Development Of A Weigh-in-motion System Using Acoustic Emission Sensors

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DEVELOPMENT OF A WEIGH-IN-MOTION SYSTEM USING ACOUSTIC EMISSION SENSORS

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Civil, Environmental, and Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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ABSTRACT

This dissertation proposes a system for weighing commercial vehicles in motion using acoustic emission sensors attached to a metal bar placed across the roadway. The signal from the sensors is analyzed by a computer and the vehicle weight is determined by a statistical model which correlates the acoustic emission parameters to the vehicle weight. Such a system would be portable and low-cost, allowing for the measurement of vehicle weights in much the same way commercial tube and radar counters routinely collect vehicle speed and count. The system could be used to collect vehicle speed and count data as well as weight information.

Acoustic emissions are naturally occurring elastic waves produced by the rapid release of energy within a material. They are caused by deformation or fracturing of a solid due to thermal or mechanical stress. Acoustic emission sensors have been developed to detect these waves and computer software and hardware have been developed to analyze and provide information about the waveforms. Acoustic emission testing is a common form of nondestructive testing and is used for pressure vessel testing, leak detection, machinery monitoring, structural integrity monitoring, and weld monitoring, among other things (Miller, 1987).

For this dissertation, acoustic emission parameters were correlated to the load placed on the metal test bar to determine the feasibility of using a metal test bar to measure the weight of a vehicle in motion. Several experiments were done. First, the concept was tested in a laboratory setting using an experimental apparatus. A concrete cylinder was mounted on a frame and rotated using a motor. The metal test bar was applied directly to the surface of the cylinder and
acoustic emission sensors were attached to each end of the bar. As the cylinder rotated, a motorcycle tire was pushed up against the cylinder using a scissor jack to simulate different loads. The acoustic emission response in the metal test strip to the motorcycle tire rolling over it was detected by the acoustic emission sensors and analyzed by the computer. Initial examinations of the data showed a correlation between the force of the tire against the cylinder and the energy and count of the acoustic emissions.

Subsequent field experiments were performed at a weigh station on I-95 in Flagler County, Florida. The proposed weigh-in-motion system (the metal test bar with attached acoustic emission sensors) was installed just downstream of the existing weigh-in-motion scale at the weigh station. Commercial vehicles were weighed on the weigh station weigh-in-motion scale and acoustic emission data was collected by the experimental system. Test data was collected over several hours on two different days, one in July 2008 and the other in April 2009. Initial examination of the data did not show direct correlation between any acoustic emission parameter and vehicle weight. As a result, a more sophisticated model was developed.

Dimensional analysis was used to examine possible relationships between the acoustic emission parameters and the vehicle weight. In dimensional analysis, a dimensionally correct equation is formed using measurable parameters of a system. The dimensionally correct equation can then be tested using experimental data. Dimensional analysis revealed the following possible relationship between the acoustic emission parameters and the vehicle weight:

\[
w = f \left( \frac{gE}{v^2}, Y, \frac{rE}{D \sqrt{A}}, \frac{cE}{\sqrt{A}}, \frac{c_p E}{\sqrt{A}}, \frac{E^3}{\sqrt{A}}, \frac{aE}{\sqrt{A}} \right)\]
The definitions of these variables can be found in Appendix A.

Statistical models for weight using the laboratory data and using the field data were developed. Dimensional analysis variables as well as other relevant measurable parameters were used in the development of the statistical models. The model created for the April 2009 dataset was validated, with only 27 lbs average error in the weight calculation as compared with the weight measurement made with the weigh station weigh-in-motion scale. The maximum percent error for the weight calculation was 204%, with about 65% of the data falling within 30% error.

Additional research will be needed to develop an acoustic emission weigh-in-motion system with adequate accuracy for a commercial product. Nevertheless, this dissertation presents a valuable contribution to the effort of developing a low-cost acoustic emission weigh-in-motion scale.

Future research needs that were identified as part of this dissertation include:

- Examination of the effects of pavement type (flexible or rigid), vehicle speeds greater than 50 mph, and temperature
- Determination of the best acoustic emission sensor for this system
- Exploration of the best method to separate the data from axles which pass over the equipment close together in time (such as tandem axles)
- Exploration of the effect of repeated measures on improving the accuracy of the system.
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# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................................................... ix

LIST OF TABLES .................................................................................................................................................. xi

INTRODUCTION .................................................................................................................................................. 1

Development of a New Low-Cost Portable WIM System .................................................................................. 3

Initial Experimentation .................................................................................................................................. 4

LITERATURE REVIEW .................................................................................................................................... 7

Weigh-in-Motion .................................................................................................................................................. 7

Tire-Pavement Contact Stress .......................................................................................................................... 14

Acoustic Emission ............................................................................................................................................ 16

EXPERIMENTS .................................................................................................................................................. 23

Definition of Terms .......................................................................................................................................... 23

Testing the Equipment ...................................................................................................................................... 24

Laboratory Experiments ................................................................................................................................. 25

Preliminary Field Tests .................................................................................................................................... 27

Weigh Station Experiments ............................................................................................................................. 28

PRELIMINARY INVESTIGATIONS ..................................................................................................................... 46

Laboratory Data ............................................................................................................................................... 46

Preliminary Field Test Data ............................................................................................................................. 53

Weigh Station Data ........................................................................................................................................ 55

EMPIRICAL MODELS ......................................................................................................................................... 68

Dimensional Analysis ....................................................................................................................................... 68
LIST OF FIGURES

Figure 1 Photograph of laboratory test apparatus ................................................................. 6
Figure 2 Relationship between axle load and ESAL, using the AASHTO design method for
flexible pavements (Yoder & Witczak, 1975) ........................................................................ 13
Figure 3 Schematic of acoustic emission testing equipment .................................................... 17
Figure 4 Depiction of acoustic emission parameters ............................................................... 17
Figure 5 Drop test ................................................................................................................ 25
Figure 6 Minisensor attachment (bottom side of metal test strip) ........................................... 32
Figure 7 Photo of attachment of WD sensor to metal test bar ............................................... 33
Figure 8 Aerial view of Flagler weigh station .................................................................... 34
Figure 9 Schematic of Flagler WIM equipment and experimental equipment ...................... 34
Figure 10 Photo of Flagler WIM equipment and experimental equipment........................... 35
Figure 11 Schematic of connections from sensors to computer ........................................... 35
Figure 12 Proposed configuration of equipment at testing location ..................................... 36
Figure 13 Speed distribution for vehicles in the data set (July 2008) .................................. 40
Figure 14 Speed distribution for vehicles in the data set ...................................................... 42
Figure 15 Axle weight distribution for all axles, separated by left and right side (July 2008).... 44
Figure 16 Axle weight distribution for all axles, separated by left and right side (April 2009).. 44
Figure 17 Axle weight distributions by number of axles per vehicle .................................. 45
Figure 18 Count as a function of weight .............................................................................. 47
Figure 19 Energy as a function of weight ............................................................................ 47
Figure 20 Absolute energy as a function of weight ............................................................... 48
Figure 21  Sum of count for each TB as a function of load and position .................................... 49
Figure 22  Sum of energy for each TB as a function of load and position .................................. 50
Figure 23  Sum of absolute energy for each TB as a function of load and position .................... 51
Figure 24  Typical pattern of energy in hits during one repetition (2 ABs) .................................. 54
Figure 25  Acoustic emission time interval as a function of truck speed ..................................... 55
Figure 26  Acoustic emission energy response with time for three different vehicles .................... 56
Figure 27  Comparison of the number of hits per AB by type of sensor .................................... 58
Figure 28  Comparison of the value of count for each hit by type of sensor ................................ 59
Figure 29  Right and left axle comparison ...................................................................................... 61
Figure 30  Accuracy of vehicle speed calculations using acoustic emission data ......................... 62
Figure 31  Accuracy of axle spacing calculations using acoustic emission data ............................ 63
Figure 32  Number of hits per AB, organized by axle weight ......................................................... 65
Figure 33  Fit for laboratory data .................................................................................................. 75
Figure 34  Fit for July 2008 field data ............................................................................................ 85
Figure 35  Fit for April 2009 field data ............................................................................................ 87
Figure 36  Fit for July 2008 field data (validation) .......................................................................... 88
Figure 37  Fit for April 2009 field data (validation) ........................................................................ 89
Figure 38  Histogram of percent error for July 2008 dataset ......................................................... 90
Figure 39  Histogram of percent error for April 2009 dataset ....................................................... 90
Figure 40  Error in weight estimation as a function of vehicle speed ............................................ 96
Figure 41  Histogram of distance to previous axle (axle spacing) by axle for 5-axle vehicles ....... 97
LIST OF TABLES

Table 1 Description of acoustic emission parameters................................................................. 18
Table 2 Characteristics of 75 vehicles selected for analysis (July 2008) ...................................... 38
Table 3 Vehicle classification description .................................................................................. 39
Table 4 Characteristics of vehicles selected for analysis (April 2009) ....................................... 41
Table 5 Source of variability from laboratory apparatus ............................................................. 52
Table 6 Comparison of maximum hit values by method of affixation (empty pickup truck) ....... 53
Table 7 Characteristics of acoustic emission sensors ................................................................. 57
Table 8 $R^2$ values from linear regression by method of aggregating acoustic emission axle hits67
Table 9 Variables for dimensional analysis .................................................................................. 69
Table 10 Parameters for laboratory data regression equation ..................................................... 74
Table 11 Statistics comparing statistical model of laboratory data to actual laboratory load ....... 75
Table 12 Acoustic emission parameter variables ......................................................................... 78
Table 13 Weight of each axle for vehicle 1636, July 2008 dataset .............................................. 81
Table 14 Parameters for field data regression equation ............................................................... 82
Table 15 Statistics comparing statistical model of field data to actual axle weight (July 2008 dataset) .......................................................................................................................... 85
Table 16 Statistics comparing statistical model of field data to actual axle weight (April 2009 dataset) .......................................................................................................................... 86
Table 17 Statistics comparing statistical model of field data to actual axle weight for validation data (July 2008 dataset) ........................................................................................................ 87
Table 18  Statistics comparing statistical model of field data to actual axle weight for validation data (April 2009 dataset)........................................................................................................... 88
Table 19  Comparison statistics for the modeled datasets by axle ................................................. 91
Table 20  Comparison statistics for the validation datasets by axle ................................................ 92
INTRODUCTION

Vehicle loads are subject to weight limits for a variety of reasons, including preservation of the highway infrastructure, equitable apportionment of the costs of freight transportation, and traffic safety. Weigh stations are built to provide the equipment necessary to carry out vehicle weight limit enforcement, but data from weigh stations can also be useful for studies of commercial vehicle volume and weight characteristics.

Weigh stations take a variety of forms, including:

- traditional weigh stations where heavy vehicles are pulled off of the highway and weighed on low-speed WIM scales and/or stationary scales, and
- Remotely Operated Compliance Stations (ROCS), sometimes called “virtual compliance stations” where heavy vehicles are weighed at highway speeds in the travel lanes (Rodier, Shaheen, & Cavanagh, 2006).

Because of the personal economic benefit, some commercial vehicle operators purposely exceed weight limits for their vehicles. These operators may willingly pay the fines associated with operating an overweight vehicle if the value of the extra goods transported exceeds the cost of the fines. Alternatively, they may adjust their routes to bypass fixed weigh stations and thus avoid the fines. A study of three weigh stations and possible bypass routes for the I-95 corridor in northern Florida examined the effects of enforcement on truck volumes and weights for each of the routes studied (Cunagin, Mickler, & Wright, 1997). The study concluded that increased enforcement at the weigh stations was most effective at reducing overweight truck traffic when
the possible bypass routes were also enforced. Where enforcement activities were not practical 24 hours a day, 7 days a week (because of the cost of enforcement personnel), the study suggested that random enforcement was necessary. The findings of this study are consistent with an economic evaluation of bypass traffic published in 2001, which found that truck carriers are more likely to comply with weight limits when portable scales along bypass routes are used in conjunction with fixed scales (Strathman, 2001).

Effectively enforcing weight limits is important because pavement deterioration has been shown to be related exponentially to the load carried by the vehicles passing over the pavement, as reflected in pavement design methodologies used in the US and abroad. Bridges are also affected by these repeated heavy loads. Thus, heavy vehicles are responsible for most traffic-related damage to pavement and other highway infrastructure components. Weight limits for heavy vehicles are established in an attempt to balance the benefit to society derived from the transportation of goods with the costs of maintaining the highway infrastructure by collecting fees from permitting or ticketing overweight vehicles (Barros, 1985; Sivakumar, Ghosn, & Moses, 2008).

The development of portable weigh stations that can detect attempts to bypass fixed weigh stations on a full-time basis at a relatively low cost is thus an extremely valuable goal. Generally, existing WIM systems require embedding relatively large sensors into the road surface. This process also requires special preparation of the roadway approach surface just prior to and immediately after the embedded sensor to eliminate potential extraneous dynamic effects produced by the wheel impact on the sensor due to unevenness of the roadway (Izadmehr & Lee,
Since one of the requirements for weigh stations that are designed to detect bypass traffic is portability, having a large embedded WIM sensor is clearly undesirable for this application. Some portable WIM systems have already been developed, namely the capacitance mat system and the fiber optic system. These will be discussed further in the LITERATURE REVIEW section.

Development of a New Low-Cost Portable WIM System

A variety of sensors have been designed to be used in non-destructive testing for detection of anomalies, assessment of fluid flow, and measurement of stresses. These technologies include laser speckle interferometry, shearography, and velocimetry, as well as acoustic and ultrasonic sensors. Recognizing that these technologies might be used to create a low-cost WIM sensor, researchers at the University of Central Florida (UCF) proposed that a pilot study of some of these sensors be implemented. The study was completed in 2003. Because it showed promise for the development of a low-cost WIM system, study of the concept was continued, as presented in this dissertation.

The proposed WIM system consists of a metal test strip that is laid across the roadway. When a vehicle rolls over an object such as the metal test strip, it creates acoustic emission waves within the object. It is possible to detect these acoustic emissions using acoustic emission sensors. Acoustic emission sensors are attached to the test strip. The signal from the sensors is run through a preamplifier which sends the acoustic emission signal on to a computer where the signal is analyzed using acoustic emission software. The relationship between the weight of a vehicle and the acoustic emission signal created in a metal test strip when it is struck by the
vehicle was determined by experimentation, using test vehicles driving over the metal test strip. The weight of the vehicle and the speed of the vehicle are known, but varied. Statistical analysis performed on the output of this experiment (the acoustic emission signal), given the input variables (weight and speed), establish the correlation between the acoustic emission signal and the weight of the vehicle.

Initial Experimentation
The earliest studies at UCF where the vibration in a metal bar was used to determine the weight of a moving vehicle took place in 2003 (Moslehy & Oloufa, 2004). In these experiments, several different types of sensors were used, including a laser vibrometer and acoustic emission sensors. The weight and speed of the vehicles tested (a bicycle and a pickup truck) were found to be correlated with the maximum wavelet coefficient, calculated using the MATLAB software program.

After the initial testing, the researchers focused on using acoustic emission sensors and obtained funding from the Florida Department of Transportation to continue the research. In the fall of 2004, a laboratory experiment was carried out to determine how impact force on a metal test strip related to the parameters of the resultant acoustic emission. This experiment used an aluminum bar with a rectangular cross section as the metal test strip. Two acoustic sensors were attached to the strip (one on each end). The impact was provided in three different ways: a steel ball dropped from various heights onto the test strip, a pencil lead broken against the test strip, and a bicycle tire rolled across the test strip. A linear correlation between the impact force and the absolute energy of the acoustic emission response was detected (Kolgaonkar, 2005).
A field test was then carried out in May 2006. For this experiment, a steel bar with an elliptical top surface was purchased. Once again, sensors were attached to each end of the bar. The bar was attached to the roadway surface using duct tape and the impact was provided by running a vehicle over the metal test strip. To vary the input, two different vehicles were used (a pickup truck and a compact car) and the vehicles were driven at a variety of speeds from 5 to 25 mph.

*Construction of an apparatus for laboratory testing*

It was concluded that to test the concept further, laboratory test apparatus was needed. The laboratory apparatus was designed to allow greater control over the application of different test weights and speeds. Four mechanical engineering students in a senior design class designed and built the test apparatus. An inverse design where the roadway rotates and the axis of the tire does not move was chosen for the final design. As seen in Figure 1, a motorcycle tire is pushed against a rotating cylindrical “road” with the metal test strip attached. The force of the tire against the “road” is varied by use of a scissor jack, with a maximum force of about 800 lbs. A motor and reducer turn the “road” at speeds ranging from 0 to 4 mph. A bicycle speedometer is used to measure the speed at which the cylinder turns. In addition, a slider and swing arm assembly allows the location of the motorcycle wheel to be adjusted from side to side (Bowie, Moslehy, & Oloufa, 2008).
Figure 1 Photograph of laboratory test apparatus

*Acoustic emission equipment*

The acoustic emission sensors, preamplifiers, and computer hardware and software were all purchased from Physical Acoustics Corporation. The sensors are wideband sensors, type WD (18 mm diameter, 17 mm height; operating frequency range of 100 to 1000 kHz). The preamplifiers are general use voltage preamplifiers, Model 2/4/6. The computer hardware is a PCI-2 card, revision 1. The software is a computer program called AEWin for PCI-2, version E1.56.
LITERATURE REVIEW

This literature review gives background information and reviews previous research on several topics related to this dissertation: weigh-in-motion technology and its uses, tire-pavement contact stress, and acoustic emission.

Weigh-in-Motion

In an effort to extend the useful life of roadway pavement and improve vehicle safety, weight limits have been set for heavy trucks utilizing the nation’s highways (Truck Weight Limits: Issues and Options, Special Report 225, 1990). To enforce the weight limits, trucks are weighed at weigh stations along the highway and overweight vehicles are ticketed and/or fined.

Types of WIM Scales

Scales used to measure the weight of commercial trucks can be either static (weighing vehicles at rest) or weigh-in-motion (weighing vehicles as they travel). In addition, the scales can either be built into the pavement or portable. Static scales measure the weight of a vehicle at rest. Because of the large size of the vehicles involved, some scales (especially portable ones) are built to weigh only one axle at a time. That is, the vehicle is parked with just the front axles on the scale and the weight is measured, then the vehicle is moved so that the second set of axles rests on the scale, and so forth. Accurate measurement relies upon level pavement around the scale and upon the elimination of other sources of error such as load shifting between measurements (Davies & Sommerville, 1987).
Weigh-in-motion (WIM) systems, on the other hand, measure the dynamic forces associated with a vehicle in motion passing over the scale. The accuracy of a WIM system is affected by the type of suspension system present in the vehicle being weighed, the type of pavement (flexible or rigid), and the profile of the pavement surrounding the scale (Cunagin, Majdi, & Yeom, 1991).

Several different technologies are currently in use in built-in WIM systems. Some of the more common include bending plate, hydraulic load cell, and piezoelectric.

The bending plate WIM system consists of steel plates surrounded by rubber and connected to strain gauges. The vehicle weight is related to the strain on the plates as the vehicle crosses over them (Sebaaly, Chizewick, Wass, & Cunagin, 1991). Similarly, a WIM system can be created by measuring strain in a structure (a bridge, for instance) (Gagarine, Flood, & Albrecht, 1992).

The hydraulic load cell WIM system consists of a steel platform that acts as the load bearing surface and transfers the load to a piston (Sebaaly, Chizewick, Wass, & Cunagin, 1991).

The piezoelectric WIM system works by measuring voltage differences that are caused by the pressure that is exerted on a sensor when the vehicle passes over it (Andrle, McCall, & Kroeger, 2002). Several different types of piezo sensors have been developed, including piezo ceramic WIM sensors and piezo sensors based on quartz dielectric. Although early versions of the quartz piezo sensors were not durable, a test of quartz piezoelectric sensors installed at two locations in Texas in 2004 and 2005 found that the updated quartz piezo sensors were accurate and durable when installed in Portland cement concrete pavements. Future testing was planned for the installation of sensors in asphalt concretes (White, Song, Haas, & Middleton, 2006).
All of the WIM systems described above are fixed systems, meaning that they are installed in the pavement in the traffic lane. A major drawback of fixed weigh stations is that their location becomes generally known among truck drivers, making it possible for non-compliant vehicles to avoid detection by using an alternate route, such as traveling on local roads in the vicinity of the weigh station. In addition, the high cost of these scales makes it impractical to create a cordon by placing them on all possible routes in an area (Cunagin, Mickler, & Wright, 1997).

To overcome some of the problems with fixed systems, portable systems have been developed. The capacitance mat is one such system. It consists of a three plate capacitor within a tuned circuit (made from three sheets of steel surrounded by rubber dielectric). A passing vehicle compresses the capacitor, changing the frequency of oscillation. This change in frequency can be related to the weight of the vehicle (Cole & Cebon, 1989; Sebaaly, Chizewick, Wass, & Cunagin, 1991).

Another portable WIM system that has been developed is a fiber optic system where the weight of the vehicle is measured by the bending of light (Mimbela, Pate, Copeland, Kent, & Hamrick, 2003).

Uses of Data from WIM Systems

Typical weigh stations collect information about axle weight, axle configuration and spacing, and gross vehicle weight. In addition to these, WIM systems can also be instrumented to collect information on vehicle speed, headway, volume, equivalent single axle loads (ESALs), lateral position of the vehicle in the lane, pavement and air temperature, and identifying characteristics.
such as DOT or container numbers. Because this information can be collected by a WIM system continuously, the possible uses of this data are broad.

*Weight enforcement*

The primary purpose of WIM systems is often for weight enforcement. When used as a sorter scale, WIM systems have been shown to decrease congestion and reduce vehicle operating costs at traditional weigh stations (Benekohal, El-Zohairy, & Wang, 2000; Newton, Frith, & Barbour, 1992). Remote (sometimes called virtual) compliance stations, where WIM scales are located on the highway where there is no weigh station, can be used for enforcement purposes as well (Regan, Park, Nandiraju, & Yang, 2006).

WIM systems can also be used more generally to focus enforcement efforts by police officers. For instance, a two-year pilot program was implemented in Montana in 2000 (Stephens, Carson, Hult, & Bisom, 2003). At the time, Montana had 19 permanent WIM systems and planned to operate 64 sites on a three-year cycle using portable WIM equipment. One year of data from these WIM sites was collected and excess ESALs were computed for each site by determining the amount of pavement damage caused by each overweight vehicle that could be attributed to the portion of its weight that was over the legal limit. This data was aggregated by month and used to determine the five sites that had the greatest number of excess ESALs each month. For the second year of the study, enforcement officers were assigned to the top five sites each month. Officers were additionally provided with information on the critical day of week, time of day, direction of travel, and vehicle classification for the typical violator at each site.
Unfortunately, the WIM stations had just been installed when the project began, so there was not time to collect trend information for use in the analysis of the program. Additionally, early in the second year of the study the weight tolerances were changed to 10% above the statutory limits, as opposed to 7% above the limits. These two circumstances make it difficult to make definite conclusions about the efficacy of the program. Nevertheless, the study found that pavement damage from overweight vehicles was reduced by 4.8 million ESALs statewide during the second year of the study compared to the first year of the study, a cost savings of approximately $500,000.

Transportation planning
WIM systems typically record information about vehicle speed, vehicle length, distance between axles, and axle weights. Some systems also record vehicle height and take photographs of the vehicle to use for identification purposes. There are a number of possible uses for this data in transportation planning, including:

- counting and categorizing vehicles for determinations of annual average daily traffic, 30\textsuperscript{th} highest hourly volumes, etc.;
- using the actual axle loads for the development of user fees to apportion the costs of pavement damage among the classes of vehicles using the roadway;
- using the actual length and axle spacing characteristics of the vehicles using the facility to determine appropriate geometric design characteristics;
informing safety analyses and computerized traffic analysis models by determining vehicle miles traveled (VMT) and examining speed and headway distributions for various categories of vehicles; and

determining design and maintenance standards for bridges based on actual loads (Hajek, Kennepohl, & Billing, 1992; Sivakumar, Ghosn, & Moses, 2008).

Pavement design

The AASHTO Guide for Design of Pavement Structures, originally published in 1972 and updated in 1986 and 1993, has historically been the most common method of pavement design. The data for the AASHTO guide was taken from a small data set, the AASHO Road Test, conducted at one geographic location (Ottawa, Illinois) in the 1950’s (Hallin, Teng, Scofield, & Von Quintus, 2007). In 1987, the Federal Highway Administration’s (FHWA) Long Term Pavement Performance (LTPP) program began. This program was a 20-year study of over 2400 pavement test sections throughout the US and Canada (Federal Highway Administration, undated). The results of the LTPP have been used to develop a new pavement design guide, known as the Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (MEPDG) and first published in March 2004. The Guide was developed as part of National Cooperative Highway Research Program (NCHRP) Project 1-37A.

Using the AASHTO method, an equivalent single axle load (ESAL) is used to determine a structural number (flexible pavement) or the slab thickness (rigid pavement). The ESAL is determined by equating the damage to the pavement caused by the actual traffic load to the damage that would be caused by 18,000 lb (18 kip) single axle loads (Yoder & Witczak, 1975).
Figure 2 shows the exponential relationship between axle load and pavement damage, as represented by ESALs. An accurate evaluation of actual traffic loadings obtained from WIM scales, can be useful for the AASHTO method (Hong, Prozzi, & Leung, 2008).

In England, a vehicle wear factor (VWF) is used to determine the effect of a vehicle on the pavement by comparing each axle weight to the standard weight of 80 kN per axle, using the equation, \[ \text{VWF} = \sum_i \left( \frac{w_i}{80kN} \right)^x, \] where \( w \) is axle weight, \( i \) indicates each axle in the vehicle, and \( x \) indicates the exponential relationship between vehicle axle weight and the damage to the pavement caused by the vehicle. Although \( x = 4 \) is typically used, experimentally determined values of \( x \) have varied depending on the failure mechanism, ranging from 0 (for types of pavement damage unrelated to vehicle weight such as raveling and skid resistance) to 9.6 (for rutting) (Collop, Al Hakim, & Thom, 2002).
Whereas the AASHTO method uses empirically-derived parameters to determine pavement design, the new MEPDG method uses the principles of engineering mechanics in combination with a rich empirical data set. The design method is extensive and involves the consideration of a number of different types of data, including consideration of the pavement foundation and possible improvements to the foundation, detailed climate information, evaluation of proposed pavement materials, and detailed information on the traffic loads, classification, and projected volumes. Because the MEPDG uses the distribution of weights for each class of vehicle, WIM data is valuable for accurately designing pavements using this method (Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, 2004).

Tire-Pavement Contact Stress
This dissertation seeks to establish a relationship between the weight of a vehicle and the acoustic emissions in a metal test strip when the vehicle rolls over it. The force of the vehicle’s weight is exerted on the metal test strip by the vehicle’s tires. This section introduces factors that might affect the interaction between the vehicle tire and the metal test strip by examining research which looks at how a vehicle’s weight is transferred to the pavement through the vehicle’s tires.

For ease of calculation, the tire contact pressure exerted on pavement is sometimes approximated as a uniformly distributed circular load, where the contact pressure is approximated to be equal to the internal tire pressure. However, the actual tire contact area has been shown to be rectangular or ovoid and the contact pressure exerted by the tire on the pavement has been shown
to be non-uniform and influenced by numerous variables, including the structure of the tire (bias ply or radial), the width of the tire, the internal tire pressure, and the load.

At the time of the AASHO Road Test, bias ply was the most common type of tire in use on commercial vehicles. Currently, however, radial tires are far more common. Bias ply tires have a relatively rigid wall structure and flexible tread whereas the treads of radial tires are reinforced with steel, making the tread relatively rigid and the wall structure relatively flexible (Myers, Roque, Ruth, & Drakos, 1999; Roque, Myers, & Birgissson, 2000). This results in very different contact stresses for the two types of tires, with the contact stress generally peaking on the sides for bias ply tires and in the center for radial tires. These structural differences also result in differences in the stresses under each tread, with the treads causing generally compressive transverse shear stress under bias ply tires and tensional transverse shear stress under radial tires. The tire tread structure itself also contributes to the non-uniformity of the contact stress, since there is no contact stress in the area between the treads (Weissman, 1999) and the number and width of the ribs influence the pavement stresses as well (Myers, Roque, Ruth, & Drakos, 1999; Novak, Birgisson, & Roque, 2003).

Tire pressure may also influence contact stress; however, Yoder and Witczak show that differences in vertical stress (and therefore deflection) due to differences in tire pressure are small at the surface of the pavement (where the metal test bar is located) (Yoder & Witczak, 1975). Since it would be impossible to measure tire pressure or determine tire and tread type using the proposed WIM equipment, these factors were generally not included in the analysis as variables.
Acoustic Emission

Acoustic emissions are naturally occurring elastic waves produced by the rapid release of energy within a material. These acoustic emissions are initiated when solids are thermally or mechanically stressed such that deformation or fracturing occurs (Mix, 2005). Audible acoustic emissions have been observed for thousands of years in such things as the making of pottery (where audible cracking sounds while the pottery is cooling indicate defects in the pottery) and metalworking (several metals make crackling or sharp noises while they are being worked) (Miller, 1987). However, the study of acoustic emission itself did not begin in earnest until the 1940s when researchers began to associate the emission of subaudible or ultrasonic sounds in materials with the loads the materials were placed under (Scott, 1991).

In acoustic emission testing, sensors are applied to the surface of the solid material that is being tested using a thin layer of a coupling material (such as Vaseline or glue). The sensor converts the mechanical acoustic emission wave to an electrical signal. The signal is amplified and then travels to a computer that has been programmed to interpret the signals. This process is shown in Figure 3.

Acoustic emission signals can be continuous (such as the signals emitted during plastic deformation or from a leaking pipe) or can be burst-type (such as the signals emitted by crack propagation or rust-formation) (Hull & John, 1988). The computer analyzes each signal to determine the acoustic emission parameters associated with it, shown in Figure 4. Descriptions of these parameters are found in Table 1. The threshold shown in the figure is set by the user.
Figure 3 Schematic of acoustic emission testing equipment

Figure 4 Depiction of acoustic emission parameters
Table 1 Description of acoustic emission parameters

<table>
<thead>
<tr>
<th>Acoustic emission parameter</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td></td>
<td>the source of an acoustic emission wave, caused by a microscopic displacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>an oscillatory signal that rises in amplitude from the background level and then gradually decreases to the initial reference level</td>
</tr>
<tr>
<td>Hit or Burst</td>
<td></td>
<td>time elapsed from when the signal first crosses the threshold level until the peak amplitude is reached</td>
</tr>
<tr>
<td>Rise time (µs)</td>
<td>( r )</td>
<td>number of times the signal amplitude exceeds the threshold level over the length of the entire hit</td>
</tr>
<tr>
<td>Count</td>
<td>( c )</td>
<td>relative energy measurement obtained by measuring the area under the waveform associated with each hit (integral of the absolute value of the voltage over time)</td>
</tr>
<tr>
<td>Energy (aJ)</td>
<td>( E )</td>
<td>time length of the hit</td>
</tr>
<tr>
<td>Amplitude (dB)</td>
<td>( a )</td>
<td>height of the highest peak in each hit</td>
</tr>
<tr>
<td>Counts to peak</td>
<td>( c_p )</td>
<td>similar to counts, except it only includes the counts until the peak amplitude is reached</td>
</tr>
<tr>
<td>Absolute energy (aJ)</td>
<td>( AbsE )</td>
<td>absolute value of the energy in each hit (integral of the squared voltage over time)</td>
</tr>
<tr>
<td>Frequency – average (kHz)</td>
<td>( f_a )</td>
<td>derived by dividing count by duration</td>
</tr>
<tr>
<td>Frequency – initial (kHz)</td>
<td>( f_i )</td>
<td>derived by dividing counts to peak by rise time</td>
</tr>
<tr>
<td>Frequency – reverberation (kHz)</td>
<td>( f_r )</td>
<td>derived by subtracting counts to peak from count and dividing by the difference between duration and rise time</td>
</tr>
</tbody>
</table>

In acoustic emission testing, the intensity of acoustic emissions can be used to determine when changes are occurring. Intensity can be measured by considering such things as the rate of acoustic emission hits, the count of individual acoustic emission hits, or the energy of the hits. In many instances, the intensity has been found to increase as a flaw approaches a critical size. The
intensity also increases when a material undergoing plastic deformation reaches the point of failure (Hull & John, 1988). This characteristic of acoustic emission makes it a useful nondestructive testing technique in such areas as pressure vessel testing, leak detection, machinery monitoring, structural integrity monitoring, and weld monitoring, among others (Miller, 1987). Because acoustic emissions can be detected without knowledge of the source location, acoustic emission testing can be done without disassembling a machine or structure and can be used to detect material failure even when the failure is occurring in areas that are difficult to reach.

The Kaiser effect is an acoustic emission phenomenon named for Joseph Kaiser, the German scientist who was the first to notice the effect. The Kaiser effect occurs when a material is loaded beyond the elastic limit of the material. After the material is released from the load, acoustic emissions are not emitted when a load is reapplied until the maximum level of the initial loading has been surpassed. The Kaiser effect has been observed in many materials (including metals, rocks, and snow). It occurs because discontinuities that were created in the material during the initial loading do not expand or move during the reapplication of the loading until the initial load has been surpassed (Bradley & St Lawrence, 1974; NDT Resource Center, ; Tensi, 2004). The Kaiser effect is not always observed. In materials that “heal” over time between loadings or in structures that are in poor condition, acoustic emissions are detected at loadings below the previous maximum load. This is known as the felicity effect. The felicity ratio is calculated by dividing the load at which acoustic emissions begin to be released by the previous maximum load. This characteristic of acoustic emission is useful in materials characterization since different materials exhibit the Kaiser effect to a greater or lesser extent and must be understood
to correctly interpret the acoustic emission response of structures that undergo repeated loads (Miller, 1987).

Acoustic emission testing is normally aimed at characterizing the stressed structure through which acoustic emissions are passing. That is, when bucket trucks are inspected using acoustic emission testing, a load is placed on the bucket truck and the resulting acoustic emission is used to determine the integrity of the components of the bucket truck. Similarly, acoustic emission testing of pressure vessels is intended to locate discontinuities in the pressure vessel by placing the vessel under pressure and examining the acoustic emission output (Miller, 1987).

Nevertheless, there are a few acoustic emission applications that are intended to relay information about the type or size of the stress (or load) that has been placed on the object in question. One example of this is the use of acoustic emission to detect impacts of loose materials on structural components for vulnerable structures such as aircraft or power plants. For instance, NASA has developed a system known as the Wing Leading Edge Impact Detection System that includes acoustic emission technology. This system is designed to detect impacts to the leading edge of the wing such as the one that led to the breakup of the Space Shuttle Columbia in 2003 (NDT Resource Center). Research is ongoing into the use of acoustic emission in impact detection, including determining the location of the impact as well as determining the force of impact. One example of this research is a study that determined the location and time history of an impact load on a thick plate using acoustic emission sensors (S.-K. Lee, Banerjee, & Mal, 2007).
A similar application that is related to acoustic emission testing is Particle Impact Noise Detection. This is a quality control test where electronic components are shaken so that loose particles within the cavities of the components can be detected by an acoustic sensor. Loose particles within the cavity of an electronic component can cause short circuiting or otherwise cause the component to fail – by holding relay contacts apart, for instance (Miller, 1987). In addition to simply detecting the loose particles in electronic components, some research has been done into classifying the loose particles to aid manufacturers in identifying the source of these loose particles. One example of this is a study done in China which divided the particles into four types: metals with strong elasticity, metals with weak elasticity, nonmetals with strong elasticity, and nonmetals with weak elasticity. The acoustic signal exhibited by each of the types of particles was examined and the effectiveness of three different feature extraction methods in distinguishing particle types was evaluated. The researchers were able to use these methods to determine the type of loose particle found in different electronic components (Wang, Gao, & Zhai, 2007).

Tribology, or the study of interacting surfaces in relative motion, is another area where acoustic emissions are being used to provide a quantitative measure of the force or load that is being applied. One set of experiments measured the acoustic emission energy emitted by the contact between a hard drive and its housing as it revs up to speed and before its speed is high enough that it “flies” – or spins without touching anything else (Knigge & Talke, 2007; McMillan, Talke, & Harrison, 1998). Another study used acoustic emission to determine the force applied to the edge of a magnetic tape by the flange of a roller the tape is passing over (Raeymaekers & Talke, 2007). Acoustic emission has also been shown to be useful as a monitoring tool in
manufacturing processes that must create very small features with high reliability (D. E. Lee, Hwang, Valente, Oliveira, & Dornfeld, 2006).

The study of acoustic emission is still relatively young and a great deal of research into both the understanding of acoustic emission itself and possible applications of acoustic emissions technology is ongoing. This dissertation presents a novel application of acoustic emission technology – the measurement of the weight of a commercial vehicle.
EXPERIMENTS

A number of experiments were carried out in order to test the proposed acoustic emission WIM system. These included laboratory experiments using the equipment described in the Introduction on page 5 as well as field tests where commercial vehicles were weighed by an existing weigh-in-motion scale and by the proposed acoustic emission WIM system. The weight of the vehicle recorded by the weigh-in-motion scale was then related to the recorded acoustic emissions.

Definition of Terms

To facilitate the discussion of the experiments that were carried out, it is necessary to define some terms. Two terms were coined as part of these experiments to describe the event that elicited acoustic emission, namely a tire striking or running over the metal test strip. One “tire bump” (TB) was considered to be one instance of a tire striking the metal test strip. One “axle bump” (AB) was considered to be one instance of an axle (two or more tires) striking the metal test strip.

These terms should not be confused with the term “hit,” which in acoustic emissions testing is used to describe the waveform which exists between when the acoustic sensor output exceeds some pre-determined amplitude and when the acoustic sensor output goes back below the threshold amplitude (see Figure 4). For more simple events (such as a pencil lead breaking against the metal strip), only one or two hits are produced per event. However, for the more complex event of a tire rolling across the metal strip, many hits are produced each time a tire strikes the metal test strip. A TB or an AB, then, is usually associated with several hits.
The software records the acoustic emission parameters for each of these hits, including time (the amount of time that has passed from when the recording began), channel (corresponding to which sensor detected the hit), rise time, count, energy, duration, amplitude, counts to peak, and absolute energy (see Table 1 for descriptions of these parameters). This line by line list of all of the parameters for each hit in a recording was imported into Microsoft Excel to facilitate analysis of the data.

Testing the Equipment
A drop test was performed to look for differences in the acoustic emission response depending on the sensor, the amplifier, or the bar that was used. The drop test consisted of dropping a metal screw through a paper towel tube onto the metal bar, as shown in Figure 5. The drop test was used for two purposes: to verify that the equipment was correctly set up and working properly before experiments were performed, and to determine if there were differences in the acoustic response recorded when different pieces of equipment were used (different amplifiers, metal bars, or sensors, for example).

Initially, the threshold was kept at the default setting of 45 dB, but at that setting, the computer detected a continuous signal regardless of whether or not a sensor was attached. Changing the threshold to 50 dB eliminated this background noise. The threshold was thus kept at 50 dB for all of the experiments described in this dissertation.

To determine if the equipment affected the acoustic emission response, an experiment was run where the combination of sensors, amplifiers, and metal test bars was varied and the acoustic
response to the drop test was recorded for each trial. A rank sum test was performed to compare all of the values of amplitude for the hits recorded in each trial according to which bar, amplifier, or sensor was used. The rank sum test found that the amplitudes of the acoustic emission hits were the same regardless of the amplifier or metal test bar used; however, the amplitudes were different for the different sensors. Thus, it is important to consider the difference in the acoustic emission parameters detected by different sensors when analyzing the acoustic emission data in the following experiments.

Figure 5  Drop test

Laboratory Experiments

This set of experiments used the laboratory test apparatus shown in Figure 1 to examine the relationship between the weight on a tire moving across a metal test strip attached to a road surface and the acoustic emissions in the metal test strip caused by this motion. In addition, the effects of the speed of the impact and the location of the impact were examined.


**Equipment**

The laboratory test apparatus was used in these experiments. The “road” consisted of a rotating concrete cylinder to which the metal test bar was firmly affixed along the length of the bar. Two WD acoustic emission sensors were attached to the metal test bar, one at either end with a distance of approximately 40 inches between them. The sensors were coupled to the metal test bar using Vaseline and were held in place with duct tape. The signal cable from the sensors ran to preamplifiers that were attached to the ends of the cylinders. From the preamplifiers, the signal cable ran to the center of the cylinder where it ended in a male BNC cable Connector. A female to female BNC cable connector was used to connect the apparatus to another cable which attached to the PCI card input on the computer. These connections allowed the cylinder to rotate without rotating the cable that attached to the computer.

**Methodology**

Two different sets of data were collected. The first data set examined the effect of speed and weight on the system. Thus, for the first data set acoustic emission responses were collected for 14 different levels of weight – from 100 to 750 lbs in 50 lb increments – and three different levels of speed – approximately 2, 3, and 4 mph, resulting in 42 repetitions of the experiment. Each repetition involved collecting the data for 30 consecutive TBs into one file at each combination of weight and speed (Moslehy, Oloufa, & Bowie, 2007).

The second data set was designed to capture the variability in the response as well as to examine the effects of tire impact location on the results. As a result, the speed was held constant at 3 mph, the tire impact location was varied (with measurements taken at 10 inches, 20 inches, and
30 inches from each sensor), and the load was varied (with measurements taken at 500, 600, 700, and 800 lbs). At each of these twelve settings, 30 repetitions of the experiment were performed. For each repetition, the acoustic emission output was collected for one TB in each file.

A description of the data and preliminary investigations into the relationship between the recorded acoustic emission parameters and the vehicle’s weight are found in the Preliminary Investigations section, starting on page 46. The development of an empirical model to describe this relationship is found in the Empirical Models section, with a discussion of the laboratory data beginning on page 73.

Preliminary Field Tests
Two preliminary field tests were carried out in a parking lot on the UCF campus, one in May 2007 and the other in June 2007. These field tests were preparation for more rigorous field tests which took place at the weight station on I-95 southbound, mile marker 286, just north of SR 100 in Flagler County in July 2008 and April 2009.

Equipment
In the preliminary experiments, the metal test strip was approximately 12.5 feet long, with an elliptical top surface. As in the laboratory testing, the top surface was filed flat in the area where the sensors were to be attached. On the test day in May 2007, the metal test strip was attached to the roadway using duct tape. On the test day in June 2007, the metal test strip was attached to the roadway using epoxy. The test vehicle was a Sierra GMC truck, with a curb weight of approximately 4,000 lbs. The weight of the test vehicle was varied by adding passengers and sandbags, with a maximum weight of approximately 5,000 lbs.
The acoustic emission system was the one used in the laboratory. Thus, for these experiments the
desktop computer was moved outside and powered using a generator. The sensors and
preamplifiers were unattached from the laboratory apparatus and attached to the metal test strip
used in the field.

Methodology
In May 2007, two speed conditions (10 mph and 20 mph) and two weight conditions
(approximately 4,000 lbs and 4,700 lbs) were tested. In June 2007, three speed conditions (10
mph, 20 mph, and 30 mph) and three weight conditions (approximately 4,000 lbs, 4,500 lbs, and
5,000 lbs) were tested. Only one test run at 30 mph was performed because this speed seemed
unsafe in the geometry of the parking lot.

A description of the data and preliminary investigations into the relationship between the
recorded acoustic emission parameters and the vehicle’s weight and speed are found in the
Preliminary Investigations section, starting on page 53.

Weigh Station Experiments
The weigh station experiments allowed examination of the test equipment in a realistic
environment: that is, using heavy vehicles that were traveling at highway speeds (30 to 50 mph).

Design of Experiment
Several factors were considered in preparing for data collection at the weigh stations; however,
the limited availability of the Flagler Weigh Station for conducting experiments combined with
difficulty in finding appropriate methods for varying some of the factors resulted in a very
simplified design with only two sets of data collected, one in July 2008 and the other in April 2009. The following sections describe each of the factors that were considered.

*Vehicle classification*

Vehicle classification is collected by the WIM scale equipment. Vehicles of class 3 through 11 can be directed to pull into the weigh station, with the majority being class 9 (the typical five-axle tractor-trailer truck combination). Since it is not possible to control the mix of vehicle classes that cross the experimental equipment, this parameter was not included in the design, but can still be considered in the model.

*Speed*

Although it is not possible to control the speed of the subject vehicles as they cross the experimental equipment, there would likely be differences in the speed distribution of the subject vehicles depending on the location of the equipment. In addition to collecting data on the weigh station ramps, thought was given to taking data on the mainline of I-95 where vehicle speeds would be much higher than those on the weigh station ramps; however, locating the equipment on I-95 would have required equipment and personnel for maintenance of traffic that was not available. In addition, it was thought unlikely that FDOT would approve such plans.

*WIM scale measurement*

Each vehicle crossing the experimental equipment was also measured on the WIM scale at the Flagler Weigh Station. As with vehicle classification, it was not possible to control the weights of the vehicles crossing the equipment or entering the weigh station; however, the WIM weight measurement was recorded to be used as the dependent variable in the model.
**Pavement surface**

It is likely that the production of acoustic emissions on rigid pavement surfaces would behave differently than those on flexible pavement surfaces. Unfortunately, the pavement throughout the weigh station is rigid, so no data was collected on flexible pavement. Therefore, it will not be possible to make any conclusions about the effect of the pavement surface on the proposed system.

**Connection to pavement**

The metal test strips could be connected to the pavement in a large variety of ways, resulting in different acoustic emission levels depending on the nature of the connection. This variable was held constant by connecting the metal test strips to the pavement using epoxy and no variable representation of this factor was included in the model.

**Temperature**

Temperature has been shown to affect the root mean square (rms) acoustic emission peak near yield of different metals (related to acoustic emission energy). For instance, in 304L steel, the peak height was 20% higher at 675 °C than at room temperature (about 25 °C) (Matthews, 1983). This corresponds to only about a 0.5% difference in acoustic emission over a typical day with a 10 °F difference in low and high temperatures. Since the effect is so small, temperature will be held as constant as possible by testing for a limited portion of the day.

**Sensors**

Two types of sensors were available for use: the WD sensors used in the laboratory experiments (18 mm diameter, 17 mm height; operating frequency range of 100 to 1000 kHz) and
Pico HF-1.2 sensors (5 mm diameter, 4 mm height; operating frequency range from 500 to 1850 kHz). Because the sensors pick up acoustic emission waves in different frequency ranges (with some overlap), the values of the acoustic emission parameters are different depending on which sensor is being used. The Pico HF-1.2 sensors were used in one set of testing (July 2008) and the WD sensors were used in the other (April 2009).

**Equipment**

For the weigh station experiments, new equipment was purchased or developed. New sensors were purchased (Pico HF-1.2 sensors sold by Physical Acoustics Corporation). These sensors were chosen because of their small size (0.2 inch diameter by 0.15 inch height) and wide frequency range (500 to 1850 kHz). In addition, the metal test strip that had been used in previous experiments was cut in half (with each piece now measuring approximately 75 inches in length) and a groove was machined from the bottom surface to allow the sensors to be embedded in the test strip and to provide protection for the cables from the sensors to the computers. Figure 6 shows the sensor attachment to the underside of the test strip with a cable running through the groove. The sensor was coupled to the metal test strip using strong glue. Epoxy was used to affix the metal test strip to the road surface.

For the second weigh station experiment in April 2009, the WD sensors that had been used in the laboratory were used instead of the Pico HF-1.2 sensors that had been used in the July 2008 field test. Using the larger WD sensors would allow lower frequency hits to be picked up by the equipment.
The Pico sensors had been protected from the traffic by placing them in a groove on the underside of the metal test bar; however, the WD sensors did not fit in the groove. As a result, they were attached to the end of the metal test bar, as shown in Figure 7. A pencil lead break test was performed in the laboratory to compare attaching the sensor to the end of the bar with attaching the sensor to the top of the bar. The rank sum test was used to look for differences in the amplitudes of the hits. No significant difference was found between the two attachment methods (p=0.7377). Also, there were no differences found between the responses in the two bars (p=0.8487); however, differences were found between the two WD sensors (p=0.0039).
Figure 8 shows an aerial view of the Flagler weigh station obtained from Google Earth ("Google Earth," 2008). Trucks that must be weighed exit the interstate on a one-lane exit ramp. The speed limit on the ramp is 45 mph and trucks are instructed to maintain 100 foot spacing. Along the exit ramp, the trucks are weighed and measured on a WIM scale. If the measured weight is compliant, the truck is then allowed to return to the main roadway. If the truck is incompliant, it must continue to the weigh station office to be weighed on the static weight scale.

So that comparisons could be made between the Flagler WIM measurements and the experimental WIM system, the metal test strip was attached to the road surface on the ramp leading from I-95 to the Flagler weigh station just downstream of the permanent WIM sensors.
Figure 9 shows a schematic of the experimental set up for July 2008 and a photo is shown in Figure 10. Figure 11 shows how the sensors were connected to the computer via a preamplifier.
Figure 10  Photo of Flagler WIM equipment and experimental equipment

Figure 11  Schematic of connections from sensors to computer

Figure 12 shows the experimental set up in April 2009. Several differences from the set up for the July 2008 data collection should be noted. For instance, for this data collection the metal test strips are offset and are both located on the same side of the lane (the driver’s right side). This configuration does not allow for the collection of data from the left side of the vehicle; however, the collection of redundant data (two data points for each right side axle) has been shown to
improve the accuracy of the measurement of other WIM systems (Cebon & Winkler, 1991; Stergioulas, Cebon, & Macleod, 2000). An additional benefit of this configuration is that the speed of the vehicle can be measured using the experimental equipment.

Initially, it was planned to place the metal test strips about six feet apart. However, there was some difficulty with finding level pavement on which to epoxy the test strips. When the strips were initially placed six feet apart, one of the metal test strips could not be adequately attached to the road surface because of an irregularity in the pavement and when vehicles drove over the strip, the strip began bouncing up and down. Level pavement could not be found until the strips were 18 feet, 8 inches apart.

Figure 12  Configuration of equipment at testing location
**Methodology**

Data was collected at the Flagler Weigh Station on July 23, 2008 and April 2, 2009. For both experiments, the weigh station was closed to allow the equipment to be attached to the road surface. After the equipment was set up, each sensor/metal test strip combination was checked to be certain it was working properly. Then the weigh station officials opened the weigh station and signaled all commercial vehicles to pass through the weigh station, so that the maximum number of vehicles could be tested. (Under normal operations, most commercial vehicles are allowed to bypass the weigh station.) The weigh station’s WIM data was obtained by printing out each WIM record on the weigh station office printer. For each vehicle, the WIM record contains: distances between axles, half and full axle weights for each axle, vehicle class, vehicle length, width, height, speed, and a unique record number. A separate acoustic emission data file was recorded for each vehicle that entered the weigh station. Each file was labeled with the record number given to the vehicle by the weigh station. In July 2008, data was collected from about 12:20 NOON to 1:20 PM. About 180 vehicles entered the weigh station during this time. In April 2009, the data was collected from about 12 NOON to 1:30 PM, during which time approximately 300 commercial vehicles entered the weigh station.

*Description of the vehicles in the data set*

The printed WIM data was entered into a spread sheet and checked for accuracy. For each acoustic emission data file, an automated method was developed to determine which acoustic emission hits belonged to each axle of the vehicle. The axle assignment was then adjusted manually as necessary and compared to the WIM data to make certain that each vehicle and hit had been assigned correctly. Vehicle records with a lot of extraneous hits or where only a portion
of the acoustic emission data for the vehicle were recorded (because of operator error during data collection) were excluded.

In July 2008, due to operator error, equipment failure, and the limits of the printer attached to the WIM scale, there were only 67 trucks for which both the acoustic emission response and the WIM output was recorded. General characteristics of these 67 trucks are shown in Table 2.

Table 3 describes the vehicle classifications as defined by the Federal Highway Administration (Office of Highway Policy Information, 2001).

The lowest speed in the data set for July 2008 was 22 mph, with 46 mph being the highest speed. Average speed was 37 mph, with the speeds distributed roughly normally as shown in Figure 13. Figure 13 also shows the speed distributions for the vehicles separated by number of axles. Although there are not enough data points to determine it statistically, there does not appear to be a meaningful difference in speed distribution related to the number of axles.

Table 2  Characteristics of 75 vehicles selected for analysis (July 2008)

<table>
<thead>
<tr>
<th>Number of axles</th>
<th>WIM identified classifications</th>
<th>Number of vehicles in the sample</th>
<th>Minimum weight (lbs)</th>
<th>Maximum weight (lbs)</th>
<th>Average weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3, 4, 5</td>
<td>6</td>
<td>9,600</td>
<td>19,400</td>
<td>15,833</td>
</tr>
<tr>
<td>3</td>
<td>4, 6, 8</td>
<td>7</td>
<td>22,300</td>
<td>55,300</td>
<td>37,814</td>
</tr>
<tr>
<td>4</td>
<td>3, 8</td>
<td>4</td>
<td>23,700</td>
<td>37,800</td>
<td>32,050</td>
</tr>
<tr>
<td>5</td>
<td>9, 11</td>
<td>48</td>
<td>34,100</td>
<td>81,900</td>
<td>58,642</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>2</td>
<td>99,900</td>
<td>110,700</td>
<td>105,300</td>
</tr>
</tbody>
</table>
Table 3  Vehicle classification description

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Number of axles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>Motorcycles. Two or three-wheeled vehicles.</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Passenger vehicles (sedans, coupes, station wagons, etc.), including those pulling light trailers</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Other four-tire vehicles, including pick-ups, panels, vans, campers, motor homes, ambulances, hearses, carryalls, and minibuses</td>
</tr>
<tr>
<td>4</td>
<td>2 or more</td>
<td>Buses, including only those vehicles built primarily for carrying passengers</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Single unit vehicles with six tires</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>Single unit vehicles</td>
</tr>
<tr>
<td>7</td>
<td>4 or more</td>
<td>Single unit vehicles</td>
</tr>
<tr>
<td>8</td>
<td>4 or fewer</td>
<td>Two unit vehicles, including one tractor or straight power unit</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>Two unit vehicles, including one tractor or straight power unit</td>
</tr>
<tr>
<td>10</td>
<td>6 or more</td>
<td>Two unit vehicles, including one tractor or straight power unit</td>
</tr>
<tr>
<td>11</td>
<td>5 or fewer</td>
<td>Three or more units, including one tractor or straight power unit</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>Three or more units, including one tractor or straight power unit</td>
</tr>
<tr>
<td>13</td>
<td>7 or more</td>
<td>Three or more units, including one tractor or straight power unit</td>
</tr>
</tbody>
</table>
For April 2009, 190 vehicles were found to be useful for the analysis. Of these 190 vehicles, 147 vehicles were class 9, the most common commercial vehicle type. Information describing the 190 vehicles in the sample set is shown in Table 4.
The lowest speed in the April 2009 data set was 20 mph, with 57 mph being the highest speed. Average speed was 37 mph, with the speeds distributed roughly normally as shown in Figure 14. Figure 14 also shows the speed distributions for the vehicles separated by number of axles. As with the July data, there is no meaningful difference in speed distribution related to the number of axles.

Table 4  Characteristics of vehicles selected for analysis (April 2009)

<table>
<thead>
<tr>
<th>Number of axles</th>
<th>WIM identified classifications</th>
<th>Number of vehicles in the sample</th>
<th>Minimum weight (lbs)</th>
<th>Maximum weight (lbs)</th>
<th>Average weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2, 3, 4, 5</td>
<td>19</td>
<td>7,600</td>
<td>31,800</td>
<td>19,221</td>
</tr>
<tr>
<td>3</td>
<td>4, 6, 8</td>
<td>9</td>
<td>22,400</td>
<td>48,99</td>
<td>34,467</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>13</td>
<td>18,400</td>
<td>59,200</td>
<td>37,108</td>
</tr>
<tr>
<td>5</td>
<td>9, 11</td>
<td>148</td>
<td>24,600</td>
<td>82,600</td>
<td>56,859</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>49,500</td>
</tr>
</tbody>
</table>
For both data sets, the axle weights follow a two-peak distribution, as has been seen elsewhere in analyses of vehicle weights (Kim, Titus-Glover, Darter, & Kumapley, 1998; Ott & Papagiannakis, 1996). Figure 15 shows this distribution for the July 2008 data and Figure 16 shows this distribution for the April 2009 data. Figure 17 shows how the axle weight distributions differ depending on number of axles for both the July 2008 and April 2009 data.
The two-peak distribution is apparent in the data for the five-axle vehicles, but the distributions for the two-, three-, four-, and six-axle vehicles are not as well defined (because of fewer data points). The two- and four-axle vehicle distributions do have enough points to tell that it appears that these vehicles tend toward lower axle weights than the five-axle vehicles.

A description of the data and preliminary investigations into the relationship between the recorded acoustic emission parameters and the vehicle’s weight are found in the Preliminary Investigations section, starting on page 55. The development of an empirical model to describe this relationship is found in the Empirical Models section, with a discussion of the field data beginning on page 76.
Figure 15  Axle weight distribution for all axles, separated by left and right side (July 2008)

Figure 16  Axle weight distribution for all axles, separated by left and right side (April 2009)
Figure 17  Axle weight distributions by number of axles per vehicle
PRELIMINARY INVESTIGATIONS

Initially, the data from each of the experiments was examined for simple correlations between one acoustic emission parameter and the vehicle weight. This section contains this analysis as well as other simple analyses that were performed on the data.

Laboratory Data
The first data set examined the effect of speed and weight on the system, with acoustic emission responses collected for 14 different levels of weight and three different levels of speed. For each combination of weight and speed, 30 consecutive TBs were collected into one file. For each TB, there were one or two hits with large values of the acoustic emission parameters while the remaining hits had very small values of the parameters. When these hits with large values of the acoustic emission parameters are isolated for the 30 TBs in each run, the maximum hit is found to be correlated with weight. Figure 18 shows count as a function of weight. When the maximum value of count for each TB is isolated, a distinct trend of increasing count with increasing weight up to about 400 lbs is shown.

Similar trends were found when energy and absolute energy were considered. Figure 19 shows a distinct trend of increased energy with increased weight when the hit with maximum energy value for each TB is isolated. Figure 20 shows similar results for absolute energy. No apparent trend was found between the parameters rise time, counts to peak, duration, or amplitude and weight.
Figure 18  Count as a function of weight

Figure 19  Energy as a function of weight
Speed did not appear to affect the acoustic emission parameters very much; however, it should be noted that the differences in speed were very small. In the field experiments, where speed differences were greater, larger changes in acoustic emissions with speed were noted.

The second data set was collected to give a good idea of the variability in the acoustic emission parameters. For each TB, a single value for each acoustic emission parameter was determined by first identifying the hits that occurred within ± 0.5 seconds of the maximum value of acoustic emission energy and then summing the values of each acoustic emission parameter for all of these hits. (Note that only values from the sensor that was attached to the computer’s channel two were used, because the connection from the other sensor to channel one was spotty, with no data for channel one in several of the records). Figure 21 shows the resultant value of count for each TB graphed against weight and graphed against position. Figure 22 is a similar set of graphs for energy and Figure 23 is the graphs corresponding to absolute energy.

Figure 20  Absolute energy as a function of weight

![Graph showing absolute energy as a function of weight](image-url)
Figure 21  Sum of count for each TB as a function of weight and position
Figure 22  Sum of energy for each TB as a function of weight and position
Figure 23  Sum of absolute energy for each TB as a function of weight and position
These graphs suggest that there is some relationship between the acoustic emission parameters and the weight placed on the wheel. There is also large variability in the responses. An examination of the laboratory test apparatus identified some sources of variability in the response. The sources of variability that were identified and the steps that were taken to correct each problem are shown in Table 5. Variability was reduced in data collected after these changes were made; however, limitations to the operation of the laboratory equipment under the reduced variability conditions made it impossible to collect a data set of sufficient size to perform a complete analysis of the data under reduced variability conditions.

Table 5 Source of variability from laboratory apparatus

<table>
<thead>
<tr>
<th>Source of variability</th>
<th>Description of problem</th>
<th>Corrective action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating of sensors to metal test strip</td>
<td>Surface of metal test strip is elliptical, resulting in poor connection between sensor and metal test strip.</td>
<td>The metal test strip was filed flat in the area where the sensor attaches to the strip.</td>
</tr>
<tr>
<td>Banging of tire assembly against the metal frame with each rotation</td>
<td>With each rotation, the metal test strip was lifting the tire assembly and dropping it, causing a loud banging sound.</td>
<td>The rotation of the cylinder was reversed. This eliminated the banging, but introduced some slipping of the tire against the “road.” In consequence of the slipping, the tire began to wear quickly.</td>
</tr>
<tr>
<td>Pressure gauge</td>
<td>After several months of testing, the pressure gauge would no longer measure zero pressure when the pressure was removed from the tire.</td>
<td>Since there was no way to reset the pressure gauge, the reading at zero pressure was recorded.</td>
</tr>
<tr>
<td>Weak electrical connection due to rotation of cylindrical “road”</td>
<td>Although the electrical connection between the preamplifier and the computer had been designed to accommodate the rotation of the cylinder, the connection for sensor one would frequently loosen.</td>
<td>The sensor connections had to be frequently monitored and tightened each time they loosened. After the direction of rotation was reversed, it was sensor two that frequently became loose.</td>
</tr>
</tbody>
</table>
Preliminary Field Test Data

One of the purposes of the field test was to determine the best method for affixing the metal test bar to the road surface. When the metal test strip was affixed using duct tape, the strip was observed to bounce up and down as the vehicle passed over it, resulting in higher maximum values for count, energy, and absolute energy. When the strip was affixed using epoxy, it remained attached to the pavement along its entire length and the maximum hit values for count, energy, and absolute energy were lower (see Table 6).

Table 6  Comparison of maximum hit values by method of affixation (empty pickup truck)

<table>
<thead>
<tr>
<th></th>
<th><strong>Duct tape</strong></th>
<th></th>
<th><strong>Epoxy</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy (aJ)</td>
<td>Absolute energy (aJ)</td>
<td>Count</td>
<td>Energy (aJ)</td>
<td>Absolute energy (aJ)</td>
</tr>
<tr>
<td>10 mph</td>
<td>30,000</td>
<td>307,000,000</td>
<td>19,000</td>
<td>200</td>
<td>38,000</td>
</tr>
<tr>
<td>20 mph</td>
<td>37,000</td>
<td>241,000,000</td>
<td>14,000</td>
<td>400</td>
<td>72,000</td>
</tr>
</tbody>
</table>

Because the pickup truck used in the experiment has two axles, during one repetition of the experiment, two ABs are collected, referred to as AB 1 (front axle) and AB 2 (rear axle).

Figure 24 shows the typical pattern of hits collected during one repetition of the experiment.

Note that the vibrations from the vehicle striking the metal strip remain for some period after the vehicle has completely passed. The time from when the vehicle first strikes the metal strip until these vibrations have died away is referred to here as the acoustic emission time interval.
A correlation was found between the acoustic emission time interval of each run and the speed of the vehicle. Figure 25 shows the values of these variables for each run and the averages for 10 mph and for 20 mph. No correlation was found between the weight of the vehicle and any of the acoustic emission parameters.
Figure 25  Acoustic emission time interval as a function of truck speed

Weigh Station Data

Each acoustic emission data file contained the hits for all of the ABs for one vehicle. Thus, the first step was to determine which hits corresponded to which axle of the vehicle. Initial assignment of hits to each AB was done using an automated process which took advantage of the fact that hits for each AB tend to clump together, as can be seen in Figure 26. Thus, a new AB was assigned to hits that followed more than 0.5 seconds after the previous hit. Visual inspection was then used to adjust the automated assignments as necessary.
Figure 26  Acoustic emission energy response with time for three different vehicles.
Comparison of acoustic emission data collected in 2008 and 2009

There are two major differences between the data collection in 2008 and in 2009 that contribute to differences in the acoustic emission data. The first is that different acoustic emission sensors were used. The second is that the metal test strips were placed in different configurations, thus measuring different portions of the vehicle axles.

Sensors
The data collected in July 2008 was done using Pico HF-1.2 sensors, whereas the data collected in April 2009 was done using WD sensors. The general characteristics of the two types of sensors are shown in Table 7.

Table 7 Characteristics of acoustic emission sensors

<table>
<thead>
<tr>
<th></th>
<th>Dimensions</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pico HF-1.2</strong></td>
<td>5 mm diameter x 4 mm height</td>
<td>500 – 1850 kHz</td>
</tr>
<tr>
<td><strong>WD</strong></td>
<td>18 mm diameter x 17 mm height</td>
<td>100 – 1000 kHz</td>
</tr>
</tbody>
</table>

The Pico sensors were attached to the bar on the underside, with the face of the sensor parallel to the length of the bar, using crazy glue as the coupler. The WD sensors were attached to the end of the bar, with the face of the sensor perpendicular to the bar, using petroleum jelly as the coupler. Thus, it is not surprising that there were some differences in the acoustic emission parameters collected in July 2008 compared to April 2009. For instance, the data taken in July 2008 using the Pico sensors tended to have more hits associated with each AB than the data taken in April 2009 using the WD sensors, see Figure 27. Also, the values of the acoustic
emission parameters tended to vary more and take on higher values for the data collected with the Pico sensors than those collected with the WD sensors. Figure 28 shows how the distribution of the values for count has a much longer tail for the Pico sensors than for the WD sensor. Because of these differences, any model created using the July 2008 data would not be accurate if it were used with the April 2009 data and vice versa; however, the same type of model can be developed for both sets of data.

![Comparison of the number of hits per AB by type of sensor](image)

Figure 27 Comparison of the number of hits per AB by type of sensor
Metal test bar layout

The configuration of the two metal test bars changed for the April 2009 test from the configuration of the bars during the July 2008 testing. In July 2008, the test bars were laid side by side across the width of the roadway such that the right vehicle axles ran over one bar and the left vehicle axles ran over the other bar (see Figure 9). In April 2009, the test bars were both laid on the right side of the roadway such that the right axles of each vehicle ran over both test strips and the left axles did not run over any test strips (see Figure 12). Thus, the July 2008 data has one measurement for every axle side and the April 2009 data has two measurements for the right side axles and no measurements for the left side axles.
Because of this difference, every value of the acoustic emission parameters for the April 2009 test represents a combination of the hits recorded by both sensors for the same axle. The value of the acoustic emission parameters for the July 2008 test, on the other hand, represents only the hits recorded by one of the sensors for each axle.

The April 2009 layout was deliberately changed to get more accurate data by taking two measurements of each axle. Although no measurements were made of the left side of the vehicle, it should be noted that the left and right side axles often weigh very nearly the same. A comparison of right axle weights with left axle weights, measured by the WIM scale at the Flagler Weigh Station, shows that, in most cases, the two sides are approximately equal, see Figure 29. Indeed, a paired t-test confirms that the right axle equals the left axle with $p = 0.8463$. This relationship makes it possible to estimate the gross vehicle weight using the data that was gathered on only the right side of the vehicle.
Determination of Vehicle Speed and Axle Spacing Using Acoustic Emission Data

Vehicle speed was determined from the acoustic emission data collected in April 2009 by dividing the distance between the two metal test bars by the time difference between when the first axle struck the first test bar and when it struck the second test bar, as shown below.

\[
v = \frac{d}{\Delta t} = \frac{18.667'}{(t_2 - t_1)} \times \frac{3600}{5280}
\]

Where:
- \(v\) = vehicle speed (mph)
- \(d\) = distance between the metal test bars (ft)
- \(t_2\) = time at which the first axle struck the second metal test bar (sec)
- \(t_1\) = time at which the first axle struck the first metal test bar (sec)

[Note that vehicle speed cannot be determined from the acoustic emission data collected in July 2008 because the two metal test bars were not offset during this test.] The vehicles speeds calculated from the acoustic emission data using this method accurately predict the vehicle speeds reported by the Flagler weigh station WIM system. Figure 30 shows a plot of the acoustic

Figure 29  Right and left axle comparison

Figure 30  Plot of the acoustic
emission data speeds compared to the WIM system speeds, including the equation and $R^2$ value for a linear regression between the two. The intercept was found not to be statistically different from zero ($p = 0.905$), so the intercept was set to zero in the equation. The slope of the regression line was slightly greater than 1 (confidence interval 1.002 to 1.013).

![Figure 30  Accuracy of vehicle speed calculations using acoustic emission data](image)

The axle spacing was calculated by multiplying the calculated speed by the time difference between when each axle struck the first metal test bar, as shown in the equation below.

$$S = v \times (t_{12} - t_{11}) \times \frac{5280}{3600}$$

Where:
- $S$ = axle spacing (ft)
- $v$ = vehicle speed (mph)
- $t_{12}$ = time at which the second axle struck the first metal test bar (sec)
- $t_{11}$ = time at which the first axle struck the first metal test bar (sec)
As with vehicle speed, the axle spacing calculated from the acoustic emission data using this method accurately predicted the vehicle axle spacing reported by the Flagler weigh station WIM system. Figure 31 shows a plot of the acoustic emission data axle spacing compared to the WIM system axle spacing, including the equation and $R^2$ value for a linear regression between the two. The intercept was 0.1807, slightly different from zero ($p = 0.191$). The slope of the regression line was slightly greater than 1 (confidence interval 1.039 to 1.048).

![Figure 31](image)

Figure 31  Accuracy of axle spacing calculations using acoustic emission data
Exploration of the Kaiser Effect

The Kaiser effect deals with the rate of acoustic emission under cyclical loading, as described in the section on Acoustic Emission, page 19. It seems unlikely that the Kaiser effect would play a role in the acoustic emission results in this data set, since the loads exerted by the vehicles on the metal test bar are below the level of plastic deformation and are dynamic, rather than static loads. Nevertheless, considering that this work represents an early stage of exploration, it seems prudent to examine the data for any possible Kaiser effect.

If the experimental system is affected by the Kaiser effect, it is expected that once an axle of a given weight has gone over the metal test bar, any ABs of lesser weight that follow afterward will produce no acoustic emission hits, or at least fewer acoustic emission hits. Figure 32 can be used to evaluate whether or not this is the case. The horizontal axis is the vehicle number for each AB. Because the vehicles were assigned numbers in sequential order, the vehicle number serves as a surrogate for time. The vertical axis is the number of acoustic emission hits that were generated by each AB. The points on the graph are coded for axle weight by color and shape. Thus, the Kaiser effect should cause the number of acoustic emission hits to drop dramatically for all lighter ABs after the heaviest ABs (the red points on the graph) have passed. However, it can be seen that this is not the case. Indeed, the number of acoustic emission hits for each AB appears to be independent of the axle weight.
The Kaiser effect is evident when discontinuities created in a material during initial loading do not expand or move during the reapplication of the loading. As shown above, the relatively small loads applied to the metal bar by the heavy vehicles apparently do not limit the availability of discontinuities in future loadings. However, over a long period of continued use, it is possible that the creation of these discontinuities will slow and the production of acoustic emission will be altered. Future work should look into whether or not acoustic emissions in the metal test bar change over time with repeated loadings.

**Correlation between Acoustic Emission Parameters and Weight**

As previously explained in the discussion of the laboratory data, there are several acoustic emission hits associated with each AB. A simplification of this data is necessary before comparisons with the axle weight can be made. In examining the laboratory data, both the
The maximum value of the acoustic emission parameter for each TB and the sum of the value of the acoustic emission parameter over all of the hits for each TB were used. In examining the data collected at the weigh station, five different methods of aggregating the hits were used:

- Sum of all hits for each AB
- Average value of all hits for each AB
- 25\textsuperscript{th} percentile value of all hits for each AB
- Median value of all hits for each AB
- 85\textsuperscript{th} percentile value of all hits for each AB

Then, simple linear regression models were developed to examine the relationship of each acoustic emission parameter with weight and with speed. Graphs showing these relationships for each of the five methods for aggregating the hits, including linear regression equations and $R^2$ values, are found in Appendix B: Graphs Of Weigh Station Data. As can be seen in Table 8, which shows the range of $R^2$ values for each aggregation method, there are no strong relationships between any of the acoustic emission parameters and axle weight. However, it can be seen that the 25\textsuperscript{th} percentile and median aggregation methods are not associated with weight as well as the other methods, with the summation method giving the best results overall.
Table 8  \( R^2 \) values from linear regression by method of aggregating acoustic emission axle hits

<table>
<thead>
<tr>
<th>Aggregation Method</th>
<th>Data collected date</th>
<th>Maximum ( R^2 ) value</th>
<th>Minimum ( R^2 ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>July 2008</td>
<td>0.06320</td>
<td>0.00240</td>
</tr>
<tr>
<td></td>
<td>April 2009</td>
<td>0.04080</td>
<td>0.00370</td>
</tr>
<tr>
<td>Average</td>
<td>July 2008</td>
<td>0.02360</td>
<td>0.00170</td>
</tr>
<tr>
<td></td>
<td>April 2009</td>
<td>0.03300</td>
<td>0.00120</td>
</tr>
<tr>
<td>25(^{th}) percentile</td>
<td>July 2008</td>
<td>0.00630</td>
<td>0.00020</td>
</tr>
<tr>
<td></td>
<td>April 2009</td>
<td>0.00830</td>
<td>0.00080</td>
</tr>
<tr>
<td>Median</td>
<td>July 2008</td>
<td>0.01020</td>
<td>0.00003</td>
</tr>
<tr>
<td></td>
<td>April 2009</td>
<td>0.01550</td>
<td>0.00140</td>
</tr>
<tr>
<td>85(^{th}) percentile</td>
<td>July 2008</td>
<td>0.02560</td>
<td>0.00100</td>
</tr>
<tr>
<td></td>
<td>April 2009</td>
<td>0.03280</td>
<td>0.00007</td>
</tr>
</tbody>
</table>
EMPIRICAL MODELS

Dimensional Analysis

Dimensional analysis is a method of suggesting possible relationships between measurable parameters of a system through the development of a dimensionally correct equation. Dimensional analysis is commonly used in the study of physics (Bridgman, 1978) and has been applied very successfully in a number of engineering applications, particularly in the area of fluid mechanics (Langhaar, 1967). The methodology involves selecting a set of variables that may be involved in the phenomenon to be examined, expressing the dimensional formula of each variable in a set of fundamental units, and then calculating a set of dimensionless products associated with the variables. The result is not an exact formula, but rather shows probable relationships between variables. Experiments can then be run to determine the exact nature of these relationships.

The first step in dimensional analysis, then, is to collect a set of variables of interest that experience has suggested may be involved in the phenomenon under examination. In the case presented in this paper of a weigh-in-motion system using acoustic emission, the set of variables comes from a consideration of pavement design parameters, simple physics, and acoustic emission parameters. Table 9 shows the various variables that were considered and the dimensional formula for each. Note that some of the possible variables have the same dimensional formulas. Dimensional analysis does not distinguish between variables with the same dimensional formulas; instead, the correct variable must be chosen using previous experience or experimentation.
Table 9 Variables for dimensional analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensional Formula(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w )</td>
<td>Weight. The weight of the vehicle on one side of one axle (measured by WIM scale)</td>
<td>MLT(^2)</td>
</tr>
<tr>
<td>( v )</td>
<td>Speed. The speed of the vehicle (measured)</td>
<td>LT(^{-1})</td>
</tr>
<tr>
<td>( g )</td>
<td>Acceleration due to gravity. Included here because ( g ) can be used to convert weight to mass.</td>
<td>LT(^{-2})</td>
</tr>
<tr>
<td>( A )</td>
<td>Tire contact area. The area of contact between the vehicle tire and the metal test bar (not measured, assumed to be 1 for first axle and 2 for all other axles since there is one tire on the first axle and two on subsequent axles for 5-axle vehicles)</td>
<td>L(^2)</td>
</tr>
<tr>
<td>( Y )</td>
<td>Elastic modulus. Stiffness of metal bar (not varied)</td>
<td>ML(^{-1})T(^{-2})</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency. The frequency of the acoustic emission waveform (measured)</td>
<td>T(^{-1})</td>
</tr>
<tr>
<td>( r )</td>
<td>Rise time. The rise time of the acoustic emission waveform (measured)</td>
<td>T</td>
</tr>
<tr>
<td>( D )</td>
<td>Duration. The duration of the acoustic emission waveform (measured)</td>
<td>T</td>
</tr>
<tr>
<td>( E )</td>
<td>Energy. The energy of the acoustic waveform (measured)</td>
<td>ML(^2)T(^{-2})</td>
</tr>
<tr>
<td>( AbsE )</td>
<td>Absolute Energy. The energy of the acoustic waveform (measured, same as units of ( E ) squared)</td>
<td>(ML(^2)T(^{-2}))^2</td>
</tr>
<tr>
<td>( c )</td>
<td>Count. The count of the acoustic waveform (measured)</td>
<td>dimensionless</td>
</tr>
<tr>
<td>( c_p )</td>
<td>Count to peak. The count of the acoustic waveform prior to the maximum amplitude (measured)</td>
<td>dimensionless</td>
</tr>
<tr>
<td>( a )</td>
<td>Amplitude. The amplitude of the acoustic waveform (measured)</td>
<td>dimensionless</td>
</tr>
</tbody>
</table>

\(^1\) M=mass; L=length; T=time

A dimensionally homogenous equation of the variables would be of the form:

\[
f(w, v, g, A, Y, f, r, D, E, AbsE, c, c_p, a) = 0\]

Buckingham’s theorem then states that this function could be written as a function of dimensionally homogenous products of these 12 variables). According to the procedure
presented in Langhaar’s Dimensional Analysis and the Theory of Models, the next step is to create a matrix of the proposed variables and determine the number of dimensionless products to be determined using these variables. The matrix is shown below, with the dimensionless variables omitted:

<table>
<thead>
<tr>
<th></th>
<th>w</th>
<th>v</th>
<th>g</th>
<th>A</th>
<th>Y</th>
<th>f</th>
<th>r</th>
<th>D</th>
<th>E</th>
<th>AbsE</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>T</td>
<td>-2</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>-2</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-2</td>
<td>-4</td>
</tr>
</tbody>
</table>

The rank of this matrix is three. Because there are 10 variables, the number of dimensionless products is $10 - 3 = 7$. Four dimensionless products pop out immediately ($fr$, $fD$, $\frac{r}{D}$, and $\frac{E^2}{AbsE}$). Note that $fr$ (frequency times rise time) is the same as count to peak ($cp$) and $fD$ (frequency times duration) is the same as count ($c$).

Removing one variable for each of the dimensionless products already found reduces the matrix to 6 variables. Rearranging the columns so that the determinate of the last three columns is not equal to zero yields:

<table>
<thead>
<tr>
<th></th>
<th>w</th>
<th>g</th>
<th>Y</th>
<th>A</th>
<th>v</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>T</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
</tr>
</tbody>
</table>
A product of the 6 variables could be written generically: $w^{k_1}g^{k_2}Y^{k_3}A^{k_4}v^{k_5}E^{k_6}$, where $k_1, k_2, k_3, k_4, k_5,$ and $k_6$ are generic variables to indicate the power of each of the variables in the equation. In order for this product to be dimensionless, three equations (each corresponding to one row in the above matrix) must be satisfied:

$$1k_1 + 0k_2 + 1k_3 + 0k_4 + 0k_5 + 1k_6 = 0$$
$$1k_1 + 1k_2 - 1k_3 + 2k_4 + 1k_5 + 2k_6 = 0$$
$$-2k_1 - 2k_2 - 2k_3 + 0k_4 - 1k_5 - 2k_6 = 0$$

Because these are three equations in 6 unknowns, there are an infinite number of solutions; however, if the first three unknowns are chosen, then the system becomes three equations in three unknowns and there is an exact solution. Solving for $k_4, k_5,$ and $k_6$ yields:

$$k_4 = \frac{1}{2}k_1 + \frac{1}{2}k_2 + \frac{3}{2}k_3$$
$$k_5 = -2k_2$$
$$k_6 = -k_1 - k_3$$

The matrix below shows the values for $k_4, k_5,$ and $k_6$ given strategically chosen values of $k_1, k_2,$ and $k_3$. The three products, $\pi_1, \pi_2,$ and $\pi_3$ (corresponding to each row in the matrix) are shown beneath the table.
Going back to Buckingham’s theorem, we find that

\[ f\left(\pi_1, \pi_2, \pi_3, \frac{r}{D}, c, c_p, \frac{E^2}{AbsE^2}, a\right) = 0 \]

Plugging in the equations for the \( \pi \) products and solving for the weight of the vehicle then yields:

\[ w = f\left(\frac{gE}{v^2}, YA, \frac{rE}{D\sqrt{A}}, \frac{cE}{\sqrt{A}}, \frac{c_pE}{\sqrt{A}}, \frac{E^3}{\sqrt{A} \cdot AbsE^2}, \frac{aE}{\sqrt{A}}\right) \]

These seven variables can be used to create possible parameters to relate the acoustic emission data to load (weight). Because the acceleration due to gravity and the modulus were not varied during the experiments, these reduce to:

\[ w = f\left(\frac{E}{v^2}, A, \frac{rE}{D\sqrt{A}}, \frac{cE}{\sqrt{A}}, \frac{c_pE}{\sqrt{A}}, \frac{E^3}{\sqrt{A} \cdot AbsE^2}, \frac{aE}{\sqrt{A}}\right) \]

Determination of Goodness of Fit and Accuracy of Results
A variety of measurements can be used to determine how well a model fits the underlying data.

For this paper, four measurements will be presented for each model that is developed: the maximum percent error, the percent of data points within 30 percent error, the standard deviation, and the confidence interval associated with a paired t-test comparing the weight
calculated from the statistical model with the weight measured by the existing WIM equipment. The confidence interval for the paired t-test expresses the likely range in values for the difference between the average weight measured by the WIM equipment and the average weight measured by the acoustic emission test and its associated model. A 95% confidence level is used. If the confidence interval spans the number zero ([-1,1], for instance), then the average WIM-measured weight and the average acoustic emission-measured weight are statistically the same. If the confidence interval does not span the number zero ([−10,-8], for example), then the weight measurements are statistically different. In addition, the confidence interval expresses the size and direction of the difference. In this example, the average acoustic emission-measured weight is between 8 and 10 lbs smaller than the average WIM-measured weight. In addition, a graph of the calculated values plotted against the measured values will be shown.

Laboratory Data
Since neither speed nor tire contact area were varied for the laboratory data, the dimensional analysis variables for the laboratory data reduce to:

\[
w = f \left( \frac{rE}{D}, cE, c_p E, \frac{E^3}{\text{Abs}E}, aE \right)
\]

In addition to the dimensional analysis variables, all of the acoustic emission parameters alone were considered for a statistical model of weight. The value of each acoustic emission parameter for each TB was calculated as the sum of the values of that parameter for all of the hits that corresponded to each TB. One additional variable was also included, namely the position (ℓ), or the distance from the sensor to the location of the tire bump.
Minitab was used to determine the best empirical model. First, all of the parameters were tested for inclusion in the final model using Minitab’s stepwise regression feature. Then, the model was determined using Minitab’s linear regression model with the parameters that had been chosen for inclusion. The table below shows the coefficient and p-value for each parameter included in the model. The equation for the final model is shown after it. Table 11 shows the fit statistics for this model and Figure 33 shows the fit graphically.

Table 10  Parameters for laboratory data regression equation (R² = 60.2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>591.04</td>
<td>0.000</td>
</tr>
<tr>
<td>c</td>
<td>0.026224</td>
<td>0.000</td>
</tr>
<tr>
<td>AbsE</td>
<td>-0.00000104</td>
<td>0.000</td>
</tr>
<tr>
<td>l</td>
<td>-9.1513</td>
<td>0.000</td>
</tr>
<tr>
<td>f_r</td>
<td>-300.1</td>
<td>0.000</td>
</tr>
<tr>
<td>r</td>
<td>0.001156</td>
<td>0.000</td>
</tr>
<tr>
<td>D</td>
<td>-0.00105</td>
<td>0.000</td>
</tr>
<tr>
<td>c_p</td>
<td>-0.25717</td>
<td>0.002</td>
</tr>
<tr>
<td>E</td>
<td>0.004687</td>
<td>0.063</td>
</tr>
<tr>
<td>f_i</td>
<td>-6.937</td>
<td>0.002</td>
</tr>
<tr>
<td>aE</td>
<td>0.00000064</td>
<td>0.004</td>
</tr>
<tr>
<td>c_p E</td>
<td>0.000265</td>
<td>0.061</td>
</tr>
</tbody>
</table>
\[ w = 591.04 + 0.026224c - 1.04 \times 10^{-6}AbsE - 9.1513 \ell - 300.1f_r + 1.156 \times 10^{-3}r - 1.05 \times 10^{-3}D - 0.25717c_p + 4.687 \times 10^{-3}E - 6.937f_i + 6.4 \times 10^{-7}AbsE \]
\[ + 2.65 \times 10^{-4}c_pE \]

Table 11  Statistics comparing statistical model of laboratory data to actual laboratory weight

<table>
<thead>
<tr>
<th>Max. % error</th>
<th>% within 30 % error</th>
<th>StDev (lbs)</th>
<th>Confidence interval</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>44%</td>
<td>99%</td>
<td>71.8</td>
<td>[-1.75, 2.19]</td>
<td>0.6017</td>
</tr>
</tbody>
</table>

Figure 33  Fit for laboratory data

This analysis of the laboratory data indicates that this is a valid methodology for developing a model of vehicle weight using acoustic emission parameters. The next step was to apply this methodology to the field data.
Field Data

Only the 5 axle vehicles were used in the analysis, since this is the most common type of heavy vehicle. Differences in the data collected in July 2008 compared to that collected in April 2009 meant that different models had to be created for each dataset. In addition to the differences in the sensors noted in the section entitled “Comparison of acoustic emission data collected in 2008 and 2009” on page 57, the methods of aggregating the data are slightly different: for the July 2008 data, the aggregated values of the acoustic emission parameters associated with each AB correspond to the data collected from one sensor, whereas for the April 2009 data, the aggregated values of the acoustic emission parameters associated with each AB correspond to the data collected from two sensors.

On the other hand, the parameters that are included in the model for each set of data ought to be as similar as possible if general conclusions about what parameters are most closely related to vehicle weight are to be made. In order to achieve this, an iterative process was used in the development of the model where the same parameters were tested for inclusion in models for both datasets at the same time and parameters were only discarded from the models if they were found to not be necessary for both models.

First, a list of parameters to test for inclusion in the models was developed. Parameters that were tested for inclusion in the final models include: binary variables to distinguish between each of the five axles, the individual acoustic emission parameters, the dimensional analysis variables, and other possibly explanatory variables (speed, the number of hits for each AB, and the distance
between the axles). Eventually, it was found necessary to include some interaction variables, as there were some parameters that were only pertinent to one or two of the axles.

To distinguish between each axle, the binary variables \textit{Axle 1}, \textit{Axle 2}, \textit{Axle 3}, \textit{Axle 4}, and \textit{Axle 5} were created such that:

\begin{align*}
\text{Axle 1} &\text{ is 1, if first axle 0, if any other axle} \\
\text{Axle 2} &\text{ is 1, if second axle 0, if any other axle} \\
\text{Axle 3} &\text{ is 1, if third axle 0, if any other axle} \\
\text{Axle 4} &\text{ is 1, if fourth axle 0, if any other axle} \\
\text{Axle 5} &\text{ is 1, if fifth axle 0, if any other axle}
\end{align*}

Only four of these variables were included explicitly in the model. The fifth axle variable then is implicitly included in the model as the case when all the other variables are 0.

For the acoustic emission parameters, a separate variable was tested for each of the aggregation methods described in the section entitled Correlation between Acoustic Emission Parameters and Weight on page 65. Although the preliminary analysis of the data showed that the parameter values created using the summation method had better correlation with weight than the values created using the other aggregation methods, it was unknown how the different aggregation methods would perform when the parameters were combined together in a model. Therefore, five values of each acoustic emission parameter were included in the initial linear regression model, one for each aggregation method.
### Table 12: Acoustic emission parameter variables

<table>
<thead>
<tr>
<th></th>
<th>Aggregation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25&lt;sup&gt;th&lt;/sup&gt; percentile</td>
</tr>
<tr>
<td>Rise time (μs)</td>
<td>$r_{25}$</td>
</tr>
<tr>
<td>Count</td>
<td>$c_{25}$</td>
</tr>
<tr>
<td>Energy (aJ)</td>
<td>$E_{25}$</td>
</tr>
<tr>
<td>Duration (μs)</td>
<td>$d_{25}$</td>
</tr>
<tr>
<td>Amplitude (dB)</td>
<td>$a_{25}$</td>
</tr>
<tr>
<td>Average Frequency (kHz)</td>
<td>$f_{a,25}$</td>
</tr>
<tr>
<td>Count to peak</td>
<td>$c_{p,25}$</td>
</tr>
<tr>
<td>Reverberation frequency</td>
<td>$f_{r,25}$</td>
</tr>
<tr>
<td>Initial frequency (kHz)</td>
<td>$f_{i,25}$</td>
</tr>
<tr>
<td>Absolute energy (aJ)</td>
<td>$AbsE_{25}$</td>
</tr>
</tbody>
</table>

The dimensional analysis variables for the field data are the full set of seven, namely:

$$w = f \left( \frac{E}{v^2, A}, \frac{rE}{D \sqrt{A}}, \frac{cE}{\sqrt{A}}, \frac{c_p E}{\sqrt{A}}, \frac{E^3}{\sqrt{A}}, \frac{aE}{\sqrt{A}} \right)$$

As with the acoustic emission parameters variables, a separate variable for each of the aggregation methods was included. The tire contact area, $A$, could not be measured in the field; however, 5 axle vehicles have two tires (one on each side) on the first axle and four tires (two on each side) on each of the remaining axles. Therefore, the value of $A$ was set at 1, if the first axle, and 2, if any other axle. Because the variable $A$ is therefore indistinguishable from the variable Axle 1, the tire contact area alone was not included as a separate variable in the linear regression model.
The distance between successive axles, $S$, was also tested for inclusion. This distance could be measured in the field (see the section entitled “Determination of Vehicle Speed and Axle Spacing Using Acoustic Emission Data” on page 61); however, there is no “distance” between the first axle of a vehicle and the axle preceding it. Therefore, for the first axle the value of $S$ was set at 0. The distance from the sensor to the location of the axle bump could not be measured or estimated and was therefore not included in these models.

The number of hits for each AB, $N$, was also tested for inclusion in the model. When Speed, $v$, is added to this list, there are a total of 87 parameters to be included in the initial model.

After the parameters to include in the initial model were chosen, the next step was to test the model to determine which parameters to keep in it. Prior to this, 25% of the data from each data set (the July 2008 dataset and the April 2009 dataset) was randomly assigned to the validation data set. The remaining 75% of the data was then imported into Minitab and to be used to make two linear regression models, one for each dataset, which contained all of the possible model parameters.

The datasets were too different to be combined together to make one model (because of differences in both the sensors and the way the metal test strips were set up); however, a methodology was developed to allow the model for one dataset to inform the model for the other, so that a more accurate model could be developed for both.

First, an iterative process was followed where the p-values for the coefficients in the models were examined to determine which parameter should be removed from the model. A high
p-value indicates that the parameter is not significantly improving the model, whereas a low p-value (<0.10) indicates that the parameter is important to the model. To determine which parameter to remove from the next model, the p-values for the coefficients of each parameter in the two models were combined and the parameter with the largest combined p-value, where the p-value for neither dataset was below 0.10, was chosen to be removed from the model. This parameter was removed and once again two linear regression models, one corresponding to each data set, were run with the revised set of parameters.

Minitab provides the user with both an $R^2$ value and an adjusted $R^2$ value for each linear regression model. The $R^2$ value corresponds to the percentage of data that is explained well by the model. The adjusted $R^2$ value takes into account that the more parameters you include in a model, the more likely it is to explain the data, even if the extra parameters you are including are not playing a significant role in explaining the data.

As insignificant parameters were removed from the model for both datasets, the $R^2$ values tended to decline, but the adjusted $R^2$ values increased until about half of the parameters had been removed from the models. After this point, both the $R^2$ value and the adjusted $R^2$ value started to decrease.

Once the maximum adjusted $R^2$ value was achieved for the two models, a new strategy was employed. It was assumed that the true model would contain the same parameters for both datasets, while the coefficients of the parameters might vary. However, it was assumed that the sign of the coefficients would probably be the same for both datasets. Thus, for the changed
strategy, the coefficients for each parameter of the two models were first compared to determine if they were of the same sign (both positive or both negative). Parameters were then only removed from the models if the coefficients of the parameters were of opposite sign and had high p-values.

One axle was found to be predicting wildly unusual weights. Upon further examination, it was determined to be unreliable data and was removed from the July 2008 dataset. Table 13 shows the axle weight values for vehicle 1636 as measured by the WIM scale. The weights for axle 2 and for axle 3 (a set of tandem axles) is very unusual because under normal circumstances both sides of the axle weigh approximately the same weight (see Figure 29 and the discussion around it). If the difference in weight on the two sides were due to a shifted load, one would expect a pattern where the weight was lighter on the same side of axle 2 and axle 3, since they are very close together. A logical explanation for the pattern of measured weights shown here is a bouncing movement, where the vehicle shifted from side to side as it passed over the WIM scale, which would have caused the WIM scale measurement to be inaccurate. Since the axle 3 right side data point significantly affected the choice of a model, it was eliminated from the data set. All other axles from this vehicle remained in the dataset.

Table 13 Weight of each axle for vehicle 1636, July 2008 dataset

<table>
<thead>
<tr>
<th></th>
<th>Axle 1</th>
<th>Axle 2</th>
<th>Axle 3</th>
<th>Axle 4</th>
<th>Axle 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>4500</td>
<td>4600</td>
<td>1200</td>
<td>4600</td>
<td>4700</td>
</tr>
<tr>
<td>Left</td>
<td>4200</td>
<td>2200</td>
<td>4300</td>
<td>4900</td>
<td>4600</td>
</tr>
</tbody>
</table>
At this point, the model was examined for how well it represented the data set and it was found that the model predicted some axle weights fairly well, but didn’t do so well for other axles. The process described above was then followed again, but this time making five different models, one for each axle. With this set of models, it was difficult to create a good model because only one-fifth of the data was used to make each model. Nevertheless, making separate models for each axle did suggest variables that were pertinent to some axles, but not to others. With this information, a final set of models for the July 2008 and the April 2009 data sets were made that used all five axles at once, but included interactions between the individual axle variables and the other variables that had been shown to be important to specific axles. The final model included 21 variables, all of which are presented below in Table 14 along with the coefficient and p-value for each variable.

Table 14  Parameters for field data regression equation (July 2008 $R^2 = 24.1$; April 2009 $R^2 = 25.6$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>July 2008 dataset</th>
<th>April 2009 dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coefficient</td>
<td>p-value</td>
</tr>
<tr>
<td>Constant</td>
<td>3802</td>
<td>0.002</td>
</tr>
<tr>
<td>$a_{sum}$</td>
<td>1.8647</td>
<td>0.005</td>
</tr>
<tr>
<td>$c_{ave}$</td>
<td>1.5535</td>
<td>0.103</td>
</tr>
<tr>
<td>$f_{i,ave}$</td>
<td>1.703</td>
<td>0.226</td>
</tr>
<tr>
<td>$\frac{E}{v^2_{ave}}$</td>
<td>8207</td>
<td>0.002</td>
</tr>
<tr>
<td>$\frac{E^3}{AbsE\sqrt{A}_{ave}}$</td>
<td>-4.668</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10026</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12.027</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>44.216</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10.137</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>24844</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-91.79</td>
<td>0</td>
</tr>
<tr>
<td>Parameter</td>
<td>July 2008 dataset</td>
<td>April 2009 dataset</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td>coefficient</td>
<td>p-value</td>
</tr>
<tr>
<td>$f_{a,25}$</td>
<td>-5.452</td>
<td>0.077</td>
</tr>
<tr>
<td>$\frac{cE}{\sqrt{A_{50}}}$</td>
<td>-0.00403</td>
<td>0.001</td>
</tr>
<tr>
<td>$a_{85}$</td>
<td>-7.02</td>
<td>0.702</td>
</tr>
<tr>
<td>Axle 4</td>
<td>22.2</td>
<td>0.974</td>
</tr>
<tr>
<td>Axle 2 × S</td>
<td>71.35</td>
<td>0.072</td>
</tr>
<tr>
<td>Axle 5 × S</td>
<td>272.2</td>
<td>0.007</td>
</tr>
<tr>
<td>Axle 1 × $a_{sum}$</td>
<td>-1.159</td>
<td>0.287</td>
</tr>
<tr>
<td>Axle 3 × $a_{sum}$</td>
<td>-1.1555</td>
<td>0.195</td>
</tr>
<tr>
<td>Axle 5 × $f_{a,25}$</td>
<td>-0.757</td>
<td>0.915</td>
</tr>
<tr>
<td>$Axle 1 \times \frac{cE}{\sqrt{A_{50}}}$</td>
<td>0.003728</td>
<td>0.003</td>
</tr>
<tr>
<td>Axle 1 × $a_{85}$</td>
<td>13.41</td>
<td>0.268</td>
</tr>
<tr>
<td>Axle 3 × $a_{85}$</td>
<td>15.94</td>
<td>0.194</td>
</tr>
<tr>
<td>Axle 5 × $f_{i,ave}$</td>
<td>2.536</td>
<td>0.22</td>
</tr>
<tr>
<td>Axle 3 × $f_{i,25}$</td>
<td>4.393</td>
<td>0.245</td>
</tr>
<tr>
<td>Axle 5 × $f_{r,ave}$</td>
<td>-12.711</td>
<td>0.001</td>
</tr>
<tr>
<td>$Axle 2 \times \frac{E^3}{AbsE\sqrt{A_{85}}}$</td>
<td>-0.0352</td>
<td>0.925</td>
</tr>
</tbody>
</table>
An examination of the model shows that there is some evidence of multicolinearity. When each variable is plotted against the other variables, many of them are seen to be correlated. Multicolinearity does not call into question the validity of the model, but it does mean that conclusions about the variables in the model based on their coefficients may not be valid.

Also, the model has a high value for the constant. This suggests that there are other factors not included in the model that would improve the model significantly.

July 2008 dataset

Based on the model, the equation for the July 2008 dataset is given as:

\[
\text{Weight} = 3802 + 1.86 \, a_{\text{sum}} + 1.55 \, c_{\text{ave}} + 1.70 \, f_{i,\text{ave}} + 8207 \, \frac{E}{v_{\text{ave}}^2} - 4.76 \, \frac{E^3}{\text{Abs} E \sqrt{A_{\text{ave}}}}
- 5.45 \, f_{a,25} - 0.00403 \, \frac{cE}{\sqrt{A_{50}}} - 7.0 \, a_{85} + 22 \, \text{Axle 4} + 71.3 \, \text{Axle 2} \times S
+ 272 \, \text{Axle 5} \times S - 1.16 \, \text{Axle 1} \times a_{\text{sum}} - 1.16 \, \text{Axle 3} \times a_{\text{sum}} - 0.76 \, \text{Axle 5}
\times f_{a,25} + 0.00373 \, \text{Axle 1} \times \frac{cE}{\sqrt{A_{50}}} + 13.4 \, \text{Axle 1} \times a_{85} + 15.9 \, \text{Axle 3} \times a_{85}
+ 2.54 \, \text{Axle 5} \times f_{i,\text{ave}} + 4.39 \, \text{Axle 3} \times f_{i,25} - 12.7 \, \text{Axle 5} \times f_{r,\text{ave}} - 0.035 \, \text{Axle 2}
\times \frac{E^3}{\text{Abs} E \sqrt{A_{85}}}
\]

The variables in the above equation are defined in Table 12 and the paragraphs that follow it.

The fit statistics and depiction of graphical fit are shown below.
Table 15  Statistics comparing statistical model of field data to actual axle weight (July 2008 dataset)

<table>
<thead>
<tr>
<th>Max. % error</th>
<th>% within 30 % error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>164%</td>
<td>70%</td>
<td>1,615</td>
<td>[-2.21, 1.72]</td>
<td>0.2414</td>
</tr>
</tbody>
</table>

Figure 34  Fit for July 2008 field data
April 2009 dataset

The equation for the April 2009 dataset is:

\[
\text{Weight} = 10026 + 12.0 \ a_{\text{sum}} + 44.2 \ c_{\text{ave}} + 10.1 \ f_{i,\text{ave}} + 24844 \ \frac{E}{v_{\text{ave}}^{2}} - 91.8 \ \frac{E^{3}}{\text{Abs}E\sqrt{A_{\text{ave}}}} \\
- 17.f_{i,25} - 0.0281 \ \frac{cE}{\sqrt{A_{50}}} - 201 \ a_{85} + 1196 \ Axle \ 4 + 91.5 \ Axle \ 2 \times S \\
+ 353 \ Axle \ 5 \times S - 9.61 \ Axle \ 1 \times a_{\text{sum}} - 7.14 \ Axle \ 3 \times a_{\text{sum}} + 44.3 \ Axle \ 5 \\
\times f_{i,25} - 0.127 \ Axle \ 1 \times \frac{cE}{\sqrt{A_{50}}} + 86.8 \ Axle \ 1 \times a_{85} + 68.3 \ Axle \ 3 \times a_{85} \\
- 19.7 \ Axle \ 5 \times f_{i,\text{ave}} - 24.9 \ Axle \ 3 \times f_{i,25} - 5.2 \ Axle \ 5 \times f_{r,\text{ave}} + 13.2 \ Axle \ 2 \\
\times \frac{E^{3}}{\text{Abs}E\sqrt{A_{85}}} 
\]

As before, the variables in the above equation are defined in Table 12 and the paragraphs that follow it.

The fit statistics and depiction of graphical fit are shown below.

Table 16  Statistics comparing statistical model of field data to actual axle weight (April 2009 dataset)

<table>
<thead>
<tr>
<th>Max. % error</th>
<th>% within 30 % error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>204%</td>
<td>69%</td>
<td>1,725</td>
<td>[-2.09, 1.84]</td>
<td>0.2560</td>
</tr>
</tbody>
</table>
Validation

The models for the July 2008 and the April 2009 data were developed using a randomly chosen 75% of the data that was collected on those days. The remaining 25% of the data was used to validate the models. The validation data was plugged into the equations developed using the model development data to determine the modeled weight for these data points. The following tables and figures show the fit parameters for the validation data.

Table 17  Statistics comparing statistical model of field data to actual axle weight for validation data (July 2008 dataset)

<table>
<thead>
<tr>
<th>Max. % error</th>
<th>% within 30 % error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>102%</td>
<td>71%</td>
<td>2,044</td>
<td>[-363, -359]</td>
<td>0.0259</td>
</tr>
</tbody>
</table>

Figure 35  Fit for April 2009 field data
Figure 36  Fit for July 2008 field data (validation)

Table 18  Statistics comparing statistical model of field data to actual axle weight for validation data (April 2009 dataset)

<table>
<thead>
<tr>
<th>Max. % error</th>
<th>% within 30 % error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>196%</td>
<td>65%</td>
<td>6,182</td>
<td>[25.2, 29.2]</td>
<td>0.0779</td>
</tr>
</tbody>
</table>
In both cases, the validation data did not fit the model as well as the data that was used to make the model. However, the model for the April 2009 dataset falls within acceptable limits. For the July 2008 dataset, the validation data shows that the modeled vehicle weight is, on average, 360 lbs lighter than the weight measured by the WIM scale at the weigh station. This represents a 6% error in the mean. For the April 2009 dataset, the modeled vehicle weight was, on average, 27 lbs heavier than the weight measured by the WIM scale at the weigh station. This represents only a 0.5% error in the mean.

Histograms of the percent error for each axle in the July 2008 dataset and the April 2009 dataset are shown in Figure 38 and Figure 39, respectively.
Figure 38 Histogram of percent error for July 2008 dataset

Figure 39 Histogram of percent error for April 2009 dataset
Looking at each axle individually, Table 19 and Table 20 show the comparison statistics for the five axles using the modeled datasets and Table 21 and Table 22 show the comparison statistics using the validation data. For the most part, the model works well for each axle group in the April 2009 dataset. As with looking at the entire dataset, the model for the July 2008 dataset is not validated for any of the individual axles. For both datasets, the model predicts Axle 1 fairly well. This is probably because the first axle is separated in time from all of the other axles, making it easy to distinguish the acoustic emission data that pertains to it. The model does not work as well for the tandem axles, with the second axle in each tandem set (axles 3 and 5) modeled less accurately than the first axle in each tandem set (axles 2 and 4). A visual representation of these differences is shown in Figure 40.

Table 19  Comparison statistics for the modeled datasets by axle (July 2008 dataset)

<table>
<thead>
<tr>
<th>Axle</th>
<th>Max. % error</th>
<th>% within 30% error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24%</td>
<td>100%</td>
<td>583</td>
<td>[-1.28, 2.71]</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>145%</td>
<td>70%</td>
<td>2,168</td>
<td>[16.8, 20.8]</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>116%</td>
<td>68%</td>
<td>1,888</td>
<td>[0.74, 4.73]</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>126%</td>
<td>47%</td>
<td>2,319</td>
<td>[-2.25, 1.74]</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>164%</td>
<td>68%</td>
<td>2,205</td>
<td>[-21.3, -17.3]</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 20  Comparison statistics for the modeled datasets by axle (April 2009 dataset)

<table>
<thead>
<tr>
<th>Axle</th>
<th>Max. % error</th>
<th>% within 30% error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26%</td>
<td>100%</td>
<td>649</td>
<td>[0.65, 4.62]</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>161%</td>
<td>71%</td>
<td>1,791</td>
<td>[-7.34, -3.38]</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>133%</td>
<td>70%</td>
<td>1,845</td>
<td>[3.63, 7.59]</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>148%</td>
<td>49%</td>
<td>2,298</td>
<td>[-1.99, 1.98]</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>204%</td>
<td>50%</td>
<td>2,417</td>
<td>[-5.44, -1.48]</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Table 21  Comparison statistics for the validation datasets by axle (July 2008)

<table>
<thead>
<tr>
<th>Axle</th>
<th>Max. % error</th>
<th>% within 30% error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22%</td>
<td>100%</td>
<td>1,986</td>
<td>[-250, -247]</td>
<td>0.0949</td>
</tr>
<tr>
<td>2</td>
<td>86%</td>
<td>63%</td>
<td>4,070</td>
<td>[557, 561]</td>
<td>0.1401</td>
</tr>
<tr>
<td>3</td>
<td>73%</td>
<td>75%</td>
<td>n/a*</td>
<td>[-286, -282]</td>
<td>0.0281</td>
</tr>
<tr>
<td>4</td>
<td>97%</td>
<td>54%</td>
<td>7,699</td>
<td>[-858, -853]</td>
<td>0.0255</td>
</tr>
<tr>
<td>5</td>
<td>102%</td>
<td>54%</td>
<td>n/a*</td>
<td>[-1,692, -1,687]</td>
<td>0.0338</td>
</tr>
</tbody>
</table>

* Not enough data points were in this group to reliably determine standard deviation.

Table 22  Comparison statistics for the validation datasets by axle (April 2009 dataset)

<table>
<thead>
<tr>
<th>Axle</th>
<th>Max. % error</th>
<th>% within 30% error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96%</td>
<td>89%</td>
<td>1.489</td>
<td>[15.1, 19.2]</td>
<td>0.0067</td>
</tr>
<tr>
<td>2</td>
<td>98%</td>
<td>79%</td>
<td>2,417</td>
<td>[-61.3, -57.3]</td>
<td>0.2382</td>
</tr>
<tr>
<td>3</td>
<td>105%</td>
<td>62%</td>
<td>2,707</td>
<td>[378, 382]</td>
<td>0.1262</td>
</tr>
<tr>
<td>4</td>
<td>122%</td>
<td>53%</td>
<td>2,807</td>
<td>[-34.3, -30.3]</td>
<td>0.0603</td>
</tr>
<tr>
<td>5</td>
<td>196%</td>
<td>47%</td>
<td>3,667</td>
<td>[-158, -154]</td>
<td>0.0412</td>
</tr>
</tbody>
</table>
The gross vehicle weight can be calculated by adding up the individual axle weights for each vehicle. Table 21 shows the fit statistics for gross vehicle weight determined by adding up all of the axle weights for both datasets. (Note that for the April 2009 dataset, the sum of the calculated axle weights was multiplied by 2, since in April 2009 only data for the right side of the vehicle was collected by the test equipment.)

Table 23  Statistics comparing calculated gross vehicle weight to actual gross vehicle weight

<table>
<thead>
<tr>
<th></th>
<th>Max. % error</th>
<th>% within 30% error</th>
<th>StDev (lbs)</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2008</td>
<td>60%</td>
<td>82%</td>
<td>16,250</td>
<td>[-595, -591]</td>
</tr>
<tr>
<td>April 2009</td>
<td>76%</td>
<td>76%</td>
<td>14,336</td>
<td>[266, 270]</td>
</tr>
</tbody>
</table>
Figure 41  Fit for Gross Vehicle Weight (July 2008 dataset)

Figure 42  Fit for Gross Vehicle Weight (April 2009 dataset)
Examination of Model Parameters

The final model developed for the July 2008 and April 2009 datasets provides insights into the parameters that are most related to vehicle weight. Parameters discussed in this section include speed, axle spacing, and the dimensional analysis variables. In addition, a discussion of the method of aggregating the acoustic emission data is included.

In many of the early attempts at creating a model, speed was found to be an important parameter in the models. For most of the acoustic emission parameters, in fact, better relationships could be found between the parameter and vehicle speed than between the parameter and vehicle weight. Nevertheless, speed does not enter into the final equation for weight except as part of the dimensional analysis variable, $\frac{E}{v^2}$. A look at the error in calculated weight (measured weight minus the calculated weight in lbs) as a function of speed, as seen in Figure 42, shows that the final model adequately accounts for the effects of speed, as there is no obvious change in error depending on speed of the vehicle. Although it may be desirable to experiment with vehicles traveling at higher or lower vehicle speeds than were observed for this dissertation, it does not appear that changes in vehicle speed will substantially alter these results.
Figure 43  Error in weight estimation as a function of vehicle speed

The reason that axle spacing \((S)\) was important to the model only for axles 2 and 5 becomes apparent upon examination of a histogram showing the variation in axle spacing by axle for the five-axle vehicles (see Figure 43). The distance between axles 2 and 3 (labeled axle 3 in the graph) varies very little compared to the distance between any other pair of axles. The spacing for axle 4 (the distance between axles 3 and 4) may not have been important to the model because it tends to be relatively large. If the distance is sufficient that there are no remaining effects from the previous axle’s passing, then axle 4 will behave similarly to axle 1.
Three dimensional analysis variables were found to be important to the model, namely, $\frac{gE}{v^2}$, $\frac{cE}{\sqrt{A}}$, and $\frac{E^3}{\sqrt{A} \cdot \text{abs}E}$. The first of these can be seen to be related to the equation for kinetic energy, as shown below:

$$E = \frac{1}{2} mv^2 \quad (1)$$

Solving for $m$, the mass, we then see:

$$m = \frac{2E}{v^2} \quad (2)$$

And since weight is simply mass times the force of gravity, $g$:

$$w = mg \quad (3)$$
If we substitute equation (2) for m in equation (3), then we have a relationship between weight and the dimensional analysis variable:

\[ w = \frac{2Eg}{v^2} \]  

(4)

Of course, this is not an exact relationship, as the weight of the vehicle cannot be fully determined by simply using this relationship. Thus, it would be more correct to write:

\[ w \propto \frac{Eg}{v^2} \]  

(5)

The second dimensional analysis variable, \( \frac{cE}{\sqrt{A}} \), seems to be related to the concept of work, the generic equation for which is:

\[ W = Fx \]  

(6)

where \( W \) is work, \( F \) is force, and \( x \) indicates the distance over which the force is applied.

If we substitute weight, \( w \), as the force (or proportional to the force) and the square root of the area the force is applied over, \( \sqrt{A} \), as the distance, then we get:

\[ W \propto w\sqrt{A} \]  

(7)

This variable then seems to be relating the work of the tire on the metal bar to the acoustic emission energy and count in the following manner:

\[ cE \propto W \propto w\sqrt{A} \]  

(8)

which becomes the dimensional analysis variable.
The last of the dimensional analysis variables that was included in the final model for the field data is \( \frac{E^3}{\sqrt{A}} \). This variable is not easily recognized as fitting into any simple kinetic or potential energy equation. It seems to show a relationship between the acoustic emission energy, \( E \), and absolute energy, \( AbsE \), and may be a normalizing factor.

The other variables included in the final model were amplitude (\( a \)), count (\( c \)), initial frequency (\( f_i \)), reverberation frequency (\( f_r \)), and average frequency (\( f_a \)). The aggregation method most commonly used in the final model is the method of averaging the values of the acoustic emission parameters over all hits for each AB. Six variables in the final model used this method of aggregation. All of the other aggregation methods were represented for at least two variables, however. It is clear that different methods of aggregation work better for different acoustic emission parameters in the formation of the models. For instance, the amplitude variables included in the final model exclusively used the summation method and the 85\textsuperscript{th} percentile method. The frequency variables, on the other hand, exclusively used the method of averaging and the 25\textsuperscript{th} percentile method.

\textit{Model Differences Due to Sensors}

There are distinct differences in the model parameters for the July 2008 data and the April 2009 data. Twelve of the parameters that were found to be significant in the model using the April 2009 dataset were not significant in the model using the July 2008 data. This difference could provide some insight into the sensors, since the Pico HF sensor was used in July 2008 and the
WD sensor was used in April 2009. With the Pico sensor, most of the “amplitude” variables were not important to the model. Also, the “initial frequency” variables were not important to the model with the Pico sensor. Thus, the Pico sensor may not detect some levels of amplitude or initial frequency that are detected by the WD sensor and appear to be important to developing a model for vehicle weight.
SUMMARY AND CONCLUSIONS

This dissertation was undertaken to develop a low-cost and portable weigh-in-motion device to measure the weight of heavy trucks as they are travelling at normal speeds along the highway. Although weigh-in-motion systems (including portable ones) do currently exist, their use is limited by the high costs of these systems. At the same time, demand for weigh-in-motion systems is increasing. Improved technology has made it possible to use the detailed information that can be provided by a weigh-in-motion system to more accurately design pavement structures as well as to more effectively enforce vehicle weight limits. A low-cost weigh-in-motion device would provide the information needed to reap these benefits cost-effectively.

This dissertation summarizes a series of experiments designed to explore the feasibility of determining the weight of a moving vehicle by measuring the acoustic emission emitted when the vehicle travels over a metal strip that has been laid across the road. The cost of such a system would be minimal, including only the cost of the metal strip or strips, the acoustic emission sensors, and a simple computer system to record and analyze the data.

After early experiments showed promise for the system, laboratory equipment was built to allow examination of the relationship between acoustic emission parameters and vehicle weight in a controlled environment. The equipment allowed the force of the tire against the metal test strip, the location at which the tire struck the metal test strip, and the speed at which the tire struck the metal test strip to all be varied, although it should be noted that the device was limited to low speeds. Relationships between acoustic emission parameters and the vehicle weight were
developed, with the parameters count, energy, and absolute energy being particularly strongly related. The acoustic emission energy was found to be inversely related to the distance of the tire bump from the sensor location. No variation in acoustic emission parameters with speed was noted. Dimensional analysis was employed to develop equations that more accurately represented the relationships between the acoustic emission parameters and the vehicle characteristics. Using the dimensional analysis parameters as well as other pertinent variables, a statistical model using acoustic emission parameters to predict the force of the tire against the metal test bar (weight) was developed. The maximum error in measured weight compared to actual weight was 44%, with 99% of the data points falling within 30% error.

Subsequent experiments were performed in the field wherein the metal test strip was attached to the road surface and vehicles of known weight were run across the strip. Two major field tests were performed. In July 2008, the test used Pico HF-1.2 sensors. Separate metal test bars were used for the right and left sides of the vehicles so that each side of each axle passed over a test bar one time. In April 2009, the test used WD sensors, which detect a wider range of frequencies. The two test bars were placed so that only the right side of each vehicle passed over the test bars and every right side axle passed over both test bars. Several methods of preparing the data for analysis were developed and tested. Two sets of statistical models, each corresponding to one of the field datasets, were created using the prepared data with the purpose of estimating the weight of individual axles; however, the models were developed in such a way to ensure that the same parameters were found in both models. These models were developed using five axle vehicles only. Twenty-five percent of the data in each dataset was reserved for use in validating the models. The model created for the April 2009 dataset was found to be a valid model, with a
maximum error of 204% and 69% of the data points falling within 30% error for both the modeled data and the data reserved for validation. The average difference between the modeled vehicle weight and the measured vehicle weight was between 25 and 29 lbs (0.5% error). The model created for the July 2008 dataset was not found to be valid, however. The greater accuracy of the April 2009 dataset is concluded to be due to either the wider frequency range of the WD sensor or the method of measuring the acoustic emission parameters twice (or both).

Major findings of this research include:

- To create a valid statistical model of vehicle weight, differences in the acoustic emission response to each axle (from axle 1, the first axle of a five-axle vehicle to axle 5, the last axle of the five-axle vehicle) must be included in the model using interaction terms.
- It is important to consider aggregating the acoustic emission hits for each individual axle bump in a variety of ways. Model variables created using the aggregation method of averaging the values of the hits for each acoustic emission parameter was most often found to be important to the statistical model, but variables representing each of the other aggregation methods tested in this dissertation (summation, 25th percentile, median, and 85th percentile) were also included in the final model.
- Dimensional analysis proved to be useful in creating a valid statistical model. Many of the parameters included in the final statistical models for the field data were developed using dimensional analysis.
RECOMMENDATIONS FOR FURTHER RESEARCH

This dissertation represents the first major exploration of the concept of measuring the weight of a moving vehicle by detecting the acoustic emissions in a metal test bar over which the vehicle passes. Considerable work is still needed if a viable commercial product is to be created. This section describes issues that were uncovered or not fully explored during the experimentation and analysis presented in this dissertation.

In the AEWIN software, a threshold value is set. This value is used to determine the beginning and ending point of each hit. Lower values of the threshold will likely result in more hits being detected, whereas higher values of the threshold will likely result in fewer hits being detected. For this research, the threshold value was set at 50 dB for all experiments. Future research should be undertaken to determine how different threshold values affect the resulting values of the acoustic emission parameters, whether the threshold should be set differently for different sensors, and if varying the threshold value results in a better calculation of vehicle weight.

The contact stress between the vehicle tire and the metal test strip may be influenced as much by the tire pressure as it is by the actual vehicle weight; however, tire pressure was not included in any of the analysis presented in this dissertation because of the difficulty of varying tire pressure experimentally or measuring tire pressure in the field. Future research should examine the effect of tire pressure on the acoustic emission parameters. Also, future research could consider surrogate measures for tire pressure. For instance, the location and width of the tire bump could possibly be measured by using a metal test bar outfitted with numerous sensors.
A number of experimental factors were identified, but not varied due to constraints of available test sites. These include the effect of the type of pavement (flexible or rigid), the effect of speed, and environmental factors, such as temperature. Because each vehicle included in the test sample had to be weighed using a reliable scale, the field experiments were performed at a weigh station where all of the pavement was rigid and speeds were limited (speed limit 45 mph) compared to the mainline (speed limit 65 mph). Since use of the weigh station for experimentation was limited, temperature could not be included as a factor. These are all variables that should be examined in the future if commercial development of the weigh-in-motion system is pursued.

Another issue that needs to be explored before commercialization is the possibility that the acoustic emission output might decrease if the equipment is used over a long period of time, even though the Kaiser effect was shown not to play a role in the short term. If the Kaiser effect is shown to play a role over time, it may be necessary to recalibrate the system after a certain amount of time or to re-engineer the device to avoid the Kaiser effect (by choosing a material that “heals” over time, for instance).

The model developed for the data collected in April 2009 was validated, whereas the model for the data collected in July 2008 was not. There were two major differences in the way the data was collected at these two different times: the type of acoustic emission sensor used and the repetition of the measurement (or lack thereof). Future experimentation could examine these two factors separately to determine the role each played in the creation of a successful model. Different sorts of repeated measurements could also be experimented with. For instance, outfitting one metal test strip with multiple acoustic emission sensors could be compared to using
several separate metal test strips to determine which type of repeated measure results in the best calculation of vehicle weight.

A multiple regression model was used to model vehicle weight from acoustic emission parameters and other pertinent variables. Future research should examine other types of models, such as a non-parametric neural network model, to determine if this type of model produces better results.

When the multiple regression models were created, the analysis was limited to 5-axle vehicles. These are by far the most common type of commercial vehicle, so it makes sense to start with them. The data collected for this dissertation could be used to extend the analysis to other types of vehicles.

Finally, when ABs are close together in time (as was the case for tandem axles), it can be difficult to determine which acoustic emission hits apply to which axle. This difficulty probably contributed to making the models less accurate. Future experiments might use multiple sets of metal test bars that are synchronized by a microprocessor so that acoustic emission hits are recorded for different axles by different metal test bars. Other methods of dealing with the tandem axles might also be explored.
APPENDIX A: LIST OF VARIABLES AND THEIR MEANINGS
<table>
<thead>
<tr>
<th>Variable</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Tire contact area</td>
</tr>
<tr>
<td>a</td>
<td>Amplitude</td>
</tr>
<tr>
<td>AB</td>
<td>Axle bump</td>
</tr>
<tr>
<td>AbsE</td>
<td>Acoustic emission absolute energy</td>
</tr>
<tr>
<td>c</td>
<td>Count</td>
</tr>
<tr>
<td>c&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Count to peak</td>
</tr>
<tr>
<td>D</td>
<td>Duration</td>
</tr>
<tr>
<td>d</td>
<td>Distance between metal bars</td>
</tr>
<tr>
<td>E</td>
<td>Acoustic emission energy</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>f&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Average frequency</td>
</tr>
<tr>
<td>f&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Initial frequency</td>
</tr>
<tr>
<td>f&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Reverberation frequency</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>i</td>
<td>Axle number (1 = axle 1, 2 = axle 2, etc.)</td>
</tr>
<tr>
<td>k&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Exponential value for dimensional analysis</td>
</tr>
<tr>
<td>ℓ</td>
<td>Distance from sensor to location of tire bump</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>M</td>
<td>Mass</td>
</tr>
<tr>
<td>n</td>
<td>Generic integer</td>
</tr>
<tr>
<td>N</td>
<td>Number of hits associated with an AB</td>
</tr>
<tr>
<td>p</td>
<td>Statistical measure of significance</td>
</tr>
<tr>
<td>π&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Product for dimensional analysis</td>
</tr>
<tr>
<td>R&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Coefficient of determination</td>
</tr>
<tr>
<td>r</td>
<td>Rise time</td>
</tr>
<tr>
<td>S</td>
<td>Axle spacing</td>
</tr>
<tr>
<td>t,T</td>
<td>Time</td>
</tr>
<tr>
<td>TB</td>
<td>Tire bump</td>
</tr>
<tr>
<td>v</td>
<td>Speed</td>
</tr>
<tr>
<td>w</td>
<td>Weight</td>
</tr>
<tr>
<td>x</td>
<td>Generic variable</td>
</tr>
<tr>
<td>Y</td>
<td>Elastic modulus</td>
</tr>
<tr>
<td>y</td>
<td>Generic variable</td>
</tr>
</tbody>
</table>
APPENDIX B: GRAPHS OF WEIGH STATION DATA
Aggregation Method: AVERAGE
July 2008

\[ y = 0.0281x + 1033.5 \]
\[ R^2 = 0.0024 \]

April 2009

\[ y = 0.0312x + 748.44 \]
\[ R^2 = 0.0153 \]
Aggregation Method: AVERAGE
July 2008

\[ y = 0.0728x + 2265.5 \]
\[ R^2 = 0.0038 \]

April 2009

\[ y = 0.0568x + 1590.1 \]
\[ R^2 = 0.0256 \]
Aggregation Method: AVERAGE
July 2008

\[ y = 0.0094x + 89.239 \]
\[ R^2 = 0.0126 \]

April 2009

\[ y = 0.0021x + 27.624 \]
\[ R^2 = 0.0319 \]
Aggregation Method: AVERAGE
July 2008

\[ y = 0.0077x + 130.14 \]
\[ R^2 = 0.0191 \]

April 2009

\[ y = 0.0004x + 60.229 \]
\[ R^2 = 0.0016 \]
Aggregation Method: SUM
July 2008

y = 0.3672x + 5468.2
R² = 0.0228

Rise time (us)
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000

April 2009

y = 0.1981x + 3207.9
R² = 0.0233

Rise time (us)
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000

y = 0.1576x + 1088.8
R² = 0.0632

Count
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000

y = 0.0231x + 270.92
R² = 0.0408

Count
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000

y = 0.0696x + 380.64
R² = 0.0517

Energy (aJ)
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000

y = 0.0155x + 227.92
R² = 0.023

Energy (aJ)
Axle weight (lbs)

0 5000 10000 15000
0 5000 10000 15000
Aggregation Method: SUM
July 2008

y = 0.995x + 11412
R² = 0.0424

y = 0.0148x + 385.5
R² = 0.0128

April 2009

y = 0.38x + 6738.9
R² = 0.0397

y = 0.0043x + 262.63
R² = 0.0124

Amplitude (dB)
Axle weight (lbs)

Average frequency (kHz)
Axle weight (lbs)
Aggregation Method: SUM
July 2008

\[ y = 0.0672x + 498.75 \]
\[ R^2 = 0.0591 \]

April 2009

\[ y = 0.0128x + 113.81 \]
\[ R^2 = 0.0348 \]
Aggregation Method: SUM
July 2008

\[ y = 0.0918x + 898.48 \]
\[ R^2 = 0.018 \]

April 2009

\[ y = 0.0059x + 250.24 \]
\[ R^2 = 0.0063 \]
Aggregation Method: 25\text{th} percentile

July 2008

\[ y = 0.0044x + 221.57 \]
\[ R^2 = 0.0002 \]

April 2009

\[ y = 0.0093x + 251.98 \]
\[ R^2 = 0.0035 \]
Aggregation Method: 25\textsuperscript{th} percentile

July 2008

\[ y = -0.0331x + 1056.7 \]
\[ R^2 = 0.001 \]

April 2009

\[ y = 0.0325x + 922.2 \]
\[ R^2 = 0.0083 \]
Aggregation Method: 25\textsuperscript{th} percentile

July 2008

\begin{align*}
\text{y} &= 0.0012x + 11.945 \\
R^2 &= 0.0007
\end{align*}

April 2009

\begin{align*}
\text{y} &= 0.0006x + 13.134 \\
R^2 &= 0.0052
\end{align*}
Aggregation Method: 25th percentile
July 2008

Initial frequency (kHz)

Axle weight (lbs)

y = 0.0032x + 54.213
R² = 0.0063

April 2009

Initial frequency (kHz)

Axle weight (lbs)

y = -0.0002x + 38.018
R² = 0.0008
Aggregation Method: Median
July 2008

y = 0.003x + 560.68
R² = 3E-05

y = -0.0013x + 143.43
R² = 6E-05

y = 0.0023x + 63.457
R² = 0.0008

Energy (aJ)

Axle weight (lbs)

April 2009

y = 0.0278x + 460.2
R² = 0.0123

y = 0.0026x + 60.698
R² = 0.0127

Energy (aJ)

Axle weight (lbs)
Aggregation Method: Median

July 2008

\[ y = 0.0134x + 1780 \]
\[ R^2 = 9 \times 10^{-5} \]

Axle weight (lbs) vs. Duration (us)

\[ y = 9 \times 10^{-5}x + 59.378 \]
\[ R^2 = 0.0007 \]

Axle weight (lbs) vs. Amplitude (dB)

\[ y = 0.0001x + 59.683 \]
\[ R^2 = 0.0033 \]

Axle weight (lbs) vs. Average frequency (kHz)

April 2009

\[ y = 0.0491x + 1381.1 \]
\[ R^2 = 0.0155 \]

Axle weight (lbs) vs. Duration (s)

\[ y = 0.0001x + 59.683 \]
\[ R^2 = 0.0033 \]

Axle weight (lbs) vs. Average frequency (kHz)

\[ y = 0.0006x + 40.869 \]
\[ R^2 = 0.0064 \]

Axle weight (lbs) vs. Average frequency (kHz)
Aggregation Method: Median
July 2008

\[ y = 0.0037x + 23.562 \]
\[ R^2 = 0.0021 \]

April 2009

\[ y = 0.0008x + 23.715 \]
\[ R^2 = 0.0056 \]
Aggregation Method: Median
July 2008

\[ y = 0.0047x + 111.27 \]
\[ R^2 = 0.0102 \]

Axle weight (lbs)

Initial frequency (kHz)

April 2009

\[ y = -0.0009x + 70.376 \]
\[ R^2 = 0.0014 \]

Axle weight (lbs)

Initial frequency (kHz)
Aggregation Method: 85th percentile
July 2008

April 2009

$y = 0.036x + 1985.6$
$R^2 = 0.001$

$y = 0.0543x + 1352.3$
$R^2 = 0.0134$

$y = 0.0335x + 446.91$
$R^2 = 0.0137$

$y = 0.0062x + 104.8$
$R^2 = 0.0327$

$y = 0.0171x + 138.35$
$R^2 = 0.0226$

$y = 0.0039x + 86.409$
$R^2 = 0.0151$
Aggregation Method: 85th percentile
July 2008

\[ y = 0.1253x + 4269.1 \]
\[ R^2 = 0.0049 \]

April 2009

\[ y = 0.0039x + 86.409 \]
\[ R^2 = 0.0151 \]
Aggregation Method: 85\textsuperscript{th} percentile

**July 2008**

\[ y = 0.0133x + 188.51 \]
\[ R^2 = 0.0075 \]

**April 2009**

\[ y = 0.0041x + 45.058 \]
\[ R^2 = 0.0328 \]
Aggregation Method: 85th percentile
July 2008

\[ y = 0.0097x + 253.61 \]
\[ R^2 = 0.0089 \]

April 2009

\[ y = 0.001x + 194.19 \]
\[ R^2 = 7 \times 10^{-5} \]
REFERENCES


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