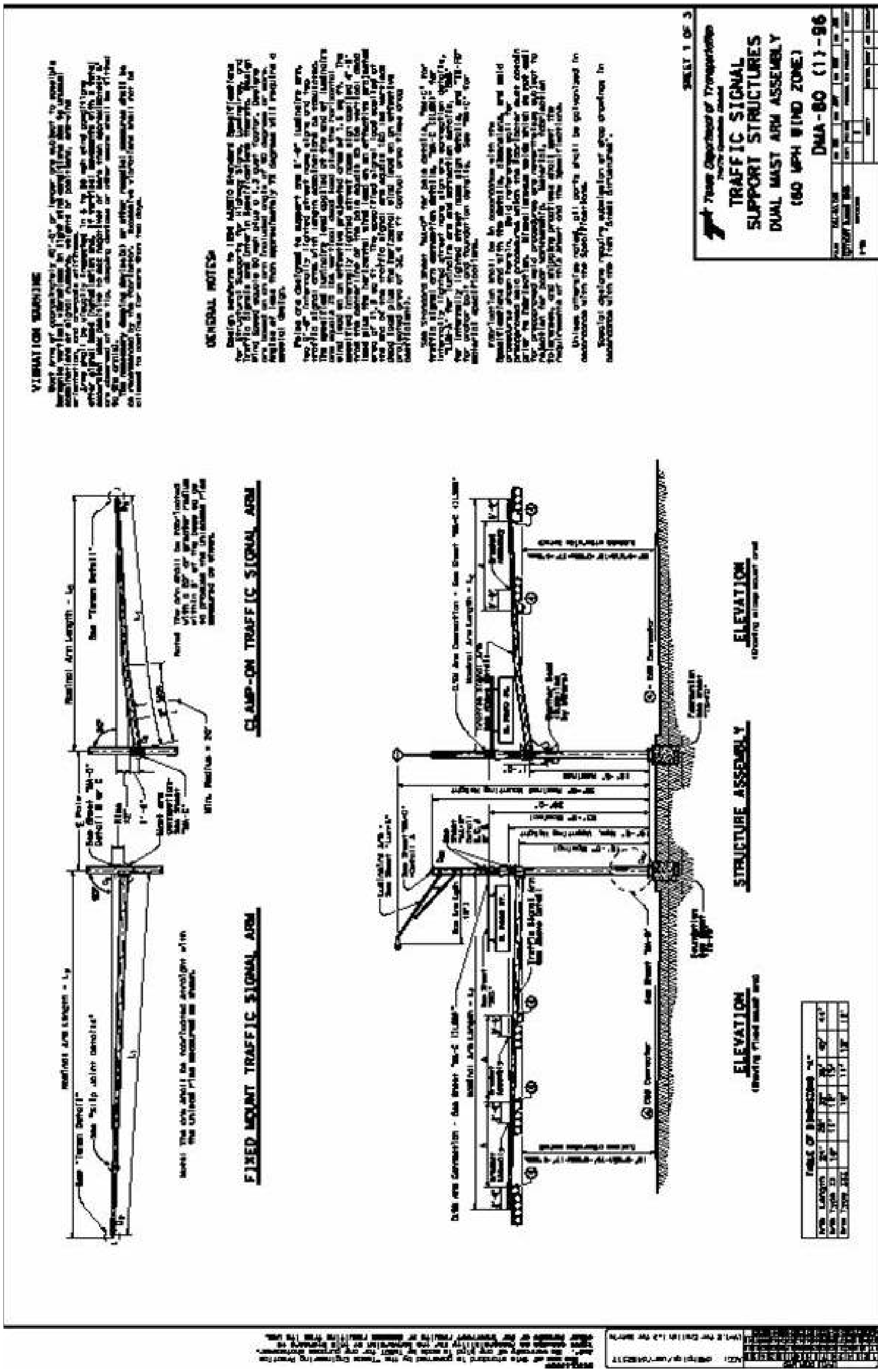
#	Site Intersection
1	~~US183 AT SH29~~
2	~~RM1431 AT FM734~~
3	~~US79 AT FM685~~
4	~~SH95 AT SL397~~
5	**US290 AT SH95**
6	**US290 AT SH95S**
7	~~US290 AT SL109~~
8	~~US290 AT 11TH ST~~
9	~~US290 AT NUTTY BROWN RD~~
10	~~US290 AT SAWYER RANCH~~
11	~~SL1 AT LA CROSSE~~
12	~~RM620 AT QUINLAN PARK RD~~
13	~~RM620 AT COMMANCHE TRAIL~~
14	~~RM620 AT STEINER RANCH~~
15	~~RM620 AT RM2222 / BULLOCK HOLLOW~~
16	~~RM620 AT FOUR POINTS~~
17	~~RM620 AT WILSON PARKE / ROCK HARBOUR~~
18	~~RM620 AT BOULDER S~~
19	~~RM620 AT BOULDER / BUCKNER~~
20	~~RM620 EFR AT FM734~~
21	~~RM620 AT NFR AT FM734~~
22	~~FM734 AT BRUSHY CREEK RD~~
23	~~FM734 AT AVERY RANCH~~
24	~~FM734 AT NEENAH~~
25	~~FM734 AT SPECTRUM~~
26	~~FM734 AT AMBERGLENN~~
27	~~FM734 AT ANDERSON MILL~~
28	~~FM734 AT TAMAYO~~
29	~~FM734 AT DALLAS~~
30	~~IH35 WFR AT US183~~
31	**RM2222 AT RIVER PLACE BLVD**
32	**RM2222 AT MCNEIL DR**
33	~~RM1431 AT VISTA RIDGE~~
34	**SH29 AT INNER LOOP**
35	**FM973 AT PEARCE LANE**
36	**FM685 AT ROWE LN**
37	~~FM685 AT KELLY~~
38	~~RM620 AT SH71~~
39	**RM620 AT HOME DEPOT BLVD**
40	~~RM620 AT FALCONHEAD~~
41	**US183 AT NEW HOPE DR (CR-181)**
42	**SH29 AT DB WOOD DR**
43	**US290 AT CONVICT HILL RD**
44	**RM620 AT LAKE TRAVIS HIGH SCHOOL**
45	**RM620 AT LOHMANS SPUR**
46	**RM620 AT LAKEWAY BLVD**

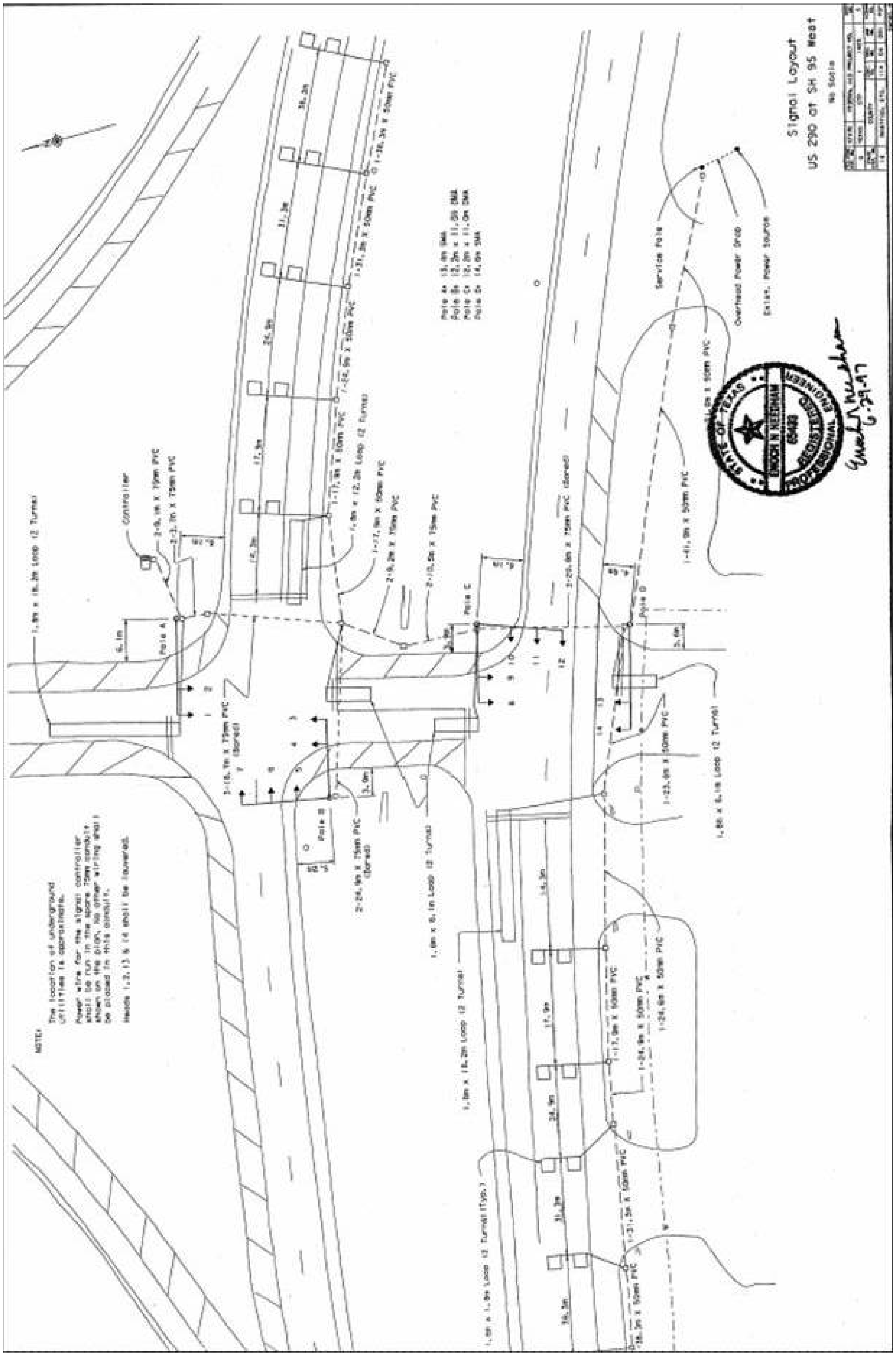
Sites with strike-though are not mast arms. They are wire-supported signals. Sites in bold are mast arms and were potential sites for the project.

Appendix D: TxDOT Drawings for the Two Field Sites and the Signal Structures There


SHIPPING PARTS LIST
TRAFFIC SIGNAL ARM
STRUCTURE ASSEMBLY
VIBRATION WARNING
Texas Department of Transportation
TRAFFIC SIGNAL
SUPPORT STRUCTURES
SINGLE MAST ARM ASSEMBLY
(80 MPH WIND ZONE)
SMA-80(1)-99
SHEET 1 OF 2


SUMMARY OF CONDUIT AND CABLES - RM 620 AT HOME DEPOT BLVD.
Home Depot Blvd
RM 620
Power Source
Overhead Power Drop
Pole A
Pole B
Pole C
Remove Center Lane Striping In The Intersection
Possible Future Road
Signal Layout
RM 620 at Home Depot Blvd.
Travis County


VIBRATION WARNING
GENERAL NOTES
FIXED MOUNT TRAFFIC SIGNAL ARM
CLAMP-ON TRAFFIC SIGNAL ARM
ELEVATION
STRUCTURE ASSEMBLY
ELEVATION
TRAFFIC SIGNAL
SUPPORT STRUCTURES
DUAL MAST ARM ASSEMBLY
(80 MPH WIND ZONE)
DMA-80 (1)-96


Signal Layout
US 290 at SH 95 West
No Scale

Appendix E: Datalogger Program

```
;----------------------------------------------------------------------------------------------------
;----------------------------------------------------------------------------------------------------
; START OF PROGRAM
;----------------------------------------------------------------------------------------------------
;----------------------------------------------------------------------------------------------------

; Program runs every 0.07 seconds or 14.286Hz
*Table 1 Program
  01: 0.07      Execution Interval (seconds)

; Set Flag 1 High to start program
1:  If Flag/Port (P91)
 1: 11       Do if Flag 1 is High
 2: 30       Then Do

; Go to Subroutine 1: Collect and Record Date and Time Once
2:  Do (P86)
 1: 1        Call Subroutine 1

; Start of the loop that collects data; it runs until the exit loop command
3:  Beginning of Loop (P87)
 1: 1        Delay
 2: 0        Loop Count

; Go to Subroutine 2: Collect Seconds and Strain Data
4:  Do (P86)
 1: 2        Call Subroutine 2

; Go to Subroutine 3: Writes Data to File
5:  Do (P86)
 1: 3        Call Subroutine 3

; Set Flag 2 High to stop program; this exits the loop and sets Flag 1 Low
6:  If Flag/Port (P91)
 1: 12       Do if Flag 2 is High
 2: 21       Set Flag 1 Low

7:  If Flag/Port (P91)
 1: 12       Do if Flag 2 is High
 2: 31       Exit Loop if True
```

```
; Ends IF statement
8:  End (P95)

; Ends IF statement
9:  End (P95)

; Sets Flag 2 Low
10:  Do (P86)
 1: 22       Set Flag 2 Low

; Turn off power to anemometer
11:  Do (P86)
 1: 59       Turn Off Switched 12V

; Table 2 Program does nothing
*Table 2 Program
  01: 6000      Execution Interval (seconds)

*Table 3 Subroutines
;-----------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------
; SUBROUTINE 1: Collect & Write Date & Time Once: (Year, Day, Hr, Min, Sec)
;-----------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------

; Beginning of subroutine
1:  Beginning of Subroutine (P85)
 1: 1        Subroutine 1

; Collects the date and time in 5 consecutive locations starting with location 1
2:  Time (P18)
 1: 3        Store Year, Day, Hr, Min, Sec in 5 consecutive locations
 2: 0000     Mod/By
 3: 1        Loc [ Year      ]

; Writes the date and time to a file
3:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

; Tell the program what data to write
4:  Sample (P70)
 1: 5        Reps
```

```
 2: 1       Loc [ Year     ]

; Turn on power to anemometer
5:  Do (P86)
 1: 49      Turn On Switched 12V

; Ends subroutine 1
6:  End (P95)

;-----------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------
; SUBROUTINE 2: Collect Sec, Strain & Wind Data: (Sec1, Strain1-6, Wind1-3)
;-----------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------

; Beginning of subroutine
7:  Beginning of Subroutine (P85)
 1: 2       Subroutine 2

; Collects the seconds in location 6
8:  Time (P18)
 1: 0       Seconds into current minute (maximum 60)
 2: 0000    Mod/By
 3: 6       Loc [ Sec1     ]

; Collects the data from the 3 strain gauges in locations 7-9
9:  Full Bridge (P6)
 1: 3       Reps
 2: 11      10 mV, Fast Range
 3: 4       DIFF Channel
 4: 1       Excite all reps w/Exchan 1
 5: 2000    mV Excitation
 6: 7       Loc [ Strain1  ]
 7: 1       Mult
 8: 0       Offset

; Collects the data from the 3 strain gauges in locations 10-12
10:  Full Bridge (P6)
 1: 3       Reps
 2: 11      10 mV, Fast Range
 3: 7       DIFF Channel
 4: 2       Excite all reps w/Exchan 2
 5: 2000    mV Excitation
```

```
 6: 10       Loc [ Strain4   ]
 7: 1        Mult
 8: 0        Offset

; Collects the data from the anemometer in locations 13-15
11:  Volt (Diff) (P2)
 1: 3        Reps
 2: 15       5000 mV, Fast Range
 3: 1        DIFF Channel
 4: 13       Loc [ Wind1     ]
 5: 1.0      Mult
 6: 0.0      Offset

; Ends subroutine 2
12:  End (P95)

;---------------------------------------------------------------------------------------------------
;---------------------------------------------------------------------------------------------------
; SUBROUTINE 3: Write Data to File: (Sec1, Strain1-6, Wind1-3)
;---------------------------------------------------------------------------------------------------
;---------------------------------------------------------------------------------------------------

; Beginning of subroutine
13:  Beginning of Subroutine (P85)
 1: 3        Subroutine 3

; Writes data to file
14:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

; Tell the program what data to write
15:  Sample (P70)
 1: 10       Reps
 2: 6        Loc [ Sec1      ]

; Ends subroutine 3
16:  End (P95)

;---------------------------------------------------------------------------------------------------
;---------------------------------------------------------------------------------------------------
End Program
;---------------------------------------------------------------------------------------------------
;---------------------------------------------------------------------------------------------------
```

Appendix F: Truck Gust Field Data

RM620 at Home Depot Blvd

Monday 08-22-05

Part 1: Start: 10:57:22.00 am Stop: 11:09:23.72 am Total: 721.72 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	12	12	N/A	1	N/A	Semi-Low
2	0	15	15	N/A	1	N/A	Semi-Low
3	0	26	26	N/A	1	N/A	Semi-Low
4	0	37	37	N/A	1	N/A	Box
5	1	43	103	N/A	1	N/A	Dump Truck
6	4	03	243	N/A	2	N/A	Box
7	6	04	364	N/A	2	N/A	Box
8	7	07	427	N/A	2	N/A	Box
9	7	18	438	N/A	1	N/A	Dump Truck
10	8	15	495	N/A	1	N/A	Semi-Low
11	9	27	567	N/A	1	N/A	Box
12	9	51	591	N/A	1	N/A	Dump Truck

Part 2: Start: 11:46:55.96 am Stop: 12:01:58.08 pm Total: 902.12 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	2	53	173	55	1	N/A	Dump Truck
2	7	42	462	53	1	N/A	Dump Truck
3	14	14	854	45	1	N/A	Concrete Truck

Part 3: Start: 12:04:12.20 pm Stop: 12:19:49.20 pm Total: 937.00 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	4	10	250	55	2	N/A	Box-Small
2	5	19	319	54	1	N/A	Dump Truck
3	8	49	529	52	1	N/A	Box-Tall
4	11	16	676	49	1	N/A	Box-Small
5	11	52	712	40	1	N/A	Semi
6	12	00	720	52	2	N/A	Garbage Truck

Wednesday 08-24-05

Part 1: Start: 10:27:53.96 am Stop: 11:08:50.64 am Total: 2456.68 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	56	56	48	1	N/A	Semi
2	2	36	156	53	2	DSCN4868	Semi
3	9	20	560	51	1	DSCN4869	Dump Truck
4	13	44	824	57	1	DSCN4870	
5,6,7,8	17	20-40	1040-1060	31,36,36,39	1	DSCN4871-74	House Trucks
9	19	02	1142	51	2	DSCN4875	Dump Truck
10	20	31	1231	50	1	DSCN4876	Semi-Low
11	21	16	1276	49	2	DSCN4877	Box-Small
12	23	24	1404	39	1	DSCN4878	Semi
13	24	39	1479	58	2	DSCN4879	Box-Small
14	24	50	1490	55	1	N/A	Dump Truck
15	27	15	1635	48	1	DSCN4881	Garbage Truck
16	29	02	1742	53	1	DSCN4882	Box-Small
17	30	05	1805	N/A	1	DSCN4883	
18	31	20	1880	48	1	DSCN4884	UPS Truck
19	32	00	1920	51	1	DSCN4885	Dump Truck w/ Attachment
20	34	42	2082	49	2	DSCN4886	Concrete Truck
21	35	07	2107	53	1	DSCN4887	Dump Truck
22	38	22	2302	51	2	DSCN4888	Box-Tall
23	39	42	2382	55	2	DSCN4889	Box-Small
24	39	49	2389	62	1	N/A	Dump Truck

Part 2: Start: 12:59:23.08 pm Stop: 13:37:26.04 pm Total: 2282.96 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	2	09	129	54	2	DSCN4895	Box-Tall
2	2	57	177	N/A	1	DSCN4896	Concrete Truck
3	3	14	194	58	1	DSCN4897	Dump Truck
4	4	24	264	46	1	DSCN4898	Concrete Truck
5	9	09	549	52	1	DSCN4899	Dump Truck
6	12	39	759	49	1	DSCN4900	Garbage Truck
7	17	04	1024	55	1	DSCN4901	Semi
8	20	07	1207	58	1	DSCN4902	Semi-Tall
9	20	52	1252	49	2	DSCN4903	Box-Small (Dump Truck)
10	23	51	1431	46	1	DSCN4904	Concrete Truck
11	27	36	1656	53	1	DSCN4905	Concrete Truck
12	30	59	1859	53	2	DSCN4906	Box-Tall
13	31	29	1889	45	1	DSCN4907	Box-Small (Dump Truck)
14	33	01	1981	45	1	DSCN4908	Garbage Truck
15	35	38	2138	41	1	DSCN4909	Semi

Tuesday 09-20-05

Part 1: Start: 10:40:35.16 am Stop: 11:23:36.40 am Total: 2581.24 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	39	39	49	1	N/A	Equipment Truck
2	1	11	71	44	1	N/A	Equipment Truck
3	1	18	78	46	1	N/A	
4	2	35	155	40	1	DSCN5073	Dump Truck
5	6	40	400	30	1	N/A	Box-Tall
6	7	10	430	58	1	N/A	Equipment Truck
7	12	52	772	56	1	DSCN5074	Concrete Truck
8	13	11	791	58	1	DSCN5075	Dump Truck
9	15	18	918	55	1	DSCN5076	Small Truck
10	18	18	1098	53	2	DSCN5077	Box-Small
11	18	24	1104	55	1	N/A	Dump Truck
12	18	30	1110	55	1	N/A	Dump Truck
13	18	35	1115	52	1	DSCN5078	Box-Tall
14	19	41	1181	66	1	DSCN5079	Box-Small
15	20	46	1246	59	2	DSCN5080	Box-Small (Dump Truck)
16	21	23	1283	54	1	DSCN5081	Semi
17	21	30	1290	44	1	DSCN5082	Dump Truck
18	22	04	1324	52	1	DSCN5083	Box-Small (Dump Truck)
19	24	04	1444	51	2	DSCN5084	Dump Truck
20	27	21	1641	54	1	DSCN5085	Box-Small
21	27	36	1656	56	1	DSCN5086	Semi
22	28	03	1683	49	1	DSCN5087	Dump Truck
23	29	58	1798	56	1	DSCN5088	Semi
24	30	04	1804	57	1	N/A	Semi
25	30	08	1808	56	1	N/A	Semi
26	31	36	1896	46	1	DSCN5089	Semi
27	33	51	2031	44	1	DSCN5090	Garbage Truck
28	36	42	2202	44	1	DSCN5091	School Bus
29	36	51	2211	45	1	DSCN5092	Concrete Truck
30	41	05	2465	N/A	1	DSCN5093	Semi
31	41	09	2469	54	2	DSCN5094	Box-Tall

Part 2: Start: 11:29:05.84 am Stop: 12:10:06.2 pm Total: 2460.68 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	51	51	46	1	DSCN5095	Dump Truck
2	1	50	110	48	1	DSCN5096	Semi
3	3	03	183	40	1	DSCN5097	Dump Truck
4	4	50	290	52	1	DSCN5098	Bucket Truck
5	6	31	391	48	1	DSCN5099	Semi
6	7	37	457	42	1	DSCN5100	Semi-Low
7	9	07	547	57	1	DSCN5101	Semi-Tall
8	12	32	752	56	1	DSCN5102	Box-Tall
9	14	44	884	52	1	DSCN5103	Box-Tall
10	16	00	960	57	1	DSCN5104	Semi
11	16	13	973	47	1	DSCN5105	Small Truck
12	18	01	1081	31	1	DSCN5106	Dump Truck
13	18	14	1094	N/A	1	DSCN5107	Box-Small
14	18	32	1112	51	1	DSCN5108	Box-Tall
15	19	26	1166	53	1	DSCN5109	Semi
16	30	40	1840	42	1	DSCN5110	Dump Truck
17	31	02	1862	53	2	DSCN5111	Semi-Low
18	32	13	1933	57	1	DSCN5112	Box-Tall
19	33	53	2033	59	2	DSCN5113	Box-Small
20	33	59	2039	53	2	DSCN5114	Semi
21	37	37	2257	44	1	DSCN5115	Dump Truck
22	38	55	2335	52	1	DSCN5116	Box-Tall
23	39	08	2348	58	1	DSCN5117	Bread Truck

Tuesday 09-27-05

Part 1: Start: 09:50:56.88 am Stop: 10:34:13.92 am Total: 2597.04 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	19	19	57	2	DSCN5123	Ambulance
2	1	26	86	50	1	DSCN5124	Dump Truck
3	2	30	150	56	1	DSCN5125	Dump Truck
4	3	35	215	54	1	DSCN5126	Gas Truck
5	3	40	220	54	1	DSCN5127	Gas Truck
6	5	35	335	54	1	DSCN5129	Dump Truck
7	6	36	396	52	1	DSCN5130	Box-Small
8	12	02	722	46	1	DSCN5131	Dump Truck w/ Trailer
9	15	55	955	38	1	DSCN5131	Dump Truck
10	15	57	957	37	1	DSCN5132	Box-Small
11	16	06	966	57	2	DSCN5133	Delivery Truck
12	16	16	976	58	1	DSCN5134	Semi-Low
13	19	53	1193	53	1	DSCN5135	Box-Tall
14	21	18	1278	58	1	DSCN5136	Box-Small
15	22	44	1364	40	2	DSCN5137	UPS Truck
16	22	55	1375	N/A	1	DSCN5138	Concrete Truck
17	24	13	1453	42	1	DSCN5139	Semi-Tall
18	26	27	1587	45	1	DSCN5140	Concrete Truck
19	27	52	1672	44	1	DSCN5141	Dump Truck
20	29	55	1795	48	1	DSCN5142	Box-Small (Dump Truck)
21	30	04	1804	55	1	DSCN5143	Box-Tall
22	34	30	2070	54	1	DSCN5144	Semi
23	34	59	2099	51	2	DSCN5145	Box-Small
24	36	07	2167	53	1	DSCN5146	Box-Small
25	39	19	2359	51	1	DSCN5147	Semi
26	39	30	2370	38	1	DSCN5148	
27	39	35	2375	42	2	DSCN5149	School Bus
28	41	01	2461	48	1	DSCN5150	Equipment Truck
29	42	02	2522	57	2	DSCN5151	Dump Truck

Part 2: Start: 11:19:49.08 am Stop: 12:01:50.44 pm Total: 2521.36 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	18	18	50	2	DSCN5152	Box-Small
2	1	38	98	55	2	DSCN5153	Small Dump Truck
3	2	41	161	52	1	DSCN5154	Semi
4	2	51	171	57	1	DSCN5155	Box-Small
5	4	49	289	40	2	DSCN5156	School Bus
6	6	56	416	47	1	DSCN5157	Concrete Truck
7	7	06	426	60	2	DSCN5158	Semi-Tall
8	8	15	495	61	2	DSCN5159	Pickup w/ Trailer
9	8	22	502	50	2	DSCN5160	Box-Small
10	8	51	531	46	1	DSCN5161	Gas Truck
11	9	41	581	52	1	DSCN5162	Equipment Truck
12	13	59	839	55	1	DSCN5163	Box-Small
13	19	18	1158	44	1	DSCN5164	Concrete Truck
14	21	02	1262	36	1	DSCN5165	Concrete Truck
15	21	52	1312	42	1	DSCN5166	Dump Truck
16	22	06	1326	59	2	DSCN5167	Flatbed Truck
17	23	35	1415	49	2	DSCN5168	Box-Small
18	24	09	1449	61	1	DSCN5169	Box-Tall
19	32	46	1966	<10	1	DSCN5170	Equipment Truck
20	36	20	2180	24	1	DSCN5171	Dump Truck

Part 3: Start: 12:06:22.16 pm Stop: 12:49:23.32 pm Total: 2581.16 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	27	27	53	1	DSCN5172	Box-Tall
2	1	13	73	36	1	DSCN5173	Semi
3	5	40	340	49	1	DSCN5174	Concrete Truck
4	6	35	395	48	1	DSCN5175	Dump Truck
5	7	35	455	54	1	DSCN5176	Box-Tall
6	9	38	578	51	1	DSCN5177	Box-Tall
7	10	30	630	28	2	DSCN5178	Semi
8	15	51	951	49	1	DSCN5179	Box-Small
9	17	55	1075	37	1	DSCN5180	Concrete Truck
10	18	17	1097	50	2	DSCN5181	Semi-Tall
11	21	03	1263	32	2	DSCN5182	Dump Truck
12	22	48	1368	50	2	DSCN5183	Box-Small
13	25	23	1523	55	1	DSCN5184	Dump Truck
14	26	10	1570	50	1	DSCN5185	Dump Truck
15	26	28	1588	51	1	DSCN5186	Box-Tall
16	27	09	1629	50	1	DSCN5187	Dump Truck
17	28	04	1684	52	1	DSCN5188	Box-Tall
18	31	04	1864	54	2	DSCN5189	Dump Truck
19	31	05	1865	55	1	N/A	Box-Tall
20	31	07	1867	55	1	N/A	Dump Truck
21	32	40	1960	45	1	DSCN5190	Dump Truck
22	34	27	2067	51	1	DSCN5191	Semi
23	37	16	2236	53	1	DSCN5192	Concrete Truck
24	37	20	2240	48	1	DSCN5193	Box-Tall
25	37	44	2264	50	2	DSCN5194	
26	40	13	2413	57	2	DSCN5195	Garbage Truck
27	42	14	2534	56	1	DSCN5196	Box-Small

Thursday 09-29-05

Part 1: Start: 10:29:54.08 am Stop: 11:11:51.44 am Total: 2517.36 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	5	14	314	52	1	DSCN5197	Semi
2	8	06	486	45	2	DSCN5198	Delivery Truck
3	9	11	551	52	1	DSCN5200	Box-Small
4	10	10	610	51	1	DSCN5201	Box-Tall
5	15	16	916	48	1	DSCN5202	Dump Truck
6	17	18	1038	31	1	DSCN5203	Dump Truck
7	18	00	1080	44	1	DSCN5204	Dump Truck
8	18	15	1095	38	1	DSCN5205	Box-Small
9	21	05	1265	57	1	DSCN5206	School Bus
10	22	53	1373	52	1	DSCN5207	Box-Small
11	23	06	1386	54	1	DSCN5208	Dump Truck
12	23	23	1403	51	2	DSCN5209	Small Box
13	23	35	1415	55	1	DSCN5210	Equipment Truck
14	24	17	1457	52	1	DSCN5211	School Bus
15	24	22	1462	49	1	DSCN5212	Small School Bus
16	25	21	1521	29	1	DSCN5213	Semi
17	25	24	1524	53	2	N/A	Pickup w/ trailer
18	26	05	1565	46	1	DSCN5214	Semi
19	27	18	1638	52	1	DSCN5215	Box-Small
20	30	20	1820	51	1	DSCN5216	Dump Truck
21	31	13	1873	51	1	DSCN5217	Semi
22	31	23	1883	48	2	DSCN5218	Small School Bus
23	32	02	1922	64	1	DSCN5219	Flat Bed Truck
24	32	49	1969	29	2	DSCN5220	Dump Truck
25	32	51	1971	46	1	DSCN5221	Dump Truck
26	33	08	1988	56	1	DSCN5222	Dump Truck
27	34	28	2068	44	2	DSCN5223	Box-Small (Dump Truck)
28	34	34	2074	48	1	DSCN5224	Concrete Truck
29	36	11	2171	50	1	DSCN5225	
30	36	37	2197	52	1	DSCN5226	Box-Tall
31	38	31	2311	52	2	DSCN5227	Box-Small (Dump Truck)
32	38	36	2316	41	1	DSCN5228	Dump Truck
33	38	45	2325	43	1	DSCN5229	Gas Truck
34	38	50	2330	55	2	DSCN5230	Box-Small (Dump Truck)
35	40	34	2434	51	1	DSCN5231	Box-Small

Part 2: Start: 11:16:39.44 am Stop: 11:58:39.96 am Total: 2520.52 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	17	17	51	1	DSCN5232	Flat Bed Truck
2	1	26	86	54	2	DSCN5233	School Bus
3	2	23	143	47	1	DSCN5234	Concrete Truck
4	4	43	283	53	1	DSCN5235	Semi
5	6	46	406	39	1	DSCN5236	Concrete Truck
6	7	51	471	34	1	DSCN5237	Box-Small
7	10	18	618	52	1	DSCN5238	Dump Truck
8	11	38	698	58	1	DSCN5239	Box-Tall
9	11	53	713	54	1	DSCN5240	Box-Tall
10	18	12	1092	38	2	DSCN5241	Semi-Tall
11	19	54	1194	35	1	DSCN5242	Dump Truck
12	20	54	1254	21	1	DSCN5243	Box-Tall
13	22	00	1320	58	1	N/A	Fed Ex
14	24	16	1456	54	1	DSCN5244	Dump Truck
15	25	00	1500	51	1	DSCN5245	Dump Truck
16	25	08	1508	49	1	DSCN5246	Concrete Truck
17	29	36	1776	22	1	DSCN5247	Semi
18	31	01	1861	37	1	DSCN5248	Garbage Truck
19	31	48	1908	44	1	DSCN5249	Semi-Tall
20	32	41	1961	48	1	DSCN5250	Semi
21	36	41	2201	51	1	DSCN5251	Dump Truck
22	37	38	2258	54	1	DSCN5252	Gas Truck
23	38	54	2334	33	1	DSCN5253	Dump Truck
24	41	03	2463	52	1	DSCN5254	Semi-Tall

US290 at SH95 Elgin

Wednesday 03-15-06

Part 1: Start: 10:58:09.88 am Stop: 12:03:32.40 pm Total: 3922.52 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	2	23	143	44	1	DSCN5664	Semi-Tall
2	4	26	266	56	2	N/A	Box-Small
3	4	33	273	46	1	N/A	Semi-Low
4	7	33	453	33	1	DSCN5665	Dump Truck
5	11	11	671	25	1	DSCN5666	Semi-Tall
6	11	37	697	47	1	DSCN5667	Box-Small
7	14	24	864	47	1	DSCN5668	Semi
8	16	56	1016	54	1	DSCN5669	Camper
9	16	59	1019	54	2	DSCN5669	Box-Small
10	20	13	1213	34	1&2	DSCN5670	Semi-Tall(1) Semi-Low(2)
11	20	20	1220	32	1&2	DSCN5671	Semi-Low(1) Box-Small(2)
12	21	36	1296	29	2	DSCN5672	Semi-Tall
13	21	40	1300	31	2	DSCN5673	Semi-Low
14	23	13	1393	29	2	DSCN5674	Semi
15	27	02	1622	43	1	DSCN5675	Semi-Tall
16	30	02	1802	42	2	DSCN5676	Semi-Tall
17	32	27	1947	50	1	DSCN5677	Box-Tall
18	32	33	1953	37	1	DSCN5678	Semi
19	32	38	1958	38	1	DSCN5679	Semi
20	34	46	2086	37	1	DSCN5680	Semi-Tall
21	38	21	2301	32	1	DSCN5681	Semi-Tall
22	42	45	2565	28	1	DSCN5682	Semi-Low
23	45	48	2748	41	1	DSCN5683	Semi-Tall
24	52	33	3153	39	1	N/A	Semi-Tall
25	52	57	3177	46	1	DSCN5684	Semi-Tall
26	53	07	3187	41	2	DSCN5685	Semi-Low
27	54	17	3257	44	1	DSCN5686	Semi-Tall
28	57	26	3446	40	1	DSCN5687	Semi-Tall
29	60	16	3616	44	1	DSCN5688	Semi-Tall
30	62	46	3766	48	1	DSCN5689	Semi-Tall
31	62	55	3775	N/A	1	DSCN5690	Box-Small

Part 2: Start: 1:13:20.27 pm Stop: 2:21:57.46 pm Total: 4117.12 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	8	23	503	31	2	N/A	Semi
2	14	05	845	44	1	N/A	Utility Truck
3	14	19	859	47	1	N/A	Box-Small
4	15	38	938	55	1	N/A	Semi-Tall
5	15	47	947	46	1	N/A	Semi-Tall
6	17	19	1039	43	1	DSCN5692	Semi-Low
7	19	52	1192	33	1	DSCN5693	Semi-Tall
8	20	11	1211	20	1	DSCN5694	Camper
9	20	25	1225	40	1	DSCN5695	Semi-Tall
10	31	53	1913	44	1	DSCN5696	Semi
11	32	33	1953	36	1	DSCN5697	Box-Small
12	32	43	1963	34	1	DSCN5698	Semi-Low
13	36	13	2173	33	1	N/A	Semi-Low
14	36	19	2179	27	1	N/A	Dump Truck
15	36	26	2186	44	2	N/A	Camper
16	41	52	2512	54	2	N/A	Box-Small
17	46	43	2803	32	1	DSCN5701	Box-Small
18	48	15	2895	39	1	DSCN5702	Semi
19	48	26	2906	42	1	N/A	Semi
20	50	41	3041	46	1	DSCN5703	Semi
21	50	43	3043	46	2	DSCN5703	Semi
22	50	46	3046	46	1	DSCN5703	Semi
23	53	50	3230	40	1	DSCN5704	Semi-Tall
24	55	17	3317	46	2	DSCN5705	Box
25	55	29	3329	46	2	DSCN5706	Semi
26	56	43	3403	45	1	DSCN5707	Semi-Low
27	56	51	3411	32	1	DSCN5708	Semi-Tall
28	58	10	3490	35	1.5	DSCN5709	Semi-Tall
29	65	27	3927	31	2	N/A	Semi-Low

Thursday 03-16-06

Part 1: Start: 9:50:28.04 am Stop: 10:57:29.47 am Total: 4021.36 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	2	23	143	42	1	DSCN5710	Semi-Tall
2	11	45	705	25	1	DSCN5711	Semi
3	12	40	760	47	1	DSCN5712	Semi-Tall
4	14	07	847	51	1	DSCN5713	Semi-Low
5	17	37	1057	39	1	DSCN5714	Semi-Tall
6	21	16	1276	39	1	DSCN5715	Semi
7	21	30	1290	38	1	DSCN5716	Semi
8	24	30	1470	42	1	DSCN5717	Delivery Truck
9	28	32	1712	42	1	DSCN5718	Semi-Tall
10	34	48	2088	42	2	DSCN5719	Garbage Truck
11	40	11	2411	39	2	DSCN5720	Semi-Tall
12	40	55	2455	43	1	DSCN5721	Semi-Tall
13	41	08	2468	48	1	DSCN5722	Semi-Tall
14	42	37	2557	50	1	DSCN5723	Semi-Tall
15	42	42	2562	49	1	DSCN5724	Semi-Tall
16	49	03	2943	49	1	DSCN5725	Semi-Tall
17	49	08	2948	46	1	DSCN5726	Semi-Tall
18	52	27	3147	47	1	DSCN5727	Semi
19	56	26	3386	30	1	DSCN5728	Semi-Low
20	60	42	3642	33	1	DSCN5729	Semi-Tall
21	61	44	3704	35	2	DSCN5730	Box-Tall
22	63	08	3788	41	1	DSCN5731	Dump Truck
23	64	46	3886	46	2	DSCN5732	Semi-Low

Part 2: Start: 11:06:29.17 am Stop: 11:37:54.34 pm Total: 1885.17 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	6	25	385	37	1	DSCN5733	Semi-Tall
2	6	31	391	42	1	DSCN5734	Semi
3	7	45	465	41	1	DSCN5735	Dump Truck
4	9	01	541	43	1	DSCN5736	Camper
5	9	19	559	48	1	DSCN5737	Semi-Low
6	11	43	703	38	2	DSCN5738	Box-Small
7	13	47	827	48	2	DSCN5739	Semi-Low
8	15	42	942	15	1	DSCN5740	Equipment Truck
9	17	43	1063	36	1	DSCN5741	Concrete Truck
10	17	48	1068	42	1	DSCN5742	Trailer
11	19	27	1167	45	2	DSCN5743	Semi-Low
12	20	30	1230	40	1	DSCN5744	Semi-Low
13	22	10	1330	44	2	DSCN5745	Box-Tall

Saturday 03-18-06

Part 1: Start: 10:52:54.02 am Stop: 12:00:40.53 pm Total: 4066.51 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	14	07	847	40	1	DSCN5747	Semi-Tall
2	39	41	2381	37	2	DSCN5748	Box-Small
3	41	40	2500	36	1	DSCN5749	Semi-Tall
4	43	39	2619	28	1	DSCN5750	Semi-Tall
5	45	57	2757	~20	1	DSCN5751	Semi-Tall
6	48	04	2884	45	1	DSCN5752	Semi-Tall
7	54	47	3287	46	1	DSCN5753	Dump Truck

Part 2: Start: 12:05:45.67 pm Stop: 1:02:32.29 pm Total: 3406.55 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	27	37	1657	36	1	DSCN5755	Semi
2	32	42	1962	26	2	DSCN5756	Semi-Tall
3	34	34	2074	45	2	DSCN5757	Trailer
4	36	36	2196	36	2	DSCN5758	Pickup Box

Monday 03-27-06

Part 1: Start: 10:48:37.16 am Stop: 11:17:42.33 am Total: 1745.10 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	0	31	31	23	2	DSCN5760	Semi
2	3	34	214	36	1	DSCN5761	Camper
3	3	46	226	43	1	DSCN5762	Semi
4	4	02	242	48	1	DSCN5763	Pickup w/ Trailer
5	5	42	342	45	1	DSCN5764	Semi-Tall
6	5	45	345	48	1	N/A	Semi-Tall
7	5	49	349	48	2	DSCN5765	Semi-Tall
8	5	52	352	50	2	DSCN5766	Semi-Tall
9	7	10	430	34	1	DSCN5767	Semi-Tall
10	12	52	772	47	1	DSCN5768	Semi-Low
11	16	02	962	45	1	DSCN5769	Box-Tall
12	16	05	965	44	1	DSCN5769	Semi-Tall
13	19	38	1178	41	1	DSCN5770	Box-Tall
14	28	03	1683	40	1	DSCN5771	Semi
15	28	12	1692	38	1	N/A	Semi-Low

Part 2: Start: 11:24:47.09 am Stop: 12:08:19.56 pm Total: 2612.47 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	4	23	263	52	2	DSCN5773	Semi-Tall
2	4	48	288	36	2	N/A	Semi-Tall
3	5	35	335	37	1	DSCN5774	Semi-Tall
4	8	22	502	47	1	DSCN5775	Semi-Tall
5	11	53	713	37	1	DSCN5778	Semi-Tall
6	16	09	969	40	1	DSCN5779	Semi-Tall
7	22	11	1331	30	1	DSCN5780	Box-Tall
8	24	29	1469	43	1	DSCN5781	Semi-Tall
9	24	33	1473	42	1	DSCN5781	Semi-Tall
10	24	49	1489	43	1	DSCN5782	Semi-Tall
11	25	49	1549	46	2	DSCN5783	Semi-Tall
12	27	27	1647	49	1	DSCN5784	Semi-Low
13	28	49	1729	50	1	DSCN5785	Semi-Tall
14	29	55	1795	30	2	DSCN5786	Semi-Tall
15	31	38	1898	41	1	DSCN5787	Semi
16	31	59	1919	37	1	DSCN5788	Box-Tall
17	33	07	1987	34	1	DSCN5789	Semi-Low
18	33	12	1992	34	1	DSCN5789	Semi-Tall
19	34	35	2075	29	2	DSCN5790	Semi
20	36	41	2201	42	2	DSCN5791	Semi-Tall
21	36	53	2213	41	2	DSCN5792	Bus
22	39	02	2342	34	1	DSCN5793	Pickup w/ Trailer

Part 3: Start: 13:19:20.25 pm Stop: 14:15:53.99 pm Total: 3393.67 sec

Truck #	(Min, Sec)		Time (Sec)	Speed (mph)	Lane	Picture File	Comments
1	2	13	133	26	1	DSCN5794	Semi-Tall
2	4	22	262	39	1	DSCN5795	Semi
3	6	10	370	46	1	DSCN5796	Semi-Tall
4	7	56	476	38	1	DSCN5797	Semi
5	11	05	665	28	1	DSCN5798	Box-Small
6	16	02	962	37	2	DSCN5799	Semi
7	16	19	979	36	1	DSCN5800	Semi-Low
8	16	26	986	40	1	DSCN5801	Semi-Low
9	18	08	1088	47	1	DSCN5802	Pickup w/ Trailer
10	19	28	1168	49	1&2	DSCN5803	Semi-Tall(1) Semi-Low(2)
11	24	40	1480	33	1	DSCN5804	Semi
12	27	11	1631	29	2	DSCN5806	Box-Small
13	27	48	1668	44	1	DSCN5807	Semi-Tall
14	30	51	1851	52	2	DSCN5808	Semi
15	34	51	2091	31	1	DSCN5809	Dump Truck
16	36	27	2187	37	1	DSCN5810	Semi-Tall
17	42	41	2561	35	1	DSCN5811	Semi
18	44	00	2640	39	2	DSCN5812	Semi-Tall
19	46	22	2782	34	1	DSCN5813	House Truck
20	49	27	2967	46	1	DSCN5814	Semi-Tall
21	49	32	2972	38	1	DSCN5815	Semi-Low
22	49	34	2974	38	1	DSCN5815	Semi-Tall
23	53	54	3234	40	1	DSCN5816	Semi
24	53	56	3236	45	2	DSCN5816	Semi-Low
25	55	43	3343	35	1	DSCN5817	Box-Small

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