Development of a Weigh-Pad-Based Portable Weigh-In-Motion System

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Installing permanent in-pavement weigh-in-motion (WIM) stations on local roads is very expensive and requires recurring costs of maintenance trips, electricity, and communication. For county roads with limited average daily traffic (ADT) volume, such a high cost of installation and maintenance is rarely justifiable. One solution to bring WIM technologies to local roads is to utilize a portable WIM system, much like pneumatic tube counters used in short-duration traffic counts. That is, a single unit is reused in multiple locations for few days at a time. This way, WIM data is obtained without the cost of permanent in-pavement WIM stations. This report describes the results of a two-year research project sponsored by the Minnesota Department of Transportation (MnDOT) to develop a portable WIM system that can be readily deployed on local roads. The objective of this project was to develop a portable WIM system that would be used much like a pneumatic tube counter. The developed system is battery operated, low cost, portable, and easily installable on both rigid and flexible pavements. The report includes a side-by-side comparison of data between the developed on-pavement portable WIM system and an in-pavement permanent WIM system.

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Executive Summary

Weigh-in-Motion (WIM) systems produce individual vehicle records of traffic information that includes lane number, time-stamp, speed, axle loads, axle spacing, and classification of the vehicle type. This detailed traffic information has been used in a wide range of applications, i.e., pavement analysis and design, overweight enforcements, traffic data analysis and reporting, freight estimation, traffic monitoring, etc. Although benefits of WIM data are evident, initial construction and the subsequent maintenance of permanent roadside WIM stations are expensive. WIM stations, therefore, have mainly been installed on roadways with heavy traffic, such as interstate and trunk highways. They are almost nonexistent on rural local roads because of low Average Daily Traffic (ADT) and difficulty of cost justification. However, low ADT on rural roads does not mean fewer overweight violations, or diminish needs for protecting the roads from overweight vehicles. Heavy truck volumes on local roads, indeed, have been increasing, caused by higher demands on agricultural commodities. This raises a grave concern for many local transportation engineers, because it could significantly shorten the life of local roadways. To monitor road wear or to protect from overweight vehicles, traffic engineers need to know the truck volumes and weights but without the cost of permanent roadside WIM stations.

One solution to bring WIM technology to local roads is to utilize a portable WIM system, much like pneumatic tube counters used in short-duration traffic counts. That is, a single unit is reused in multiple locations for few days at a time. This way, WIM data is obtained without the cost of a permanent WIM station. Unfortunately, WIM development efforts have mainly been given to in-pavement permanent systems; consequently, portable WIM systems are not available on the market. This report describes the results of a two-year research project sponsored by the Minnesota Department of Transportation (MnDOT) to develop a portable WIM system that can be readily deployed on local roads.

The objective of this project was to develop a portable WIM system that would be used much like a pneumatic tube counter. The sensor chosen was the RoadTrax BL sensor strip (or simply “BL sensor”), which is a thin, narrow piezoelectric strip. To accomplish the project objective, the BL sensor strips were sandwiched and glued between two strong conveyer belts. Conveyer belts provide flexibility and durability needed for on-pavement installations. A standard sensor constructed has a length of 24 ft. covering two lanes of roads and a width of 1 ft. This new sensor is called a “weigh-pad.” The final completed system is called a weigh-pad system and consists of a pair of weigh-pads and a console computer. For installation, two weigh-pads are laid across the traffic lane separated by a known distance (typically 12 to 16 ft.) and fastened on the pavement surface using sleeve anchor screws. The edges are then taped using strong-bonding utility tapes. Since on-pavement installations produce much stronger charge signals than in-pavement installations, a customized charge amp was developed to handle the different charge responses. In addition, a durable, field-ready enclosure that houses all necessary electronic components and a computing unit was designed and fabricated. The final system consists of two parts, a console box and a pair of weigh-pads, and is truly portable. One of the advantages of the weigh-pad system is that sensor installation does not cut into the pavement. Since the installation does not weaken the pavement structure, it would be safe to use on structurally sensitive areas such as on bridge decks.

To verify WIM capabilities of the weigh-pad system, driving tests were conducted at the MnRoad facility and also on Minnesota Trunk Highway 53 (TH-53). Two types of effects were tested at MnRoad, which are the effects of temperature and speed to the weight measurements. For temperature tests, a single test vehicle with a known weight was driven over the weigh-pads repeatedly in the pavement temperature range, 85 - 135 ºF, and the corresponding gross vehicle weights (GVWs) translated from the axle waveforms were analyzed. The expected trend was for the GVW to increase as the pavement temperature rose, since heat increases charge production of the piezoelectric sensors, but the data did not show any trend. This outcome is mainly attributed to the charge amp design in which it filters out any signal components that have a period longer than 20 sec. Pavement temperatures, in general, change over a longer time period, such as in the order 10s of minutes, which are clearly outside the 20 sec time constant. Consequently, most charge signals generated by the pavement heat must have been drained from the charge amp.

The next test was speed effect on vehicle weight. Since weigh-pads are installed on the surface of the pavement by fastening the pads, they are slightly extruded. When a vehicle drives over the installed weigh-pads, a sound of hitting a small bump can be clearly heard. This bumping sound becomes louder as the vehicle speed increases. This begs the question: Does the vehicle speed affect the vehicle weight measurements? To answer this question, the same test vehicle was driven multiple times at speeds close to 10, 20, 30, 40, 50, 60, 70, and 80 mph, and the corresponding weights were analyzed. The data showed an increasing trend of weights as the speed increased. This result explains the bigger bumping sound as the vehicle speed increases and suggests that there is a need for a calibration of the measured weight with respect to the vehicle speed.

The final tests were conducted at an existing in-pavement WIM site for a side-by-side comparison. The chosen road was one of the Minnesota trunk highways and had an average traffic speed of about 67 mph. The weigh-pads were installed right next to a WIM site constructed using Kistler Lineas quartz sensors and an IRD iSync WIM system. A total of 3,235 vehicle records were compared for three parameters: GVW, speed, and axle spacing. Normalized Root Mean Square Errors (NRMSEs) between two systems on GVW, speed, and axle spacing were 3.88%, 2.22%, and 0.5%, respectively. Correlation coefficients between two systems for GVW, speed, and axle spacing were 0.97, 0.97, and 0.99, respectively. The coefficient of determinations, denoted as R^2, were 0.93, 0.93, and 0.99 for GVW, speed, and axle spacing, respectively. Lastly, the difference in vehicle classifications between the two systems was merely 1.5%. All of the comparison measures indicate that the WIM data obtained by the weigh-pad system is only a few percentage points different than the data of the same traffic obtained by a permanent in-pavement WIM system. This test result suggests that the weigh-pad system developed in this project provides WIM data with a quality similar to that of a permanent in-pavement WIM system.

In conclusion, this project successfully demonstrated that a reusable, portable WIM system that would work much like a pneumatic tube counter can be built and deployed. A side-by-side comparison verified that the data quality difference between the portable on-pavement and a permanent in-pavement system is minute. With few improvements, the researchers believe that the weigh-pad system is a solution for bringing the WIM technology to local roads at a low cost.

Chapter 1: Introduction

A linear increase in load is known to have a forth power exponential increase in the acceleration of road wear, which has been the basis for pavement design and maintenance for many years [1]. Weigh-in-Motion (WIM) systems provide this vital traffic load data as the inputs for pavement design and management [2-7]. In the NCHRP 2002 Mechanistic-Empirical Design Guide [3], which is simply referred to as the 2002 Guide, traffic is handled in terms of annual load distribution (spectra) by axle configuration. The full spectra for single, tandem, tridem, and quadrem axles are directly used as the design inputs. On the other hand, the traditional Equivalent Single Axle Load (ESAL) [8], which represents damage to pavement, is still popularly used for pavement designs by many transportation departments. Regardless which method is used, WIM systems provide essential traffic load information for multiple applications. WIM data also meets standard traffic monitoring needs [9].

Although there are many benefits, infrastructure cost for building permanent roadside WIM stations is expensive. For example, installing a WIM station for a four-lane highway typically costs over $220,000 at the time of this writing. In addition, maintenance of a WIM site requires a recurring cost of sensor maintenance, electricity, communication, and system upgrades. Nevertheless, building WIM stations could be readily justified for heavy traffic highways, such as interstate and trunk highways. Unfortunately, installing a WIM station on a rural local road is rarely justifiable, considering that rural roads have limited Average Daily Traffic (ADT). Low ADT does not mean fewer overweight violations or diminish the need for protecting the roads from overweight vehicles. In fact, heavy truck traffic volumes on local roads of Midwestern states have been increased due to new demands on renewable energy or ethanol related agricultural products such as corn and soybeans. This increased truck volume raises a grave concern for many local transportation engineers, as it could significantly shorten the life of the local roadways. To estimate the road wears or to protect from overweight vehicles, it is essential to collect truck weight data. Therefore, local roads with load ADT also need WIM stations.

One solution to bringing WIM technologies to local roads is to develop a low-cost portable WIM system that can be used as a short-duration WIM data collection system, similarly to the use of pneumatic tube counters. Portable WIM systems could be used for just few days in the area where frequent weight violations likely occur. There are several benefits of using a portable WIM system over an in-pavement permanent WIM station for certain cases. First, since portable WIM sensors are not installed by cutting pavements, it does not weaken the pavement structure. With this property, a portable WIM system would be more favorable to be installed on structurally sensitive areas such as on bridge decks. Second, the measurement locations can be freely selected and moved. This property could be used as a preliminary study to locate a permanent WIM site. Third, since a single system can be reused for many locations by moving around, the deployment cost is very low. Forth, the maintenance cost is lower than that of permanent WIM stations because no electricity or communication link cost is required. Consequently, there are sufficient motivations as well as needs to develop a practical portable WIM system.

There are enormous challenges to develop a practical portable WIM system. First, sensors must be durable and have a strong enough grip on the pavement surface to hold against the traction forces of heavy trucks. Second, the sensors must be easy to install and remove from pavement. These two factors are a kind of opposing conditions and difficult to be met at the same time. More specifically, if sensors are strongly fastened on the pavement, they would produce more accurate readings because of less vibration, but they would not be easily removable.

Regardless how good a portable installation would be, it would not be as secure as the sensors of an equivalent permanent WIM station that are installed inside the pavement. Consequently, accuracy of a portable WIM system must be achieved from signals generated by obscure sensor installations. Each passage of a heavy truck may slightly move or vibrate the sensors, which would create superfluous signals. In order to filter out these unwanted signals, an intelligent algorithm that can isolate faulty forces from the main load force must be developed, which would not be simple.

In order to successfully meet the mentioned challenges, it is important to have working knowledge on WIM sensors and axle forces, understand materials and pavement properties, and have experienced in processing of real-time WIM signals. Much of such information is not available in the literature, because WIM systems are mostly developed from a proprietary environment. The PI (Principal Investigator) and MnDOT have been involved in several WIM system development projects for a number of years. The following paragraph describes the past related research and development (R&D) efforts.

In 2003-2004, the PI developed a signal probe for Kistler Lineas sensors as one of the sponsored projects. The result was presented at the NATMEC 2004 conference [10] and in the project report [11]. This system is equipped with charge amps and provides real-time plots of axle load waveforms from the charge signals of Lineas Quartz WIM sensors. At the same time, it can record the raw axle waveforms in a binary form for future reviews. This system was designed as a portable diagnostic tool to be used in the field for testing Kistler Lineas sensors. Field tests revealed several abnormal conditions of charge signals [13]. In 2006, the PI and his graduate students successfully completed development of an eight-channel real-time WIM system based on a PC and off-the-shelf components and installed as a working WIM station [12]. This real time WIM system allows the users to examine the raw axle signals without removing the sensor connections from the WIM system, i.e., it combines the WIM probe ideas with a regular WIM system. This project demonstrated that a WIM system can be easily built using off-the-shelf components. During this project, new signal processing techniques and signal modeling for WIM systems were developed and published in [13]. Another innovation created during this project was development of a hardware-in-the-loop (HIL) simulator for generating real-time axle-load waveforms in voltages using mathematical axle models [14, 15]. The HIL simulator can generate ideal, as well as faulty axle signals; consequently, the WIM systems can be tested under simulated traffic conditions. The HIL simulator was a critical tool for developing the PC-based WIM system. The HIL simulator was also extensively used during the software development phase of the new portable WIM system, saving a huge amount of development time.

In the past, most R&D efforts on WIM systems have been given to in-pavement permanent WIM stations. Little efforts have been given to development of portable WIM systems. One early research that was showing a promise as a portable WIM system was fiber optic sensors [16, 17]. The pressure on the sensor causes optical fiber deformed, which leads to the loss of output light. The vehicle weight is obtained through measuring the variation of light intensity in optical fiber.

Since optical fibers are very thin, they have an attractive physical form factor for developing a portable WIM sensor. Although this line of research has been commercialized for in-pavement installations, it has yet to evolve to a portable WIM system.

This research utilizes a piezoelectric load sensing technology because it is still the most widely used load-sensing technology. Some of piezoelectric strips are now specifically designed for WIM applications and readily available [18, 19]. For example, the quartz piezoelectric sensors developed by Kistler Inc. [19] have been widely accepted for in-pavement implementation by many states and successfully used for collecting WIM data for many years. For this project, the research team decided to use the RoadTrax BL (Brass Linguini) sensors (referred to as "BL sensors") [18] which are piezoelectric strips designed for WIM applications (classified as Class-1 or WIM applications, according to the manufacturer's classification). The BL sensor strips are thin, long, and strong, which are the desirable properties for developing portable WIM sensors.

One of the objectives of this project was developing a portable WIM system that would be used much like a pneumatic tube counter. In order to accomplish that goal, the BL sensor strips were sandwiched and glued between two thin conveyer belts. Conveyer belts provide flexibility and durability needed for on-pavement installations. This new sensors were called weigh-pads. A standard weigh-pad has a length of 24 ft. covering two lanes and a width of 1 ft. The thickest part of the pad is in the middle and only 0.3 in. The leading and trailing edges of weigh-pads are sanded off to create a smooth rising and falling slopes, respectively. It can be easily wrapped around as a roll (about 19 in diameter), i.e., packed like a roll of pneumatic tubes. Since the thickest part of the pad is only 0.3 in and the edges are smooth, motorists of the traffic in general do not feel any bump from the pads installed on the roads. For installation, sensors are laid across the traffic lane and fastened on the pavement using sleeve anchor screws. In addition, the edges are taped using strong-bonding utility tapes.

Piezoelectric sensors produce charges in response to loads, and a circuit must convert the charge into a voltage. A circuit that can convert from charges to voltage is called a charge amp. One of the challenges of designing a charge amp for BL sensors is that they are sensitive to heat, i.e., charges are not only produced by loads but also by heat. In order to overcome this problem, a charge amp integrated with a heat-effect filtering circuit was developed and integrated.

Lastly, the system must run on a battery and must be able to sustain its operation for a certain period of time. Due to the heavy computations involved in WIM systems, it is not easy to design a computer system that uses only a small amount of energy and yet provides a sufficiently high computational performance. To strike the balance of the system cost, performance, and battery time, the current system is designed to continuously run for minimum 24 hours with the built-in internal battery pack. External battery packs must be used, if the system has to run longer than 24 hours.

The proposed and envisioned portable WIM system in this project was successfully developed. A complete working prototype was built and tested. This report describes all aspects of the developed weigh-pad system. Chapter 2 describes the hardware designs which include weigh-pad, charge amp, and the console computer designs. Chapter 3 describes the software part of the system, including the axle computational model and the overall system software. Chapter 4 shows a highway installation method and discusses issues related to air cavity in the sensor pad.

The weigh-pads were initially tested on the MnRoad facility and then later tested on real highway traffic. Chapter 5 summarizes various test results and analysis. Chapter 6 concludes the report with final remarks and future recommendations.

Chapter 2: Hardware Design

2.1 Overall System

The hardware portion of the weigh-pad system consists of four modules: axle weight sensors, charge amplifiers (amps), Analog-to-Digital Converter (ADC), and a computing unit. A block diagram of these modules along with their signal flow is illustrated in Figure 1. This chapter describes details of the design and implementation of each module.

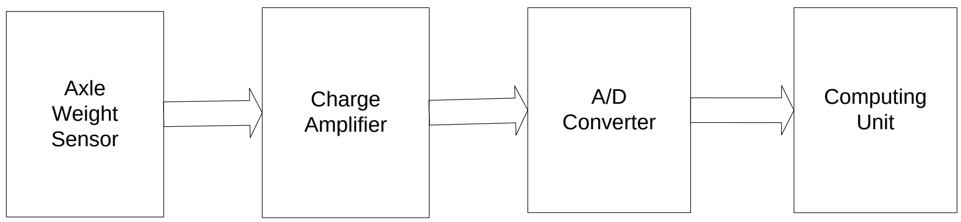


Figure 1: Hardware block diagram of the weigh-pad WIM system

2.2 Axle Weight Sensors and Weigh-Pad Design

2.2.1 Axle Sensor and the Pad Material

Axle load sensors must produce measurable electrical signals in response to axle loads. Since the objective of this project was to develop a portable WIM system that can be installed much like a pneumatic tube counter, thin and flat sensor strips are most desirable. The sensor that satisfies these two conditions was the Roadtrax BL (Brass Linguini) Piezoelectric Axle Sensor (or simply "BL sensor") made by Measurement Specialties, Inc [18]. Specifications of the BL sensor supplied by the manufacturer are summarized in Table 1 (source from [18]). The sensor length chosen was 12 feet to match with the standard U.S. traffic lane width. The length of the coaxial cable attached to the sensor can be ordered between 100 – 300 feet. A 100 feet coaxial cable was used for the prototype. The product data did not specify the thickness neither the width of the BL sensor, so both values were manually measured in the lab. The measured thickness of the sensor strip was 0.07874 in (2.00 mm), while the width was 0.263 in (6.68 mm).

Table 1: RoadTrax BL Sensor Specifications

Sensor Model	RoadTrax BL Traffic Sensor
Sensor Length	12 ft
Sensor Thickness	0.07874 in
Sensor Width	0.263 in
Capacitance	10.67 pF
Cable Length	100 - 300 ft
Cable Type	RG 58 with burial rated
Capacitance of Cable	8.05 nF ≤ C ≤ 14.50 nF
Dissipation	0.0294
Average Sensitivity	49 pC/N
Material Uniformity	±7 %
Weight	3 pounds
Part Number	6-1005438-1

The next consideration is finding a strong material that can effectively embed the sensor strips and coaxial cables to protect from the abusive loads of highway traffic. Initially tested heavy duty materials include 1050 Ballistic nylon, Toughtek Neoprene fabric, Toughtek non-slip rubberized mesh, and textured Neoprene rubber sheets. However, none of these materials met the three requirements the research team was looking for, which are durability, flexibility, and manufacturability from the University lab.

After searching through a number of different materials, the research team eventually decided to use industrial conveyer belts. It was learned that the type of conveyer belts used in mining are flexible, durable, and thin, all of which are good properties for embedding the BL sensor strips into the material. The flat and thin shape of conveyer belts allows easy assemble of sensor pads because weigh-pads can be simply built by placing and gluing a RoadTrax BL sensor strip between two conveyer belts. There are hundreds of different types of conveyer belts available for many different applications. Conveyer belts with the product code 908860 made by Forbo Movement Systems were selected as the final pad material after consulting with the conveyer belt experts. The specifications of the conveyer belt material selected are summarized in Table 2. Notice, from the table, that this material can handle heat up to 225°F (100°C). This property is important because pavement temperatures in summer months can reach as high as 180°F (42°C) in Arizona. The color of the material is black and would blend well with pavement. The material is durable but can be sanded to produce smooth edges. The measured thickness of a single 908860 conveyer belt was about 0.1476 in (3.75 mm). When two 908860 belts are sandwiched together, the thickness was 0.295 in (7.5 mm). This would be the center and the thickest part of the weigh-pad. The leading and trailing edges of the weigh-pads are sanded down to about 1 mm to reduce the bumpiness.

Table 2: Weigh-Pad Material Specifications

Product Model	UTILITY 2-160 GRADE II 1/32X1/32-NA
Transtex Product Code	908860
Product Construction	2 Ply Filament Polyester Carcass, Black smooth Rubber Cover Both Sides
Color	Black
Compound Formulation	Grade II Rubber
Nominal Overall Gage, inches (mm)	0.154 ± 0.015 (3.9 ± 0.4)
Nominal Weight, in lbs/ft^2(Kg/m^2)	0.98 ± 10%
Rated Working Tension	160 lbs/in, 28 N/mm @ 2%
Top Cover Surface	Semi-Smooth
Bottom Cover Surface	Semi-Smooth
Minimum Pulley Diameter	4 inches (102 mm)
Temperature Range	-20°F to 225°F (-29°C to 107°C)
Special Standards	RMA Grade II Covers
Cover Coefficient of Friction, Steel	0.75, Nominal
Bottom Coefficient of Friction, Steel	0.75, Nominal
Production Width	72 inches (1829 mm)
Manufacturer	Forbo Movement Systems
Product family	Transtex

2.2.2 Single-Lane Weigh-Pads Design

The first sensor built and tested was a single-lane, single-strip weigh-pad shown in Figure 2. First, the 908860 belt was cut to two 6 x 144 in (15 x 366 cm) pads. A 144 in (366 cm) long groove with the cross section of the groove size (width x thickness), 0.275 x 0.075 in (6.985 x 1.905 mm), is made at the bottom pad (conveyer belt). The sensor strip is inserted to the slot and glued. The top pad is next glued to the bottom pad. During this process it is important to eliminate any air pockets between the glued pads and sensor strips because these air pockets can pop by a load and influence the BL sensor strips to create superfluous signals. As the last step, the leading and trailing edges of the pads are tapered by sanding the edges to create a smooth slope. The measured thickness of the weigh-pads when two 908860 pads are sandwiched together was 0.295 in (7.5 mm). This would be the thickest part of the weigh-pad. The total weight of a finished single-lane, single-strip weigh-pad was 11.4 lbs (5.17 Kg). Figure 3 shows a single-lane, single-strip weigh-pad constructed according to the specification in Figure 2. The weigh-pad can be easily wrapped around as a loop, as shown in Figure 2 for easy carrying. The length of the coaxial cable is 100 ft.

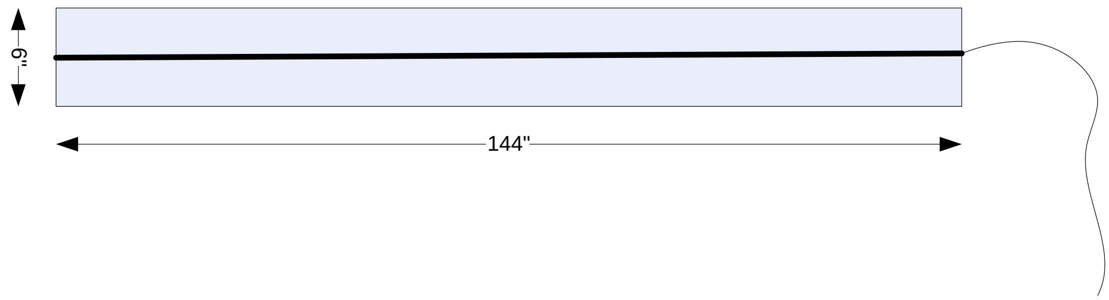


Figure 2: Dimensions of single-lane, single-strip weigh-pad

Figure 3: A single-lane, single-strip weigh-pad prototype

In order to be a complete WIM sensor, a pair of sensors is needed. More specifically, two identical sensor pads must be installed, separated by a known distance, to compute the speed of the weighing vehicles. The vehicle speed is used to normalize the axle waveforms so that the weight of a vehicle is independent of its speed. If two sensors are needed, one way of making the installation convenient is to embed two sensor strips in parallel in a large single pad. This idea was tested, and the design of embedding two sensor strips in parallel is shown in Figure 4. The actual prototype constructed for the Figure 4 specifications is shown in Figure 5. We refer this sensor as a single-lane, dual-strip weigh-pad. The signals are carried by two 100 feet coaxial cables. The advantage of embedding dual sensor strips in a single pad would be the known distance between two sensors set at the factory level. It simplifies the installation process by eliminating the user responsibility of measuring the sensor spacing by installing only one pad. However, there were three critical drawbacks observed during the initial tests. The first was the weight of the weigh-pad. The weight of the Figure 5 dual-strip weigh-pad was measured at 55 lb (23 Kg), and it was heavy for carrying around. Second, since it requires much more pad material, the cost of the sensor pad was significantly increased. Third, the tail portion of the axle signals were bouncy, due to a shockwave propagation which will be explained later.

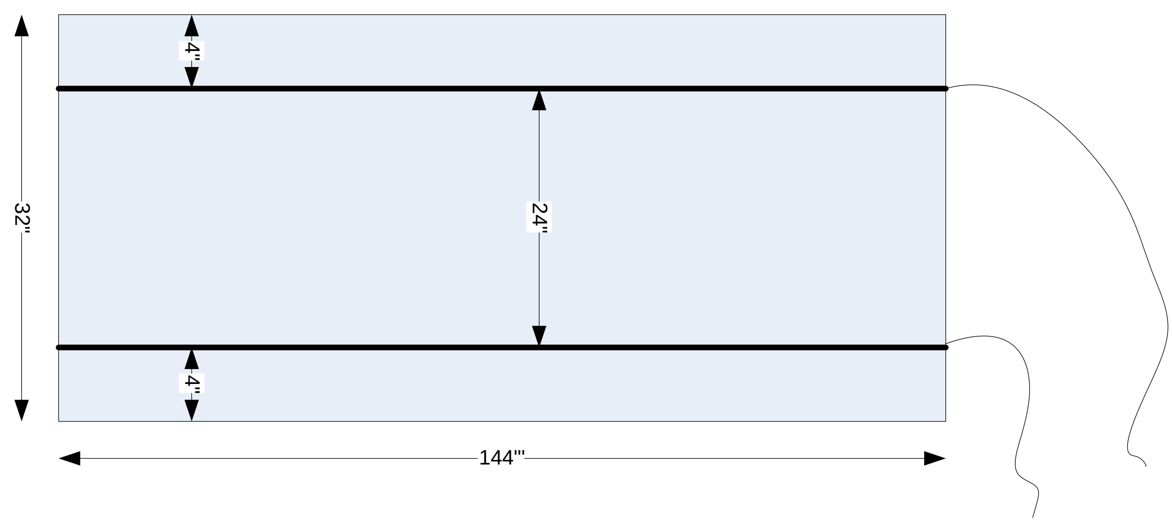


Figure 4: Dimensions of single-lane, dual-strip weigh-pad

Figure 5: A single-lane, dual-strip weigh-pad prototype

In order to test the charge signals of the constructed weigh-pads, the sensor outputs were first connected to charge amps and then the output signals of the charge amp were observed using an oscilloscope. The weigh-pads responded very well for human weights when it was simply tested by stepping onto it. Next, the research team tested the weigh-pads using test vehicles. This time, the charge amp outputs were connected to an ADC board in order to save the waveform. The first vehicle test was performed at the low volume road of the MnRoad facility on June 4, 2010. MnRoad is a test track owned and operated by MnDOT for evaluation of new pavements or road sensor technologies. The setup and test pictures are shown in Appendix-A. As shown in the picture, a pair of single-strip weigh-pads and a dual-strip weigh-pad were installed side-by-side. A 2005 Toyota van and a five axle semi-trailer truck were used as the test vehicles. Figure 6 shows a waveform of the Toyota van driven over the single-strip weigh-pad. The data was sampled at 4,096 samples per second. It clearly shows waveforms of the two axle load signals with some ripples in the beginning and at the end of the axle signals. The idle level of the signal between axles stays close to ground, which is desired and important for threshold detection of axle load signals. Before MnRoad tests, several tests were conducted at the UMD parking lots. All test results showed that single-strip weigh-pads are good enough to obtain stable axle load signals.

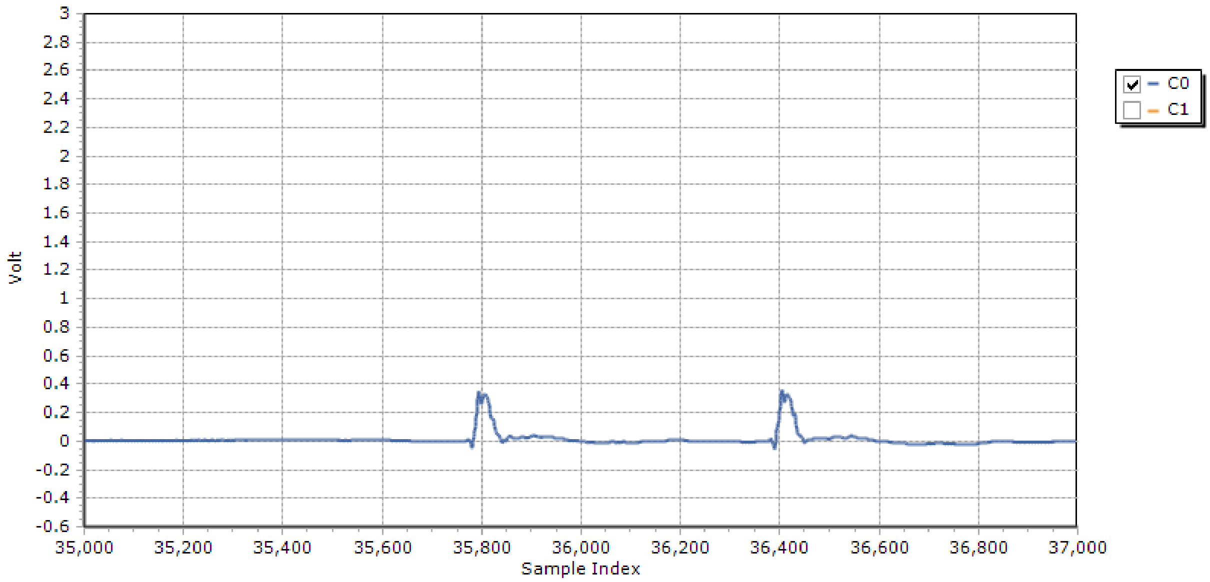


Figure 6: A waveform generated by a single-lane, single-strip weigh-pad for a Toyota van

Waveforms of a semi-trailer truck (a test truck available at MnRoad) generated from a single-lane, dual-strip weigh-pad, are shown in Figure 7. In the graph, the channel-0 (Ch-0) signals come from the leading (upstream) sensor strip, and the channel-1 (Ch-1) signals come from the trailing (downstream) sensor strip with respect to the traffic direction. It should be noted that the magnitude of the trailing sensor signals are bigger than that of the leading sensor signals. This might be due to sensor characteristics, i.e. the sensitivity of the trailing sensor strip expressed in terms of Coulombs/Newton is higher. Also notice that the signals from the trailing sensor strip have more ripples in the axle signals. All piezoelectric sensors generate electricity not only from the direct load to the sensor but also from vibration. It is evident from the rippling effect of the signals that the trailing sensor receives a high level of vibration energy. During the test, the researchers were able to visually observe a shockwave propagating from the leading to trailing edges of the dual-strip weigh-pad when truck wheels were moving from the leading to trailing sensor strips. More specifically, one can see multiple ripples or shockwaves in front of a turning wheel, moving from the leading to trailing edges. Energy transfer by this shockwave traverse would be negligible if the two sensor strips are separated by a sufficient distance, since the vibration energy would be dampened before it reaches the trailing sensor strip.

In summary, a pair of single-strip weigh-pads separated by a sufficient distance (such as 14 ft.) would not be affected by this shockwave propagation while dual-strip weigh-pads do. The dual-strip weigh-pads are less accurate, while they use more material and are bigger in size and heavy in weight. The research team concludes that the idea of dual-strip weigh-pads is not a good one for a portable WIM system.

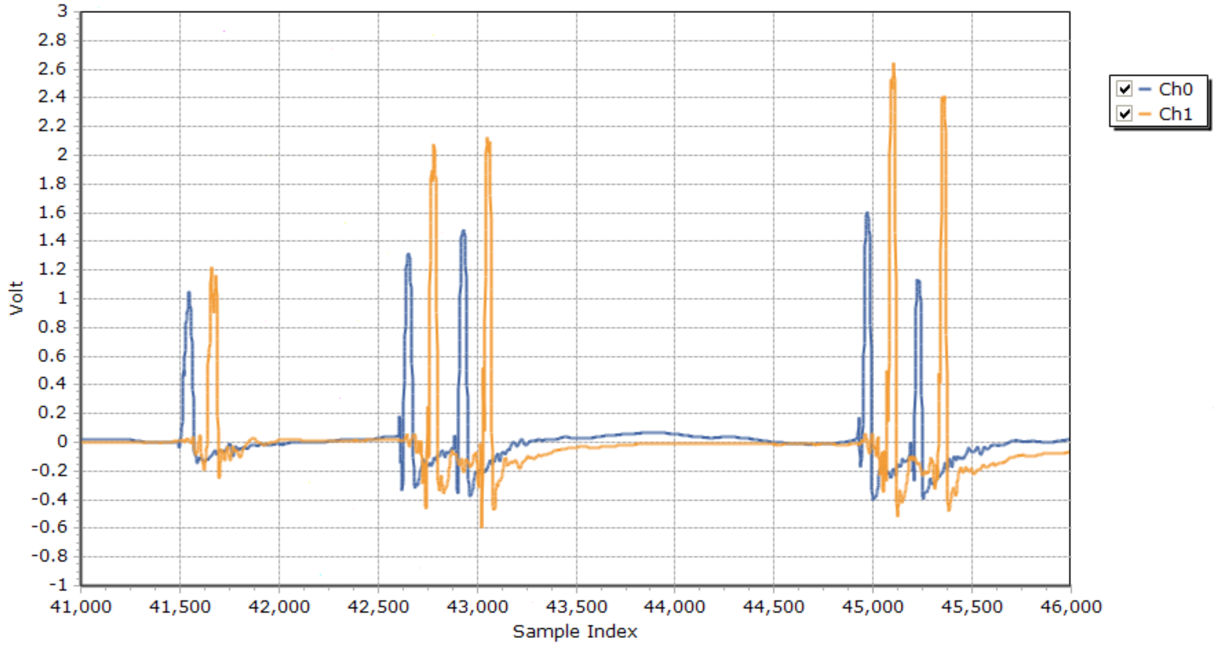


Figure 7: Five-axle semi-trailer truck WIM signal recorded from a single-lane, dual-strip weigh-pad

2.2.3 Two-Lane Weigh-Pad Design

Most of rural roads (targeted roads of weigh-pads) are two-lane roads. It is thus more practical to develop a pair of two-lane weigh-pads than two pairs of single-lane weigh-pads. After a successful demonstration of single-lane prototypes, the MnDOT TDA (Office of Transportation Data & Analysis) recommended the research team to develop two-lane weigh-pad prototypes as an additional task.

Learning from the single-lane weigh-pad experiences, the clear choice of the two-lane design is creating two-lane, single-strip weigh-pads. One of the difficulties in creating two-lane length is that the coaxial cable of the sensor strip from the far lane must run through the weigh-pad material without affecting the near-lane sensor-strip running in parallel. This problem was solved by milling out the coaxial cable and sensor strip slots in parallel, as well as increasing the weigh-pad width to 12 in (30.5 cm) from 6 in (15.2 cm). The final weigh-pad length was 25.5 ft. (7.7 m) which is 24 ft. (7.3 m) sensor length plus 1.5 ft. (0.46 m) extra length for protecting the connector of lead wires and a flap for screw installation. The final design is shown in Figure 8, and the prototype weigh-pads constructed according to the specification are shown in Figure 9. Figure 10 shows a pair of two-lane, single-strip weigh-pads installed for a test road. Figure 11 shows a visual comparison of a two-lane weigh-pad roll (left) against a single-lane weigh-pad roll (right). In a ballpark figure, a two-lane weigh-pad is 24 x 1 ft. (7.3 x 0.3 m), and a single-lane weigh-pad is 12 x 0.5 ft. (3.7 x 0.15 m). Figure 12 shows axle load waveforms of a Toyota Siena van generated by a pair of two-lane weigh-pads. In the graph, channel-0 (C0) is the signals from the leading (upstream) sensor strip and channel-1(C1) is the signals from the trailing (downstream) sensor strip. Channels, C2 and C3, are connected to the far lane sensor strips where no axle loads are present in this example.

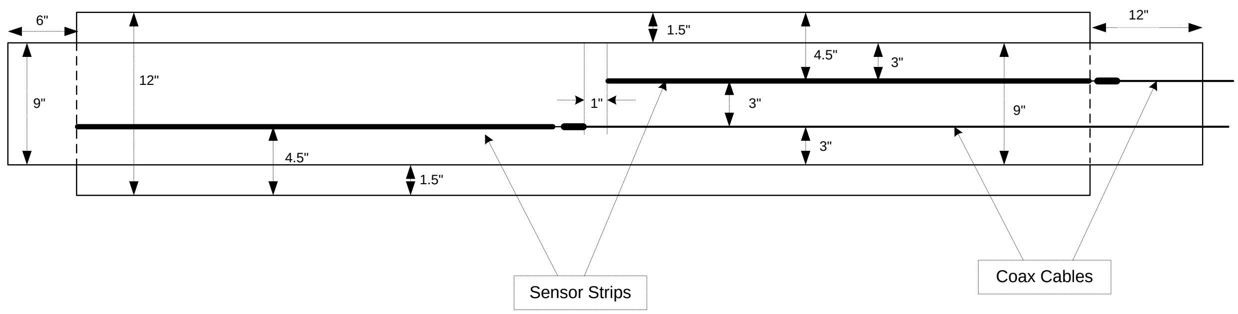


Figure 8: Dimensions of the Two-lane, single-strip weigh-pad: top view

Figure 9: Prototypes of a pair of two-lane, single-strip weigh-pads

Figure 10: Two-lane single-strip weigh-pads installed on the MnRoad test site

Figure 11: Comparison of a two-lane (left) and a single-lane (right) weigh-pads

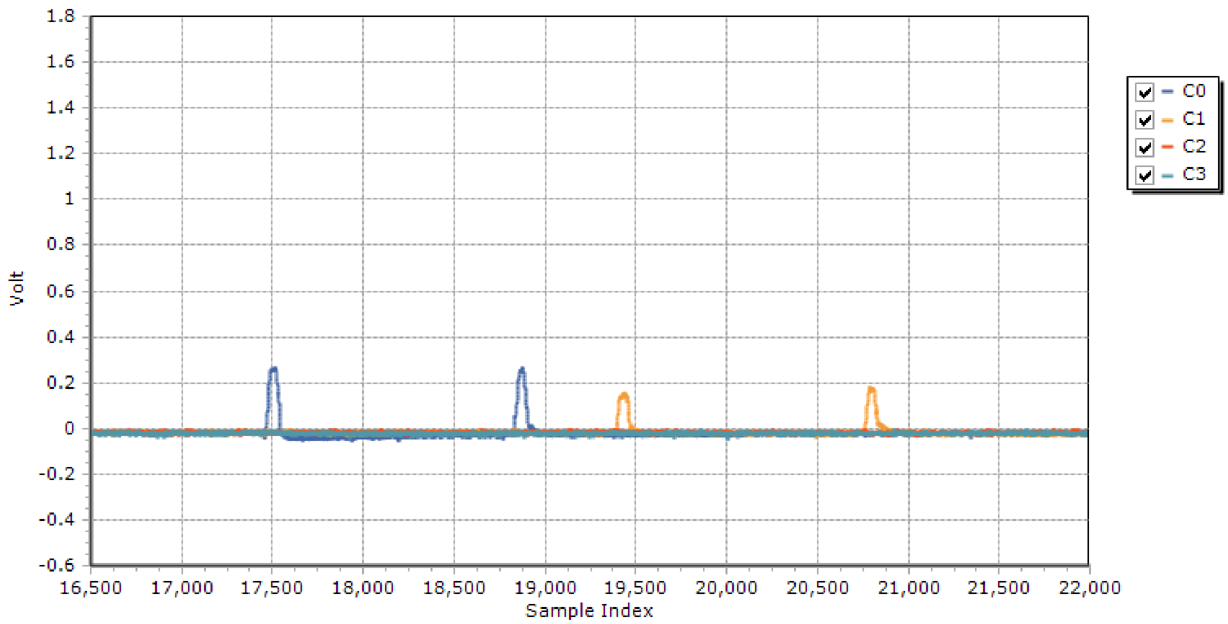


Figure 12: WIM waveforms of a Toyota Sienna van captured from a pair of two-lane, single-strip weigh-pads

2.3 Charge Amplifier

The RoadTrax BL sensor is a piezoelectric sensor that produces charge signals in response to acceleration or load. The charge signals must be converted to voltage signals in order to be able to sample the values using an ADC. The converter that converts from a charge signal to a voltage signal is called a charge amplifier (or charge amp in short). Presently, charge amps for the BL sensor are not commercially available, thus the research team had to design and build new charge amps for this project. This section describes the design.

One of the challenges in developing a charge amp for BL sensors is that it generates charge signals in response to heat. This heat sensitivity can be a serious problem in some regions. For example, in Arizona peak asphalt temperatures have been recorded up to 160 ^{0}F (71.1 ^{0}C) in June and July. Since weigh-pads directly touch the pavement on installation, the pavement heat is directly transferred to BL sensors, which causes generation of a large amount of charge signals. To find out the effect of heat on BL sensors in the lab, the sensors were heated using a heat gun, and the voltage generated was measured using a voltmeter. When a two-feet segment of the BL sensor strip was heated to 200^{0}F, about 200 mV was produced even though no loads were applied. When this heat generated signal was connected to a regular charge amp, this signal was able to damage the field-effect transistor (FET) of the input stage of a typical charge amp circuit. Consequently, the conditioning circuit of a charge amp must not only compensate for the heat effect but also should protect the input stage from a large flow of charges generated by heat.

The solution to the heat problem sought in this research was to design the circuit so that it quickly dissipates the heat generated charges before they damage the input-stage op amps without affecting the charges generated by axle loads. In order to design such a circuit, temperature characteristics of pavement must be understood. Pavement temperature is generally affected by two factors, the amount of sun radiation and air temperature. One important property is that air temperature or the heat of pavement tends to change slowly in comparison to the load changes of moving vehicles. More specifically, axle loads of a moving vehicle on weigh-pads change within tens of milliseconds while pavement temperature changes in a much slower rate, such as tens of minutes. The design of BL charge amp should utilize this discrepancy, i.e., the heat effect is removed by adding a dissipation path. This path can be designed to only remove slowly changing charge signals, and it is often called a DC servo loop. In the actual circuit, a discharge path with a 20 second time-constant was added. This means that any charge signals that do not change for the duration longer than 20 seconds are gradually dissipated to zero. In effect, it removes the DC component of the charge signals that are generated by heat or other factors. The time constant of the axle signals in the charge amp is set at a half second so that any signal that has a rate of change less than a half second is passed through without activating the dissipation path.

The basic charge amp circuit is shown in Figure 13. A typical charge amp with T-resistor network is shown in the first stage, consisting of U1, R2, R3, R4, and C1. The resistor R1 is used to protect the input stage of U1; a 500 Ohm resistor was used. The capacitor value of C1 determines amplification and the V_{out} signal range. Since the sensitivity of BL sensors is around 49 pC/N, a high Newton value corresponding to a single signal component of an axle load is about 34,000 Newton. The charge signal generated by 34,000 Newton is 34,000 x 49 = 1,666,000 pC. Since V=Q/C, if 5V is used as the peak voltage, the C1 value comes out to be 0.33 μF. However, this value has to be reduced by a factor influenced by the DC servo loop that pulls down the overall signals as described in the previous paragraph. The final C1 value selected was 0.06 μF. The second part of the circuit is a DC servo loop that consists of U2, C3, R5, C2, and R6. This circuit pulls the DC level down close to the signal ground. The resistor/capacitor value relationship in this circuit should be (C2*R6 = C3*R5), and the passive component values must be determined based on the time constant required. Since the time constant of the DC level removal was set at 20 seconds, component values, R5=R6=10M Ohm and C2=C3=2.2 μF, were selected as the final values.

Two-channel charge amp circuits were constructed according to the Figure 13 design. Figure 14 shows the final PCB with components soldered onto the board. For the PCB design, the Mentor Graphics PADS software tool was used. The PCB was manufactured from a PCB prototype outlet.

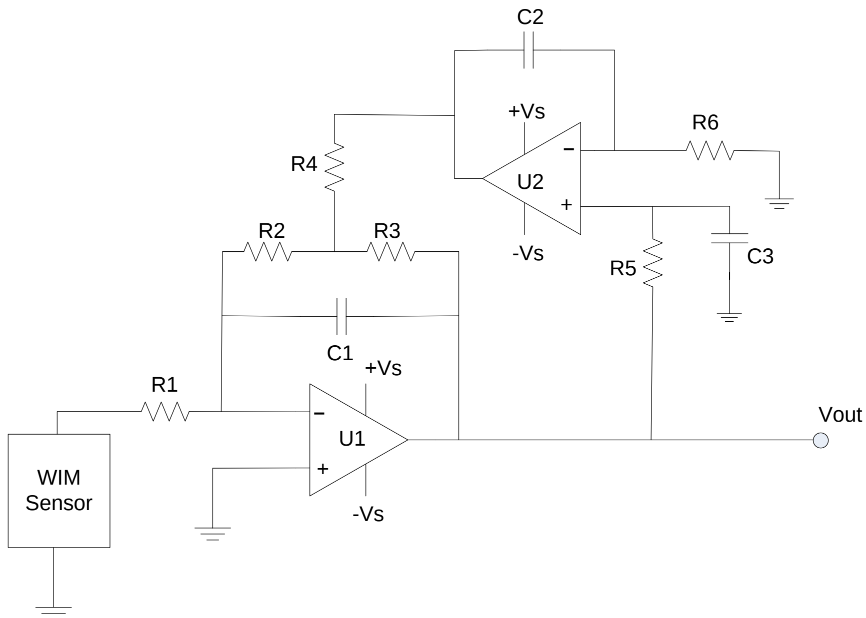


Figure 13: Basic charge amp circuit

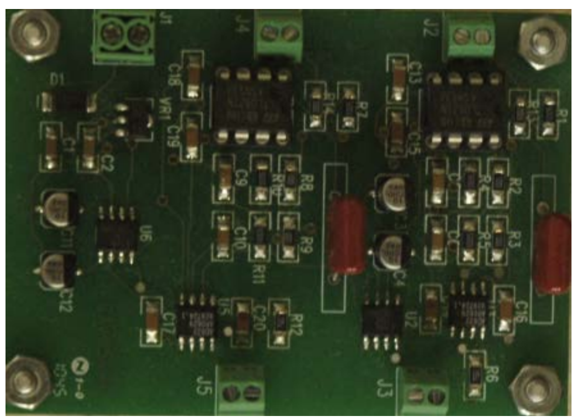


Figure 14: A prototype two-channel charge amp built for this project

2.4 Analog-to-Digital Converter (ADC)

What type of ADC to be used is one of the key decisions that must be made based on the choice of the computing system (console computer), required sampling rate, and signal resolution. The ADC choice often falls into two types: (1) USB-based ADC or (2) PCI-based ADC. Initially, the PI considered a laptop computer as the console computer of the weigh-pad system, in which case USB-based ADCs are the natural choice. Three USB-based data acquisition products were purchased and tested. Two basic ADC requirements were set: (1) all boards must have 16-bit resolution in the analog-to-digital conversion and (2) at least 100K samples per second (S/s) sampling rate must be supported. The three boards purchased and tested include USB-7202 (8 channels with 16-bit resolution at max 200K S/s) made by Measurement Computing Inc, USB-AI16-16A (16 channels with 16-bit resolution at 500K S/s) made by Access I/O Products Inc, and USB-6210 (16 channels with 16-bit resolution at 200K S/s) by the National Instruments Inc.

All three boards were programmed and tested for the performance and software development efficiency using a laptop computer. Figures 15, 16, and 17 show the test setup of the three different boards mentioned. In the case of the USB-7202 board, data over-run errors were frequently observed, resulting in much less than the claimed 100K S/s sampling rate. The cause of less than specified sampling rate was found to be caused by the inefficient software driver. The next board tested was the USB-AI16-16A. This board had a much better real-time data rate than the USB-7202 board but the software development DLL tool was hard to use. In addition, the connectors occupied too much space for a portable enclosure. Lastly, the USB-6210 was tested. The software development environment, called the NI Measurement Studio, included many examples and made the software development extremely easy. The drivers were stable and facilitated the claimed sampling rate. If a USB-interface was to be used for the weigh-pad ADC, the USB-6210 board would have been the best choice among the three tested.

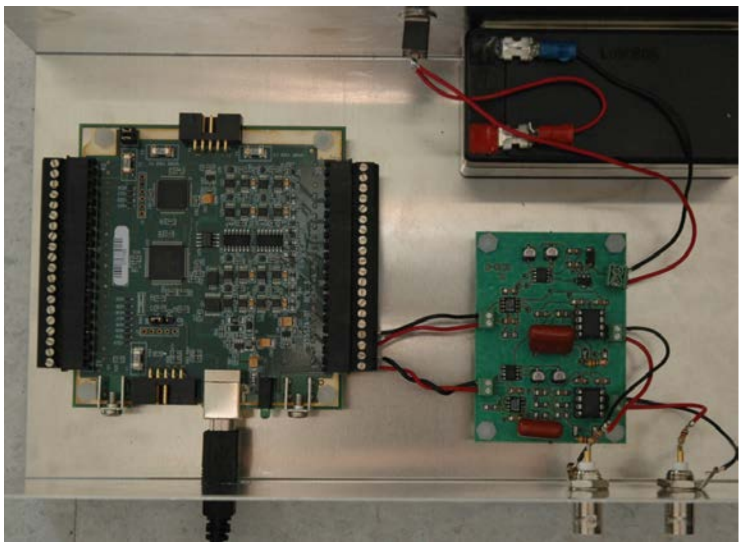


Figure 15: Measurement Computing USB-7202: 200K S/s, 16-bit ADC

Figure 16: Access I/O Products Inc. USB-AI16-16A: 500K S/s, 16-bit ADC

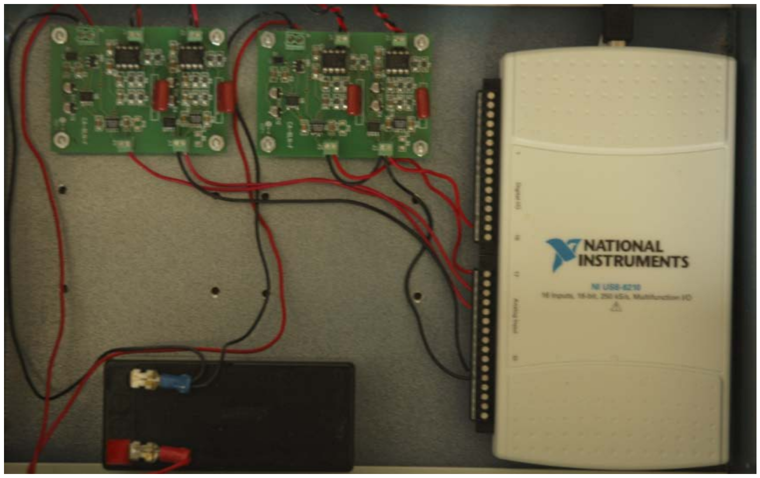


Figure 17: NI USB-6210: 200K S/s, 16-bit ADC

In the end, a laptop computer platform was not selected as the console computer because of their energy consumption, which is discussed in the subsection 2.5. The final console computer selected for this project was a single board computer based on an Intel dual-core Atom processor. Such boards consume much less energy than common laptop computers and come with a PCI interface slot. The PCI interface provides a higher data rate transfer than USB-2 but more importantly it provides a reliable data transfer and proven software drivers that have been used in the field for a long time. On the other hand, USB boards have high overheads and the drivers are often unstable when the ADC continuously runs with a high sampling rate for long hours (more than 24 hours).

The final PCI board selected for the weigh-pad ADC was PCI-DAS6013 manufactured by the Measurement Computing Inc., and its picture is shown in Figure 18. This board provides a true 200kS/s at 16-bit resolution up to 16 analog inputs (channels). The same type of boards has been used by the PI in the previous WIM system development projects. This board ran multiple years without an error.

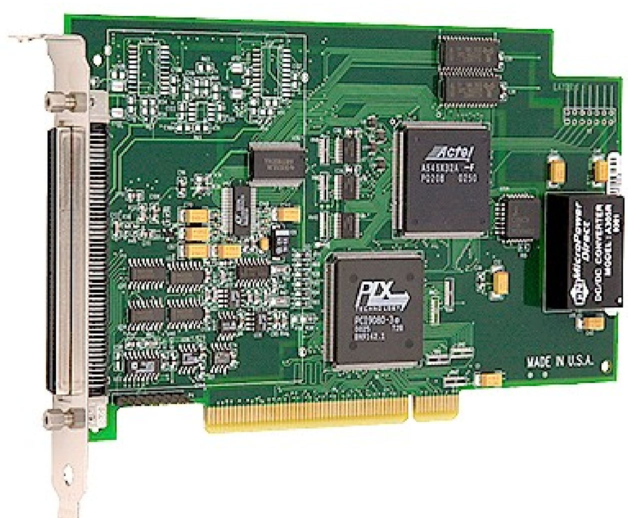


Figure 18: PCI-DAS6013 ADC board

2.5 Console Box and Enclosure

A console box (or computer) in this report refers to a single enclosure that houses all necessary components of the stand-alone weigh-pad WIM system, excluding the sensor pads. With this console definition, the weigh-pad system simply consists of weigh-pad sensors and a console box. The console box includes a mother board, a keyboard with a mouse pad, charge amps, A/D converters, an LCD monitor, batteries, and a charger.

At the beginning of this project, a laptop computer was going to be used as the computing unit of the console since it is already equipped with a display, a large amount of data storage, a keyboard with a mouse, and I/O interface ports. However, the laptop idea was quickly abandoned, mainly due to the battery capacity that must be able to continuously support a minimum of 24 hours without charging. The problem with laptop computers is that they are not energy efficient, mostly lasting only up to six to eight hours. In addition, it is not simple to modify the battery management module embedded in a laptop computer to accept a large capacity external battery bank. Another problem experienced is that there is no hard switch that can completely shut off the LCD monitor which would have saved a significant amount of energy since the LCD monitor is no longer needed after the initial settings. It comes down to fact that there is less freedom and more limitation in designing a system with a laptop computer. Consequently, the research team decided to use a mother board and build all necessary components from the mother board.

The motherboard selected for the computing unit belongs to a form factor called mini-ITX, and they are commonly used in embedded PC applications. The processor used is an Intel 1.66GHz dual-core Atom, which consumes less energy while it provides sufficient computing power through dual cores. Another important aspect of mother boards is the availability of a PCI slot that can interface with a PCI-based ADC board. In general, a PCI-based ADC board is more reliable and provides a better data transfer bandwidth than the USB-based boards. The mother board also includes an external Video Graphics Array (VGA) port which can connect an open-frame LCD monitor with a hard On/OFF power switch (instead of just a sleep state in a laptop PC case). The specification of the motherboard used for the weigh-pad console is summarized in Table 3.

Table 3: Console Mother Board

Processor	1.66GHz Dual Core Atom D510
Memory	240-pin DDR2 800 DIMM 2GB
Hard Disk	2.5” Segate SATA 5400rpm 160GB
OS	Windows XP Pro Embedded
Keyboard/Mouse	PS2
Display Port	VGA
Form Factor	Mini-ITX
Battery	External, not included
I/O Connectors	USB, PCI, RS-232 COM port
LAN	10/100/1000 M bps Ethernet

A block diagram of the computer developed for the weigh-pad console is shown in Figure 19. The system's computing is powered by an Atom-based Mini-ITX board specified in Table 3. The ADC is interfaced through a PCI bus, and an SVGA LCD monitor is connected through a VGA port. The SVGA monitor has a resolution of 800 x 600 pixels, which is low in today's graphic standards but is sufficient to provide a rich graphical user interface (GUI) for the current portable WIM system. The LCD monitor is an open frame and LED back-lighted LCD, designed for outdoor applications. The screen was indeed easily readable under sunlight. Once the system is initialized and if it is in a run state that no longer requires visual human interface, the LCD monitor is turned off by a hard on/off switch on the power supply line. A thermocouple is interfaced through a USB port of the motherboard and is used for measuring pavement temperature. A summary of key console components is summarized in Table 4. It should be noted that all of them are off-the-shelf products.

Table 4: Key Console Box Components

Component	Product Model	Manufacturer
Motherboard	Custom M350 Mini-ITX	Logic Supply
ADC	PCI-DAS6013	Measurement Computing
USB Thermocouple	USB-2001-TC	Measurement Computing
Type-K thermocouple	SC-GG-K-30-36	Omega
LCD monitor	LBT-10420, 1.4"	Caltron Industries
Battery Charger	TLP 2000	Tenergy
Battery	14.8V, Li-Ion Polymer, 16Ah	Tenergy

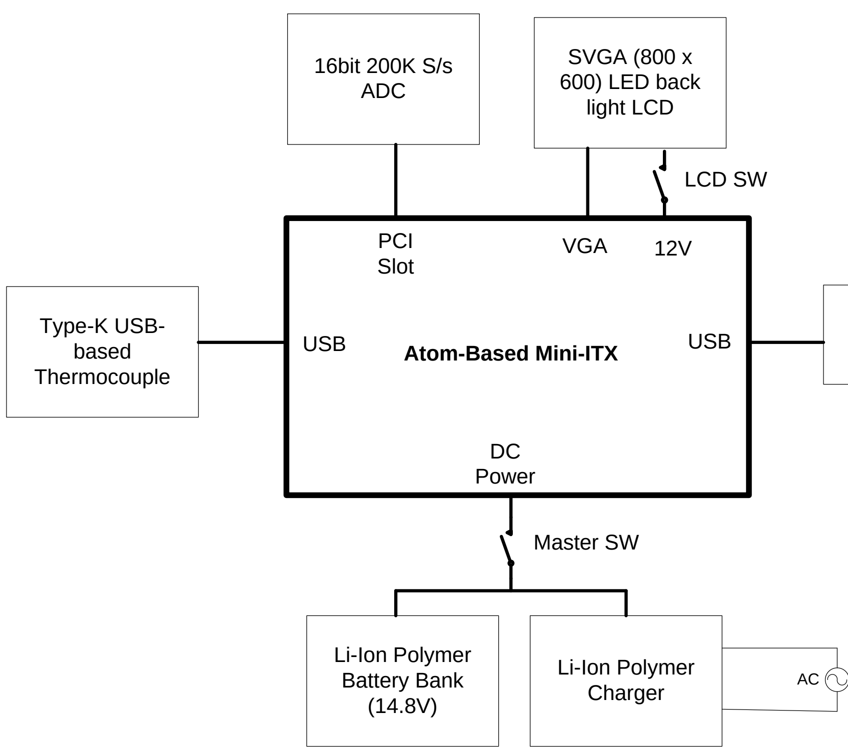


Figure 19: Console computer block diagram

The enclosure design of the console box is shown is Figure 20. A local sheet metal fabricator constructed the enclosure using aluminum sheets (1/4” thickness), which is shown in Figure 21. The inside of the box consists of three vertically stacked layers of compartments. In the bottom layer, two 14.8V Li-Ion Polymer 16,000 mAh batteries and a USB-thermocouple are enclosed along with an AC input plug for the battery charger. Figure 22 shows the middle layer. As shown in the picture, a mini-ITX board, charge amps, 2.5” SATA hard disk, and a PCI ADC board are mounted. Figure 23 shows the top layer. Note that an SVGA LCD monitor, a keyboard with a mouse pad, a shut-off master switch, a shut-off LCD monitor switch, and a battery charger are mounted. A reset switch is placed on the lid of the enclosure for an easy access. It can be seen in Figure 24 as lit LEDs in the left top corner. A USB hub is also available and is placed under the LCD monitor (see Figure 23). The USB hub was added to allow easy download of the collected WIM data using a USB flash drive. Figure 24 shows the back side of the enclosure. There are four BNC connectors. The first two BNC connectors from the right edge are for the first lane: the first BNC for upstream and the second for downstream. The last two BNC connectors are for the second lane. In the low right-side corner of the back side, an input port for thermocouple type-k probe can be seen (Figure 24). This is to measure the pavement temperature which might be needed in the future to compensate the weight values with respect to the pavement temperature.

The enclosure is built using .25” thick aluminum sheets, thus it is exceptionally strong. The user may actually sit on it while he or she is working in the field. The lid can be locked using a padlock. A drawback of the tough enclosure was its weight. When all of the components are enclosed, the console box weighed about 35.5 pounds (16.1 Kg), which was slightly heavier than originally expected. However, this weight should still be acceptable for most people to carry around in the field.

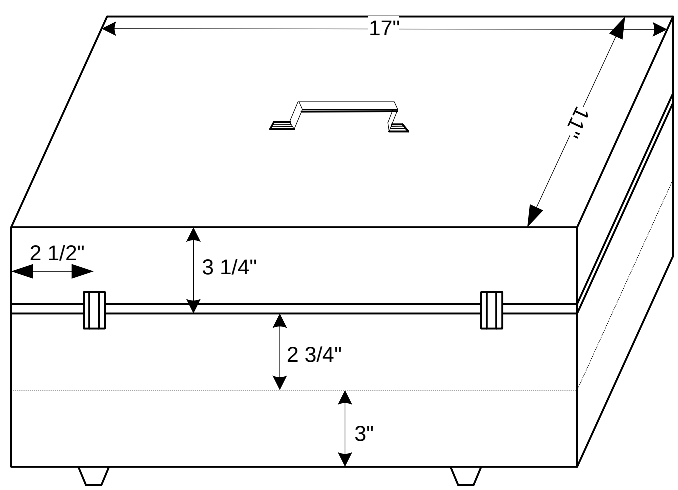


Figure 20: Console computer enclosure specification

Figure 21: Custom enclosure built using aluminum sheets

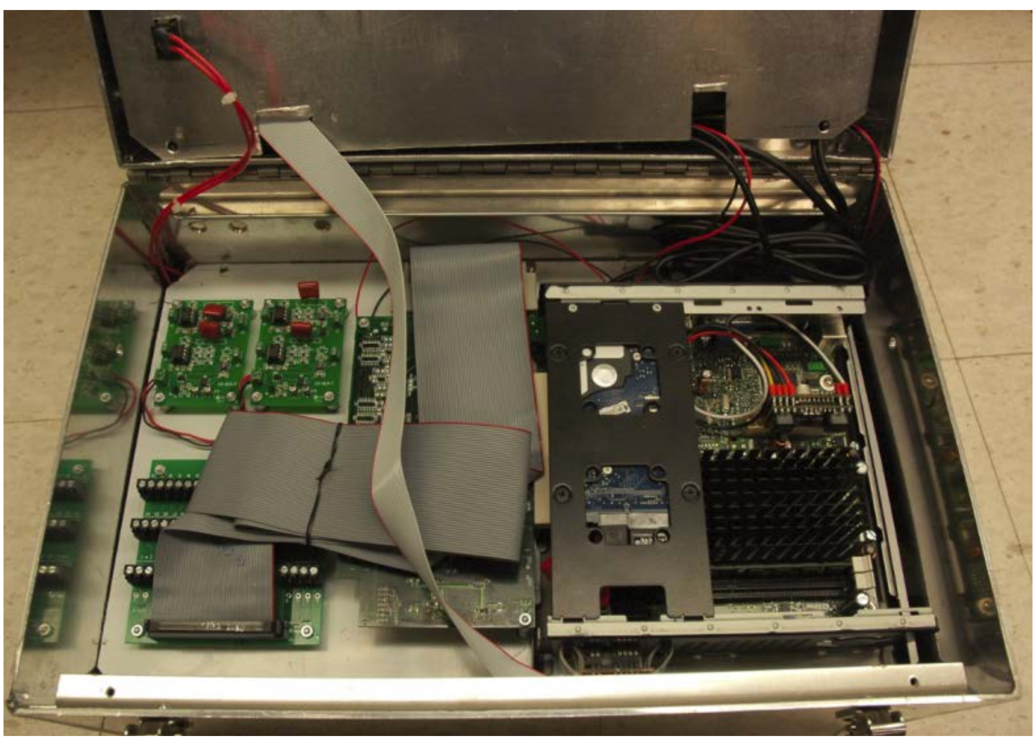


Figure 22: Middle layer of the console computer

Figure 23: Top layer of the console computer

Figure 24: Back side of the console computer enclosure

Chapter 3: Weigh-Pad System Software Design

The weigh-pad WIM system may be divided into two parts: hardware and software. This chapter describes the software part of the system, and it includes description of the computational model and the overall software design at the system level.

3.1 Axle Computational Model

The hardware-in-loop (HIL) WIM signal simulator, which was developed by the PI and his student in 2007 [14, 15], was extensively used in the software development phase of the weigh-pad system. The HIL simulator is a WIM hardware/software hybrid simulator and can replace axle-load and loop signals with software simulated electric voltage signals by passing the axle model generated values to a Digital-to-Analog Converter (DAC). It operates in real time and produces axle-load waveforms based on a set of user defined inputs. These include vehicles per minute, mix of vehicle types, speed range, and definition of each vehicle axle-load characteristics (number of axles, axle weights, tire footprint lengths, and axle spacing). Axle signals of various traffic conditions and any mix of vehicle types can be generated in real time using the HIL simulator. The HIL simulation allows for any real WIM system to be directly tested under various traffic conditions without installing sensors on the road. In addition, a number of faulty conditions of axle sensors can be simulated and tested using the HIL simulator [14, 15].

Figure 25: Hardware-in-Loop (HIL) WIM signal simulator

The HIL simulator requires an axle-load signal model to generate the axle-load waveforms. In the original HIL version, a trapezoidal signal model was developed and used [14]. In this research, a more realistic model was developed and used. The closed form of the new axle signal model in a continuous form is shown next by two equations.

$$f(x) = ae^{-(x-b)^2/c^2} \tag{1}$$

$$\int_{-\infty}^{+\infty} f(x) = ac\sqrt{\pi} \tag{2}$$

In Eq. (1), *a* is the peak of the Gaussian function, *b* is the amount of shift in *x*-axis, and *c* controls the width of the signal. This function is plotted in Figure 26. The function *f(x)* in Eq. (1) has a close form solution for its integration and it is shown in Eq. (2). Since the computational model cannot use the signal support range from a negative to positive infinity, some limit has to be applied. The width of the signal support area is selected as *5c* as shown in Figure 26.

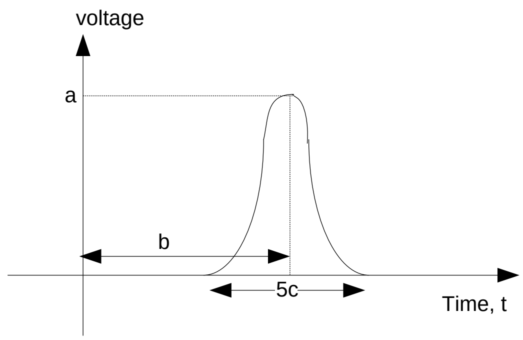


Figure 26: Gaussian axle signal model

3.1.1 Signal Modeling and Digital Signal Generation

This subsection shows an example of finding *a* and *c* of the model (1) given the complete list of parameters of an axle as shown below.

Axle Weight: W_{pound}
Sampling Rate: R Samples/Sec
Footprint Length: l feet
Speed: v foot/sec
Sensor width: w feet
Multiplication factor: f_{pound}

Since the signal support area is the footprint of the tire and sensor width, it can be expressed as:

$$5c = \frac{l+w}{v} \quad \text{sec}$$

Therefore, *c* is computed as:

$$c = \frac{l+w}{5c} \qquad (3)$$

The time it takes to go through a single sensor width is,

$$t_w = \frac{w}{v} \quad \text{sec} \qquad (4)$$

Let the area under the axle signal be A_{sig} , i.e.

$$A_{sig} = \int_{-\infty}^{+\infty} f(x)dx = ac\sqrt{\pi} \tag{5}$$

Deriving from Eq (1), if the signal is continuous, the signal area and weight are related as:

$$W_{pound} = \frac{A_{sig}}{t_w} \times f_{pound}$$

Thus,

$$A_{sig} = \frac{W_{pound} t_w}{f_{pound}} \tag{6}$$

Equating Eqs. (5) and (6) gives,

$$ac\sqrt{\pi} = \frac{W_{pound} t_w}{f_{pound}}$$

Finally, a is computed as:

$$a = \frac{W_{pound} t_w}{f_{pound} c\sqrt{\pi}} \tag{7}$$

Collecting these results, the final axle waveform with computed parameters of a and c is obtained as:

$$f(x) = ae^{-(x-b)^2/c^2} \qquad \text{for } 0 \le x \le 1$$

where a and c are give as:

$$a = \frac{W_{pound} t_w}{f_{pound} c\sqrt{\pi}}$$

$$c = \frac{l + w}{5c}$$

Example-1) This example shows how the actual numerical values from the given model are generated for the DAC. Assume that the following axle characteristics are given:

Axle Weight: W_{pound} = 20,000 pounds
Sampling Rate: R = 4000 S/sec
Footprint Length: l = 0.656167979 feet
Speed: v = 88 foot/sec
Sensor width: w = 0.16404199475 feet
Multiplication factor: f_{pound} =(1541.4768) * 2

Using Eqs. (7) and (3), the parameters, *a* and *c,* are calculated as:

a=3.66

c=0.003728

For sampling rate 4000 S/sec, the digitized signals of $f(x_i)$ are generated as:

For i=0 to 3999

{

$x_i = (i - 2000)/4000$ //shift of signal to right 2000 points

$f(x_i) = ae^{-x_i^2/c^2}$

}

The plot of these values is shown in Figure 27. It should be noted that the non-zero data image is located at:

$$2000 - (2.5c)4000 < i < 2000 + (2.5c)4000$$

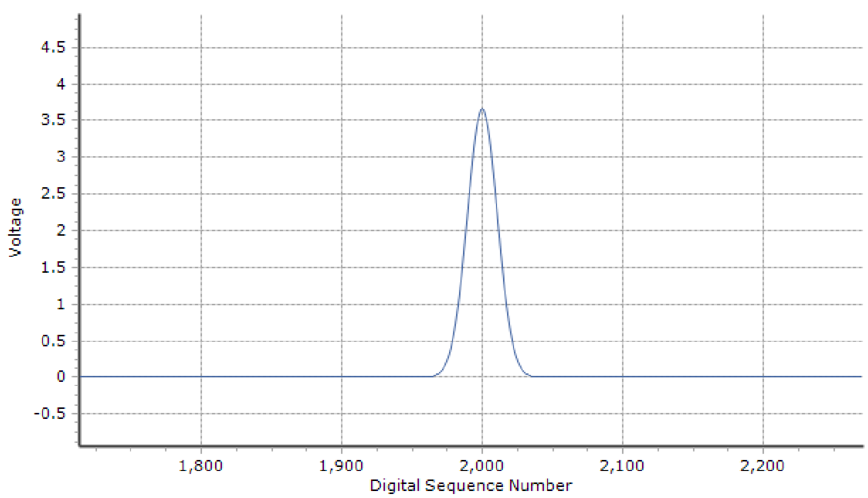


Figure 27: Plot of the Example-1 axle signal

3.1.2 Computing the Digitized Signals Back to Weight for Verification

From the discrete signals generated, the signal area is computed by simply adding each sample point as shown in Eq. (8). The signal area represents the weight, and the actual weight can be computed using Eq. (9). Computation of these two equations occurs in the weigh-pad console.

$$A_{sig} = \sum_i v_i \quad (8)$$

$$W_{pound} = \frac{A_{sig} f_{pound}}{t_w R} = \frac{A_{sig} f_{pound}}{(w/v)R} = A_{sig}\left(\frac{f_{pound}}{wR}\right)v \quad (9)$$

where

$v =$ vehicle speed in foot/sec
$w =$ sensor width in feet
$R =$ sampling rate in samples/sec

Example)

If the area of the signal generated for the given example is summed up,

Continuing from Example-1, the area under the axle waveform is now computed back to the corresponding weight. It started with 20,000 pounds of axle load in Example-1 and should end up 20,000 pounds when it computes back.

Example-2) When the digital samples generated by Example-1 is added up, the total is 96.74431. This sum represents the weight of the axle and should be converted to pounds using Eq. (9), i.e.,

$$A_{sig} = 96.74431$$

$$t_w = \frac{0.164}{88} \text{ sec}$$

$$W_{pound} = \frac{96.74431 \times (1541.4765 \times 2)}{t_w \times 4000} = 20,000 \text{ pounds}$$

This example illustrates that the axle signal model defined in Eq. (1) is correct. In the WIM system programming, Eqs (8) and (9) were used to compute the axle weights.

3.2 System Software

3.2.1 Overall GUI and Tool Sets

The console computer (described in Section 2.5) runs on a Windows embedded XP OS and is equipped with an SVGA LCD monitor (800 x 600 pixels). Although this LCD monitor's resolution is limited in comparison to today's high-resolution monitors, it is good enough to create an easy-to-use Graphical User Interface (GUI) for operation of the weigh-pad WIM system.

For the software design of the weigh-pad WIM system, operational needs of the system and a list of required components were created first. Visual modeling of vehicle records was one of the requirements, since a visual form can serve as an excellent verification or diagnostic tool for maintenance operations at the site, i.e., the vehicle model in the screen can be visually compared with the actual vehicle. The information displayed on the visual vehicle model includes:

- axle weights
- axle spacing
- speed
- classification
- GVW
- ESAL
- time
- error message
- lane number
- lane direction
- vehicle identification number

The method of visual modeling adopted in this research is developing a dll .net component so that it can be drag and drop into any window. The c# language of the Microsoft Visual Studio provides an excellent tool for developing visual components and was used in this project. The component named "vehShow.dll" was developed and its visual interface is shown in Figure 28. In this vehShow component, vehicle information items mentioned above are implemented as properties.

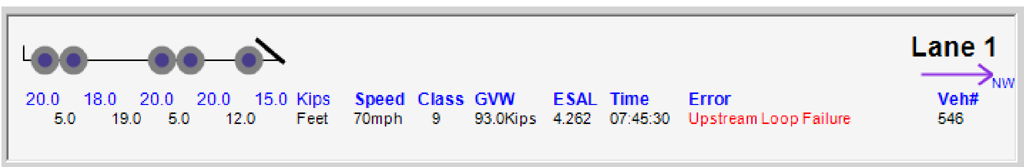


Figure 28: .Net component "vehShow.dll" developed for visual modeling of individual vehicle records

In addition, there should be a table or a spread sheet of vehicle records so that the user can trace back a list of vehicle records. This table should be equivalent to the actual vehicle records stored in the WIM data file. In addition, for a diagnostic purpose it is useful to have a real-time plot of the charge amp waveforms. This real-time plot could be used like an oscilloscope to check whether the charge amp or ADC is working properly or not. The plots could also be used for checking the resting voltage levels of the charge amp or line noise conditions. At the end, the following items were selected as the console functions. A screen capture of the final GUI of the system is shown in Figure 29.

- Table of WIM vehicle records
- Real time display of pavement temperature
- A real time plot routine for the ADC raw signal
- A recording utility for the real time ADC binary data
- A text reading tool for the WIM vehicle record data
- GUI interfaces for setting of all sorts of parameters

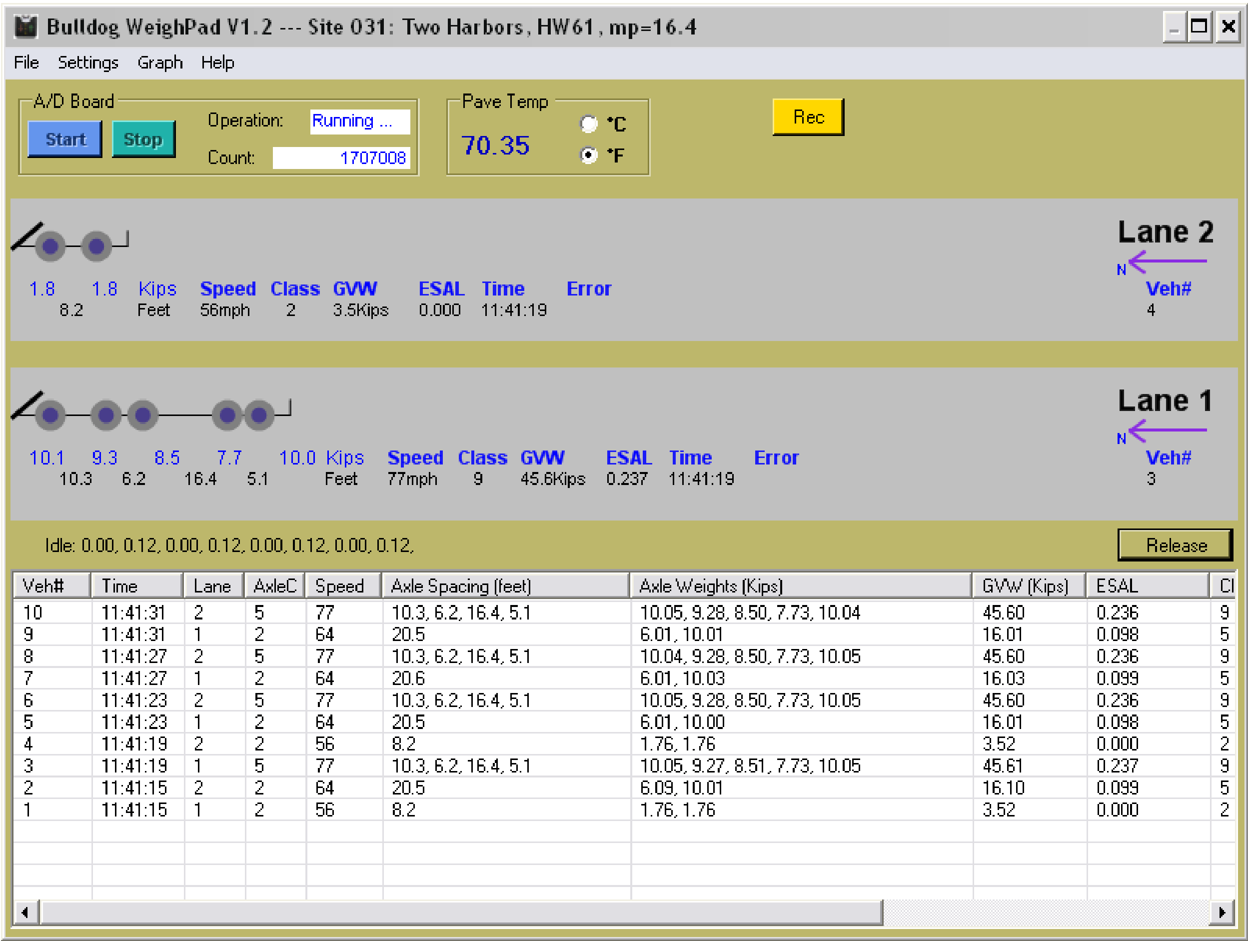


Figure 29: GUI screen shot of the developed weigh-pad console

In the Figure 29 screen, both lanes are set to a northbound along with the arrows indicating the traffic direction in reference to the console box. When the arrow direction is changed, drawing of the vehicle model automatically changes its heading to match up with the arrow direction. There is also a Release button in the middle right. This button toggles its states between “Hold” and “Release”. If it is pressed when the button text is “Hold,” the vehShow controls are immediately frozen holding the display of the last vehicle on that lane. If the button is pressed when its text shows “Relaese”, the vehShow control is released and turns back to a normal mode, i.e., the display is continuously updated as a new vehicle arrives. This Hold/Release function is useful when there is a need to inspect details of a vehicle record. For example, when a calibration vehicle passes by, the operator may freeze the vehShow control to carefully look at the details of the measured values.

A yellow “Rec” button can be seen next to the “Pave Temp” groupbox (the third row from top of the window). When this button is pressed, the binary ADC outputs of the axle signals are recorded into a file. A red “Stop” button appears right next to the “Rec” button, which is used to stop the recording. The recorded raw data can be later used for signal analysis.

The main window also includes a display of pavement temperatures either in Fahrenheit or Celsius depending on the user’s selection. A type-k thermocouple must be taped on the pavement and its lead must be plugged in to the console box to properly display the temperature: otherwise, “N/A” is displayed

Under the graph menu, there is a menu item called “Show Graph”. When this item is selected, real time axle signals from a pair of upstream and downstream channels assigned to a lane are plotted. A sample screen is shown in Figure 30. Because the graph must be displayed while computing the axle weights and all of the WIM values, only 256 samples per second out of 4,096 samples are displayed. Thus the plot appears blocky. It displays one lane at a time, and the display lane can be selected using the Channels menu. If more detailed signal analysis is necessary, the operator should always record the raw data using the Rec button. The main usage of this real-time plot is to quickly inspect the waveforms against visual observation of axles of a vehicle.

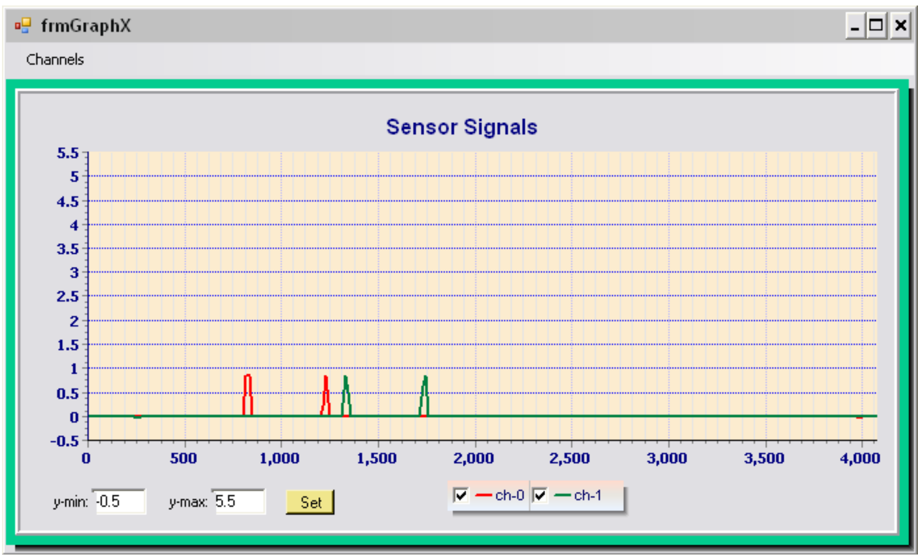


Figure 30: Real time plot of ADC channels

After recording the raw ADC data using the Rec button, the user may need a plot tool to analyze the data. For such a purpose, a utility tool called “WeighPad-Plot” was created as one of the tools available inside the weigh-pad system. This tool allows for the plot window to move forward or backward in the sample space, as well as zoom in/out using a setting of the Y-range and/or X-range values. A sample screen of the WeighPad-Plot utility is shown in Figure 31. This is a useful tool to diagnose signal problems, such as pad vibration problems or abnormal signal idle levels. This utility is available as a separate program from the main weigh-pad program.

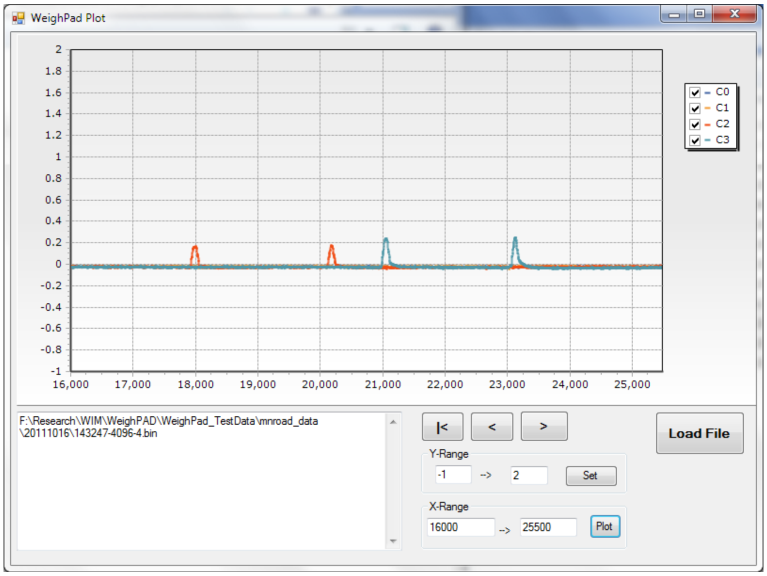


Figure 31: Weigh-Pad plot utility

3.2.2 Setting Wizards

The weigh-pad system requires many system settings. All of the user settings are listed under the "Settings" menu in the main window. The items in this menu are

- Site Setup
- Axle Sensor Setup
- Calibration Factors
- Speed Adjustment Factors
- ESAL Setup
- Limit Parameters
- Signal Thresholds

Selecting any of the menu items above would pop up a setup wizard that guides the user using easy-to-understand GUI entries. Among the setups, the Site Setup is explained here as an example. The rest of the setup windows are summarized in Appendix-C.

The Site Setup window is shown in Figure 32. All of the items in this window are prerequisite to system startup and must be set before any data collection is initiated. The items include Site ID, Location, Lane setups, classification definition, and the data root directory. The site ID should be a numeric number, but the location can be any text that describes the location. The site ID number is extremely important since all WIM data files produced are named using the date of the data collected and the site ID. The lane direction and arrow direction combo-box determines the lane direction and traffic flow direction displayed inside the vehShow controls.

The weigh-pad software uses the identical vehicle classification algorithm and software components deployed in the BullConverter [21] which requires a class definition file. The "Browse" button in the second GroupBox allows navigation of files and directories for the selection of a class definition file. It accepts either a metric (.tym) or English unit definition file

(.tye) in the same way the BullConverter reads in. The last important entry is setting up where to store the data in the file system. The user must set the root directory of the WIM data to be stored using the Browse button in the GroupBox named "WIM Data Root Folder." The data is then stored in a subdirectory named with a "yyyymmdd" format. If the subdirectory does not exist, the software will automatically create the directory. The user is only responsible to set the root folder for the WIM data. As the last step, the user must press the "Save" button to save all entries. If the "Exit" button is pressed without saving, all of the new entries are not updated and the old entries will be remained. It should be noted that the setup window only serves as a GUI for users, and the values are not actually stored in the window but in a Settings.ini file.

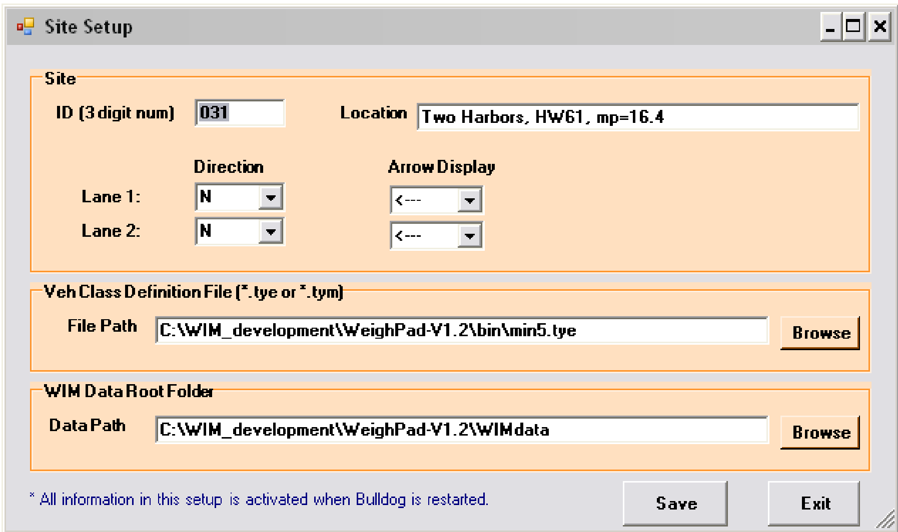


Figure 32: Site setup window

3.2.3 Output Data Format

The weigh-pad system produces text-based CSV files for the WIM data. The filename follows a format that consists of the date and site ID text strings as follows:

yyyymmdd.###.csv

where yyyymmdd is (year, month, day) and ### is the three digit site ID. The column format is summarized in Table 5. The columns up to #32 are identical to the BullConverter column format. The column #33, which is the pavement temperature, is only available for the weigh-pad system. The CSV file is stored in the yyyymmdd folder of the data root path defined in the Site Setup menu.

Table 5: Weigh-Pad CSV Column Format

Column Number	Column name	Description
1	Index	Vehicle record is numerically indexed and this column shows the index
2	Lane#	Lane number of the vehicle passed through
3	Time	Time in hh:mm:ss where hh is military hour
4	AxleC	Number of axles on the vehicle
5	Speed	Speed of the vehicle in mph
6-16	Axle Spacing (AS): AS1,…,AS11	Axle spacing in feet. It contains total 11 fields separated by comma.
17-28	Axle weights(AW): AW1,…,AW12	Axle weights in Kips. It contains total 12 fields separated by comma.
29	GVW	Gross Vehicle Weight (GVW) in Kips. It is simply a summation of each axle weight.
30	Class	Vehicle class determined by the classification algorithm
31	Err#	It is a numeric code that represent an error
32	100thSec	100^{th} seconds of the time in Column 3.
33	pavTemp	Pavement temperature in Fahrenheit

Chapter 4: Weigh-Pad Pavement Installation

One of the challenges of developing a practical portable WIM system is to design a simple and effective installation procedure that securely attaches the weigh-pads on the pavement. After installation, the sensor pads should retain the tightness to avoid vibration, endure tire traction forces, and provide accurate readings of the axle loads for the duration of the data collection. Because the sensors must be quickly installed and removed in portable applications, it is a challenge to develop a good installation method. Any movement of sensor position or vibrations would decrease the accuracy of the sensor readings. This chapter describes how to install weigh-pads on highways and discusses issues related to installation.

4.1 Installation on Highways

Initial installation and driving tests were conducted using only one or two test vehicles from the low volume road at the MnRoad facility. The installation methods tested are (1) Gorilla tapes (a strong bonding utility tape) on leading and trailing edges of the weigh-pad, (2) carpet tapes at the bottom and Gorilla tapes on leading and trailing edges of the weigh-pad, (3) carpet tapes at the bottom, Gorilla tapes on leading and trailing edges, and concrete screws on the center of the weigh-pad, (4) Gorilla tapes on leading and trailing edges and sleeve anchor screws with a flat-washer in the middle of the weigh-pad. All four approaches were tested at the MnRoad facility. Among them, the forth one provided a relatively quick as well as secure installation, thus it was chosen as the installation method for high-speed highways in this project.

The road selected for testing highway traffic was the Minnesota Trunk Highway 53 (TH-53). The posted speed limit of TH-53 at the test site is 65 mph (104.6 Km/h) but the majority (70%) of vehicles drives between 70 – 75 mph (113 – 121 Km/h). The weigh-pads were installed on the northbound two lanes of TH-53 at the Cotton WIM station. A newly constructed weigh-pad pair that does not have air cavity was installed. MnDOT Office of Transportation Data & Analysis (MnDOT TDA) ordered the lane closure and supplied the installation tools needed. The three tools used are listed in Figure 33.

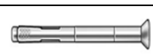
	Hammer drill with ¼” diameter , 6” long drill bits
	Strong bonding utility table - black color (black Gorilla tape was used)
	Sleeve Anchor, ¼ “ diameter, 2-1/4” length with ¼” washer (produced by Red Head was used)

Figure 33: Tools needed for weigh-pad installation

After traffic control has shut down the lane, the weigh-pad installation steps applied are as follows. First, a 1/4" diameter hole is drilled through the pad and pavement for a total depth of 2 ¼" using a hammer drill, and then a sleeve anchor is inserted to the drilled hole after placing a ¼" washer. The screw on top of the sleeve anchor is turned clockwise to expand the sleeve, which fastens the washer and thus the pad to pavement. Sleeve anchors are installed by spacing approximately 2 feet apart, requiring 24 sleeve anchors for installing a pair of weigh-pads. After fastening the pads by sleeve anchors, the leading and trailing edges of the pads are taped using a strong-bonding utility tape, such as a Gorilla tape shown in Figure 33. Taping prevents the sensor edges lifted by air drag or rolling resistance generated by wheels traveling through the weigh-pad. The taping also reduces trapping of air underneath the pads. Although it was not used in this installation, application of a carpet tape or any double sided tape underneath the sensor pads would help to further fasten the pads to the pavement. For the Cotton TH-53 tests, double-sided (carpet) tapes were not used.

Two-lane installation can be done by closing one lane at a time. The sensor pads are installed by first unrolling the initial half of the roll and then fastening the pad to the pavement as shown in Figure 34. While the crew was installing the weigh-pads, the install time was measured. The total time that took to install two 24 ft. (7.32 m) weigh-pads for the two-lane highway took about 30 minutes, or 15 minutes per lane. The crew mentioned that 20 minutes would be sufficient for two-lane installation if it was not the first time installation. To be conservative, the PI believes that allocating 15 minutes per lane would be a good estimate for installation planning.

Figure 34: Weigh-pad installation at Cotton, Minnesota, TH-53

Figure 35 shows a segment of the completed installation of a sensor pad. The spacing between two sleeve anchor screws shown is two feet. The taped edges can be seen in the picture. Although it cannot be seen from Figure 35, some part of the pads was not tightly fastened to the pavement. Figure 36 shows a defect portion of the installation. This picture was taken after one day of operation, and it was clear that the pads were not stretched and tightened before placing the anchor screws; consequently, wrinkles were formed in few places. Initially, the research team assumed that taping would hold down the wrinkled portion of the pad on the pavement. It turns out that taping alone was not sufficient to hold down the wrinkled portion of the pad. The pad edges were ripped out of the tape after passing of just a few vehicles, creating a space between the pavement and weigh-pad as shown in Figure 36. According to the recorded sensor signals and data, these wrinkles in the pad caused vibration and created false axle signals, reducing the accuracy of measurements. The lesson learned from this installation experience is that the pads should be laid flat and stretched before fastening the sleeve anchors.

The next day, the sensor pads were removed, and the removal time was measured. For removal, a MnDOT traffic control crew was again called in, and the lanes were closed one at a time. Removing the sensor pads took a total of 14 minutes or 7 minutes per lane. Table 6 summarizes installation and removal time of weigh-pads. The weigh-pads did not show any signs of damage after running 24 hours of run under the TH-53 traffic that included many five-axle semi-trailer trucks. The date of this installation was November 4th and the pavement was covered with frost in the early mornings. Although the research team expected that this cold temperature may stiffen the sensor pads and result damages, but no such evidence was found.

Both the MnRoad and the TH-53 tests were performed on bituminous pavements. Most lower ADT roads in Minnesota have bituminous surface so this technology was note concrete pavements.

Figure 35: Sleeve anchor screws are fastened in 2 ft. spacing

Figure 36: Some portions had wrinkles that caused vibration and error on the axle signal

Table 6: Weigh-Pad Installation and Removal Time

	Installation	Removal
Single Lane (two 12 ft. weigh-pads)	15 minutes	7 minutes
Two Lanes (two 24 ft. weigh-pads	30 minutes	14 minutes

4.2 Air Cavity and Vibration Problems

During the initial prototype weigh-pad tests, it was accidently discovered that existence of air cavity in the sensor pads adversely affects the axle load signals. The sensor pads were fabricated by a local company called the Industrial Rubber and Supply (IRS) which specializes in customized conveyor belts. The research team supplied the RoadTrax BL sensors described in Section 3.4 to IRS, and the IRS technician cut long grooves for the BL sensor strips and coaxial cable, glued two pads together along with the BL sensor strips and the lead cables, and then sanded edges to produce smooth, gradual leading and trailing edges. Air cavity was created accidently by leaving a portion of groove unfilled. The location of unfilled groove is illustrated in Figure 37. IRS technicians created two parallel grooves for the entire 24 feet (7.32 m) of the pad, although the Channel 0 (C0) groove is only needed for the first half (12 ft.). The Channel 3 (C3) groove of the Weigh-Pad 1 was filled by a 12 ft. (3.6 m) BL sensor and the lead coaxial cable along with adhesives so no air cavity exists in C3. However, only the half of the Channel-0 groove of the Weigh-Pad 1 was filled by a 12 ft. (3.6 m) BL sensor, and the remaining groove was left empty forming an air cavity. The second weigh-pad produced (Weigh-Pad 2) did not have this problem because IRS technicians did not make unfilled grooves as the Weigh-Pad 1 in Figure 37.

In order to test these two different weigh-pads, two 24 feet sensor pads were installed in the MnRoad low-volume road. The test vehicle and installed weigh-pads are shown in Figure 38. The test vehicle traveled in the direction shown by the large arrow in Figure 37. When the vehicle travels in this direction, the signals in C0 and C1 should be close to the signal ground since no loads are present, and the axle signals should only appear on C2 and C3. However, that was not the case. Figure 39 shows a plot of the actual signals of all four channels. Notice that C0 has signals that appear for every axle signals of C2 and C3 even though no axle load was present. To show that C0 signals are false, plot of C0 line was disabled, and the rest signals are shown in Figure 40. Notice that two axle signals from C2 and C3 are clearly visible as they are supposed to be, and C1 signals remain close to ground. This verifies that C0 signals are the superfluous faulty signals that should not exist.

In order verify that if the air cavity indeed produced the unwanted signal, one third of the air cavity was filled with glues and then tested again. The magnitude of superfluous C0 signals was significantly reduced. This was encouraging, so the air cavity was completely sealed and tested again. The false signals did not completely disappear from C0, but its magnitude was small enough to ignore, i.e., it was less than the axle-signal threshold. This experimentally proves that air cavity in weigh-pads can introduce faulty superfluous axle signals.

A question still remained is why C0 has axle-like spikes for every axle signals from other channels. It is reasoned as follows. It should be first noted that piezoelectric materials generate charge signals when loads (acceleration) are applied but also when vibration is present. When a vehicle passes through a weigh-pad, the weigh-pad acts as a small bump that creates a vibration. This vibration is propagated to C0 but it is amplified by the air cavity before it reaches to the C0 sensor. When an axle hits the air cavity, the air is compressed and then it is transferred to the sensor strip. Another important factor is that piezoelectric materials generate high amplified signals if vibration is within the range of its resonant frequency. It appears that C0 signals in Figure 39 were in the range of sensor resonant frequency since the amplitude of the signals is as high as real loads. Clearly, the air-cavity problem is avoidable if the pads are carefully manufactured without any air cavities. Indeed, the second set of weigh-pads was produced with caution and did not have any superfluous signal problems when it was tested on the same road using the same test vehicle. This new sensors were used in the final tests.

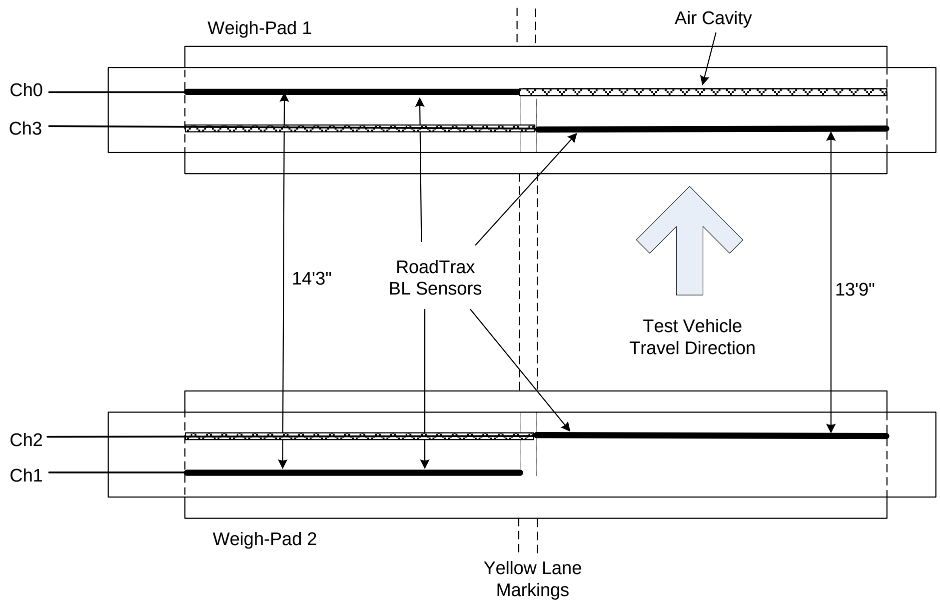


Figure 37: Location of weigh-pad air cavity

Figure 38: Installed weigh-pads with air cavity and the test vehicle

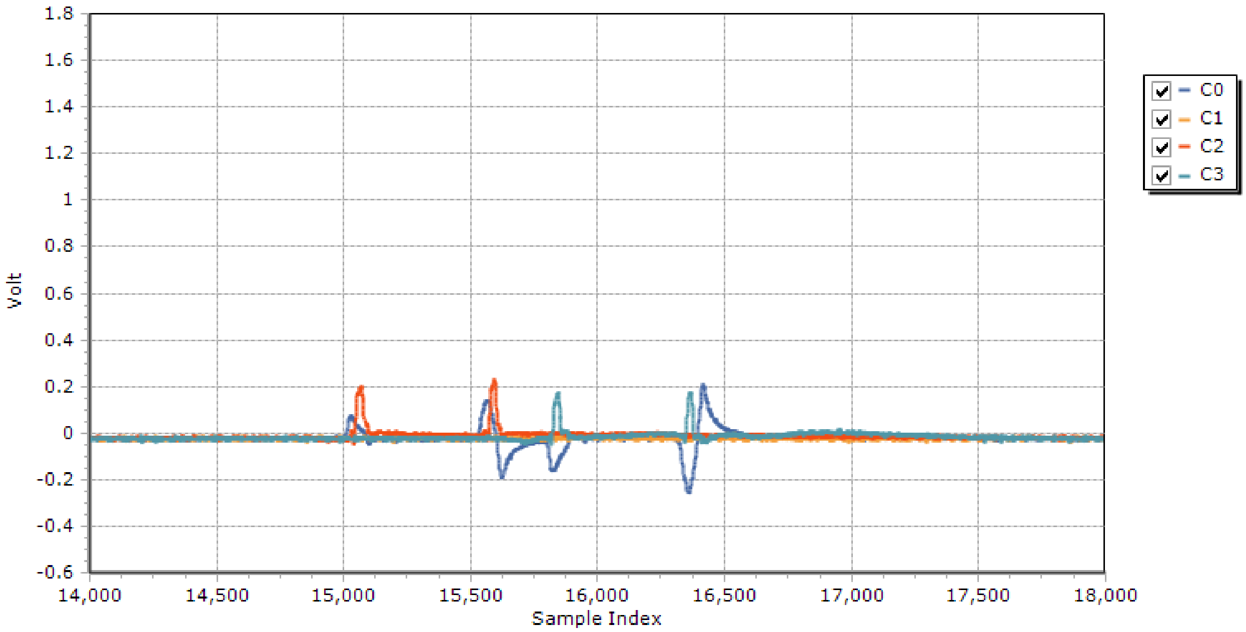


Figure 39: Air cavity generated noise on Channel-0 (C0).

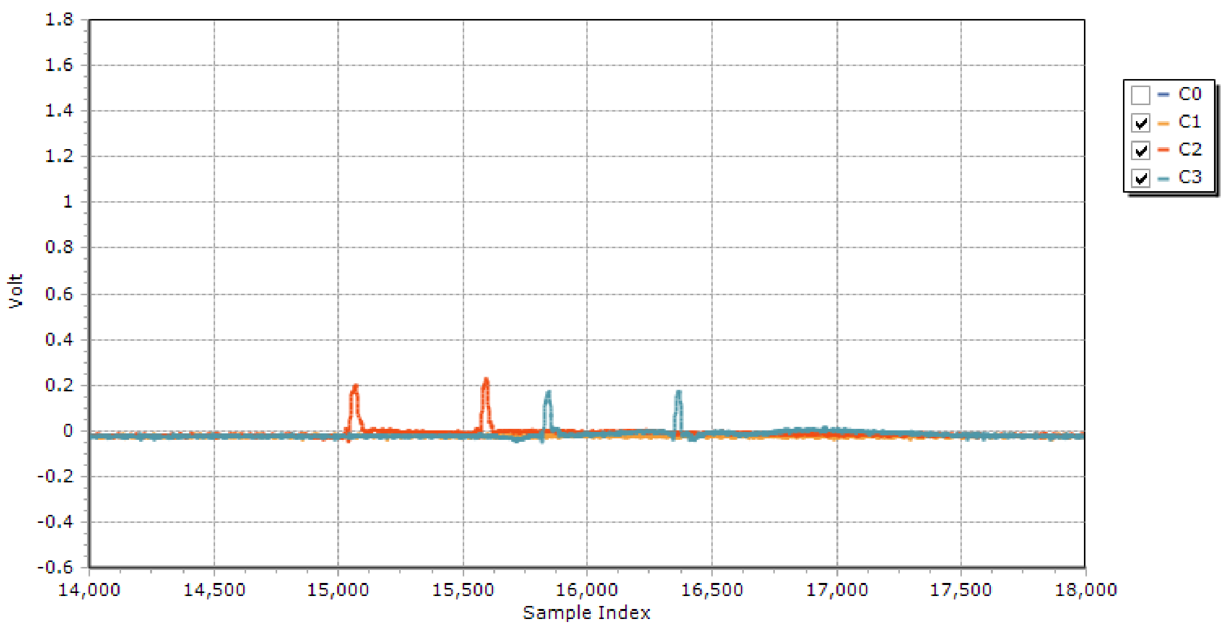


Figure 40: Removing Channel-0 signal clears the superfluous signals

Chapter 5: Experimental Results

5.1 Charge Amp Tests

Charge amplifiers (amps) are a crucial part of any WIM system and must be carefully designed and tested. The charge amps for this project were custom designed and fully described in Section 2.3. The initial Printed Circuit Board (PCB) prototypes for building charge amps were produced using an LPKF machine (PCB milling machine) available in one of the research labs at UMD. The charge amp built using the LPKF machine can be seen in Figure 15. The final PCBs were commercial grade boards, produced in a factory through one of the PCB prototyping services and they can be seen from Figures 14 and 17.

One of the early tests of the charge amps was a heat test. The input of the prototype charge amp was connected to a BL sensor while the output was connected to an oscilloscope. The BL sensor was heated gradually up to 350ºF using a hot-air heat gun, and the output of the charge amp was monitored. The voltage level was initially rising but constantly pulled down to the signal ground level as soon as the heat gun was removed. In order to hold the charge amp output at a certain voltage level, the heat had to be constantly applied at an increasing rate. This indicates that the charge amp was able to remove the charge signals generated by the heat. Since the charge amp was designed to remove any slowly changing signals, a static weight test was conducted to verify the signal response to an unchanging weight. About 60 pounds of weight was placed on top of the test BL sensor, and then the charge amp output was observed. The voltage level rose when the weight was initially placed on the BL sensor, but it was gradually decreased to the signal ground as the weight becomes static and initially generated charges are depleted. The charge amp responded as expected to the heat and static weights.

After confirming the operation of charge amps in the lab, the next step was to test its waveforms on moving vehicles. Low speed tests were done at one of the UMD parking lots while high speed tests were conducted at the MnRoad facility. The charge amps responded well for the slow speed tests in parking lots, producing reasonable axle load waveforms. Many driving tests were conducted at MnRoad, and the two test results shown in Figures 41 and 42 are next described. For sampling of the charge amp output signals, a PCI based ADC, MCC PCI-DAS6013, was used in both cases. The voltage signals were sampled at 4,096 samples per second. Figure 41 shows a waveform of a two-axle vehicle produced by a two-channel charge amp. The test vehicle in this case was a Toyota Siena van with the GVW, 4,600 pounds. The waveform shape and size was within the expected range. Next, a 5-axle semi-trailer truck (which is a test truck available at the MnRoad facility) was tested, and one of the waveforms is shown in Figure 42. The known GVW of this vehicle was 79,720 pounds. If the areas under the curve of the two test vehicle signals, which would represent axle weighs, are compared, the factor is around 18. This is close to the weight ratio of the two vehicles. This indicates that the axle waveforms approximately correspond to the axle loads of the two vehicles. Accuracy tests are later discussed in Section 5.3.

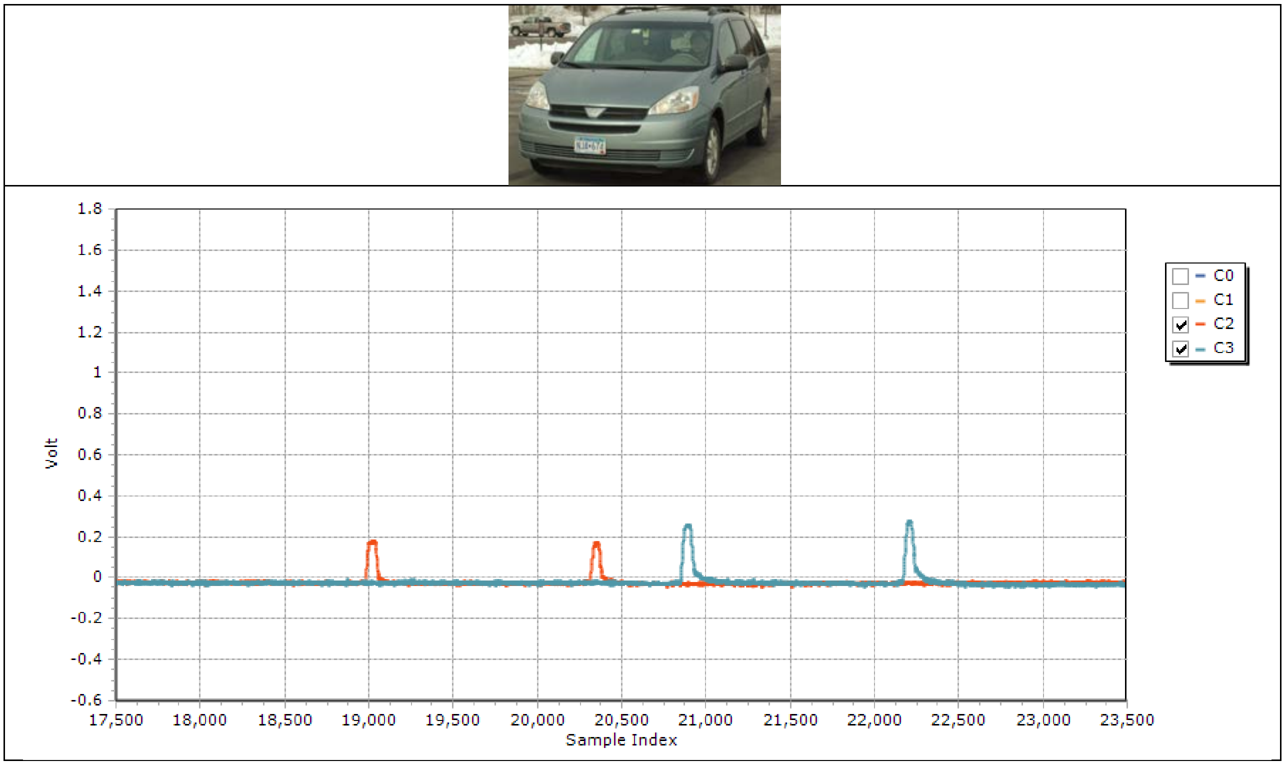


Figure 41: Charge amp signals of a van (Oct 16, 2011)

Figure 42: Charge amp signals of a five-axle semi-trailer truck (Aug 16, 2011)

In all test cases, the charge amps behaved as expected, producing waveforms (such as shown in Figures 41 and 42) close to the ideal axle model developed in Section 3.1. The resting level of the signals returned quickly to the signal ground when the load was removed, i.e., the charges stored in the measurement capacitor were discharged with the designed time constant which is necessary in order to be ready for the next measurement.

To examine the pavement heat effect, the weigh-pads and charge amps were tested under the pavement temperature range of 85 – 134 ºF. This pavement temperature range was available at MnRoad in the summer of 2011 in Minnesota. The idle levels of the signal observed for the entire temperature range remained close to the signal ground. The voltage level movement was almost none existent in comparison to the lab tests which applied the temperatures up to 350 ºF using a heat gun. The effects to the axle waveforms by the tested temperature range (85 – 134 ºF) were insignificant or negligible.

In summary, the charge amp circuit was designed to remove any signals that change slower than the period defined by the designed time constant of 20 seconds. The next question is then "Does this slow signal removal adversely affect the fast changing axle-load signals?" According to many observations and example waveforms like the ones shown in Figures 41 and 42, it did not affect the actual axle signals because most axles move much faster than the 20 second time constant for traveling the sensor width of 0.7 mm (this translates to an equivalent speed of 0.000747 mph). Pavement temperatures, on the other hand, slowly change such as the rate in the order of 10s of minutes, which triggers removal of the signals.

5.2 Experiments on Influence of Speeds on Weight

5.2.1 Theory

Because weigh-pads are fastened on the surface of the pavement, they are extruded even though they are thin (less than 1/3 inches in the center) and the edges are tapered to a gradual slope. When a vehicle drives over the weigh-pads on a high speed, a sound of hitting a small bump can be clearly heard. This bumping sound becomes louder as the vehicle speed increases. This begs the question: Does the vehicle speed affect the vehicle weight measured by the weigh-pad? This section describes a brief theoretical analysis and the experimental results.

To analyze the loading of an extruded weigh-pad sensor, we consider a load (axle) sensor installed on a slope of θ as opposed to installed on a flat surface. A slope installation and the related forces are illustrated in Figure 43. In the diagram, the little rectangle on the slope is the axle load sensor. If the slope is zero (right side diagram), the sensor load due to the vehicle's horizontal force becomes zero because $F_h \sin(0°) = 0$; thus, the load received by the sensor, F_s, is equal to the gravitational force only, i.e., the weight F_g. On the other hand, if the senor is installed on a slope as shown in the left side of the diagram in Figure 43, the total force received by the sensor is the summation of the horizontal force generated by the acceleration and the weight of the vehicle by gravity, i.e.,

$$F_s = F_h + F_g \tag{10}$$

In theory, as the vehicle's speed increases the horizontal force, F_h, applied to the load sensor should increase while the gravitational weight of the vehicle remains the same. This means that the force of the same vehicle on a higher speed would result in applying a higher load to the sensor when the sensor is on a slope. This relationship was tested in this experiment.

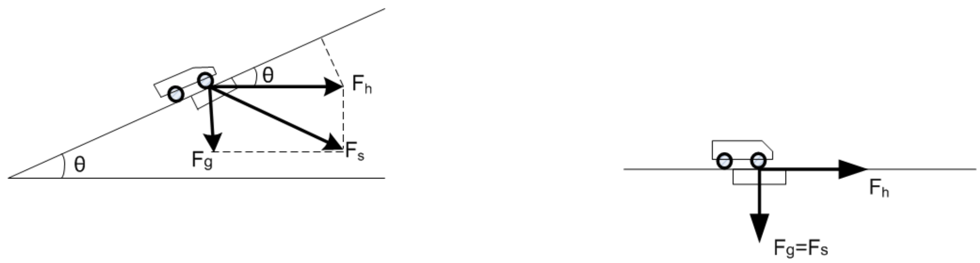


Figure 43: Force and slope relationship

5.2.2 Data Collection

To verify the theory shown in Section 5.2.1, weigh-pads were set up at the low-volume road of the MnRoad facility. The Toyota Siena van shown in Figure 41 was again used as the test vehicle. The static weight of the test vehicle was approximately 4.6 Kips (2,087 Kg). This test road is flat and can be driven above 80 mph (129 Km/h) without interference or dangers associated with other traffic. The setup is shown in Figure 44. The system includes a pavement temperature sensor in order to ensure that the data is collected within a small range of temperature variance. The weigh-pads were fastened on the pavement surface using a carpet tape at the bottom and Gorilla tapes (high-strength duct tape) on both leading and trailing edges of the sensor pads. The weigh-pads used were newly constructed two-lane weigh-pads that had no air cavity.

The test date was Oct 16, 2011, and the weather was clear. The pavement temperature fluctuated between 66 – 75 ºF (19 - 24 ºC) during the measurement period which was 2:25pm-4:41pm. The wind was blowing at 20 - 30 mph (32 – 48 Km/h) east. The test vehicle was driven multiple times at speeds close to 10, 20, 30, 40, 50, 60, 70, and 80 mph, and the corresponding axle waveforms along with vehicle records computed by the weigh-pad software were recorded. The test vehicle was driven over the weigh-pads a total of 56 times. The data was collected from both Lane-1 and Lane-2. However, the weight data from Lane-2 was noisy due to unstable pad installation, so Lane-1 data was used for the analysis.

Figure 44: Speed effect test setup at MnRoad: the weigh-pads were fastened by high-strength tapes on leading and trailing edges and carpet tapes at the bottom

5.2.3 Analysis

As the first step of the analysis, an x-y scatter graph of speed vs. weight was plotted to observe the data trend. Figure 45 shows the data points of speed vs. weight along with a linear regression line. The data clearly shows an increasing trend of weights as a function of the speed. For example, the average weight is 5 Kips (2.27 ton) at 30 mph, but the average weight becomes 6.5 Kips (2.9 ton) at 60 mph. Linear regression of this data was computed and shown along with the x-y scatter graph, and the equation is given by:

$$y = 0.0533x + 3.2478 \text{ Kips} \quad (11)$$

where x is the speed in mph and y is the vehicle weight in Kips. This function has $R^2 = 0.7897$ (R^2 is a measure of goodness-of-fit, 0 representing the worst fit and 1 representing the best fit). Calibration (or multiplication) factors for different speeds could be obtained from this regression, which is summarized in Table 7. The relationship between the calibrated weight and the corresponding calibration factor (*calfac*) is defined by:

$$calibrated\_weight = calfac * recorded\_weight \quad (12)$$

This linear regression estimate, however, exhibits poor fit in the region of speeds less than 20 mph (32 Km/h) and also in the above 70 mph (112.7 Km/h). Therefore, a better fit function is desirable.

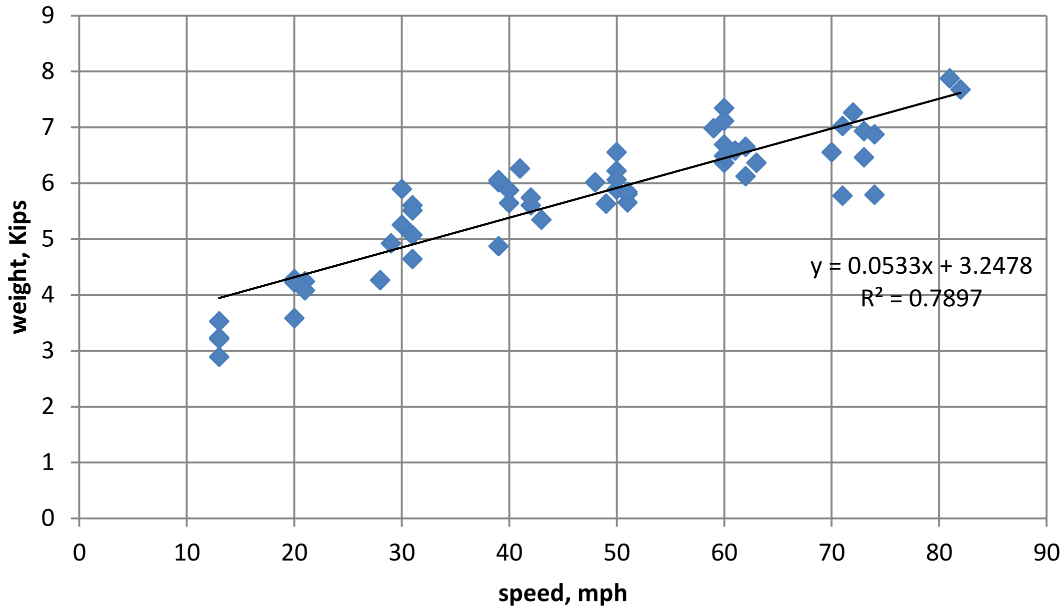


Figure 45: Scatter plot of speed vs. weight of the same vehicle and linear regression

Table 7: Linear Calibration Factors (multiplication factors) for Different Speeds

speed	5 mph	15 mph	25 mph	35 mph	45 mph	55 mph	65 mph	75 mph	85 mph
calfac	1.3089	1.1366	1.0043	0.8996	0.8147	0.7444	0.6853	0.6349	0.5914

A better fit function chosen is a log fit function. This fit function is shown in Figure 46. Note that it has a better fit in the areas of below 25 mph and above 70 mph speeds. This log fit function is given by:

$$y = 2.1248\ln(x) - 2.2045 \qquad (13)$$

where *x* is the speed in mph and *y* is the vehicle weight in Kips. This function has: $R^2 = 0.8566$, which tells us that the log function is a better fit than the linear regression ($R^2 = 0.7897$). Substituting *x* with the computing speed and dividing this by 4.6 Kips (static weight of the test vehicle) gives the inverse of *calfac* (multiplication factor). The final *calfac* computed for different speeds using the log estimate is summarized in Table 8. Because it is a log function, the curve drops too quickly in the area of below 10 mph. Therefore, it is necessary to adjust back to a slower rate than the log function for below 10 mph. A piecewise linear function, for a practical implementation of speed calibration, could be used to allow implementation of any non-linear mapping relationships. This approach was used in the weigh-pad system implementation, and the user can enter *calfac* in 5 mph (8 Km/h) spacing up to 90 mph (145 Km/h).

In summary, the theory presented in the Sub-Section 5.2.1 and the test results from MnRoad show that speed of a vehicle influences the total force applied to the weigh-pad axle sensor. However, there must be a caution in interpreting this data. The obtained data may be influenced also by installation variances and the associated vibration. If weigh-pads are not securely fastened to the pavement, the pads vibrate when a tire hits the sensor. As the vehicle increases the speed, the amount of this vibration also increases. Since piezoelectric sensors produce higher charge signals in response to vibrations, another factor influencing on top of the speed might be vibration. More specifically, vibration effect is amplified by higher speed, resulting stronger charge signals. What this suggests is that the weight vs. speed relationship derived through the speed data may be an overestimate, and the weight values would be reduced if the sensor pads are more securely fastened to the pavement. The vibration effect could be diminished if installation is ideal, but the slope effect would not diminish. Collection of more data is recommended to finalize the speed effects.

Table 8: Log Calibration Factors

speed	5 mph	15 mph	25 mph	35 mph	45 mph	55 mph	65 mph	75 mph	85 mph
calfac	1.7692	1.2959	0.9925	0.8598	0.7818	0.7290	0.6902	0.6600	0.6358

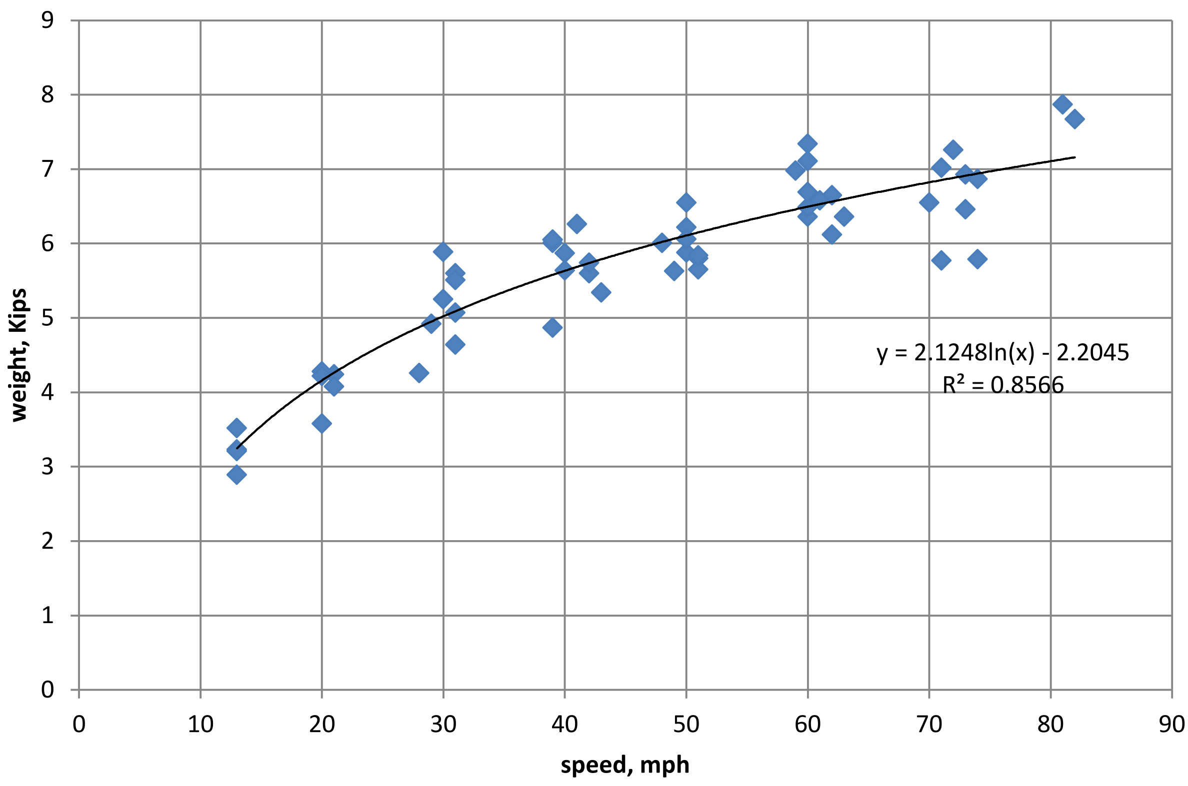


Figure 46: Log regression of weight data by different speeds

5.3 Side-by-Side Tests of Weigh-Pad Vs. IRD WIM Systems

5.3.1 Test Setup and Data Collection

It is interesting to compare how the weigh-pad-based portable WIM system performs against an in-pavement installation such as the Kistler Lineas Quartz sensors with an IRD iSync WIM system (most of MnDOT WIM systems). One of the simplest ways to compare two systems would be a side-by-side comparison at the same location for the same traffic by installing the weigh-pads side-by-side along with the Kistler quartz sensors.

The location selected for the side-by-side comparison was the Cotton WIM site on the Minnesota Trunk Highway 53 (TH-53) at the mile point 42. The posted speed limit of TH-53 at the test site is 65 mph but the majority (70%) of vehicles drives between 70 – 75 mph. This WIM site has four lanes in which Kistler Lineas quartz sensors are installed and operational. An IRD iSync WIM system is available in the roadside cabinet, which collects the WIM data of this site. For this comparison, the weigh-pads were installed on the northbound two lanes using the installation method described in Section 4.1. The office of Transportation Data & Analysis (TDA) at MnDOT requested the lane closure and supplied the tools needed for installation. The lane closure was provided by District-1 personnel from their maintenance office. Installation of weigh-pads for the two northbound lanes took 30 minutes. Figure 47 shows a picture of the TH-53 weigh-pad installation and a vehicle passing through in lane-2. It is not visible in this picture but the Kistler sensors are located about 18 ft. (5.49 m) before the weigh-pads.

Figure 47: Weigh-pad installation at the northbound of TH-53 at the Cotton, Minnesota

The spacing between the upstream and downstream weigh-pads was 14 ft. (4.267 m); sensitivity was set to the default value of 6.25; and the weight data was not calibrated (i.e., Calibration Factor =1) for all sensor segments. Table 9 summarizes the setup parameters. The limit parameters required by the weigh-pad console are summarized in Table 10. The data was collected between 11/3/2011 11:21:57 AM, Thursday and 11/4/2011 9:55:27 AM, Friday. The road surface was covered with frosts in the early morning but cleared at the time of installation (cleared around 8.30am).

Since the sensor pads stayed overnight, a good portion of time the system was in a frosty condition which was a concern for physical sensor-pad damages, but no damage was found from the sensor pads or the controller. The console battery was able to support more than continuous 24 hours of operation.

Table 9: Setup Parameters

Setup Parameter	Lane #	Value
Sensor Strip Spacing	Lane 1	14 ft
	Lane 2	14 ft
Sensitivity	Lane 1	Upstream=6.25
		Downstream=6.25
	Lane 2	Upstream=6.25
		Downstream=6.25
Calibration Factor	Lane 1	Upstream=1
		Downstream=1
	Lane 2	Upstream=1
		Downstream=1

Table 10: Limit Parameters

Parameter	Value
Maximum Vehicle Length Possible	75 ft
Maximum Axle Spacing Possible	45 ft
Maximum Tire Footprint Length Possible	2 ft
Minimum Possible Vehicle Speed	15 mph
Maximum Possible Vehicle Speed	110 mph
Axle Signal Threshold	0.12V for All

5.3.2 Data Analysis

The data was collected after manually adjusting the weigh-pad console clock to closely match with the IRD's system clock at the Cotton station. The time synchronization made easy to locate the matching vehicle records between the two system outputs. In the recorded data, exactly 17 seconds were different between the two system's vehicle records for the entire data collection period. This time difference was caused by manual clock synchronization of the two systems and not trying hard enough to match up to the second. In the weigh-pad system data, 587 out of 3,822 vehicle records had errors (15%). After looking through the data and error messages, it was found that the erroneous records were mainly due to vibrations generated by the air gap of the wrinkles in the sensor pad (Figure 36). Flapping of the pad edges created false axle signals, which led to an error message that indicates mismatch of left and right axle counts. The weigh-pad console presently does not filter false axle signals, and it simply gives an error message without computing the axle weights. This experience clearly taught us that it is extremely important to minimize or eliminate wrinkles during the weigh-pad installation. Moreover, a filtering algorithm that could identify and remove false axle signals is needed as a part of the weigh-pad signal processing. This would be one of the future recommended works.

Since the bad records cannot be used for a meaningful comparison against the IRD vehicle records, all of the 587 bad vehicle records were removed from the weigh-pad data. The remaining 3,235 vehicle records were used for analysis. In the subsequent analysis, the weigh-pad vehicle records referred would be the error-free records with the raw data recorded using the default setup shown in Tables 9 and 10. If the data was calibrated afterward, it will be stated.

In order to measure the difference between the IRD and Weigh-Pad vehicle records, a Root Mean Square Error (RMSE) is used as the first similarity test. The RMSE is defined by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N}} \qquad (14)$$

where x_i is the IRD data and y_i is the weigh-pad data. The RMSE was computed for GVW, speed, and vehicle length (or simply length) defined by a summation of axle spacing, i.e., the distance from the front axle to the last axle of a vehicle. The results are:

- GVW RMSE = 4.10696 Kips
- Speed RMSE = 1.28684 mph
- Length RMSE = 0.32029 feet

According to this result, GVW has the highest RMSE, and length has the lowest RMSE. This is expected due to its absolute range of values. Since RMSE only represents differences of absolute values between two observations and cannot objectively compare different parameters, a Normalized RMSE (NRMSE) is used in place of RMSE. NRMSE essentially represents a percent error and is a better measure for comparison of different numerical range of parameters. A commonly used NRMSE is obtained by dividing RMSE by the range of the observed values, i.e.,

$$NRMSE = \frac{RMSE}{y_{\max} - y_{\min}} \qquad (15)$$

The NRMSEs computed according to Eq. (15) are:

- GVW NRMSE=0.03880 (3.88%)
- Speed NRMSE=0.02219 (2.219%)
- Length NRMSE=0.00514 (0.514%)

The percent differences between the IRD and weigh-pad data are 4% for GVW, 2% for speed, 0.5% for length. Based on this data, it can be said that the two systems produced a very similar data. GVW had the most difference and the vehicle lengths (=total axle spacing) had the least difference.

According to above data, the weight data had most differences, which is expected because weights are affected by several environmental factors independent of the sensor quality. *Weight measurements of moving vehicles are often most inconsistent because vehicles have a suspension system that oscillates the weight over a time and space.* In order for two weight measurements to be identical, the tension of the vehicle suspension must be identical as well as the speed and wind condition. The weigh-pads and IRD sensors were in a close proximity (18 feet apart), but the tension of individual vehicle suspension at two different positions is a factor that cannot be controlled.

An RMSE or NRMSE measurement provides a single numerical representation of average one-to-one differences, thus they do not show the details of data trends or relations within. In order to investigate the trends or relations in data, scatter graphs between the IRD vs. weigh-pad data on GVW, speed, and vehicle length is plotted along with computation of the correlation coefficients (see Figures 48-50). The correlation coefficient of X and Y, denoted by *Corr(X,Y)*, is defined by

$$Corr(X,Y) = \frac{Cov(X,Y)}{\sigma_x \sigma_y} \tag{16}$$

where $Cov(X,Y)$ is the covariance between two random variables X and Y, and σ_x and σ_y are the standard deviations of X and Y. If *Corr* is closer to 1, two random variables are more strongly linearly correlated. In general, $Corr > 0.8$ suggests a strong linear relationship [20]. The coefficient of determination, denoted as R^2, is also computed [20]. This value represents a statistical measure of how well the regression line approximates the real data points. Table 11 summarizes the computed correlation coefficients and the coefficients of determination between the IRD and weigh-pad data. Notice that every coefficient is above 0.9, which indicates a very strong correlation. Among these coefficients, length (i.e., axle spacing) coefficients are above 0.99, which indicates both data are nearly identical. GVW and speed also have strong linear relationships, correlation coefficients exceeding 0.96.

Table 11: Correlation Coefficients and R^2 Between IRD and Weigh-Pad data

Measurements	Correlation Coefficient	R^2
GVW	0.965023	0.9313
Speed	0.966612	0.9343
Length	0.999721	0.9994

In the above fit tests, vehicle length had the best linearity relationship and the best goodness of fit. GVW and speed had strong linear relationships but the percentage of linearly related data drops to 93 percent. Notice from the scatter graphs in Figures 48-50 that vehicle length (axle spacing) and speed had very tight linear relationships with almost no exceptions. On the other hand, GVW was not tightly bunched to the linear line. Again, these plots confirm that weight data had the least consistency, which agrees with Table 11.

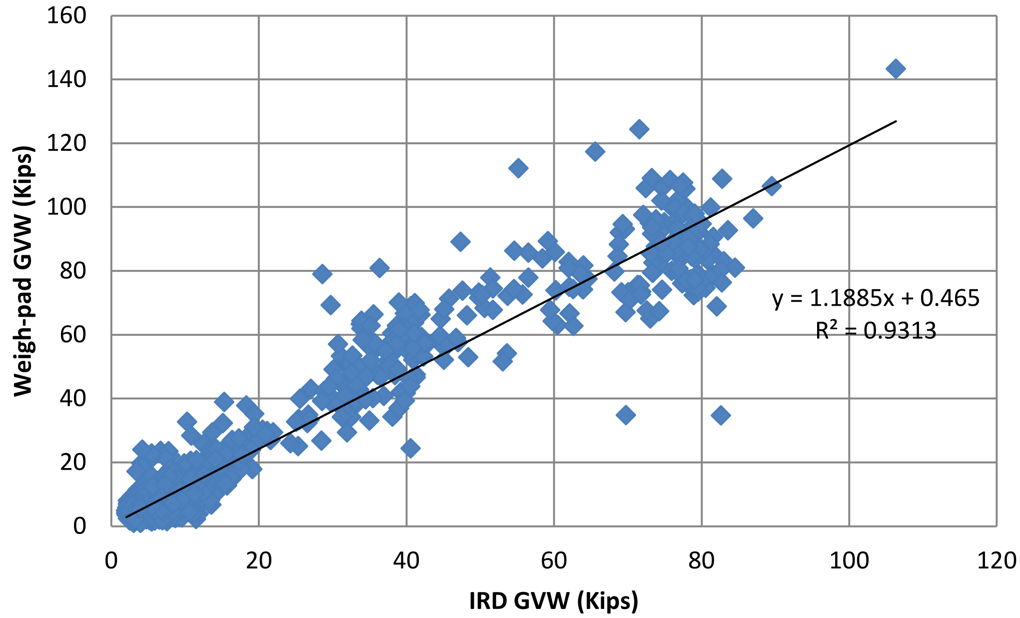


Figure 48: Scatter plot of IRD vs. Weigh-Pad GVW data

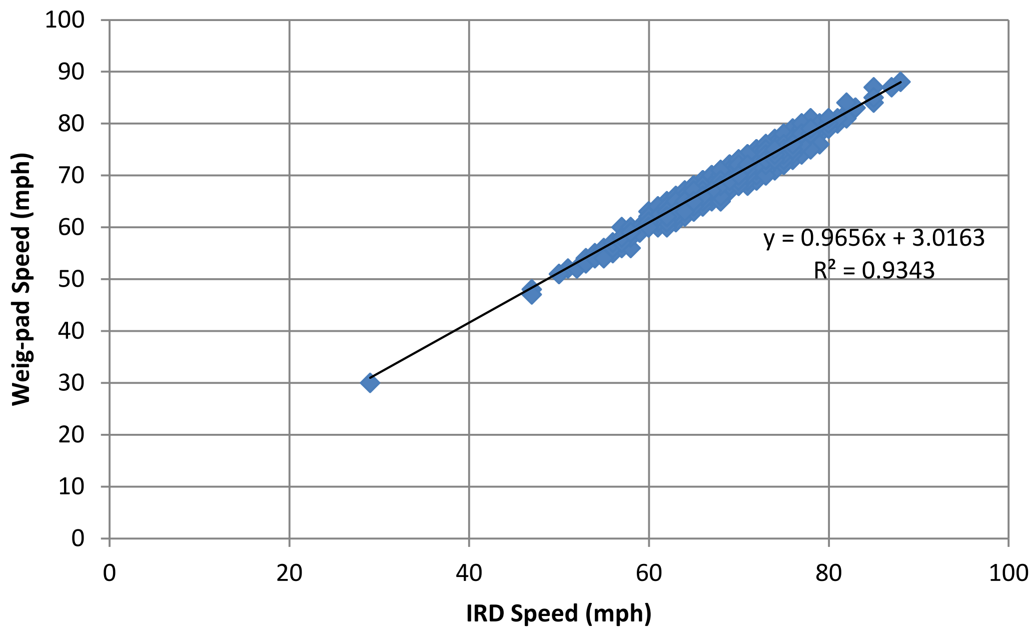


Figure 49: Scatter plot of IRD vs. Weigh-Pad speed data

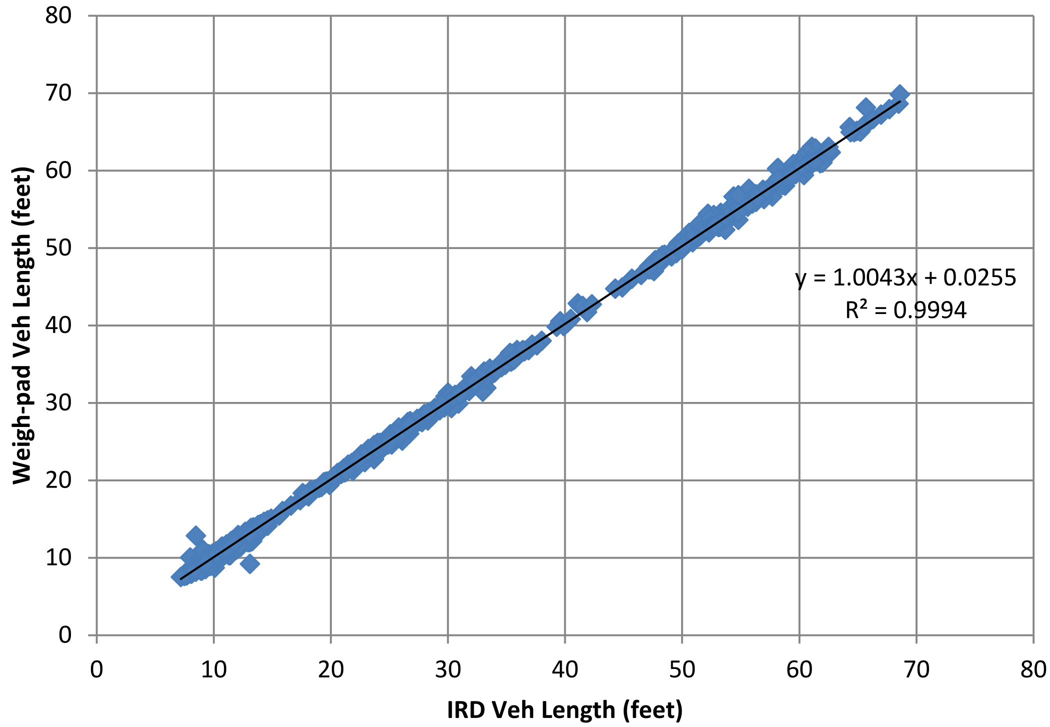


Figure 50: Scatter plot of IRD vs. Weigh-Pad vehicle length data

In Figure 48 (a scatter graph of IRD vs. weigh-pad GVW), the data points are not tightly bunched to the linear line. Initial assessment of this spread effect is that the vehicle weight is influenced by the springing effect of vehicle suspension. This spring effect is independent of the sensor accuracy and should lead to random differences of weights between the IRD and weigh-pad measurements within a certain range of GVW. In order to investigate whether speed was a part of the cause of the spread in Figure 48 or not, a two-dimensional GVW ratio table with respect to speed was created and shown in Table 12. GVW ratio is defined by:

$$\text{GVW Ratio} = GVW_{WPad}/GVW_{IRD} \qquad (17)$$

Here, GVW_{WPad} is the raw weigh-pad GVW data that was not calibrated. In the table, speeds were spaced by 10 mph (16 Km/h)), while the GVW was spaced by 10 Kips (4,535 Kg). Each table entry is the average of the GVW Ratio values in Eq. (17) in the defined range. The number of vehicle records in each GVW Ratio bin for average computation is shown in Table 13. Because this data was collected from a Trunk Highway, most vehicles are clustered around the speed range of 60 - 90 mph (96.6 – 144.8 Km/h). The average of GVW Ratio is 1.26 which indicates that weigh-pad GVW is 26% higher. However, this trend is inconsistent, and some cases it was below 1. This test indicates that the speed effect is less significant than the tests observed from the MnRoad tests. We believe that the differences in setup resulted in a different effect. For the MnRoad speed tests, the sensor pads were fastened to the pavement only using tapes. For the TH-53 tests, the sensor pads were fastened using sleeve anchors with washers and then the edges were taped. This installation difference appears the cause of the differences in speed effect.

In summary, speed impact appears less significant according to Table 12 as the sensor pads are more tightly fastened to the pavement, but oscillation of physical weights by the suspension system of vehicles seems a more dominant factor in the GVW differences between the two systems. It also suggests the accuracy of WIM measurements is limited by the suspension oscillation effect and cannot be improved by instrumentation accuracy of any WIM systems.

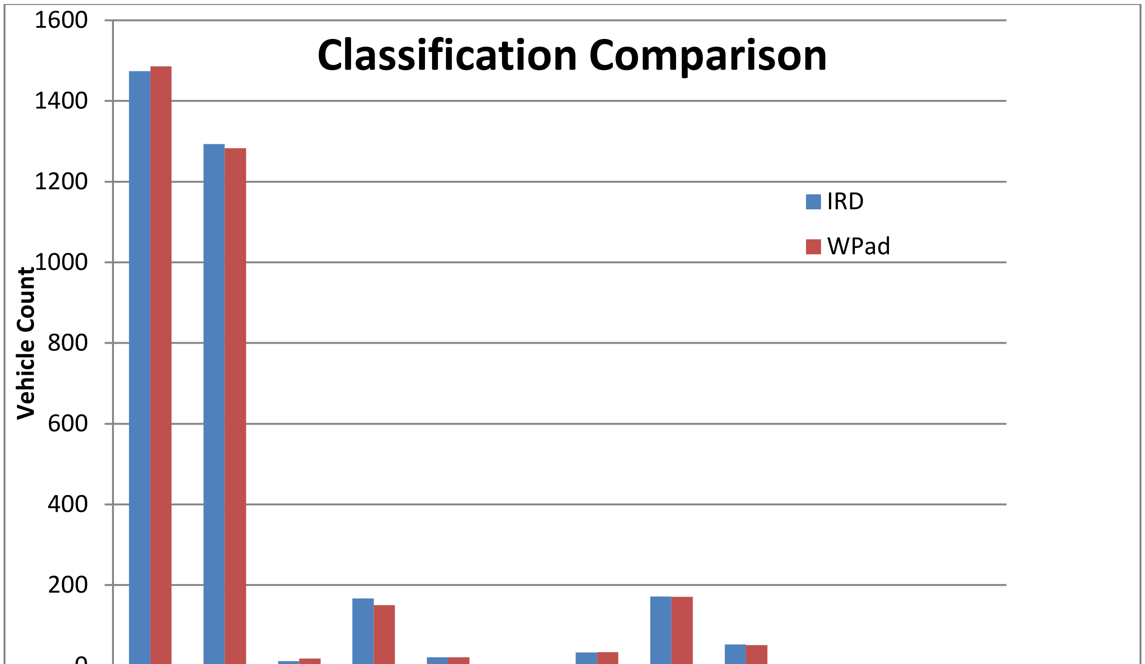
Table 12: Average GVW Ratio over GVW Ranges in Kips and Speed Ranges in mph

	GVW Range in Kips									
speed	0->10	10->20	20->30	30->40	40->50	50->60	60->70	70->80	80->90	90->
0->20 mph	0	0	0	0	0	0	0	0	0	0
20->30 mph	1.16	0	0	0	0	0	0	0	0	0
30->40 mph	0	0	0	0	0	0	0	0	0	0
40->50 mph	1.61	2.14	0	0	0	0	0	0	0	0
50->60 mph	1.34	1.4	1.3	1.57	1.62	1.33	1.13	1.1	0	0
60->70 mph	1.36	1.23	1.45	1.43	1.37	1.4	1.18	1.16	1.04	1.35
80->90 mph	1.19	1.09	1.31	1.34	1.26	1.01	1.53	1.18	0.93	0
90-> mph	0.95	0.37	0	0	0	0	0	0	0	0

Table 13: Number of Vehicle Records in the Defined Range

	GVW Range in Kips									
speed	0->10	10->20	20->30	30->40	40->50	50->60	60->70	70->80	80->90	90->
0->20 mph	0	0	0	0	0	0	0	0	0	0
20->30 mph	1	0	0	0	0	0	0	0	0	0
30->40 mph	0	0	0	0	0	0	0	0	0	0
40->50 mph	1	1	0	0	0	0	0	0	0	0
50->60 mph	71	12	1	2	1	2	2	2	0	0
60->70 mph	1506	139	19	66	29	15	20	61	16	1
80->90 mph	1138	70	2	9	5	1	2	16	5	0
90-> mph	18	1	0	0	0	0	0	0	0	0

The last test is to compare vehicle classification results of the two systems using the same class definition table. According to the GVW R^2, about 7 percent of the weight data did not follow linearity. This test is to investigate whether this 7 percent would affect vehicle classification. Figure 51 shows the vehicle classification results of the two systems using blue and red bars. No class-1 vehicles were detected during the test period, so the classes shown are from class-2 to class-13. Total 49 vehicle records out of 3,235 records were classified as different classes between the IRD and weigh-pad WIM systems. This difference in classification is only 1.5%. Also, the differences of classification were mostly within the neighboring classes such between as class-2 and class-3. Since the axle spacing difference is minimal as shown in the previous data, 1.5% classification difference must have caused by the weight differences. It should be mentioned that the weigh-pad data was not calibrated. Therefore, only 1.5% difference should be considered that classification results by the two systems are remarkably close.



	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13
IRD	1474	1293	12	167	21	1	33	172	53	3	1	2
WPad	1486	1283	18	150	21	1	34	171	51	3	1	2

Figure 51: Classification comparison between the IRD and Weigh-Pad system vehicle records

Chapter 6: Conclusions and Future Recommendations

6.1 Conclusions

This report presented the results of a MnDOT-sponsored project on the development and evaluation of a portable WIM system referred to as a weigh-pad system. The original objective was to bring WIM technologies to rural local roads by developing a low-cost WIM system that would be portable and reusable much like pneumatic tube counters.

After many trials and errors, the final working sensor, called weigh-pad, was constructed by gluing piezoelectric sensor strips between two thin and long conveyer belts. A standard weigh-pad has a length of 24 ft. (7.3 m) covering two lanes and a width of 1 ft. (0.3 m). For installation, two weigh-pads are laid across the traffic lane separated by a known distance (typically 12-16 ft. or 3.7-4.9 m) and fastened on the pavement surface using sleeve anchor screws. The edges are then taped using strong-bonding utility tapes. Installation takes about 15 minutes per lane, while removal takes about 7 minutes per lane.

The developed weigh-pad system was tested in a number of different ways. Among them, a side-by-side test with an in-pavement permanent station on a truck highway provides a meaningful comparison. According to the data comparisons, axle spacing and speed were nearly identical (0.5% different) while GVW was about 4% different in NRMSE measurements. Comparison of vehicle type classification revealed a difference of only 1.5%. All of the comparative numbers presented in Chapter 5 suggest that data quality of the weigh-pad system is within a few percentage points of in-pavement permanent systems.

This project successfully demonstrated that a reusable, portable WIM system that would be installed much like a pneumatic tube counter can be built. A side-by-side comparison verified that the data quality difference between the portable on-pavement and a permanent in-pavement system is minute. It should also be noted that the data downloaded from the weigh-pad system is compatible with the data format required by the BullReport (a standard WIM data tool used by MnDOT): consequently, the same data tool developed for in-pavement systems can be reused for the portable weigh-pad system. With few improvements, the researchers believe that the weigh-pad system is a solution for bringing the WIM technology to local roads at a low cost.

6.2 Future Recommendations

The developed system is battery operated, but it only lasts for about 25 hours. In traffic data collection, traffic engineers typically collect short-duration counts for two to three days using portable traffic counters [9]. The battery run time of a portable WIM system should at least support an equivalent duration to be acceptable as a practical tool. Extending the battery run time can be accomplished in two ways: (1) increase the battery capacity or (2) use a low-energy circuit. Application of both approaches along with cost optimization is recommended.

Currently, the life of weigh-pads is completely unknown. Since the pad material is reinforced rubber, it will wear out and will need to be replaced at some point in time. The breaking point or useable life of the weigh-pads may be expressed in terms of traffic volume or Equivalent Single Axle Load (ESAL). Whatever measurement is used, an experimental study must be conducted to determine useable life. Since weigh-pads must be replaced, the next issue would be finding low-cost replacement solutions. Considering the high cost of BL sensors, a new fabrication method in which the BL sensor is reused would lower the replacement cost. This new fabrication method is recommended as a future study.

Piezoelectric materials generate charge signals proportionally to acceleration as well as to vibration. WIM systems utilize the piezoelectric response to acceleration. It is important to understand that piezoelectric sensors can generate charge signals in response vibration as well. In particular, large amplified charge signals are generated when the vibration matches with the sensor's resonance frequency. In Section 4.2, amplified superfluous signals were observed during the experiments with a weigh-pad that had an air cavity. This signal was generated by propagation of vibration at the resonance frequency, caused by air cavity in the sensor pad. The superfluous signals disappeared when the air cavity was filled. Therefore, it is recommended that vibration damping material is used in the slot where the BL touches the re-enforced rubber material. Dampening the vibration force before it reaches the sensor strip would increase the accuracy of the WIM measurements.

During the installation, wrinkles can be formed on the weigh-pad as described in Section 4.1 and shown in Figure 36. These wrinkles tend to flop when a wheel passes over, causing generation of false axle signals. It is important not to create the wrinkles during the installation, but it is also recommended that an intelligent algorithm is developed to filter such false axle signals since careful installation is not always warranted.

This research used only flat-bottom conveyer belts to construct weigh-pads. Some conveyer belts have horizontal or vertical grooves at the bottom. These grooves are there to increase the friction against pulleys. In the same way, the grooved conveyer belts should increase the friction against the pavement surface and could provide a better fastening capability and stability. However, it is unclear whether it would help or harm the accuracy of the weight measurements. An experimental study is recommended to test grooved weigh-pads.

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Appendix A: Weigh-Pad Test Picture

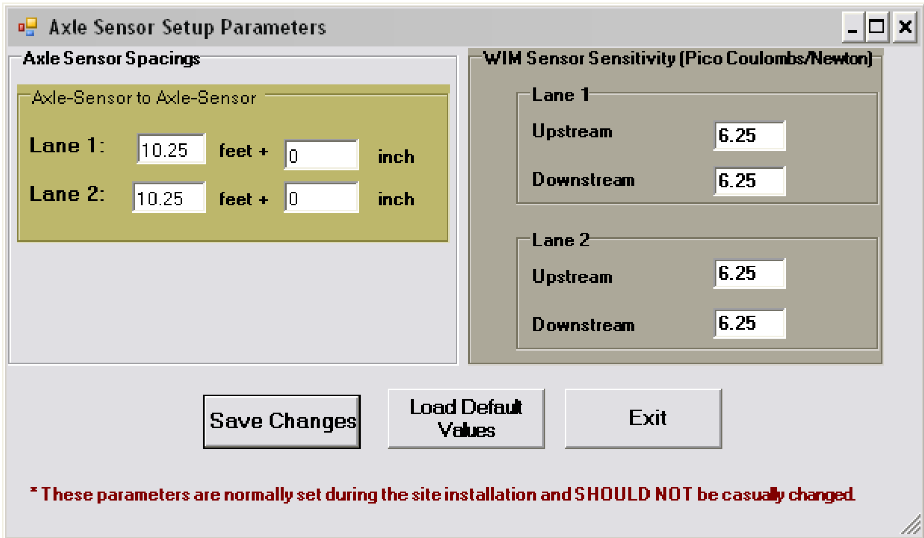
June 4, 2010 Test at MnRoad. The weigh-pads are setup much like a pneumatic tube counter. The sensors in the pictures are the first built weigh-pads. The left side two black strips are a pair of single-lane, single-sensor weigh-pads. The right side wider strip is a single-lane, dual-sensor weigh-pad that contains two parallel BL sensor strips.

Aug 16, 2011, MnRoad Demo Day. About 25 people from MnDOT, State Patrol, Center for Transportation Studies, and industry were invited for a weigh-pad demonstration and presentations at the MnRoad facility. The event started 10:00am and ended 2:30PM.

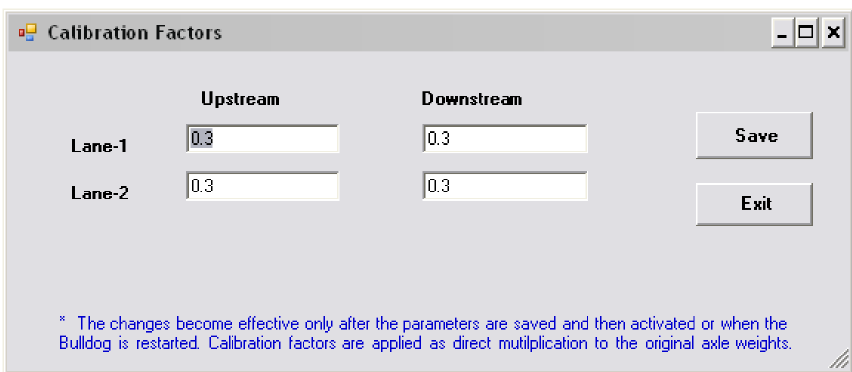
Nov 3 and 4, 2011, Cotton TH-53 Test. The top photograph shows an installation process of weigh-pads on TH-53. A temporary traffic control truck was called in, which can be seen in the back. The bottom picture shows the removal process of weigh-pads on the next day. The weigh-pad data was successfully collected for a side-by-side comparison with the IRD system in this site.

Appendix B: Weigh-Pad System Setting Wizards

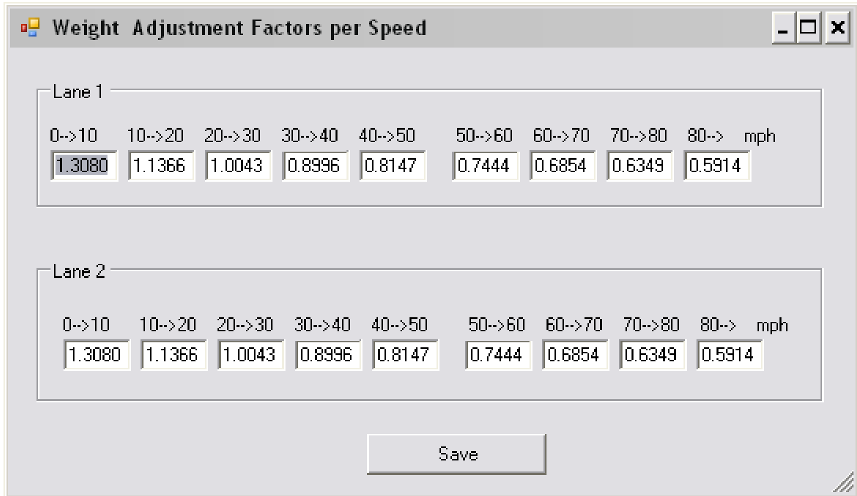
To measure vehicle speeds, spacing of axle sensors in each lane must be set. As shown below, the spacing can be set using both feet and/or inches, but the final value is always converted into feet and set. Sensitivity for each sensor segment must be set, which is supplied by the sensor manufacturer.



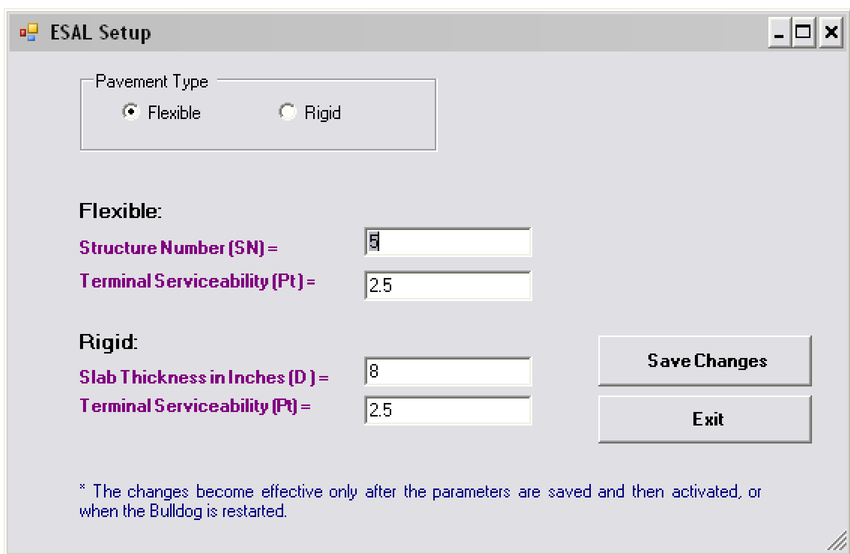
Calibration factors can be entered using the Calibration Factors window. These values are simply multiplied to the final weight computed from each sensor strip. For example, if it is set to 0.5, the weight computed would be halved.



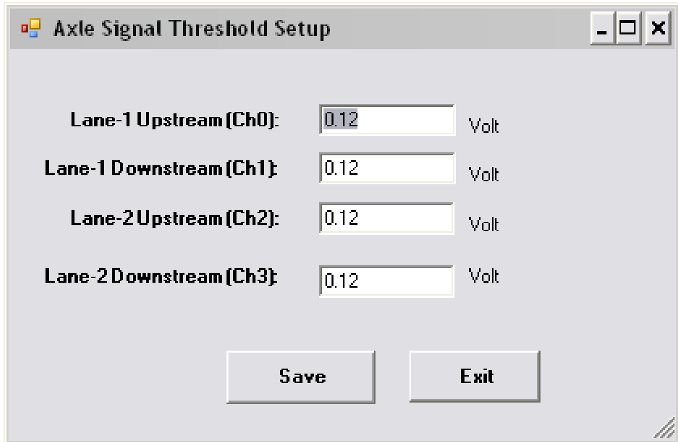
Weights can be calibrated using speed ranges. For example, if the system tends to overestimate weights at a high speed, it can be easily calibrated using the wizard shown below. This window pops up when the menu item, Speed Adjustment Factors, is selected. The entries represent the mid-point of the speed range, from which the rest of points are linearly interpolated.



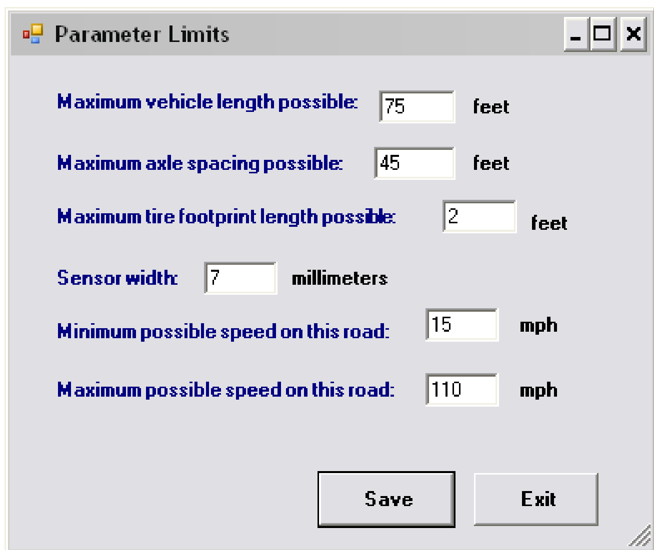
The weigh-pad system computes the ESAL of each vehicle using the parameters set by the ESAL Setup window. This window appears when the menu item, ESAL Setup, is selected. The default values are shown below.



The axle detection is done when the charge amp signal is greater than the threshold value added to the signal idle (resting) level. In the real implementation, the beginning of the axle start signal is traced back from the threshold detection. Because the signal condition of each channel can be different, a threshold value is set for each channel. This window is selected from the menu item, Signal Thresholds.



The weigh-pad software utilizes several limit parameters supplied by the user. For example, the parameter, “Maximum axle spacing possible,” is used to determine the boundary between vehicles. The limit parameters are supplied through the Parameter Limits window.



Appendix C: Sample Weigh-Pad WIM Data

veh#,Lane#,Time,Axle#,speed,AS1(feet),AS2,AS3,AS4,AS5,AS6,AS7,AS8,AS9,AS10,AS11,AW1(kips),AW2,AW3,AW4, AW5,AW6,AW7,AW8,AW9,AW10,AW11,AW12, GVW,Class,Err#,100thSec,pavTemp

----

1,1,11:21:57,2,69,8.3,,,,,,,,,,,3.13,2.93,,,,,,,,,,,6.06,2,0,70,37.6

2,1,11:22:00,3,69,12.0,13.3,,,,,,,,,,4.74,4.03,2.27,,,,,,,,,,11.04,3,0,55,37.5

3,1,11:22:27,3,66,18.7,4.6,,,,,,,,,,12.10,7.94,14.23,,,,,,,,,,34.27,6,0,41,36.4

4,2,11:22:28,2,69,11.8,,,,,,,,,,,5.13,3.32,,,,,,,,,,,8.45,3,0,59,36.4

5,2,11:22:30,2,76,14.1,,,,,,,,,,,4.63,5.33,,,,,,,,,,,9.96,5,0,98,36.2

6,1,11:22:50,2,65,9.5,,,,,,,,,,,3.42,3.46,,,,,,,,,,,6.88,2,0,4,35.7

7,1,11:23:53,2,59,11.9,,,,,,,,,,,4.85,5.08,,,,,,,,,,,9.94,3,0,45,35.5

8,1,11:24:11,0,61,,,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,35.7

9,1,11:24:35,2,72,11.5,,,,,,,,,,,4.88,3.05,,,,,,,,,,,7.92,3,0,59,35.7

10,1,11:24:40,0,67,,,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,35.9

11,2,11:24:50,2,70,8.6,,,,,,,,,,,2.13,1.47,,,,,,,,,,,3.60,2,0,51,36.0

12,1,11:24:55,2,67,9.7,,,,,,,,,,,3.26,3.02,,,,,,,,,,,6.27,2,0,98,36.1

13,2,11:24:57,0,20,,,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,36.1

14,1,11:25:30,5,67,16.6,4.3,36.1,4.0,,,,,,,,16.41,23.41,18.15,13.26,20.80,,,,,,,,92.02,9,0,66,35.7

15,1,11:25:42,2,65,11.5,,,,,,,,,,,7.15,5.57,,,,,,,,,,,12.72,5,0,30,35.5

16,1,11:25:53,2,67,10.0,,,,,,,,,,,3.88,3.44,,,,,,,,,,,7.32,3,0,67,35.6

17,1,11:25:54,0,61,,,,,,,,,,,,,,,,,,,,,,,,0.00,15,12,0,35.6

18,2,11:26:06,0,20,,,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,35.5

19,2,11:26:07,2,72,9.5,,,,,,,,,,,2.77,2.97,,,,,,,,,,,5.75,2,0,80,35.6

20,1,11:26:20,6,67,15.0,4.5,24.5,4.8,5.0,,,,,,,12.98,10.48,9.58,8.49,9.59,10.75,,,,,,,61.87,10,0,73,35.4

21,1,11:26:29,6,67,16.7,4.3,18.7,4.8,4.8,,,,,,,13.16,18.63,18.60,12.58,22.28,20.49,,,,,,,105.74,10,0,61,35.4

22,1,11:26:37,2,65,10.1,,,,,,,,,,,5.15,5.45,,,,,,,,,,,10.60,3,0,55,35.3

23,1,11:26:44,2,66,9.0,,,,,,,,,,,3.15,2.28,,,,,,,,,,,5.43,2,0,24,35.3

24,1,11:27:05,2,69,11.7,,,,,,,,,,,4.73,4.03,,,,,,,,,,,8.76,3,0,89,35.3

25,2,11:27:15,2,71,9.7,,,,,,,,,,1.86,2.14,,,,,,,,,,3.99,2,0,10,35.3

26,1,11:27:17,2,68,9.3,,,,,,,,,,1.63,2.77,,,,,,,,,,4.41,2,0,36,35.3

27,1,11:27:34,2,71,8.7,,,,,,,,,,3.82,3.18,,,,,,,,,,7.00,2,0,42,35.1

28,1,11:27:43,2,62,11.4,,,,,,,,,,3.22,2.89,,,,,,,,,,6.12,3,0,83,35.2

29,1,11:27:45,2,69,8.8,,,,,,,,,,2.17,1.55,,,,,,,,,,3.72,2,0,38,35.2

30,1,11:27:53,4,65,21.2,23.5,2.7,,,,,,,,9.60,29.94,8.39,8.56,,,,,,,,56.49,4,0,36,35.2

31,1,11:28:12,2,69,9.9,,,,,,,,,,4.51,3.84,,,,,,,,,,8.34,3,0,7,35.3

32,2,11:28:21,0,46,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,35.5

33,2,11:28:23,2,30,13.2,,,,,,,,,,3.61,3.14,,,,,,,,,,6.75,3,0,80,35.5

34,2,11:28:28,2,70,12.1,,,,,,,,,,1.72,0.68,,,,,,,,,,2.40,3,0,71,35.6

35,1,11:28:30,2,65,11.6,,,,,,,,,,3.04,2.52,,,,,,,,,,5.56,3,0,21,35.6

36,1,11:28:46,2,67,9.4,,,,,,,,,,2.87,2.15,,,,,,,,,,5.02,2,0,87,36.1

37,1,11:29:29,6,64,16.2,4.3,18.6,4.9,4.9,,,,,,14.30,17.89,18.36,9.42,19.82,20.27,,,,,,100.06,10,0,13,45.5

38,2,11:29:32,2,69,8.6,,,,,,,,,,2.30,1.97,,,,,,,,,,4.26,2,0,0,47.0

39,1,11:29:55,3,70,11.6,15.4,,,,,,,,,3.33,5.07,2.16,,,,,,,,,10.57,3,0,26,48.6

40,1,11:30:16,5,69,17.8,4.3,29.8,4.0,,,,,,,16.06,20.56,22.73,23.02,6.89,,,,,,,89.26,9,0,16,47.5

41,1,11:30:28,3,68,10.5,15.5,,,,,,,,,1.97,2.76,1.65,,,,,,,,,6.38,3,0,33,46.9

42,1,11:31:13,2,67,9.8,,,,,,,,,,5.31,5.59,,,,,,,,,,10.90,3,0,15,45.4

43,2,11:31:13,2,69,8.7,,,,,,,,,,1.44,1.27,,,,,,,,,,2.70,2,0,56,45.4

44,1,11:31:17,0,62,,,,,,,,,,,,,,,,,,,,,,0.00,15,12,0,45.4

45,1,11:31:38,2,64,10.2,,,,,,,,,,3.68,2.58,,,,,,,,,,6.25,3,0,42,45.4

46,1,11:32:12,2,69,12.0,,,,,,,,,,3.29,3.40,,,,,,,,,,6.69,3,0,90,45.6

47,1,11:32:20,2,70,11.8,,,,,,,,,,3.83,2.89,,,,,,,,,,6.71,3,0,12,45.9

1,1,11:33:10,2,72,9.4,,,,,,,,,,3.56,2.48,,,,,,,,,,6.04,2,0,29,46.8

2,1,11:33:35,2,77,10.1,,,,,,,,,,3.04,2.64,,,,,,,,,,5.68,3,0,61,48.3

3,1,11:33:42,2,70,10.6,,,,,,,,,,1.72,1.62,,,,,,,,,,3.34,3,0,23,48.7

4,1,11:34:24,0,66,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,50.7

5,1,11:34:25,2,71,9.0,,,,,,,,,,3.91,2.36,,,,,,,,,,6.28,2,0,58,50.6

6,2,11:35:01,2,61,9.6,,,,,,,,,,2.48,2.09,,,,,,,,,,4.57,2,0,57,48.9

7,2,11:35:15,3,69,10.9,13.2,,,,,,,,,2.45,2.61,0.54,,,,,,,,,5.60,3,0,50,49.5

8,1,11:35:28,2,65,10.2,,,,,,,,,,3.35,2.81,,,,,,,,,,6.17,3,0,71,48.6

9,2,11:35:29,2,68,12.2,,,,,,,,,,2.99,1.71,,,,,,,,,,4.70,3,0,5,48.6

10,1,11:35:30,0,67,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,48.5

11,2,11:35:30,2,65,8.8,,,,,,,,,,2.44,1.89,,,,,,,,,,4.33,2,0,99,48.5

12,1,11:35:34,2,71,8.5,,,,,,,,,,4.24,4.10,,,,,,,,,,8.34,2,0,18,48.2

13,1,11:35:39,2,67,10.5,,,,,,,,,,2.76,2.77,,,,,,,,,,5.53,3,0,15,47.8

14,1,11:35:46,2,65,8.6,,,,,,,,,,2.09,1.81,,,,,,,,,,3.90,2,0,93,47.3

15,1,11:35:50,3,62,11.6,15.9,,,,,,,,,4.63,3.61,3.88,,,,,,,,,12.12,3,0,21,46.8

16,1,11:36:06,2,71,9.5,,,,,,,,,,4.11,3.82,,,,,,,,,,7.93,2,0,4,45.6

17,1,11:36:51,2,70,10.2,,,,,,,,,,3.05,2.25,,,,,,,,,,5.30,3,0,0,44.6

18,1,11:37:15,0,69,,,,,,,,,,,,,,,,,,,,,0.00,15,9,0,44.0

19,1,11:37:16,2,72,9.3,,,,,,,,,,2.34,1.29,,,,,,,,,,3.63,2,0,91,43.9

20,1,11:37:29,2,71,12.0,,,,,,,,,,3.75,2.60,,,,,,,,,,6.35,3,0,17,43.5

21,1,11:38:01,0,70,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,42.9

22,2,11:38:14,2,72,13.4,,,,,,,,,,2.82,1.50,,,,,,,,,,4.32,3,0,7,43.1

23,1,11:39:04,2,71,9.4,,,,,,,,,,3.71,3.30,,,,,,,,,,7.01,2,0,4,41.7

24,2,11:39:11,0,68,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,41.6

25,2,11:39:12,2,73,10.8,,,,,,,,,,2.35,2.92,,,,,,,,,,5.27,3,0,43,41.5

26,1,11:39:23,0,71,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,41.3

27,1,11:39:31,2,65,11.2,,,,,,,,,,2.41,2.31,,,,,,,,,,4.71,3,0,91,41.3

28,1,11:40:19,0,68,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,44.2

29,1,11:40:39,2,64,9.6,,,,,,,,,,2.45,2.18,,,,,,,,,,4.63,2,0,80,44.3

30,1,11:41:07,0,66,,,,,,,,,,,,,,,,,,,,,0.00,15,9,0,46.2

31,1,11:41:27,2,67,8.9,,,,,,,,,,2.61,2.63,,,,,,,,,,5.24,2,0,58,47.9

32,2,11:41:34,3,70,10.5,12.5,,,,,,,,,1.98,1.67,1.32,,,,,,,,,4.97,3,0,63,48.3

33,1,11:42:36,0,66,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,44.0

34,1,11:42:37,2,67,9.4,,,,,,,,,,2.49,2.16,,,,,,,,,,4.65,2,0,43,43.8

35,1,11:42:47,2,69,9.4,,,,,,,,,,2.58,2.04,,,,,,,,,,4.62,2,0,75,43.2

36,1,11:42:55,5,65,12.1,4.3,28.5,4.1,,,,,,,10.71,14.60,13.52,13.24,11.68,,,,,,,63.75,9,0,44,42.7

37,1,11:43:17,2,66,19.7,,,,,,,,,,9.40,10.45,,,,,,,,,,19.85,5,0,92,41.7

38,1,11:43:29,2,48,14.6,,,,,,,,,,17.15,12.22,,,,,,,,,,29.37,5,0,66,41.4

39,1,11:43:43,2,71,11.8,,,,,,,,,,2.84,2.17,,,,,,,,,,5.01,3,0,8,41.1

40,1,11:44:47,5,65,18.4,4.3,28.6,4.1,,,,,,,3.76,3.55,3.26,3.00,2.97,,,,,,,16.54,9,0,72,45.9

41,2,11:44:47,5,65,18.4,4.3,28.8,4.1,,,,,,,4.72,3.69,3.43,2.83,2.88,,,,,,,17.54,9,0,71,45.9

43,1,11:45:18,2,67,13.7,,,,,,,,,,5.82,11.41,,,,,,,,,,17.23,5,0,43,46.7

44,1,11:46:37,2,71,9.4,,,,,,,,,,4.33,2.70,,,,,,,,,,7.03,2,0,54,45.6

45,1,11:46:40,4,64,10.8,20.8,2.6,,,,,,,,2.96,3.34,2.66,3.13,,,,,,,,12.09,3,0,16,45.3

46,2,11:46:48,2,69,11.7,,,,,,,,,,3.38,2.54,,,,,,,,,,5.92,3,0,58,44.7

47,1,11:47:03,2,71,8.7,,,,,,,,,,2.48,2.56,,,,,,,,,,5.04,2,0,63,45.1

48,1,11:47:18,2,65,9.3,,,,,,,,,,2.31,2.55,,,,,,,,,,4.86,2,0,47,46.8

49,1,11:47:42,2,61,9.1,,,,,,,,,,3.12,2.82,,,,,,,,,,5.94,2,0,92,49.3

50,2,11:47:44,2,67,11.7,,,,,,,,,,4.03,4.13,,,,,,,,,,8.16,3,0,19,49.5

51,1,11:48:07,3,57,18.4,4.5,,,,,,,,,11.06,15.75,14.48,,,,,,,,,41.30,6,0,91,51.0

52,1,11:48:20,3,60,12.0,13.2,,,,,,,,,3.57,4.08,2.34,,,,,,,,,9.99,3,0,57,50.3

53,1,11:48:22,0,60,,,,,,,,,,,,,,,,,,,,,,0.00,15,8,0,50.3