
**Innovations Deserving
Exploratory Analysis Programs**



Highway IDEA Program

Battery-Less Wireless Weigh-in-Motion Sensor

Final Report for
Highway IDEA Project 165

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Battery-Less Wireless Weigh-in-Motion Sensor

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Executive Summary

This project focuses on the development of a new generation battery-less wireless weigh-in-motion (WIM) sensor.

The WIM sensor utilizes an energy harvesting system previously developed by the research team. As each axle of a vehicle travels over the sensor location in the road, vibrations are induced in the sensor and energy is harvested from these vibrations to power both sensor operation and wireless transmission. This results in a battery-less wireless sensor. No wires are required for powering the sensor or for obtaining the weight measurement signal from the sensor.

Major shortcomings in the previous WIM sensor included the use of a baler belt top for the sensor and inability to grout the sensor for permanent installation in pavement. These shortcomings are addressed in this project by developing an all-metal design for the sensor. The all-metal design encloses all of the electronics, protecting them from debris and water, while providing a rugged sensor capable of withstanding repeated heavy truck loads. An enclosure with a flexible top allows the sensor system to be grouted to the pavement without significant reduction in axle loads transmitted to the sensor for energy harvesting.

A smart phone app is developed that allows internet access to the weight measurements from the sensor both on Android smart phones as well as tablets. A roadside transceiver and router system is used to place the measured WIM sensor data at a dynamic IP address on the internet. The smart phone app reads this data from the IP address and presents it in a convenient graphical user interface (GUI) for the user. Operation of the smart phone app and its GUI are presented in the report.

The performance of the sensor is evaluated at the Minnesota Road Research Facility (MnRoad) in an asphalt pavement. A number of test vehicles including a passenger sedan, pick-up trucks, a minivan, a snowplow and a semi tractor-trailer are used to evaluate the performance of the system. The WIM system provides weight measurements that increase monotonically with increasing axle weights. However, significant variability is found from one test to another for the same vehicles and same axle loads. Vibrations measured on the truck axles show low vibrations at 10 mph, and high vibration levels reaching up to 500 mg rms at 50 mph. Since significant variability in measured axle weights is seen even at 10 mph, it is concluded that the measurement variability is not purely due to truck suspension vibrations. The variability is diagnosed to be due to the sensor enclosure box, which provides variability in load depending on the lateral position of the vehicle in the lane.

A new WIM sensor is then designed, fabricated and evaluated that is based on measurements of strain in the enclosure box itself. As expected in the design, the new sensing system provides better performance that reduces measured weight variability by more than 50%. However, there is no easy path to integrate the new design with a battery-less wireless energy harvesting system.

The research team recommends that the second year of the project (which involved extensive testing of the sensor with varying temperature and environmental conditions) be abandoned, since the sensor developed in year 1 did not provide adequately satisfactory performance.

Acknowledgments

The research team would like to thank the Minnesota Department of Transportation for providing access to the MN Road Research Facility for this project and to Ms. Deborah Walker from FHWA for serving as the IDEA advisor for this project.

I. INTRODUCTION

This project focuses on development of a new generation battery-less wireless weigh-in-motion (WIM) sensor.

In previous research funded by the ITS Institute, University of Minnesota, and the Minnesota Department of Transportation (MnDOT), a prototype WIM sensor had earlier been developed by the research team. An early generation prototype sensor utilized a 6-feet long beam structure that covered half the width of a 12-feet wide highway lane (1). A photograph of this prototype sensor is shown in Figure 1.1.



Figure 1.1: Prototype first generation WIM sensor.

The sum of forces measured by all the legs of the sensor equal the total vehicle axle load on the sensor. Figure 1.2 shows a close-up of each leg of the WIM sensor (1). The leg has a two-layer structure. The top layer is the axle weight measurement layer while the bottom layer is the energy harvesting layer (2). Bending motion in both layers is utilized and exploited using piezoelectric film transducers. In the top layer the bending strain is measured using thin film transducers. This layer is constructed of thicker steel plates which undergo linear elastic bending to obtain a sensor response proportion to the load on the sensor. By having the load on the leg act through the center of the leg, the strain is influenced only by the magnitude of the load on each leg.

The lower layer of the leg is used for energy harvesting. As seen in Figure 2.1, this layer is constructed with thinner steel plates and has been designed to undergo larger deflections under axle loads. Further, the plates encounter a stop that prevents strain beyond a pre-determined limit value. This ensures that the lower layer undergoes a large strain for low loads and subsequently undergoes no more strain. Since the harvested energy depends on the magnitude of strain, adequate energy is harvested even for low-weight vehicles. Due to saturation of strain at high vehicle loads, failure in the sensor is prevented, in spite of large strains for low vehicle loads (1).

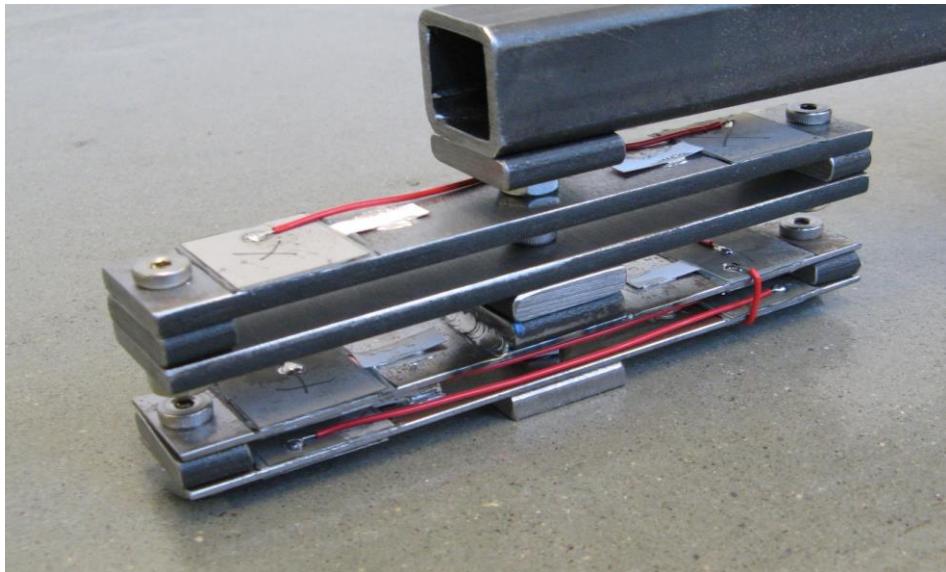


Figure 1.2: Two-layered leg design for first generation WIM sensor.

A major shortcoming of the previous generation sensor was that it had only been tested by wedging the sensor into a slot in concrete pavement. The sensor had not been grouted to the pavement. It could not be grouted to the pavement because that would increase the overall stiffness of the sensor-road system and reduce the load transmitted to the piezo transducers for energy harvesting. A design with a baler belt top for the sensor had been proposed to allow adequate transmission of forces to the energy harvesting piezo transducers after grouting.

This project develops a new all-metal design for the WIM sensor. The new design, as described in Chapter II, allows the sensor system to be grouted to the pavement so that it can be permanently installed. The piezo stacks in the re-designed sensor legs obtain adequate loads from each vehicle axle in spite of the grouting to the pavement, so that adequate energy is harvested from each axle to power the operation of the sensor. Further, the design ensures that all of the electronics inside the sensor are enclosed and protected fully from debris, water and other road environmental intrusions.

This project also develops a smart phone app using which any user can access the signals measured by the WIM sensor. The measurements from the WIM sensor in the highway lane are transmitted to a roadside receiver located on the shoulder. The roadside receiver uses a router to set up an IP address at which all measurements from the sensor are made available. The smartphone app accesses the data at this IP address and displays the data in a friendly graphical user interface. The smart phone app is designed for Android operating systems and can be used on both smart phones as well as tablets.

Chapter II of this report describes the challenges addressed by the new design of the sensor and presents the new generation design.

Chapter III of the report describes the smart phone app and its design. The electronics that enable smartphone access to the WIM sensor readings are also described.

Chapter IV of the report describes the experimental performance of the sensor. As shown in the experimental results, a monotonic sensor response that increases monotonically with increasing axle weights is demonstrated with a variety of vehicles. However, the sensor displays significant variability from one test to another test for the same vehicle axle loads. The reasons for this variability are discussed.

Chapter V describes a new sensor design that addresses the variability in sensor response with vehicle lateral location. The results in this chapter show that the variability is reduced by more than a factor of two with the new design.

Chapter VI discusses the conclusions from this research project.

II. WIM SENSOR DESIGN AND INSTALLATION

2.1 CHALLENGES

A number of changes were made to the earlier design of the weigh-in-motion (WIM) sensor to address the following challenges:

- 1) The sensor needed to be converted into an all-metal device, without requiring the use of a baler-belt top for the sensor. The challenges in an all-metal construction are that the sensor needs to provide adequate motion for piezo stack compression, so as to harvest adequate energy. Allowing for such sensor motion when the sensor device is grouted and fixed to the pavement is difficult.
- 2) The piezo stack needs to be protected from excessive loads when a heavy truck travels over the sensor. At the same time, the piezo stack needs to experience enough fraction of the load to harvest adequate energy when a much lighter vehicle travels over the sensor. In previous designs of the sensor, there were issues with failure of the piezo stack during heavy truck loads.
- 3) The WIM piezos that measure the axle weights of the vehicle need to experience a load proportional to the axle weight for a huge range of vehicle weights ranging from 2,000 pounds to 40,000 pounds. The weigh-in-motion piezos need to show both good sensitivity and a large load range.
- 4) There were also issues with failure of the electronics during heavy truck loads. This likely happened due to high voltages generated in the piezo stack during heavy vehicle loads.

2.2 SENSOR DESIGN

The sensor consists of a main body and four sensor legs. The four sensor legs were moved into slots in the sensor body so that the total height of the sensor was reduced to 3.75 inches and so that it could be accommodated into an asphalt pavement. Figure 2.1 shows a photograph of the new design of the sensor. Please note that in this picture the sensor is placed on its side, so as to

show the four legs. During actual operation, the sensor is placed with its four legs in a slot on the pavement.

All metal design: An earlier design of the sensor used a baler belt top for the sensor. Figure 2.2 shows a photograph of an earlier sensor with a baler belt top. The new design of the sensor uses an all-metal casing in which the entire sensor is placed inside a metal box with a thin plate top. The metal casing can be grouted to the pavement. The sides of the metal box do not need to move. The thin plate top of the casing bends and transfers load to the sensor inside the box. The metal casing and grouting is discussed in Section 2.4.



**Figure 2.1: Photograph of sensor body and four sensor legs
(sensor is placed on its side for this photograph).**



Figure 2.2: Photograph of earlier sensor with baler belt top.

The actual design of each leg of the sensor is shown in Figure 2.3. Some features of the design are:

- 1) The use of a Bellville washer as a spring below the piezo stack allows the displacement of the piezo stack to be better predicted and controlled.
- 2) The piezo stack is protected from excess loads by allowing it to slip below the surrounding steel tube after a pre-determined level of displacement of the piezo stack. Further load is then experienced by the steel tube and is not transferred to the piezo stack. This design allows the piezo stack to harvest adequate energy even from light vehicles, while being protected from overloading from heavy trucks.
- 3) The WIM piezo transducers have springs both in series and in parallel with the transducers. The springs in series are soft while the springs in parallel are very stiff. This allows the WIM transducers to experience only a small fraction of the total weight of the vehicle axle. At the same time, the fraction of weight experienced by the transducer never saturates.
- 4) For small vehicle loads, the springs in series with the piezo transducer determine the sensitivity to axle load. Hence the sensor is expected to show good sensitivity for lighter vehicles. For higher loads, the springs in parallel determine the sensitivity to axle load. This ensures that the sensor has adequate range for measuring axle weights of very heavy trucks.

Figure 2.3 shows full details of the components used in the new sensor leg design. Figure 2.4 shows a cutaway view of the whole sensor.

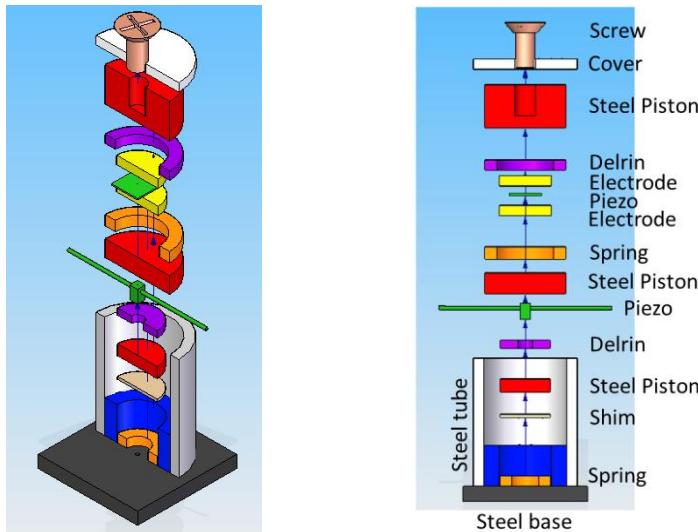


Figure 2.3: Details of new sensor leg design.

Figure 2.4 shows the overall sensor design, including the sensor legs inside the sensor main body.

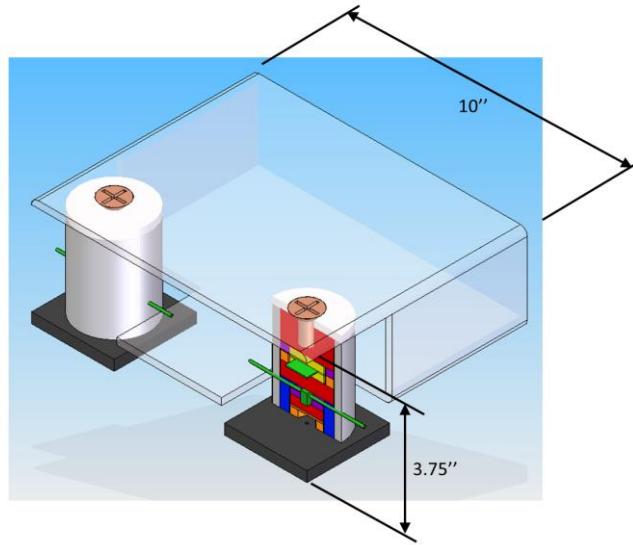


Figure 2.4: Overall design of second generation sensor showing legs inside main body.

2.3 SENSOR FABRICATION

The legs of the sensor were fabricated. The fabricated parts assembled together are shown in the photograph below in Figure 2.5.

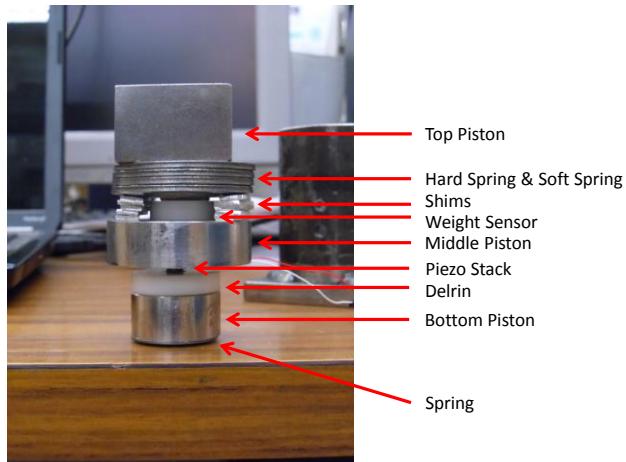


Figure 2.5: Fabricated and assembled sensor leg components.

The sensor leg components and their assembly process are shown in Figure 2.6

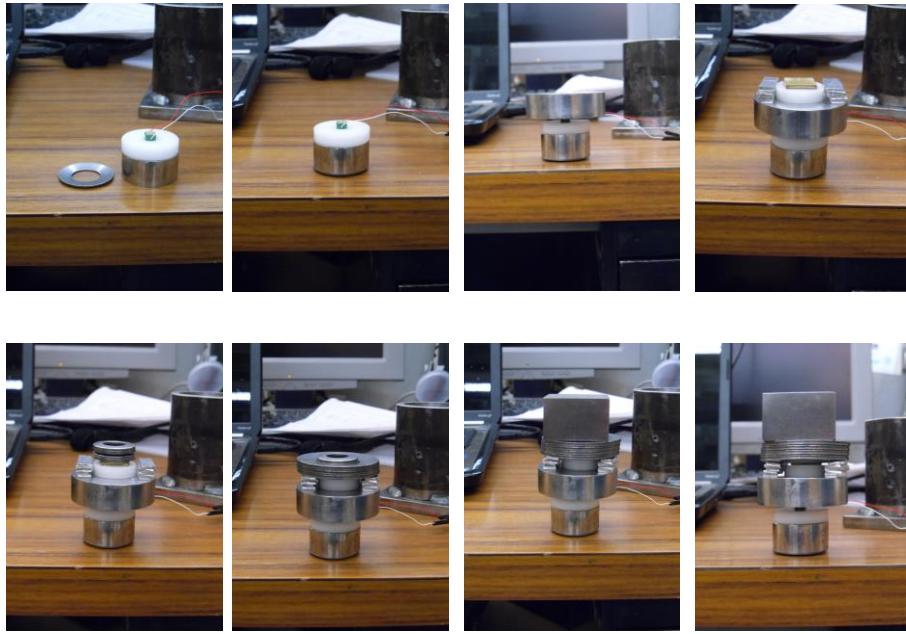


Figure 2.6: Sensor leg components and assembly.

A side view of the complete sensor showing the shape and structure of two of the legs of the sensor is shown in Figure 2.7.

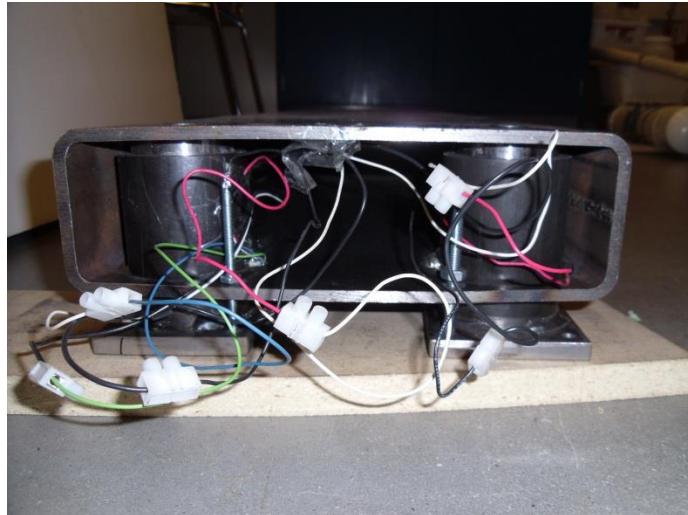


Figure 2.7: Side view of sensor and two legs.

2.4 SENSOR INSTALLATION

A key challenge relates to having the sensor installed in the pavement and yet allowing adequate deflection of the piezo stack and the piezo transducers in the legs of the WIM sensors. This challenge has been addressed by using a box as an external casing for the sensor. The box is grouted to the pavement and is thus permanently installed, as shown in Figure 2.8. The sensor (Figure 2.9) is placed inside the box. The top of the box is sealed with a thin plate top (Figure

2.10). The bending of the top allows the legs of the WIM sensor to undergo compressional motion. This solution allows the device to be fixed to the road and yet have adequate motion inside the sensor for energy harvesting.



Figure 2.8: A box enclosure for installation of sensor inside asphalt pavement.



Figure 2.9: Fabricated sensor showing four legs of the device
(sensor is upside down in this photograph).

A photograph of the grouted metal casing with the sensor inside is shown below in Figure 2.10.

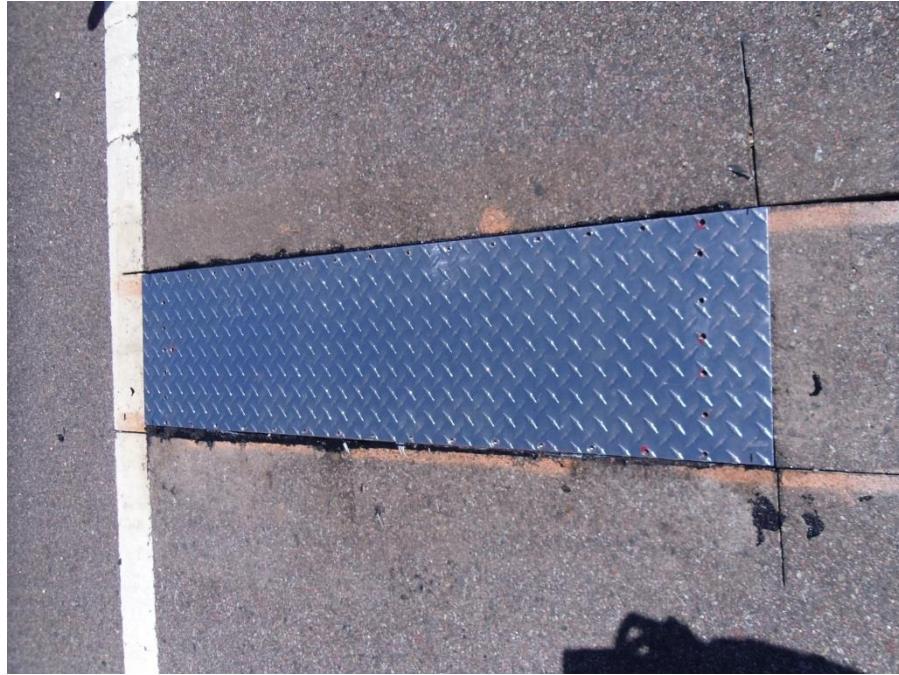


Figure 2.10: Photograph of sensor in external box that has been grouted in asphalt pavement

III. SMART PHONE APP FOR WIRELESS SENSOR ACCESS

3.1 ELECTRONICS INSIDE WIM SENSOR

Figure 3.1 shows the electronic circuit used for harvesting energy from the piezoelectric stack. The circuit uses the Linear Technology LTC3588-1 chip. The piezo stack AE0505D08F from Thor Labs is used as the energy generation element. The mechanical design for accommodating the piezo stack in the legs of the WIM sensor was discussed earlier in Chapter II. The input capacitor in the circuit is used to store energy after rectification of the voltage from the piezo stack. The output capacitor receives power from the input capacitor, after the voltage on the input capacitor has adequately built up. An in-built voltage regulator on the LTC chip ensures that a constant voltage of 3.6 volts is supplied across the output capacitor. This output port supplies the energy required for the weight measurement and wireless transmission circuits.

Figure 3.2 shows the circuit used to measure the weight of each axle. The voltage from the sheet piezo is passed through a half-rectifier and used to charge a weight measurement capacitor. The voltage across the capacitor is proportional to the charge generated in the piezo and hence the weight of the axle. MOSFETs and the CC430 microprocessor (3) are used to discharge the capacitor after the voltage across it has been measured and before the next axle loads the sensor.

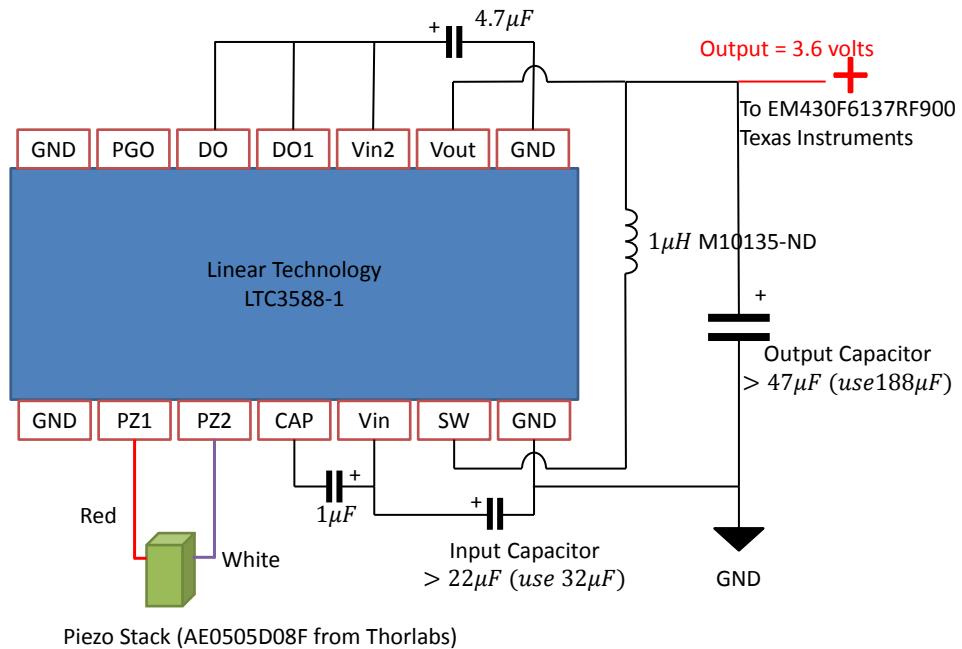


Figure 3.1: Energy harvesting circuit that interfaces with piezoelectric stack.

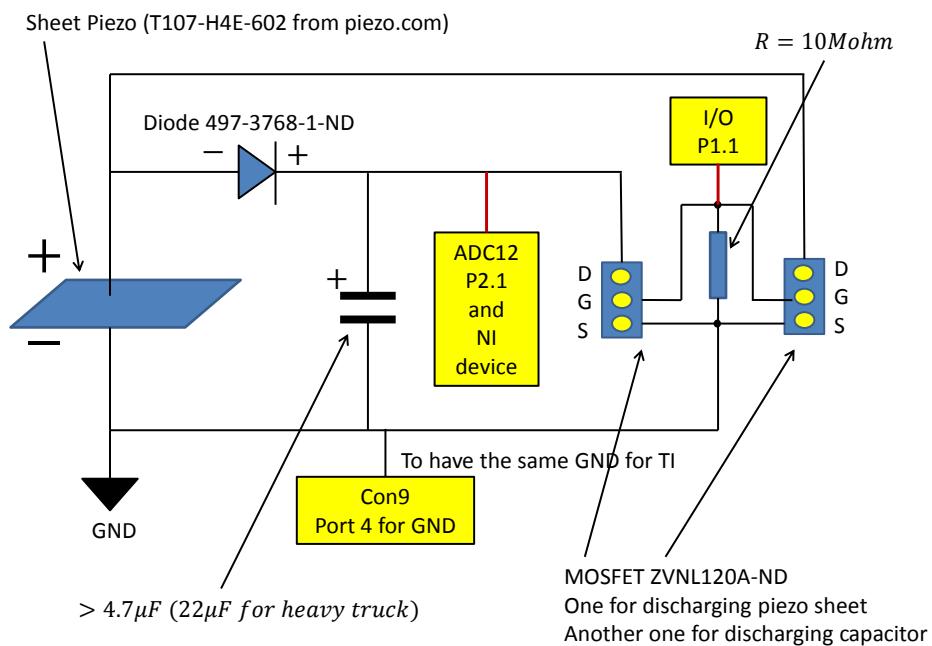


Figure 3.2: Weight measurement circuit that uses piezo film and charge amplifier circuit.

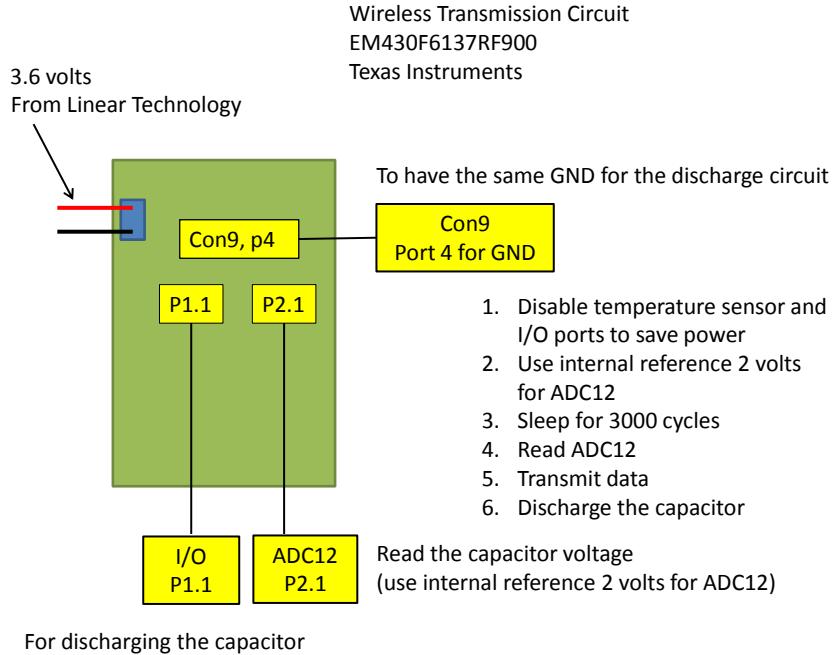


Figure 3.3: Wireless transmission circuit.

Figure 3.3 shows the wireless transmission circuit for the WIM sensor. The CC430 (3) chip that contains an integrated microprocessor and transceiver is used. The energy harvesting circuit provides a regulated 3.6 volts to the CC430 chip. The CC430 chip wakes up when it receives input power, reads the weight measurement signal from the WIM capacitor, transmits the measured data wirelessly and then discharges the capacitor. The sequence of steps executed by the CC430 chip is shown in Figure 3.3.

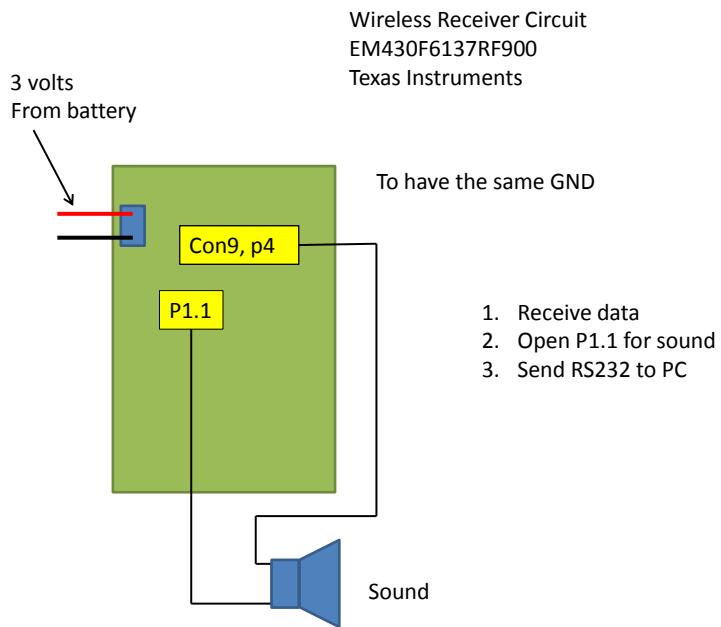


Figure 3.4: Wireless receiver circuit.

Figure 3.4 shows the wireless receiver circuit used to read the wireless signals received from the WIM sensor. This circuit board is placed on the roadside shoulder. It receives the wireless signals using a CC430 Texas Instruments chip and then uses I2C serial communication to send the data to a laptop or other device over a RS232 serial port.

3.2 SENSOR INTERFACE WITH WIRELESS INTERNET

The CC430 microprocessor situated at the side of the road wirelessly receives the weigh-in-motion signals from the sensor. The CC430 then connects with an Arduino processor to create an IP address which can be accessed by the smart phone. The process is as follows.

The information of each axle being detected by the WIM system is transferred to the Arduino board through serial communication from the CC 430. The Arduino board receives the axle information and adds a time tag to it. Time is obtained from a real time clock with a resolution of 0.1 seconds through SPI connection. If the current axle information is received within a threshold time from the previous received axle information, it is assumed that the current axle information is a part of the same vehicle as the previous vehicle. For example, if two axles are detected within the time threshold, it is assumed that these two axles belong to a two-axle passenger vehicle. As another example, if five axles are received within the time threshold of each other, it is assumed that these axles belong to a five-axle vehicle. This information is then stored into “variables” in the Arduino board. The “variables” include the detected vehicle number, number of axles, weight of each axle and time of detection of each axle. The “Arduino Ethernet shield R3” can be programmed to resemble a little web server. Similar to a regular web server, html code can be used to generate a webpage. The html code for the website can be written inside the program of the Arduino board, and as soon a new vehicle is detected, the html code is updated to

include the information of the newly detected vehicle. The created webpage can be accessed through the Ethernet port of the Arduino board, and if a wireless router is connected to this port, the webpage can be accessed through any wireless device. The smart phone application accesses this webpage and shows it properly on the phone using a graphical user interface. It also updates the data contents at regular time intervals.

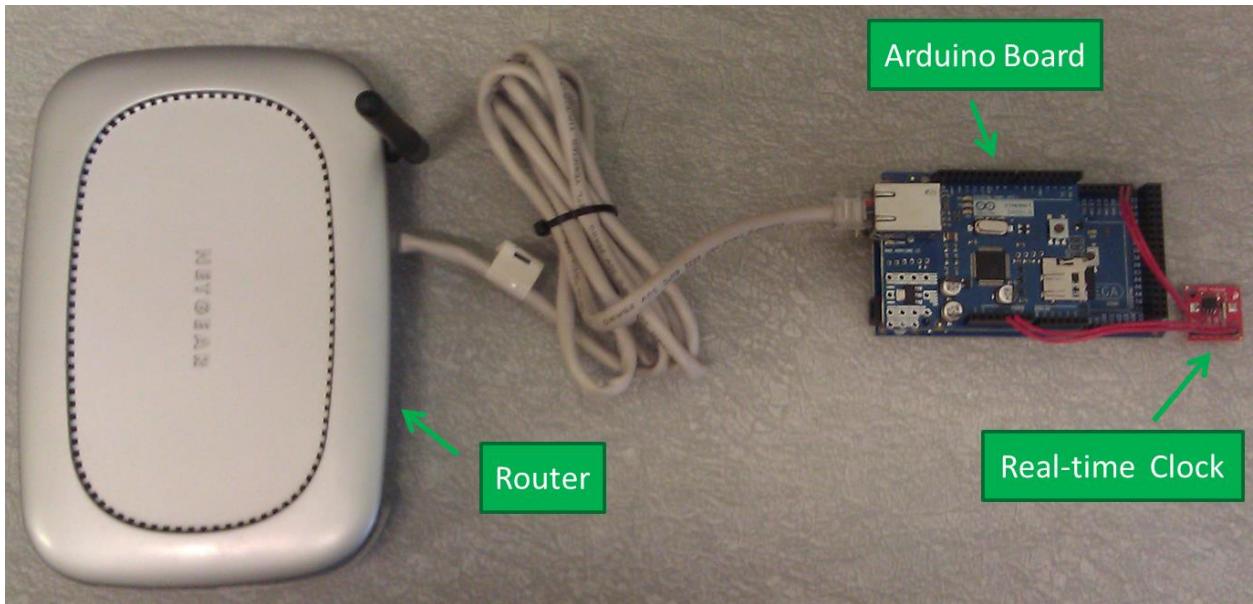


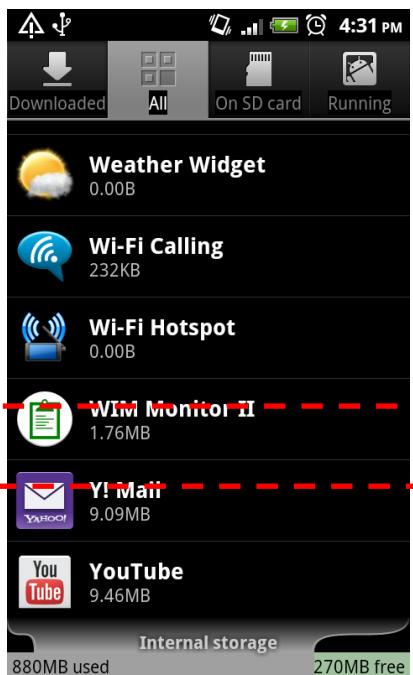
Figure 3.5: Arduino board and router which set up website for app on smart phone.

3.3 SMART PHONE APP

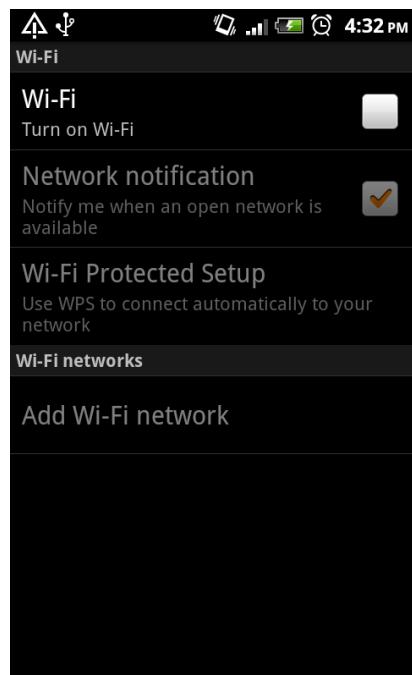
A smart phone app has been designed to access the WIM sensor's IP address and obtain weigh-in-motion data of cars and trucks that have travelled over the sensor. The smart phone app has been designed for Android smart phones and can be accessed over phones and tablets. The following figures (3.6, 3.7, 3.8, and 3.9) show the smart phone app in operation.

The Java programming language and the Eclipse IDE (Integrated Development Environment) with built-in ADT (Android Developer Tools) have been used to develop a smart phone application for WIM system. The main task of the developed application is to access the webpage created by the Arduino board and refresh the contents at regular time intervals. Besides, the application configurations like the name of the application, current version, icon, auto-rotate feature, adjusting the page to the screen, and etc., are developed and set through Eclipse IDE. The “Arduino Ethernet shield R3 with micro SD connector” is used in order to create a webpage to be accessed by the smart phone application, as described in Section 3.2.

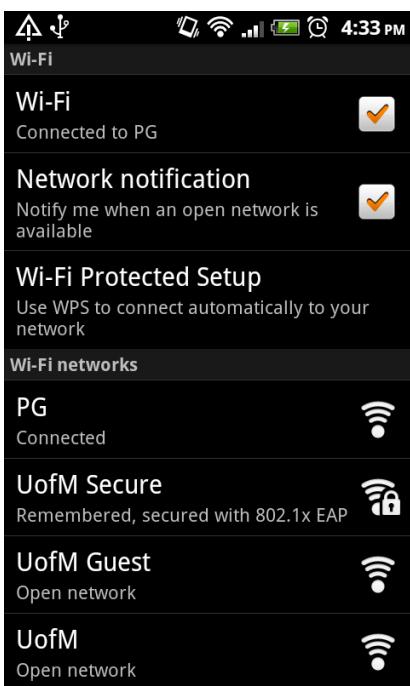
1. Install the application on the device



2. Turn on Wi-Fi



3. Get connected to WIM network, here called PG



4. Start "WIM Monitor" application. This is how it looks like when no vehicle has been detected

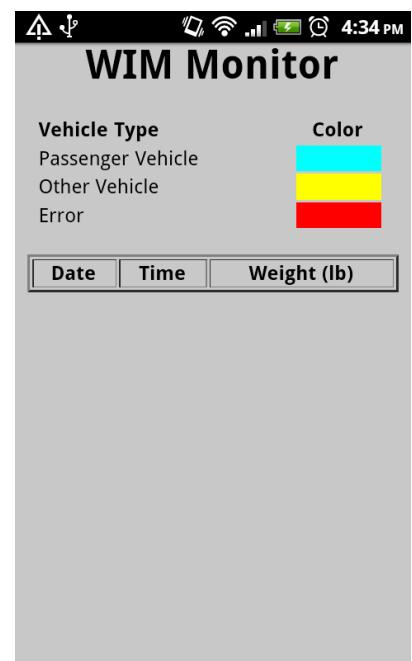
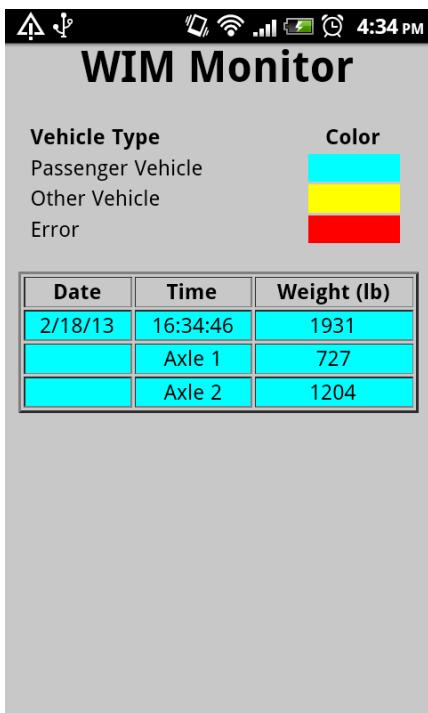
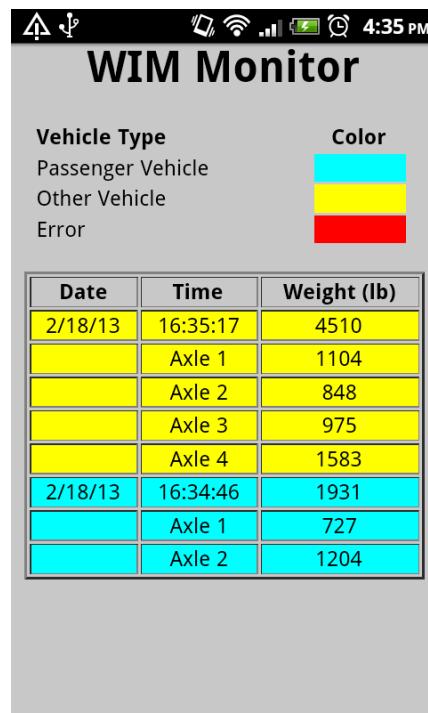


Figure 3.6: Start "WIM Monitor" application: Screen appearance when no vehicle has been detected.

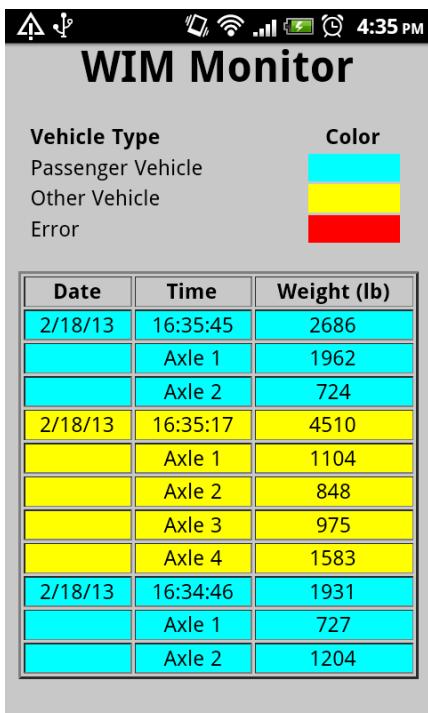
1. A two-axle vehicle is detected



2. A four-axle vehicle is detected



3. A two-axle vehicle is detected



4. A three-axle vehicle is detected

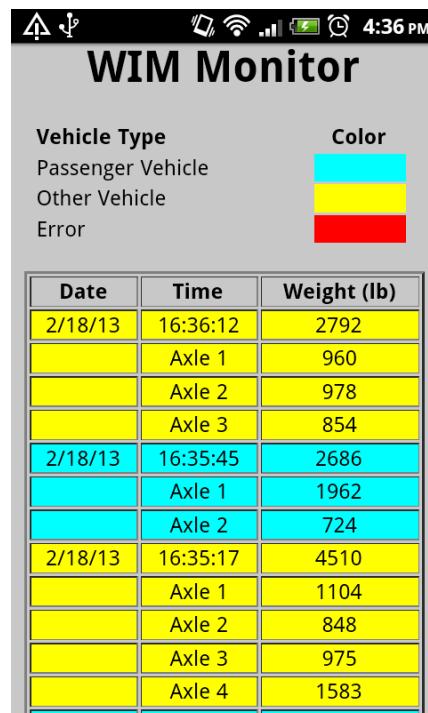


Figure 3.7: Two-axle, four-axle, and three-axle vehicles are detected and shown on the app.

The screenshot shows a smartphone application titled "WIM Monitor". At the top, there is a legend for "Vehicle Type" and "Color": "Passenger Vehicle" is cyan, "Other Vehicle" is yellow, and "Error" is red. Below this is a table with three columns: "Date", "Time", and "Weight (lb)". The data in the table is as follows:

Date	Time	Weight (lb)
2/18/13	16:38:58	6322
	Axle 1	1103
	Axle 2	960
	Axle 3	1217
	Axle 4	1702
	Axle 5	1340
2/18/13	16:36:12	2792
	Axle 1	960
	Axle 2	978
	Axle 3	854
2/18/13	16:35:45	2686
	Axle 1	1962
	Axle 2	724

Figure 3.8: A five-axle vehicle is detected and shown on the app.

This screenshot shows the same "WIM Monitor" application interface, but the table is much longer, indicating many more vehicle detections. The data is identical to Figure 3.8, showing a five-axle vehicle with weights for each axle across three different times on 2/18/13. The table continues downwards, suggesting it is scrollable.

Axle 1	1103
Axle 2	960
Axle 3	1217
Axle 4	1702
Axle 5	1340
2/18/13	16:36:12
Axle 1	960
Axle 2	978
Axle 3	854
2/18/13	16:35:45
Axle 1	1962
Axle 2	724
2/18/13	16:35:17
Axle 1	1104
Axle 2	848
Axle 3	975
Axle 4	1583
2/18/13	16:34:46
Axle 1	1931
Axle 2	727
Axle 2	1204

Figure 3.9: Smart phone app: It is possible to scroll down and see the vehicles detected earlier.

Experimental Results

4.1 AXLE WEIGHT READINGS

Experiments were conducted at the MnRoad road research facility with a variety of test vehicles that included a passenger sedan, a small pick-up truck, a large pick-up truck, a snowplow and a semi tractor-trailer. Over 20 tests at a variety of speeds from 10 to 50 mph were conducted with each vehicle. The mean voltage response from the WIM sensor for some of the axle weights are shown in Figure 4.1. The voltage signal provided by the sensor was a monotonically increasing function of vehicle weight.

First, it was found that adequate energy was harvested even from the smaller vehicles using the piezo stacks for both weight measurement and wireless transmission. Thus, battery-less wireless operation was achieved with no major problems.

Approximate Weight Per Axle vs. Voltage

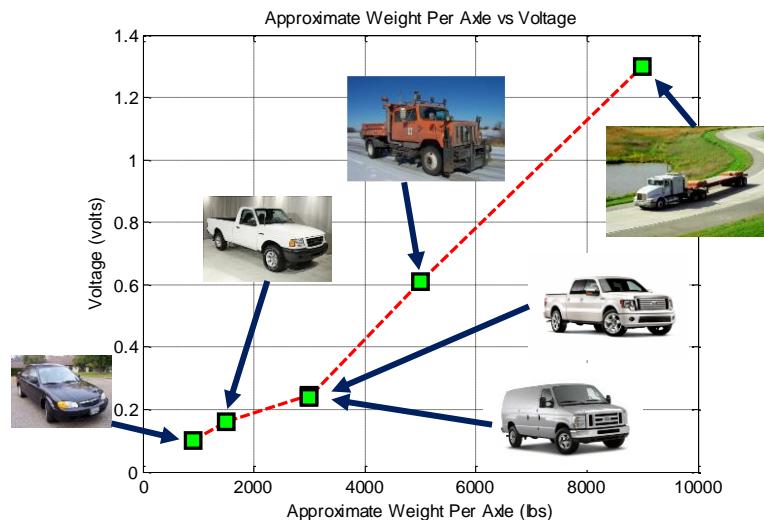


Figure 4.1: Sensor signal as a function of vehicle weight.

From Figure 4.1, it is clear that the sensor generated a voltage signal that increases monotonically with vehicle axle weight. Hence a one-to-one relationship between voltage and weight can be utilized for automatic weight determination.

4.2 VARIABILITY IN AXLE WEIGHT READINGS

The weigh-in-motion measurements of the sensor for various vehicles are shown in Figure 4.2 below for speeds from 0–40 mph. The vehicles used in the tests are a small pick-up, a mini-van, a large pick-up, a snowplow, and a five-axle 80,000 pound semi truck. The weights shown are half-axle weights. Figure 4.3 shows half-axle weights for the same vehicles for the speed range 0–50 mph.

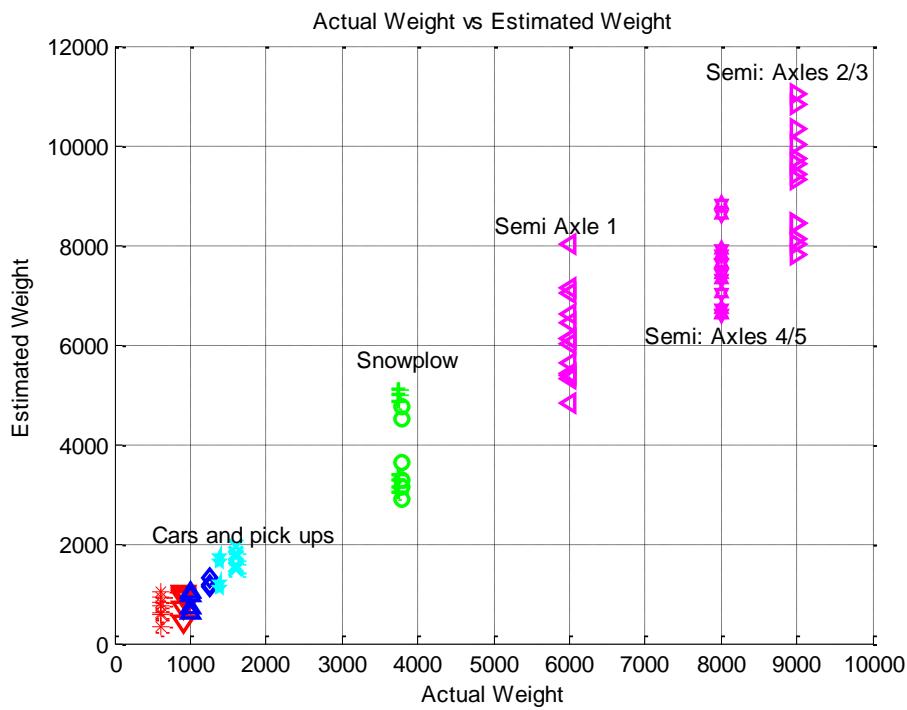


Figure 4.2: Half-axle weight measurements for various vehicles at speeds from 10–40 mph.

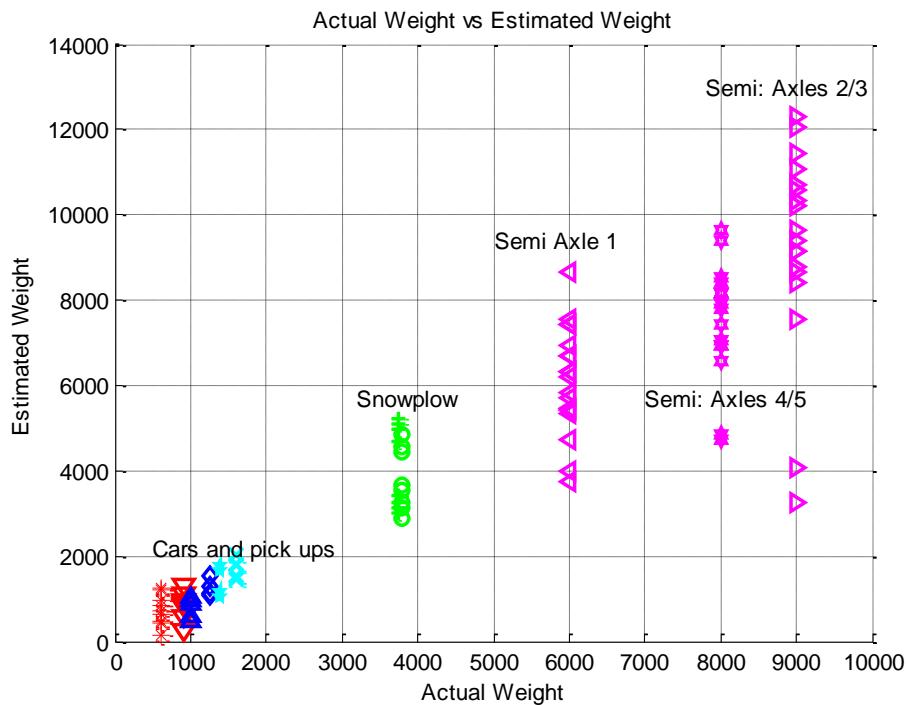


Figure 4.3: Half-axle weight measurements for various vehicles at speeds from 10–50 mph.

It can be seen that there is a significant spread in the weight measurements for the semi tractor-trailer and that this spread is worse for the 10–50 mph speed range compared with the 10–40 mph speed range.

4.3 TRUCK VIBRATIONS

Since the variability in measured weight is worse for the 10–50 mph speed range compared with the 10–40 mph speed range, it was suspected that the variability is due to vibrations in the truck suspension (In other words, the large variations in weight are due to actual variations in load on the sensor resulting from dynamic suspension vibrations).

The figures below (Figures 4.4–4.8) show axle vibrations on the first and second axles of the semi truck at speeds ranging from 10 mph to 50 mph. It can be seen that vibrations are low at 10 mph (< 100 milli-g's rms), increase to 500 mg rms at 40 mph and increase significantly to 900 mg rms at 50 mph.

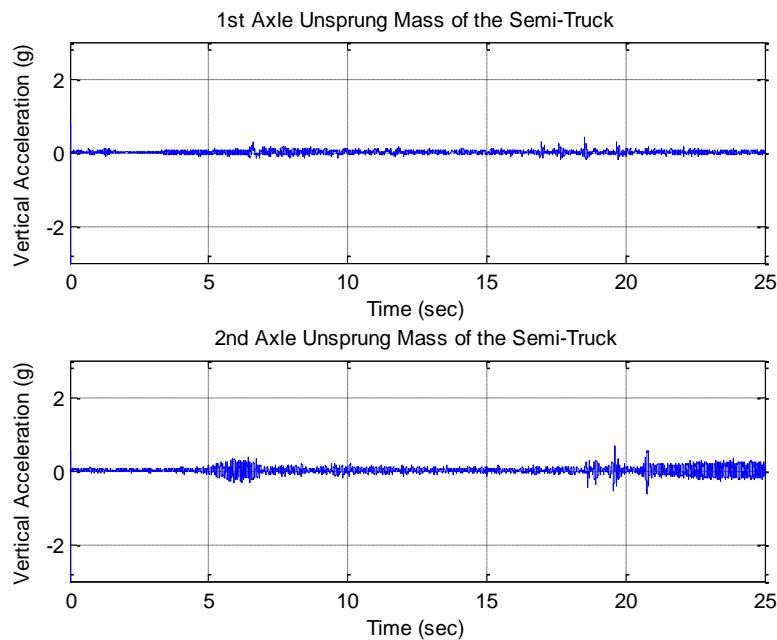


Figure 4.4: Axe vibrations on semi truck at 10 mph.

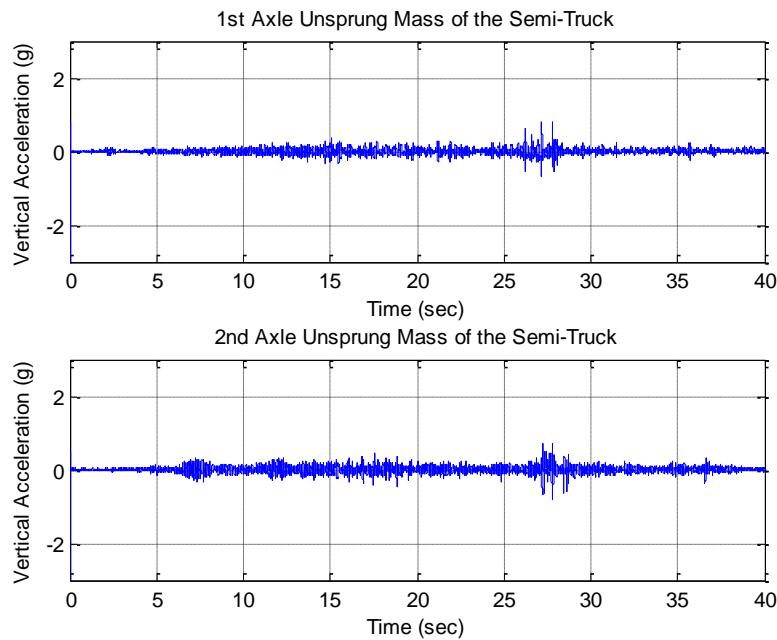


Figure 4.5: Axle vibrations on semi truck at 20 mph.

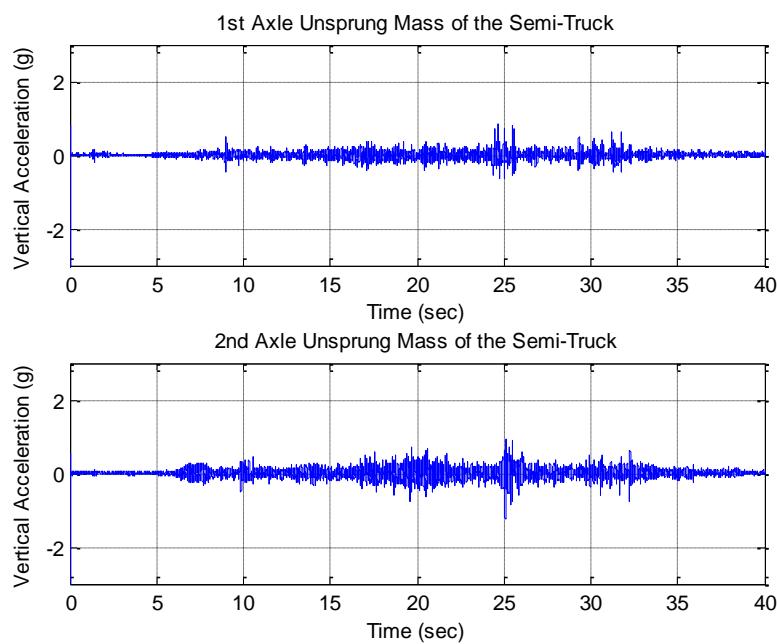


Figure 4.6: Axle vibrations on semi truck at 30 mph.

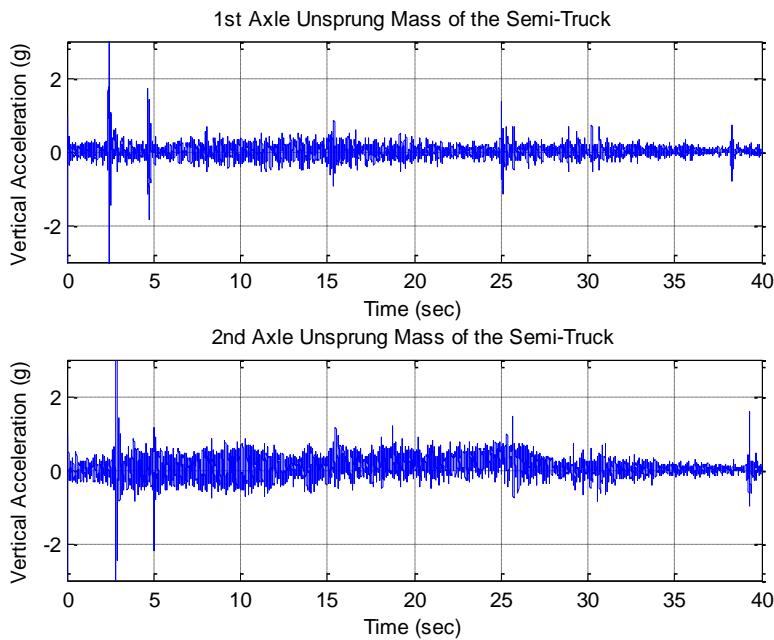


Figure 4.7: Axe vibrations on semi truck at 40 mph.

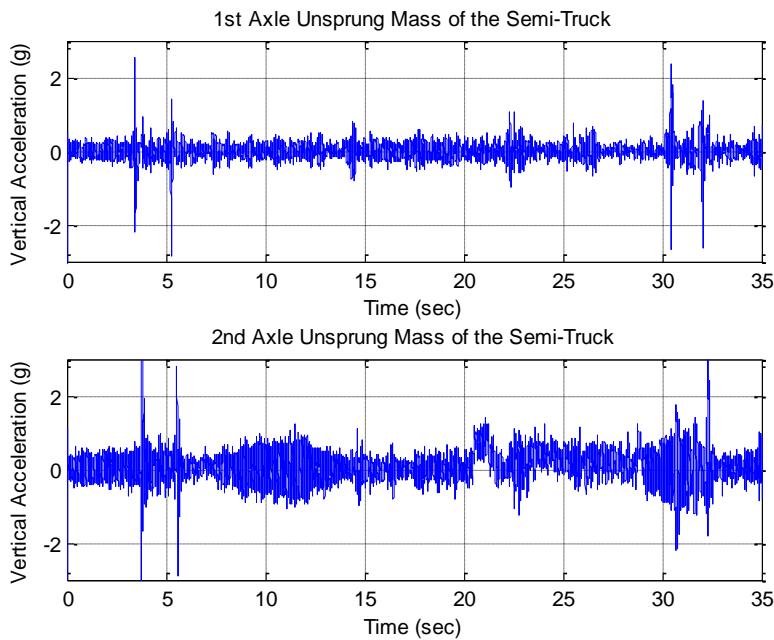


Figure 4.8: Axe vibrations on semi truck at 50 mph.

4.4 DIAGNOSIS

The sensor has a monotonically increasing voltage response to vehicle weights. However, there is significant variation in the weight measurement from one test run to another test run for the

same vehicle. At the same time, there are also significant vibrations in the truck suspensions, as seen in the vibration data collected by using accelerometers on the truck axles.

Tests were conducted at a low vehicle speed of 10 mph with the same set of vehicles described in Section 4.2. The results are shown in Figure 4.9. From Figure 4.9 it can be seen that even when the vehicle speeds are low and the vibration levels are small, there is still significant variability in measured axle weights from one test to another. For the semi tractor-trailer, the variability was as much as 3,000 pounds at 10 mph, which is as much as one-third of the nominal axle weight.

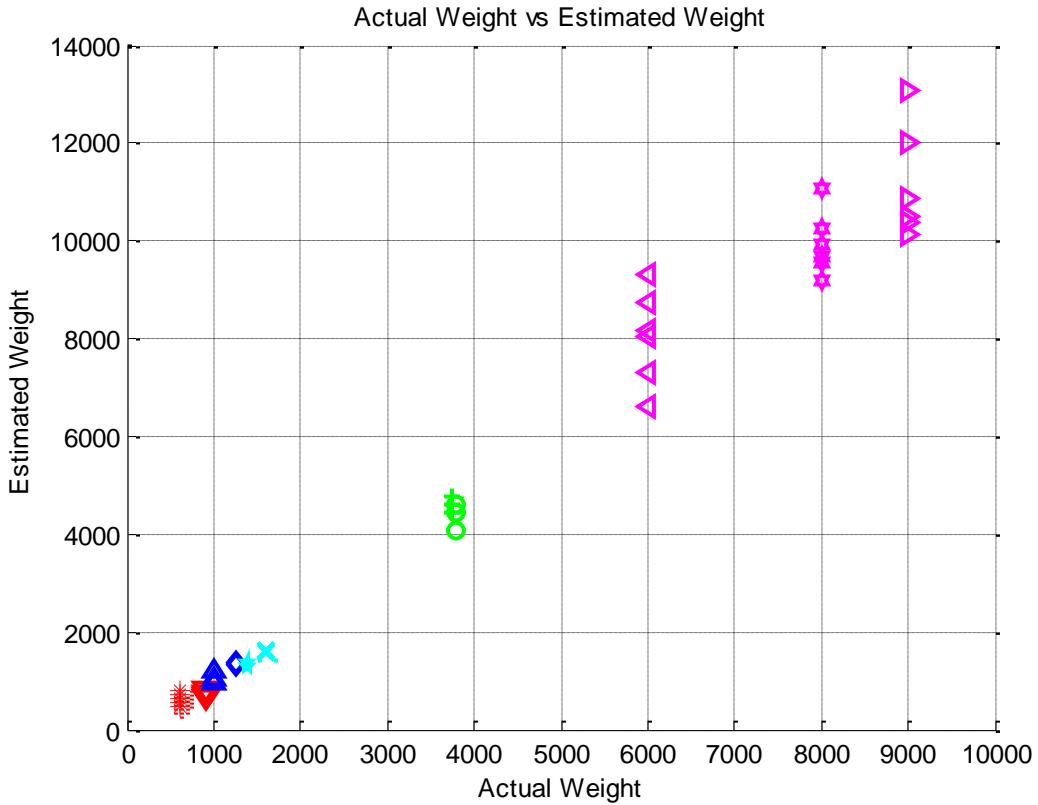


Figure 4.9: Axle weight measurements at 10 mph.

Strain Sensor Based Weigh-in-Motion Results

5.1 SENSOR DESIGN

As discussed in Chapter IV, a battery-less wireless WIM sensor was developed that utilized translational vertical compression of a piezo stack and a piezo film for energy harvesting and weight measurement respectively. The results presented so far in this report have shown that

- a) Adequate energy is harvested from the piezo stack by the loads on the sensor from each axle. The harvested energy is adequate to power the operation of the electronics for measurement and to power wireless transmission.

- b) The axle weight measurements obtained from the sensor had a monotonic relationship with actual axle weights. However, there was significant variability in sensor response from one test to another.

It was found that the variability in sensor response occurred even when the vehicle tests were restricted to very slow 10 mph runs. Hence, it was determined that the variability in sensor response was not just due to truck suspension vibrations. Further, it was determined that the bending mechanism for the top of the sensor box would be sensitive to the lateral location in the lane at which the vehicle passes over the sensor. Variability in sensor response would be obtained depending on whether the vehicle passes at the center or the left or the right over the sensor. The bending of the sensor top was used in this project to allow the sensor to be grouted (permanently fixed) to the pavement. Some of the load, however, is taken up by the bending of the top plate.

In order to determine a better mechanism for weight measurement that still allows grouting of the sensor to the pavement, measurement of the deflections of the top plate of the sensor box was felt to yield a better sensing approach. This chapter therefore describes a weigh-in-motion (WIM) sensor based on measurement of strains of the top plate of the grouted sensor box.

A 12 inch wide by 38 inch long by 3/8 inch thick A36 hot rolled steel plate was mounted on a welded steel box embedded in 5 inch thick asphalt pavement at the MnRoad pavement testing facility. The plate was oriented so that the 12 inch wide dimension was aligned with traffic flow. Twelve inches is wide enough so that the entire contact patch of a standard diameter truck tire will be completely supported by the plate. On the underside of the plate seven sets of two strain gages were installed on 4.5 inch centers. The strain gages were from Omega.com (part number KFH-20-120-C1-11L1MR2) (4) and were cemented to the steel plate using Omega's SG401 cyanoacrylate adhesive. The two strain gages in each set were connected as two opposing sides of a Wheatstone bridge circuit. The output of each of the seven Wheatstone bridges was amplified by an Analog Devices AD-627 instrumentation amplifier and recorded on a laptop computer using a Labjack U3 USB data collection device to do the analog to digital conversion. Data from each set of strain gages was collected at a rate of 250 samples per second.

5.2 SENSOR TESTS

During the field test a Ford Ranger pickup truck and a fully loaded (80,000 lb) semi- truck trailer combination were driven over the instrumented plate at various lateral locations (see Figure 5.2). Peak voltage readings for each strain gage were used to estimate the lateral position of the tires with respect to the center of the plate. The sums of the peak voltage readings, as sensed by the strain gages, for each axle were used as the basis of the calculation of weight. A correction factor was calculated that was a function of the measured lateral position of the vehicle over the sensor.

Figure 5.1 shows a photograph of the sensor box with the instrumented steel plate top. The underside of the steel top is instrumented with a line of laterally distributed strain sensors.

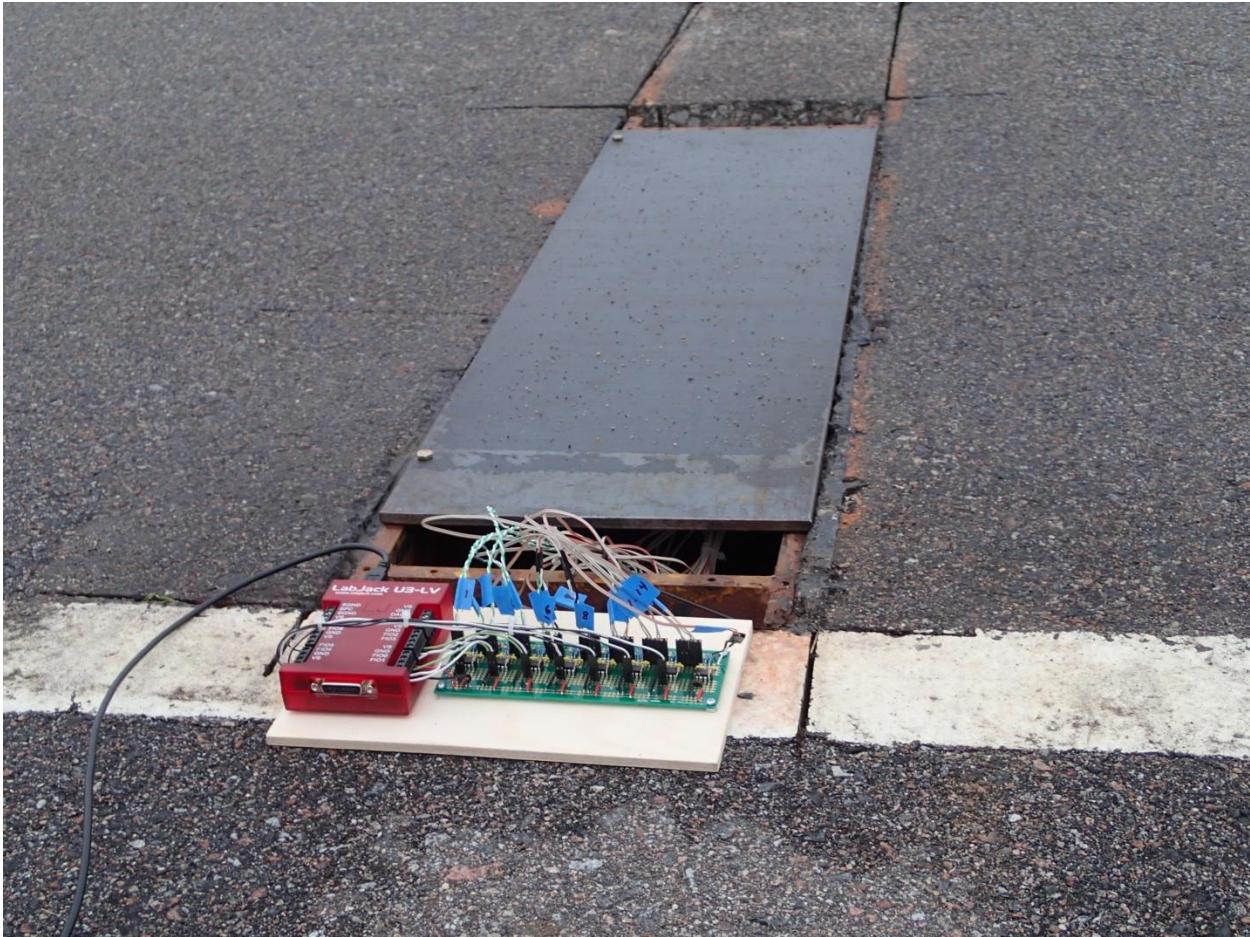


Figure 5.1: Instrumented steel plate top for sensor box.

Figure 5.2 shows a photograph of the semi tractor-trailer traveling over the sensor with the instrumented steel top. Figure 5.3 shows the strain sensor responses for a pick-up truck and the semi tractor-trailer for a number of tests.



Figure 5.2: Photograph of semi tractor-trailer traveling over sensor.

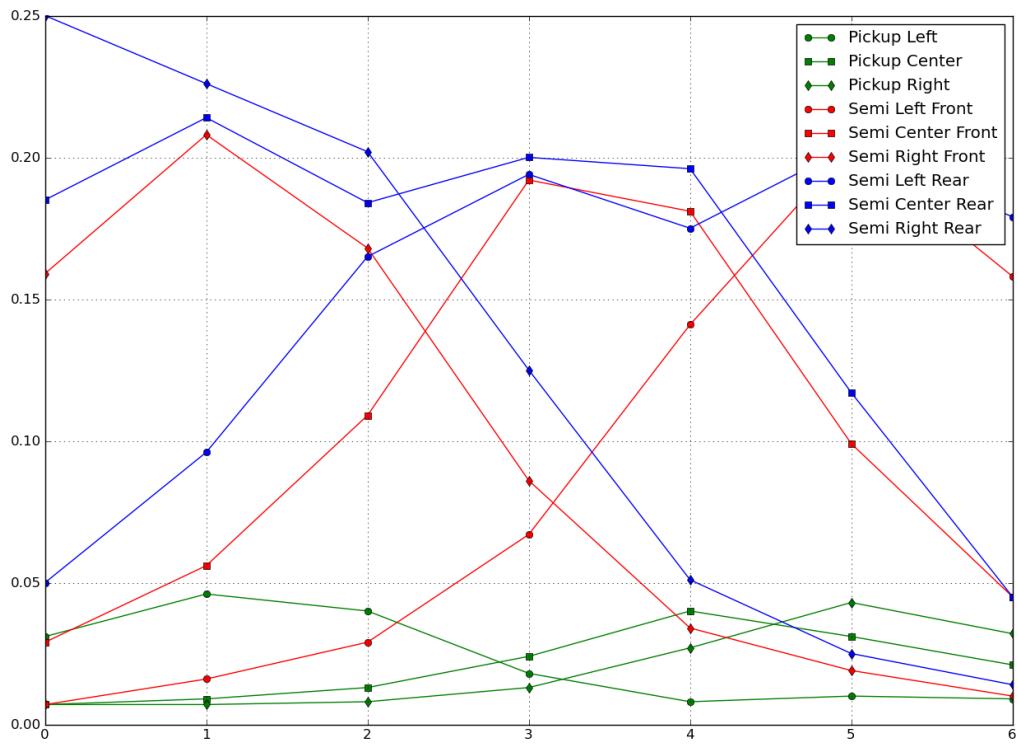


Figure 5.3: Sensor response to pick-up truck and semi tractor-trailer axle weights.

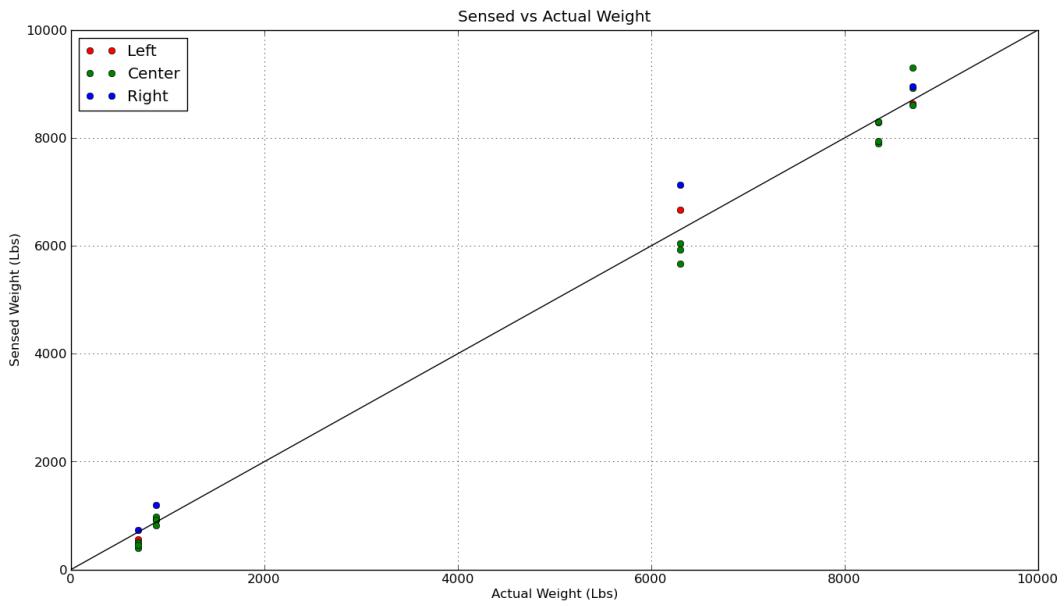


Figure 5.4: Calculated weights for pick-up truck and semi tractor-trailer axes

A speed of approximately 30 mph was used in the tests. The calculated weight from the strain sensor responses to the pick-up truck axle loads and the drive axle, trailer front and trailer rear axles of the semi are shown in Figure 5.4. It can be seen that the variability is significantly less than the variability seen earlier in Figures 4.2 and 4.3. The peak-to-peak variation is less than 1,000 pounds and is less than 50% of the variation seen with the earlier version of the sensor.

VI. CONCLUSIONS

The design of a battery-less wireless weigh-in-motion (WIM) sensor was improved so as to convert it into an all-metal device wherein the top baler belt was replaced using a steel design. Further, an enclosure box was developed which could be grouted into the pavement and in which the sensor was placed. The vehicle load was transmitted to the sensor through bending motion of the top steel plate of the box. This design allowed permanent grouting of the WIM system into the pavement.

A smart phone app was developed for wireless access to the WIM sensor readings. The smart phone app was designed for Android smart phones and tablets and can be downloaded by the user. Wireless axle weight signals received from the WIM sensor are placed at an IP address on the internet by a roadside receiver and router. These weight measurements can then be accessed at any geographic location through the smart phone app. The smart phone app displays axle weights, date and time. It also records previously accessed weight measurements which can be read by scrolling down the screen on the app.

The new prototype of the WIM sensor was tested at MN Road (Minnesota Road Research Facility) in asphalt pavement. The tests showed that adequate energy was harvested from each axle load on the sensor to power the operation of the sensor and to power wireless transmission. This was true not only for the heavy semi tractor-trailer, but even for the smallest vehicles such as the passenger sedan. Thus the sensor could indeed function as a battery-less wireless device. Also, the sensor had in general a monotonic response that increased monotonically with an increase in axle weight. However, the problem with the sensor response was that it had significant variability from one test to another for the same vehicle and same axle loads.

The variability in sensor response was diagnosed to be due to the sensitivity of the response of the top metal plate to lateral vehicle location. As the lateral vehicle location changes, the load transmitted to the sensor inside the enclosure box changes.

A new sensor design was therefore developed and evaluated in which deflections of the top enclosure plate were directly measured to infer vehicle weight. These deflection measurements were made using a line of strain sensors distributed laterally across the steel plate. Tests conducted with a pick-up truck and with a semi tractor-trailer showed that the peak-to-peak variability in measured weight was reduced to less than 1,000 lb from more than 2,000 lb with the previous sensor.

Although a sensing method with better repeatability and less variability has been designed, there is not a direct and easy path to link this new sensing mechanism with the battery-less wireless energy harvesting system. Given that the project is at the end of its first year, there is no budget and no time remaining to develop a battery-less wireless system that links together the new weigh-in-motion and the energy harvesting systems.

The second year of the project was to be dedicated to evaluation of the sensor with varying temperature and environment conditions in the road. The research team recommends that the second year of the project be abandoned in view of the fact that the previously developed sensor does not have adequate repeatability and consistency under nominal test conditions. The budget for Year 2 will consequently be returned to the Idea Program and Year 2 of the project will not be funded.

References

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2. Vijayaraghavan, K. and R. Rajamani, "Ultra Low Power Control System for Maximal Energy Harvesting from Short Duration Vibrations," *IEEE Transactions on Control Systems Technology*, Vol. 18, No. 2, Mar. 2010, pp. 252–266.
3. Texas Instruments, SLAS554E - CC430F613x Data Sheet, Nov. 2010.
4. Omega Pre-Wired Strain Gauges, Data Sheet [Online]. Available: <http://www.omega.com/pptst/KFH.html>.