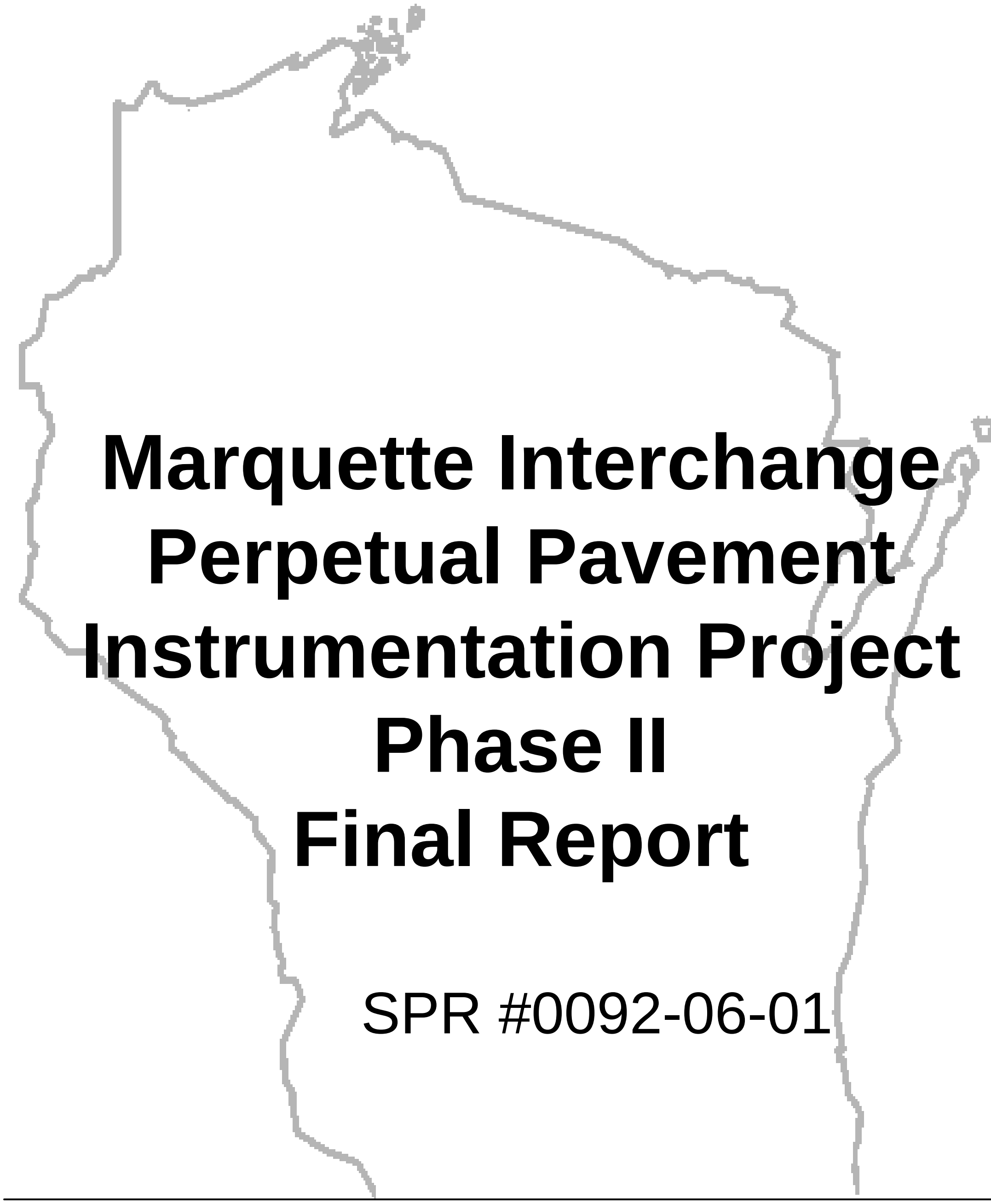
Wisconsin Highway Research Program



Marquette Interchange Perpetual Pavement Instrumentation Project Phase II Final Report

SPR #0092-06-01

Nicholas J Hornyak & James A Crovetti
Transportation Research Center
Marquette University

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Final Report WHRP 08-04

WisDOT Highway Research Study
SPR# 0092-06-01

Nicholas J. Hornyak & James A. Crovetti
Marquette University
Transportation Research Center
Department of Civil and Environmental Engineering
P.O. Box 1881, Milwaukee, WI 53201-1881

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16. Abstract
This report presents findings from the second phase of the Marquette Interchange instrumentation project and focuses on the maintenance of data recordation systems, development of computer programs to analyze data, and development of data packages for redistribution. The product of this research is a set of data which includes dynamic pavement response due to live traffic, vehicle information (weight, class, length, et cetera), and environmental data for the test site. The tasks within this project were not oriented for findings regarding pavement performance, but important and helpful conclusions can be drawn for similar future projects. The recordation systems have been maintained and recordation has been continuous. A handful of sensors did require attention and only a fraction of the critical strain sensors have ceased to function, making the project a success. The results of the computer programs written to analyze data show that reasonable accuracy has been achieved. Future work can help to generate more intricate programming making the processes more accurate.

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Executive Summary

Project Summary

The first phase of this project focused on the design and construction of an instrumented pavement test section for purposes of studying the dynamic response to live traffic. This report covers the second phase of the project which focused on maintaining the data recordation systems, developing computer programs to analyze data, and developing data packages for distribution. The product of this research is a set of data which includes dynamic pavement response due to live traffic, vehicle information (weight, class, length, etc.), and environmental data for the test site.

Background

Pavement design practices have relied on concepts developed years ago through road tests conducted by AASHTO and other agencies. These design practices are currently being transitioned from the largely empirical based design methods to those that are based heavily on mechanics of materials with some empirical elements still residing within. This transition in design practices requires careful consideration of the variables which are sensitive to location, traffic patterns, pavement materials and environment of the region. In April 2005 a proposal to instrument a HMA perpetual pavement was submitted to the Wisconsin Highway Research Program and subsequently awarded to the Transportation Research Center at Marquette University.

The pavement test section was constructed during the summer of 2006 and has been online since the installation of the final instruments in late October of 2006. Data collection has since continued through the time of this report.

Process

The second phase of this project contained 4 separate tasks; maintaining system integrity, develop data packages, develop automated data processing techniques, and project reporting. These proposed tasks have been completed and the actions taken are outlined in this report. The following is a list of the respective chapters herein for each task.

- Chapter 1 – Task 1 – Maintain system integrity
- Chapter 2 – Task 2 – Develop Automated Data Processing Techniques
- Chapter 3 – Task 3 – Develop Data Packages

Since the initial construction of the test section and the systems needed to record data, day-to-day maintenance was needed to ensure that data was being collected and that the data collected was quality information. To accomplish this, sensors were checked for functionality and calibrated as needed. Faulty equipment was either repaired as necessary or replaced as possible. The computer systems housing the database and the database itself were managed for efficient operation and data redundancy.

The large amount of data being recorded meant that analyzing data by hand would be an insurmountable task. Programs have been developed to automatically analyze the data and store the results to a database for later use. Of interest was the peak tensile strains and peak compressive pressures, duration of the tensile load pulses, and the area beneath the tensile load pulse. Since the data is stored and never destroyed, analyses can be re-run at any time.

To be of any benefit to the engineering community, the data needed to be distributed and made accessible. Data packages have been developed in the form of compressed text files and posted to the project webpage at www.mchange-strain.com/data.html.

Findings

The tasks within this project were not oriented for findings regarding pavement performance, but important and helpful conclusions can be drawn for similar future projects. The recordation systems have been maintained and recordation has been continuous. A handful of sensors did require attention and only a fraction of the critical strain sensors have ceased to function, making the project a success.

The results of the computer programs written to analyze data show that reasonable accuracy has been achieved. Future work can help to generate more intricate programming making the processes more accurate.

Recommendations

Since the number of operational pavement sensors is still high, it is recommended that the system should be supported to continue to collect data. The recordation process is simple to maintain and requires little human input – sufficient storage space exists on the servers for data storage. It is almost certain that some environmental equipment may need to be replaced; however these are relatively low cost items but provide important information for pavement analysis.

It may also be possible and beneficial, to test retrofitted strain gauges. If a method can be developed to successfully implement retrofitted strain gauges, pavements can be analyzed at anytime in the life of the pavement. Most if not all instrumented pavements were done so at construction – analyses of these new pavements may never demonstrate long term effects on performance.

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Chapter 1 - Maintaining System Integrity

A significant portion of this project phase was spent maintaining system stability to ensure data quality and completeness. In addition to this, many improvements were made to the overall system as problems were realized. Many maintenance items included physical items such as instrument replacement; however the majority of the work was done on the software and computing side of the system. When necessary, equipment was calibrated to make sure measurements were as accurate as possible. All maintenance items were documented so that changes or corrections to past data can be conducted as needed.

In general the maintenance work can be divided into three categories.

- Equipment replacement and calibration
- Database maintenance
- Data management

Work items for these categories will be discussed in detail in the following sections. This is to serve not only as documentation, but also to illustrate problems and solutions encountered during the development of this project.

1.1 - Equipment Replacement and Calibration

With over fifty sensors installed in the test section, it can be expected that some of the instruments might fail. Sensors that have been installed into the pavement structure cannot easily be repaired or replaced at all. On the other hand some equipment can easily be replaced or repaired as needed. All operational sensors can be calibrated or checked in some way to get an indication of their accuracy.

The environmental conditions found at this project site are extremely harsh. Milwaukee experiences many different weather conditions from temperatures well below freezing and hot summer days with temperatures exceeding 100 degrees Fahrenheit. In addition, the use of deicing materials during the winter exacerbates corrosion and can cause shorts in electrical circuits.

On a regular basis, the project equipment has been checked for basic functionality. When discovered, inoperable equipment was diagnosed and repaired if possible. The winter weather months proved to be especially harsh on some the instruments exposed to the de-icing materials. The following series of tables presents the current status of the systems instruments.

The weigh-in-motion system and PK piezos appear to be functioning normally. Visual inspection shows no evidence of damage to the Kistler or PK piezos and they appear to maintaining a flat profile. The majority of the strain sensors and all pressure cells are all functioning normally.

Table 1-1 - Status of strain and pressure sensors.

Strain Gauge	Functional	Notes
A0	Y	
A1	Y	
A2	Y	
A3	Y	
A4	Y	
A5	Y	
A6	Y	
A7	Y	
B0	Y	
B1	Y	
B2	Y	
B3	Y	
B4	Y	
B5	Y	
B6	Y	
B7	N	Became erratic and failed shortly after installation.
C0	Y	
C1	Y	
C2	Y	
C3	Y	
C4	Y	
C5	Y	
C6	Erratic	Erratic behavior started upon installation.
C7	Erratic	Erratic behavior started upon installation.
Pressure Cells	**Functional**	**Notes**
A0	Y	
A1	Y	
B0	Y	
B1	Y	

The A1 and B0 to B2 subgrade moisture sensors became erratic and eventually stopped working not long after initial installation. Subgrade temperature B1 appears to be working, but is producing data not consistent with the other sensors and is suspected to be damaged. The pavement temperature gradient probe and the pavement surface probe both failed to survive the winter of 2008. A new pavement temperature gradient probe has already been installed and the surface temperature probe has been sent to the manufacturer for diagnosis.

Table 1-2 - Status of environmental sensors.

Environment	Functional	Notes
Air Temperature	Y	
Wind Speed	Y	
Surface Temperature	Erratic	3/15/2008 - Sensor becoming erratic - currently being diagnosed.
Pyro_1	Y	
Pyro_2	Y	
Subgrade Moisture A0	Y	
Subgrade Moisture A1	N	Stopped functioning shortly after installation.
Subgrade Moisture A2	Y	
Subgrade Moisture B0	N	Became erratic and stopped functioning beginning on 3/23/2007.
Subgrade Moisture B1	N	
Subgrade Moisture B2	N	
Subgrade Temp A0	Y	
Subgrade Temp A1	Y	
Subgrade Temp A2	Y	
Subgrade Temp B0	Y	
Subgrade Temp B1	Erratic	Sensor appears to be functioning, but data not consistent with other data.
Subgrade Temp B2	Y	
Pavement Temperature_A0	Erratic	2/2/2008 - Sensor became erratic - replacment installed 4/5/08. Weather conditions delayed installation of new sensor.
Pavement Temperature_A1	Erratic	
Pavement Temperature_A2	Erratic	
Pavement Temperature_A3	Erratic	
Pavement Temperature_A4	Erratic	
Pavement Temperature_A5	Erratic	

1.1.1 - Equipment Replacement and Service

Five sensors have failed during service thus far in the project. The causes of these failures have been investigated and the sensors have been replaced if possible. In particular the failed and replaced components were two pavement temperature gradient probes, one infrared temperature probe, and two pyranometers.

Initially two pavement temperature gradient probes were installed in the structure just prior to placement of the SMA wearing surface layer. The leads for these probes were placed into a groove saw-cut into the existing pavement surface and the probes were dropped into drilled holes. The paving crews simply paved over the equipment and it was felt that enough protection was given against the extreme heat of the hot pavement layer. However, it is has been concluded that the most likely cause of failure of these probes was due to this extreme heat. This most likely weakened the insulation on the leads and the instruments ultimately shorted out.

One new probe was constructed, in house, using a similar design as the two originals and installed on 6/28/2007. This new probe has fewer temperature sensors within it, meaning that temperatures are not measured at one inch intervals. Instead fewer temperature probes were used so that a smaller lead wire could be used, but still provide the necessary temperature information needed for analysis. The smaller lead wire was required to minimize surface effects since it would be installed in the finished pavement. The layout of the probe is shown below – the drawing is not to scale.

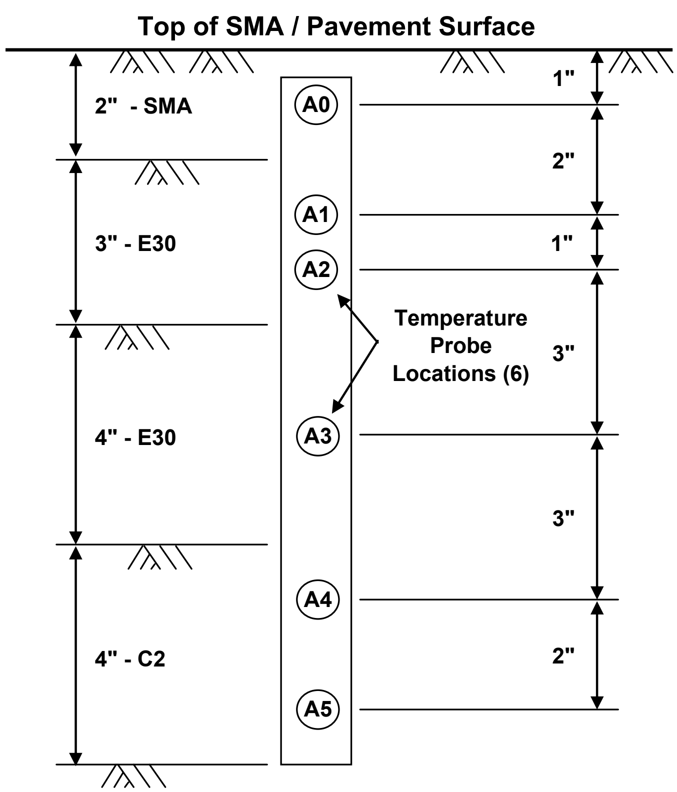


Figure 1-1 - Pavement temperature gradient probe.

The new probe is located roughly between the two original probes. A section of the pavement was removed along the face of the gutter of the curb and gutter to access the existing conduits used for the old probes. The old probes were not removed, but the leads were cut away and the excess wire leading to the cabinet was removed, pulling in the new lead simultaneously.

The excavated SMA pavement was reheated, along with some excess left over from construction, and recompacted into the void in the pavement. The saw cut made for the instrument lead and any other voids created were filled with an approved sealant (Bondo Corporation P-606 Flexible Sealer).

The infrared temperature probe, which measures the surface temperature of the pavement in the test section, is mounted along the roadside on the column supporting the variable message board. The original probe began producing erratic results in June, 2007. The problem was investigated and upon close inspection it was noted that deicing material had penetrated the housing and shorted out the circuitry onboard. The probe requires a constant air supply to pressurize the internal chamber of the probe. The supply was likely interrupted (power failure, kinked hose, etc.) and contaminants were allowed to penetrate.

A new probe was purchased that is rated for outdoor use (IP 65/NEMA 4) and installed on 7/30/2007. The probe operated flawlessly until the winter of 2008 when it started producing erratic data in mid-March, 2008. The probe is currently with the manufacturer and undergoing diagnosis.

Two pyranometers failed during service. The first stopped working abruptly in late June, 2007. The other became erratic in late March, 2008 and appeared to be functioning, but close inspection indicated the probe had failed. Upon inspection by the manufacturer, it was concluded that the sensors underwent a power surge, destroying the amplifiers.

Two new pyranometers were purchased from the same company, but a separate model was purchased to prevent future power surge failures. The original set of instruments required a 5.0 VDC supply power while the new set only required 2.5 VDC. Both models advertise that any power supply over 5.5 VDC would damage the units; the only trade-off is a small decrease in precision. It was felt that running the power supply at 2.5 VDC would offer a larger cushion against power surges. For example, if the power supply is 2.5 VDC and there is a power surge of 0.5 VDC, the total voltage of 3.0 VDC would not exceed the 5.5 VDC damage threshold. These instruments were installed on 9/18/2007.

The wireless link that transmits data from the test site back to Marquette University did not need replacement, but did receive some attention. The bandwidth through the modems was less than satisfactory at times. Different channel settings were tested, but changing the orientation of the antennas proved to give the largest benefit.

The antennas were originally mounted in a vertical orientation. According to the manufacturer this would provide the best signal quality. However, modern radio equipment is set up in a similar fashion, thus causing excess noise in the particular radio frequencies. Changing the orientation improved the link quality by reducing the amount of noise in the frequency range.

The data acquisition software was also modified to help compress data and handle large queues and backlogs. The link operates in good condition, but during periods of high traffic volume can cause the system to get behind. Normally the backlog diminishes during the low volume hours. In the event that the link is lost completely, the software then stores data locally to an archive file for later uploading.

Periodically, the data acquisition computer, WIM computer, or other equipment can become unresponsive and require a manual shut down and restart. An ethernet power switch was added to the equipment cabinet so this could be done remotely. A user can access an interface using any available web-browser and turn power on or off as needed.

1.1.2 - Calibration

The maintenance of any device used to make measurements should include calibrations to ensure proper readings. In this instance, some very thorough and in depth maintenance work was done to make sure that all parts of the project are functioning properly. There are in essence two major components in this system that require a watchful eye; the data acquisition system and the instruments.

The data acquisition system runs on a proprietary operating system that runs a user generated program. Because of this, there are both software and hardware issues that can go awry. On the software side, the user writing the program can simply make a “typo” and data being acquired can be wrong. On the other hand, there are may be hardware related malfunctions that cause errors in the data.

Instruments are typically calibrated by a manufacturer for the end user. It is not uncommon for these calibrations to fluctuate with time due to a variety of factors. When possible, sensor calibrations should be completed to provide the highest level of precision. Due to these facts, all aspects of recordation system have been check and calibrated.

1.1.2.1 - Data Acquisition and Gauge Calibration 7/18/07 - 7/27/07

Some of the data coming into the system was under scrutiny due to the relatively small strain readings being recorded. It was thought that the acquisition program might have been recording incorrectly by a factor of ten or some other mathematical error. To diagnose whether the readings were accurate or if there actually was an error, a separate data acquisition system owned by Marquette was used to read the strain, pressure, and PK piezo sensors.

The independent acquisition system was set up in the lab and a CTL gauge owned by Marquette was connected and some simple experiments were done to validate the setup and readings. These simple tests were compared with analytical calculations and results showed the correct answer. A strain gauge simulator was then connected to the independent acquisition system and the output was checked against the simulated value. Again the measurement values were correct.

The independent acquisition system was then taken to the test site and strain gauges A0, A1, A2, and A4 and earth pressure cell A1 were connected to the data acquisition system. A test vehicle owned by Marquette was used to generate instrument signals. Random vehicles passing over the test section were also recorded for additional reference.

Below is an example of the strain and earth pressure cell outputs generated form the test vehicle traveling at about 30 mph with the driver side tires centered on the wheel path center line (directly over senor A1). The test truck is a two axle vehicle with weights of 2240 lbs and 8900 lbs for the front and rear axles, respectively. Note the two spikes following the larger spikes; these were caused by a car traveling behind the test vehicle. The largest strain recorded was 9.7 microstrain (strain$\times 10^6$) and the maximum pressure recorded in the base was 1.85 psi. For the other test trials, the maximum tensile strains ranged from 8 up to 15 microstrain. The lateral positioning of the test vehicle varied considerably, thus causing the variability between the maximum tensile strain measurements between trials.

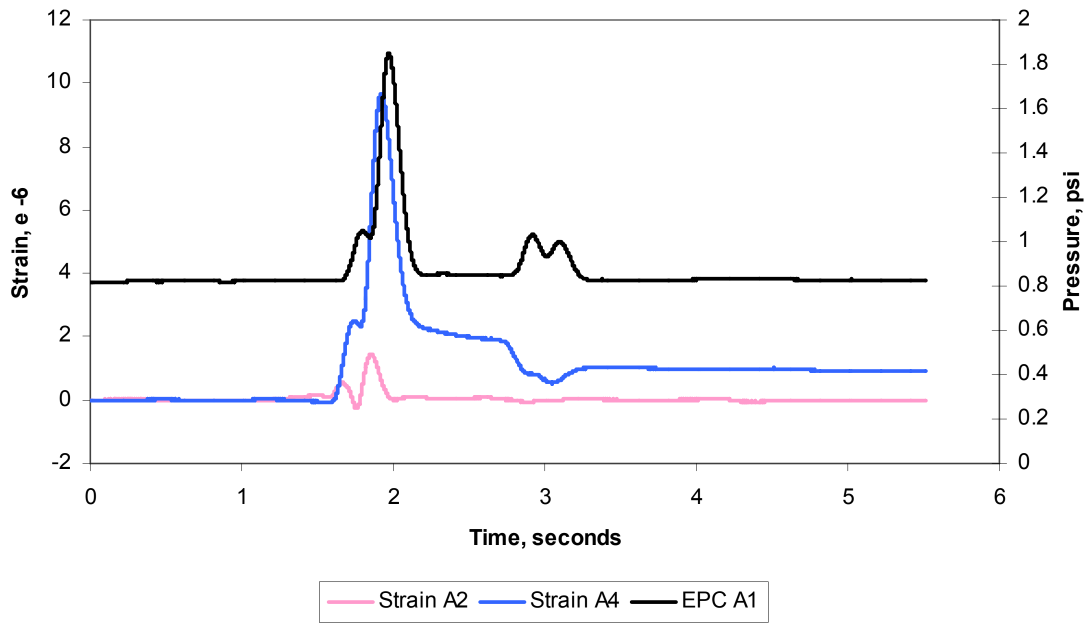


Figure 1-2 - Strain and pressure signals from test vehicle.

A comparison was made based upon results generated by the linear elastic pavement analysis program, KENLAYER and using very general layer moduli. The KENLAYER model estimated the maximum tensile strain in the bottom for the asphalt layer to be about 35 microstrain. It should be noted that the actual layer moduli were not used because they were not available, however the moduli used could be considered typical values.

More importantly to the significance of this test was the comparison with values recorded by the project acquisition system. During the test the project system was recording all other strain gauges and the data from this show maximum strain values that are nearly identical in the 8 to 15 microstrain range. This indicated that the project acquisition system was recording data accurately.

The next system check involved using a strain gauge simulator. The tool generates an electrical signal that simulates a full-, half-, or quarter-bridge strain gauge. This was used as a double check against both acquisition systems. The simulator was setup at multiple levels of simulated strain up to about 10,000 microstrain. Data recorded by the acquisition system was then compared to the simulation. Results showed that the data acquisition system was measuring correctly and accurately.

The last set of system checks was to measure the acquisition rate and sequencing/timing of the acquisition software. This was accomplished by setting up a signal generator in the field and connecting it to an open strain gauge channel on the acquisition system. A sinusoidal signal was then set for 10 Hz and was run for a period of days for debugging purposes.

This test allows for two important calibration checks. First it allows the user to analyze the signal and check if the acquisition rate is correct. For instance, if the signal is cycling at 10 Hz, then for one minute of time, one would expect to see 600 signal cycles.

Secondly, this test shows how the data acquisition software is managing the data buffers. It was found during this diagnostic period that in certain instances, the data buffers were not cleared and “left over” data were being recorded as new data. Below is a plot of the simulated strain versus time.

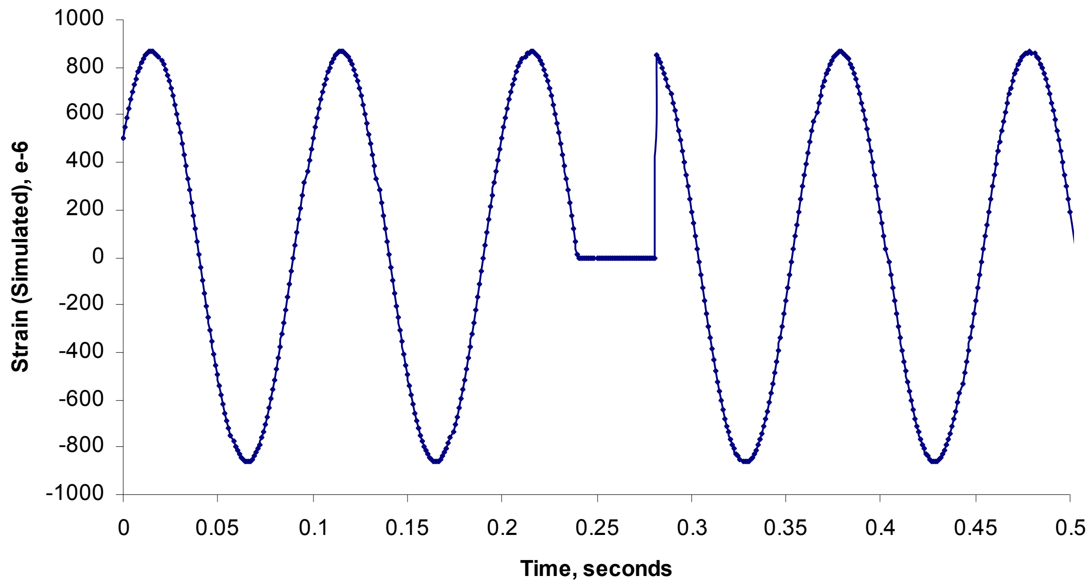


Figure 1-3 - Recorded sinusoidal signal.

Figure 1-3 shows the signal generation at 10 Hz, but it also shows the incorrect data storage. Inspection of this plot and a handful of others, indicate that the data following the flat-line portion are likely data left over in the buffer that was not cleared. This problem was identified and corrected. Subsequent testing showed that this problem was eliminated.

The last portion of the calibration testing was to check the accuracy of the temperature probes. This was a simple check to ensure their proper function. An infrared temperature probe was used to measure the surface temperature of the pavement and this was compared with the system's infrared temperature probe and the upper pavement temperature gradient probes.

It was found that the project infrared temperature probe was faulty and the newly installed temperature gradient probe was working properly. As indicated in a previous section, the infrared probe was replaced.

1.1.2.2 - WIM and Gauge Calibration 8/29/07

The second round of calibrations served to check the accuracy of the WIM system and wheel wander sensors. Because the test section has both a downgrade and a cross slope (about 2.5% and 2.0% respectively), a more accurate weight measure was needed, other than axle weights, to verify the WIM system.

A commercial vehicle inspector from WisDOT was contacted and they agreed to come to Marquette and weigh out a test vehicle. WisDOT inspectors are equipped with portable wheel scales that can be placed under each wheel to measure the wheel load. Marquette has since purchased a portable wheel scale for future needs. Figure 1-4 shows the wheel pad and vehicle being weighed out.

Figure 1-4 - Truck driving onto weigh pad.

Since there was a suspected weight bias due to the cross slope and downgrade, the vehicle was placed on different angles while on the scales in order to simulate the effects of the pavement conditions. Because of the configuration, it was not possible to measure all of the wheel loads while the vehicle was positioned on blocking. Table 1-3 provides the results of these measurements. It was found that the amount of weight bias was minimal and was about equal to the readability of the scale.

Table 1-3 - Test vehicle wheel loads.

Cross Slope Angle β, %	Downgrade Angle α, %	Weight, lbs			
		Drivers Side		Passenger Side	
		Front Axle	Rear Axle	Front Axle	Rear Axle
0.0	0.0	1150	4800	1450	4950
0.5	0.0	NA	NA	1500	5000
2.0	0.0	NA	NA	1550	4950
2.0	0.0	NA	NA	1500*	4950*
0.0	2.0	1350	NA	1500	NA
0.0	2.0	1250*	NA	1450*	NA

* Driver was not in vehicle during measurement.

Obviously this may not be the case for vehicles that have a higher center of gravity such as a concrete mixer, dump truck, etc. stressing the need to measure individual wheel weights, which is accomplished by the project's in-place WIM system. Figure 1-5 shows the test vehicle ready to be weighed on the simulated downslope (α=2.0%).

Figure 1-5 - Wood used to simulate grade during weighing.

As a cautionary note, it is very important to make sure that the area directly in front of and behind the vehicle being weighed is clear of people and other obstructions. Since the scales are designed to be driven on to, it is possible that a small amount of wheel spin can occur, potentially throwing the scale or wood blocking in the direction of the wheel spin.

When using the wheel scales, it is good practice to place wood blocking under the other tires while weighing to keep the vehicle level (if taking a flat and level measurement). Additionally, since the payload in almost any vehicle can be shifted laterally, it is likely that wheel loads on one axle will not be equal, thus preventing accurate axle load estimations from only one wheel load measurement.

The test vehicle was weighed soon after the test runs had been made to accommodate the work schedule of the WisDOT inspector. Several test runs were made with the vehicle and the time of day was recorded for each in order to better locate the data in the database. The recorded data were compared to the static wheel load measurements.

Of particular interest are the three main measurements which include the individual wheel loads, wheel speeds, and the axle spacings. Speed can also be verified via calculations from the wheel wander grid.

For purposes of weight enforcement, there are also specifications for axle weights and axle group weights. Since this WIM system has both measurement strips in one wheel path, axle weight and axle group weights can only be estimated by doubling of the measured values. Table 1-4 provides the functional performance requirements for different classes of WIM systems as specified in ASTM E1318-02 (1, 2).

Table 1-4 - WIM tolerances from ASTM E1318-02 (1, 2).

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				value ≥ kg (lb)*	± kg (lb)
Wheel Load	± 25%	n.a.	± 20%	2,300 (5,000)	100 (250)
Axle Load	± 20%	± 30%	± 15%	5,400 (12,000)	200 (500)
Axle-Group Load	± 15%	± 20%	± 10%	11,300 (25,000)	500 (1,200)
Gross Vehicle Weight	± 10%	± 15%	± 6%	27,200 (60,000)	1,100 (2,500)
Speed	± 2 km/h (1 mph)				
Axle Spacing	± 150 mm (0.5 ft)				

*Lower values are not normally a concern in enforcement

Table 1-5 provides the results for the wheel load case and Table 1-6 provides the mean, standard deviation, and 95% confidence interval for the measurements. It is also apparent that the rear axle was consistently measured heavy and the front axle measured light. The bias in these measurements is not directly related to vehicle speed and may be due the single and dual tire arrangements. These results, however, do show that the WIM system is functioning within the ASTM specifications for a Type I WIM system.

Table 1-5 - Wheel load calibration results.

Experimental/Control Data					WIM0734 - Recorded Data				ΔWheel Load, %
Run Number	Axle	Est. Time	Est. Speed, mph	Wheel Load, kips	WIM ID	Gross Weight, kips	Speed, MPH	Wheel Load, kips	
1	Front	3:18 PM	45	1.50	288853	13.7	44	1.4	-6.7%
	Rear	3:18 PM	45	5.00	288853			5.5	9.0%
2	Front	3:24 PM	46	1.50	288953	13.5	46	1.4	-6.7%
	Rear	3:24 PM	46	5.00	288953			5.4	7.0%
3	Front	3:31 PM	35	1.50	289064	14.3	34	1.5	-3.3%
	Rear	3:31 PM	35	5.00	289064			5.7	14.0%
4	Front	3:38 PM	40.5	1.50	289176	12.7	41	1.3	-16.7%
	Rear	3:38 PM	40.5	5.00	289176			5.1	2.0%
5	Front	3:45 PM	29	1.50	289294	13.9	28	1.3	-13.3%
	Rear	3:45 PM	29	5.00	289294			5.7	13.0%

Table 1-6 - Wheel load calibration statistics.

Wheel Load Case	
Mean Δ =	-0.2%
Std. Dev Δ =	10.8%
95% CI =	6.7%

Table 1-7 and Table 1-8 represent the results for the gross vehicle weight case. Again, the results indicate the WIM system is operating within specification tolerances for a Type I WIM system.

Table 1-7 - Gross vehicle weight calibration results.

Experimental Data				WIM0734 - Recorded Data						ΔGVW Load, %
Run Number	Axle	Est. Time	GVW, kips	WIM ID	Axles	Class	Gross Weight, kips	Axle Spacing, ft	GVW, kips	
1	Front	3:18 PM	6.50	288853	2	5	13.7	13.7	6.9	5.4%
	Rear	3:18 PM		288853						
2	Front	3:24 PM	6.50	288953	2	5	13.5	13.7	6.8	3.8%
	Rear	3:24 PM		288953						
3	Front	3:31 PM	6.50	289064	2	5	14.3	13.7	7.2	10.0%
	Rear	3:31 PM		289064						
4	Front	3:38 PM	6.50	289176	2	5	12.7	13.7	6.4	-2.3%
	Rear	3:38 PM		289176						
5	Front	3:45 PM	6.50	289294	2	5	13.9	13.6	7.0	6.9%
	Rear	3:45 PM		289294						

Table 1-8 - Gross vehicle weight statistics.

GVW Case	
Mean Δ =	4.8%
Std. Dev Δ =	4.6%
95% CI =	4.0%

An analysis of the axle spacings showed that the WIM system is well within the ± 0.5 ft requirement. The actual mean, standard deviation, and confidence interval are shown in Table 1-9 below.

Table 1-9 - Axle spacing statistics.

Axle Spacing Case	
Mean Δ, ft =	-0.12
Std. Dev Δ, ft =	0.04
95% CI, ft =	0.04

Figure 1-6 indicates the temperature profiles for the majority of the day during testing; the duration of the test period is shown. Ambient air temperature varied considerably throughout the day, but was about 70° F during testing. The pavement temperatures throughout the pavement structure were relatively constant at about 80° F. The pavement surface temperature was not included in this plot because the instrument was becoming erratic during this time period and wasn't yet replaced. Subgrade temperatures (subgrade sensor A1 – 4 in. below top of native materials) were consistently just below 70° F.

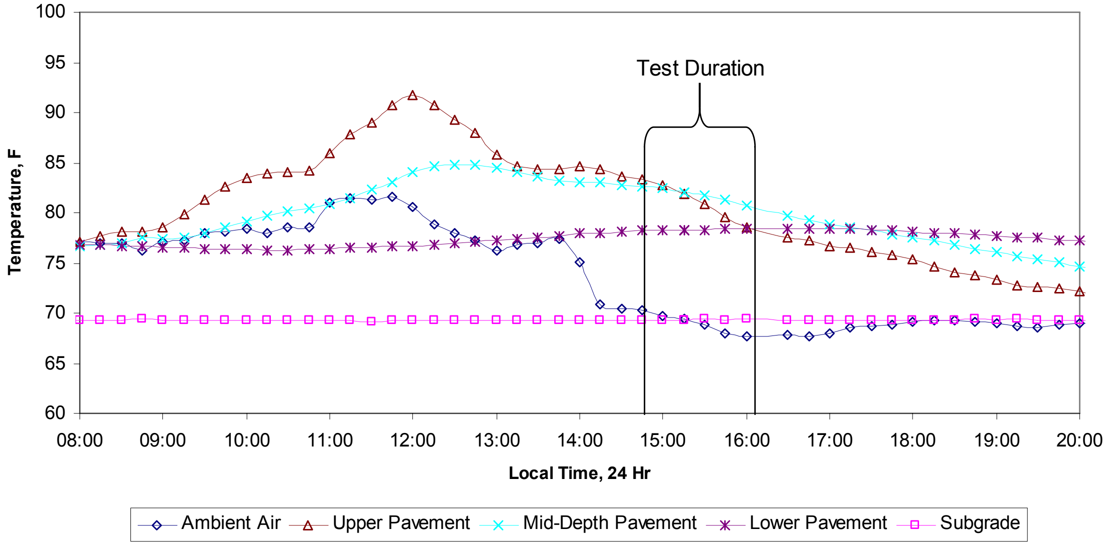


Figure 1-6 - Pavement temperatures during testing.

1.1.2.3 - 9/18/07 – 9/21/07 Wheel Wander Analysis

While performing the analysis of the WIM system, offset calculations were made and compared to the recorded offsets. It was found that they were somewhat inaccurate. Because of this, the calibration equation was checked and some simple field work was done to verify the accuracy of the wheel wander system.

As the system evolved, theoretical equations were used to calculate the offset from the data generated from the PK piezo sensors. However, the as-built geometry was slightly different from the proposed layout, hence requiring adjustments to the equation used to calculate the offset.

Video of passing vehicles was used to measure tire offsets for comparison to the offsets stored in the database. A digital camera was used to record short videos at 60 frames per second (fairly common function on modern digital cameras). The videos were then analyzed frame by frame and the offset from the edge stripe was scaled from this video. It should be noted that measurement reference marks were spray painted onto the pavement surface to aid in scaling the offset measurements from the still frames.

The video was taken from the roadside and the event time was recorded to aid in finding the data in the database. The general appearance was caught on the video clips, so the vehicles could be positively identified from the snap-shot images in the database.

The scaled and measured offsets were compared. It was found that the offset was measuring improperly and the calibration equation was modified. Since the updates of the calibration equation were known, past data were corrected for this adjustment.

Figure 1-7 illustrates the differences between the control and recorded offsets, both before and after the calibration equation was corrected. As shown, the corrected mean virtually eliminates the error in offset measurement.

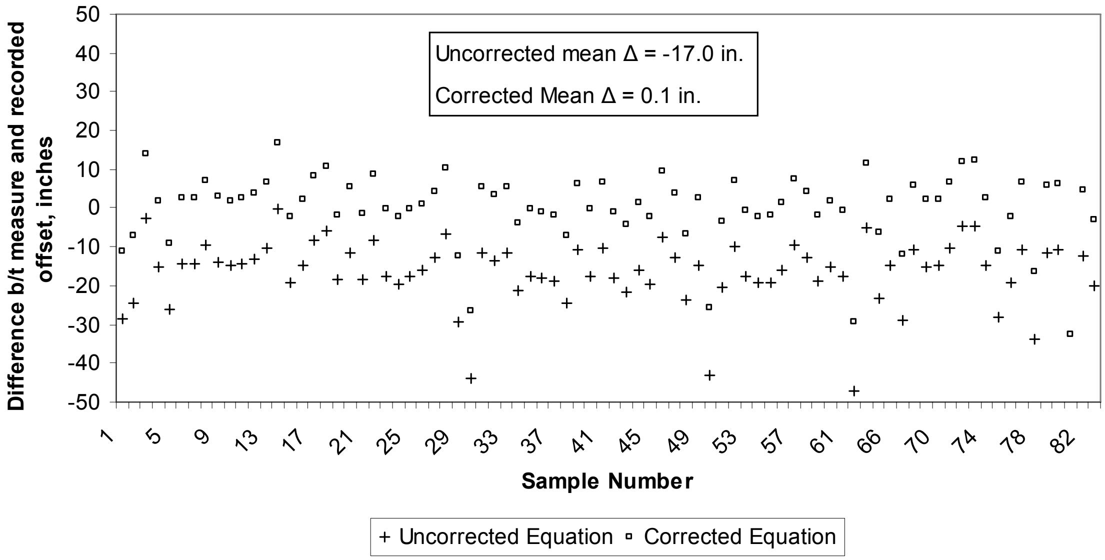


Figure 1-7- Wheel wander offset calibration data.

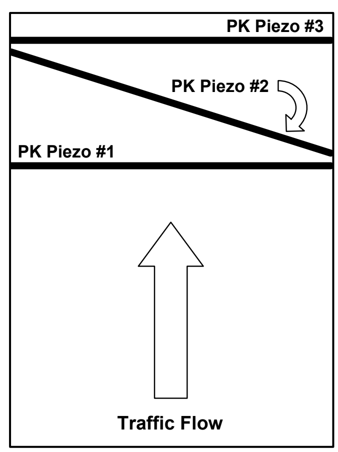
Equation 1-1 represents the current formula used to compute lateral offset from the wheel wander sensor array. The individual trigger values are taken when the charge generated from the sensor exceeds a preset threshold value.

Equation 1-1 - Wheel wander offset equation.

$$Offset = \frac{147.136T_1}{T_3} - 81.7806$$

Where:

$$T_1 = t_3 - t_2$$
$$T_3 = t_3 - t_1$$
$$t_i = \text{time of } i^{th} \text{ piezo trigger}$$



1.1.2.4 - 11/28/07 – WIM and Strain Analysis with Heavy Vehicle

Since the first analysis of the WIM system was done with a relatively light vehicle, a heavier vehicle was requested from Payne & Dolan Inc. of Waukesha, WI. Specifically a quad-axle dump truck loaded with aggregate was used, as shown in Figure 1-8 below. The strains induced in the pavement from this vehicle were also analyzed.

Figure 1-8 - Truck used for calibration.

The same WisDOT inspector(s) were scheduled to weigh out this particular truck. However, only the flat and level weights were obtained. It was observed that the wheel weights varied from driver and passenger sides of the vehicle. It also appeared that the payload was shifted to one side of the bed, causing most of this discrepancy between the wheel loads. The measured static weights can be found in the ‘experimental’ column of Table 1-10 and Table 1-12 (the static weight data can be found, in its entirety, in appendix A).

The truck was weighed with different combinations of pusher axles engaged. After the weights were recorded, several passes were made over the test section. Multiple pusher axle arrangements were used to vary responses. After testing, system checks similar to those done for the Marquette test vehicle were completed.

Table 1-10 through Table 1-14 provide individual wheel loads, gross vehicle weights, and axle spacing results similar to the previous WIM results presented in Table 1-5 through Table 1-9. The results of these tests show that conformity has been met with respect to the ASTM standard. It should be noted that the first trial was omitted from the calculations because the test vehicle tracked very far to the right, barely hitting the WIM sensors, if at all.

Table 1-10 - Wheel calibration results.

Experimental Data				Recorded Data				Δ wheel Load, %
Run Number	Axle	Est. Speed, MPH	Wheel Load, kips	Wheel ID	WIM ID	class	Wheel Load, kips	
1*	Front	48	9.25	250646179	432061	7	0.45	-95.1%
	Rear		2.90	250646180	432061	7	0.45	-84.5%
	Rear		7.60	250646181	432061	7	5.50	-27.6%
	Rear		7.65	250646182	432061	7	4.80	-37.3%
2	Front	45	9.25	250646322	432135	7	8.20	-11.4%
	Rear		2.90	250646323	432135	7	4.05	39.7%
	Rear		7.60	250646324	432135	7	8.20	7.9%
	Rear		7.65	250646325	432135	7	7.55	-1.3%
3	Front	46	10.20	250646451	432206	6	8.65	-15.2%
	Rear		8.70	250646452	432206	6	10.70	23.0%
	Rear		8.55	250646453	432206	6	8.95	4.7%
4	Front	35	10.20	250646592	432283	6	9.65	-5.4%
	Rear		8.70	250646593	432283	6	10.25	17.8%
	Rear		8.55	250646594	432283	6	8.80	2.9%
5	Front	45	10.20	250646739	432361	6	9.60	-5.9%
	Rear		8.70	250646740	432361	6	10.70	23.0%
	Rear		8.55	250646741	432361	6	8.80	2.9%
6	Front	55	10.20	250646851	432426	6	9.05	-11.3%
	Rear		8.70	250646852	432426	6	10.00	14.9%
	Rear		8.55	250646853	432426	6	8.60	0.6%
7	Front	55	10.20	250646960	432485	6	9.20	-9.8%
	Rear		8.70	250646961	432485	6	11.15	28.2%
	Rear		8.55	250646962	432485	6	8.75	2.3%
8	Front	45	10.20	250647072	432548	6	9.75	-4.4%
	Rear		8.70	250647073	432548	6	11.10	27.6%
	Rear		8.55	NA	432548	6	9.30	8.8%

* First test run was omitted due to a known error.

Table 1-11 - Wheel calibration statistics.

Wheel Load Case	
Mean Δ =	6.3%
Std. Dev Δ =	14.9%
95% CI =	6.2%

Table 1-12 - Gross vehicle weight calibration results.

Experimental Data				Recorded WIM Data			ΔGVW Load, %
Run Number	Number of Axles Used	FHWA Class	GVW, kips	WIM ID	FHWA Class	GVW, kips	
1*	4	7	54.8	432061	7	22.4	-59.1%
2	4	7	54.8	432135	7	56	2.2%
3	3	6	54.9	432206	6	56.6	3.1%
4	3	6	54.9	432283	6	57.4	4.6%
5	3	6	54.9	432361	6	58.2	6.0%
6	3	6	54.9	432426	6	55.3	0.7%
7	3	6	54.9	432485	6	58.2	6.0%
8	3	6	54.9	432548	6	60.3	9.8%

* First test run was omitted due to a known error.

Table 1-13 - Gross vehicle weight statistics.

GVW Case	
Mean Δ =	4.6%
Std. Dev Δ =	3.0%
95% CI =	2.2%

Table 1-14- Axle spacing statistics.

Axle Spacing Case	
Mean Δ =	0.10
Std. Dev Δ =	0.08
95% CI =	0.03

While the tests were being performed the acquisition system was fully operational and recording data during the tests. Some of the larger strain responses are shown below. Figure 1-9 illustrates two strain traces for the test vehicle with one pusher axle down and one up for 4 total axles (one steering and three rears, average offset = +26.2 inches). Figure 1-10 provides one strain trace for the test vehicle with the pusher axles in the up position for a total of 3 axles (1 steering and 2 rear, average offset = +7.6 inches).

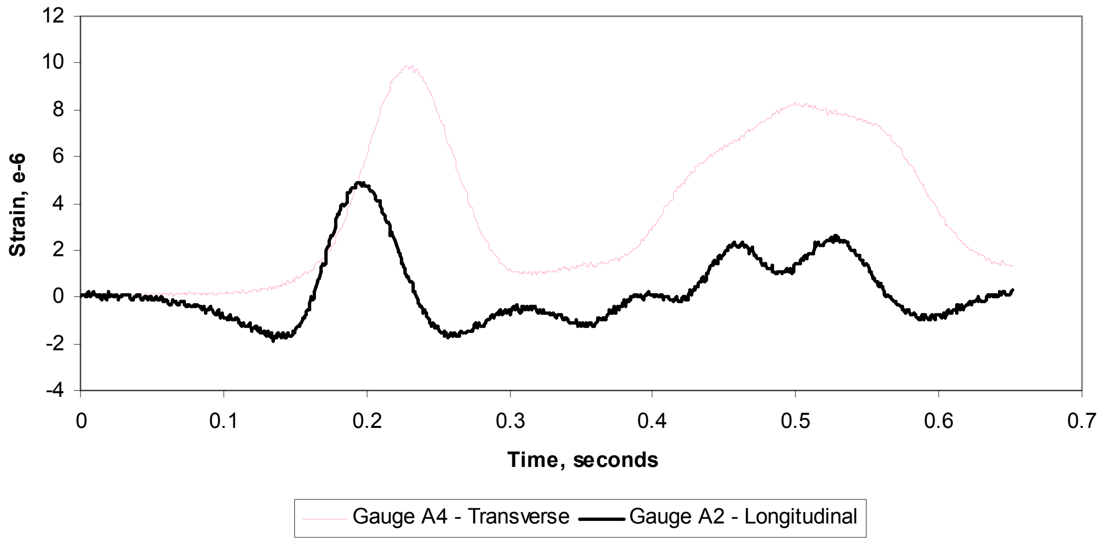


Figure 1-9 - Strain response from quad-axle dump truck.

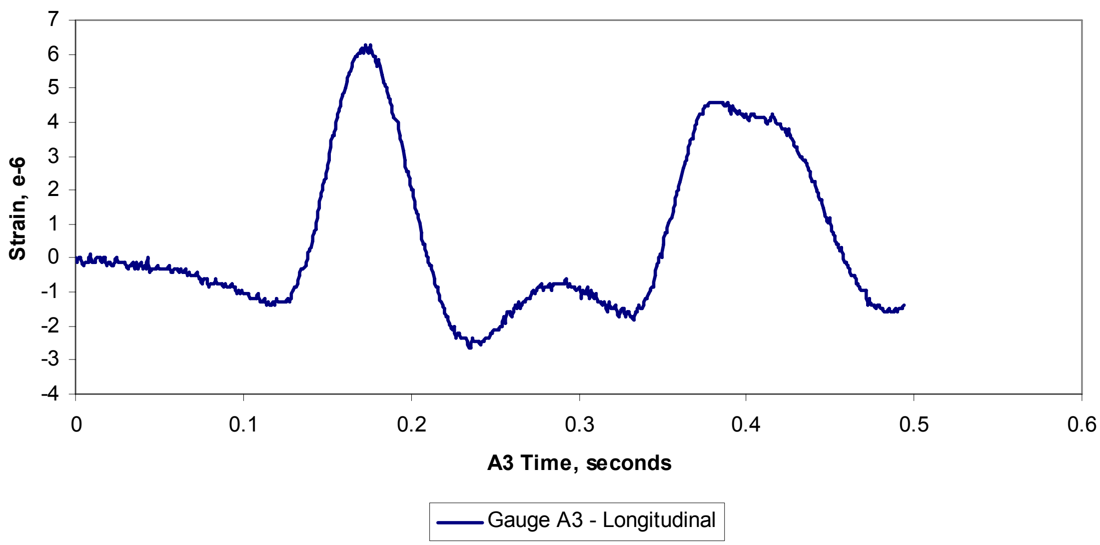


Figure 1-10 - Strain response from quad axle dump with pusher axle up.

Since pavement temperatures can significantly affect the stiffness of the pavement, a summary of the temperatures recorded are provided in Figure 1-11. The period of testing is marked on the plot. Ambient air temperatures ranged from about 37° to 40° F and the mid-depth pavement temperatures were around 31° to 32° F. Subgrade temperatures were well above freezing.

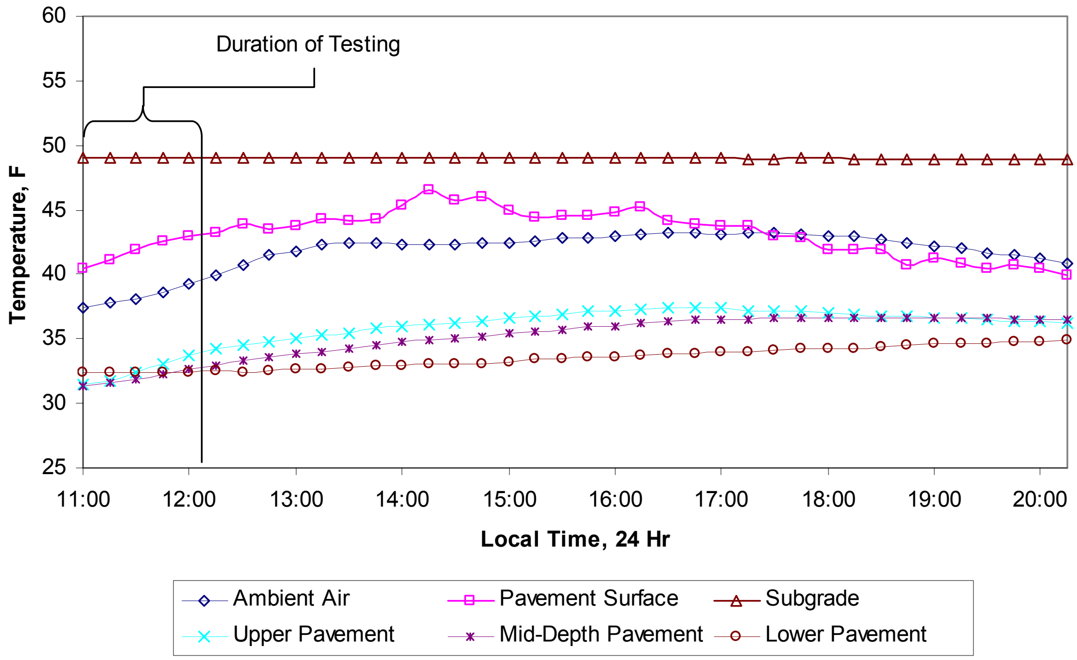


Figure 1-11 - Pavement temperatures during testing.

1.2 - Database Maintenance

Maintenance of the database consisted of small changes and modifications that either corrected bugs or were considered improvements. Some of these changes may seem mundane, but are still important.

When the database was first started and data began streaming into it, only one table for each type of data was created. In other words, one table stored WIM data, another stored environmental data, and so on for the wheel and strain/pressure (aka profile) data. However, in basic database architecture, the time to execute queries against a database increases with the number of rows in the database.

For the environmental table, this was not an issue because a sample is collected every 15 minutes, implying a total of 365 days X 24 hours X 4 15-

minute intervals = 35,040 rows of data for one complete year. While this is half the row limitations in a spreadsheet program such as Microsoft Excel, this volume is relatively small for a database.

The database volume issues arise for the wheel and especially the profile tables. If there are 20,000 vehicles per day and the collection system catches all axles, assuming an average of 2.7 axles per vehicle we would expect 54,000 rows generated in one day. Furthermore, each wheel event generates, on average, about 250 rows of acquired strain/pressure data, or about 250 X 54,000 = 13.5 million rows in one day. Even at this volume, database queries are still relatively fast, but better performance is attained by reducing the total number of rows.

Mitigation of this issue led to many data tables representing one week's worth of data for the WIM, wheel, and profile data; the environmental data table is estimated to remain small enough for years of data. The table names remained the same except for an extension that represented the year and week shown in Table 1-15.

Table 1-15 - Database table naming scheme.

Original Tables	→	New Tables
wim	→	wimYYWW
wheel	→	wheelYYWW
profile	→	profileYYWW
environment	→	environment

In each table name, the YYWW portion represents the year in two digit form and the week number. For example, data from January 4, 2008 would reside in tables with the 0800 extension and data from January 8, 2008 reside in 0801 tables. It should be pointed out that the first week of the year starts as zero (zero based index). To calculate the week number, simply divide the day of the year by 7 and truncate the value to an integer.

Since this system was adopted after data collection began, the older tables were systematically parsed into their respective weeks and added to the proper tables. The original data table still exists in the database, but data download/analysis will use the newer table format.

The original date and time formats designed during the conception of the database have been changed. The wheel and WIM tables both contained three columns to contain the date and time information as date, time, and milliseconds. It was seen beneficial to convert the date and time data into a DateTime object. A DateTime object is simply a concatenation of the date and time – the format is much easier to work with in spreadsheet programs and most programming languages are setup to readily use it. For example, the date “January 4, 2008” and time “15:21:04”, would be concatenated into one DateTime object represented as “January 4, 2008 15:21:04” or “39451.6396296296” in raw numerical format.

All past data tables were modified to reflect this change to DateTime objects. This eliminated one column of data in these tables. The millisecond columns were left alone and still exist – no plans have been made to change them.

In addition to this modification to the DateTime values, a collection of time data was taken from the database to quantify the magnitude of the inaccuracies of the system clock on the data acquisition computer. It was well understood the system clock was highly inaccurate, however no attempt was made to reset the clock at a regular intervals because of the possibility of creating system instability. Instead a relationship between actual time and the data acquisition time was created so corrections can be made. Figure 1-12 below shows the relationship between the drift in the clocks for both the data acquisition system and the WIM system. It has been calculated that the National Instruments (NI) clock drifts ahead about 39 seconds per day. The drift in the WIM system is negligible, although the clock is set just slightly slow (although the data here suggest the WIM system to be running ahead by almost 14 minutes, it is actually running slow by this amount).

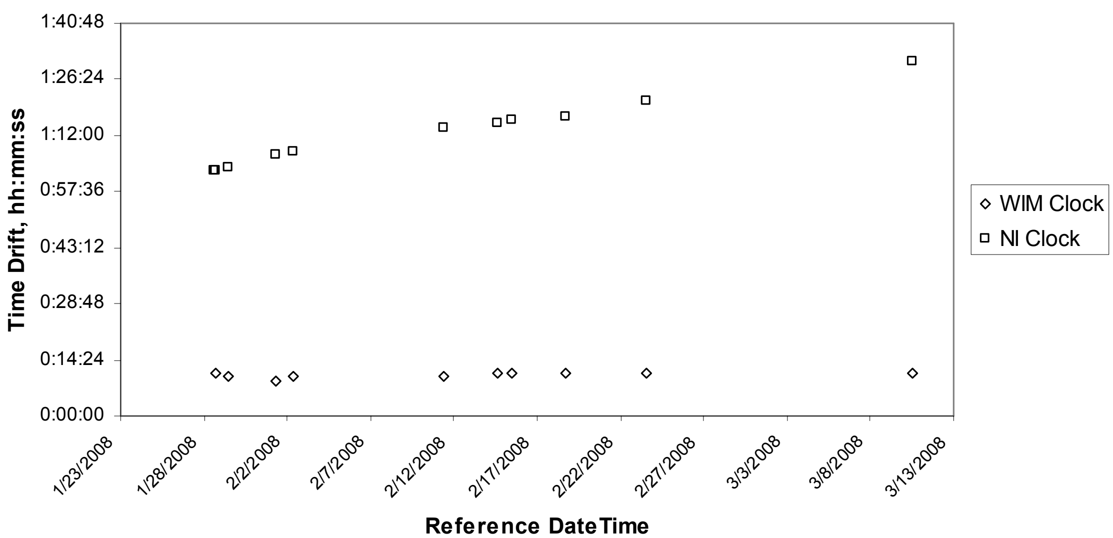


Figure 1-12 - Time drift for WIM and NI systems.

The last modification to the data that was made was to revert all measured values back to their real value. To better explain, all of the measurement values were multiplied by factors of 10 or 100 in order to produce integer values. Integer values require less physical storage space then decimal values. However, storage space (in the form of hard drives) is relatively inexpensive compared to original estimated costs at the project conception. Because of this fact, it was determined that unmodified values should be stored to simplify the use of the database.

When this change was made, all previous data tables were corrected to reflect these changes. Table 1-16 through Table 1-19 indicate the units for all data columns presently stored in the database tables.

Table 1-16 - Environmental table values types.

Environment								
Date	**Time**	**Ambient Air Temperature**	**Wind Speed**	**Pyro 0 and 1**	**Pavement Surface Temp.**	**Subgradge Moisture A0 → B2**	**Subgrade Temp. A0 → B2**	**Pavement Temperature A0 → A11**
YYYY-MM-DD	hh:mm:ss	° F x 10	MPH	W/M^2 x 10	° F x 10	Θ, % x 10	° F x 10	° F x 10

Table 1-17 - Wheel table values types.

Wheel							
Wheel ID	**Date Time**	**Milliseconds**	**Offset**	**Speed**	**Image**	**Timer**	**WIM ID**
Integer	YYYY-MM-DD hh:mm:ss	Integer	Inches	MPH	JPEG image	Integer	Integer

Table 1-18 - WIM table values types.

WIM									
Date Time	**Milliseconds**	**Axles**	**Class**	**Weight**	**Length**	**Speed**	**WIM ID**	**Axle Spacings (all)**	**Wheel Load (all)**
YYYY-MM-DD hh:mm:ss	Integer	Integer	FHWA 1- 14	Kips	Feet	MPH	Integer	Feet	Axle Load, Kips

Table 1-19 - Profile table values types.

ProfileYYWW		
wheel_id	**Strain A0 → S0**	**Pressure A0 → B1**
Integer	in/in E -6 (microstrain)	lbs / in^2

1.3 - Data Management

When the acquisition and recordation system was originally setup, data were wirelessly transmitted from the field site to the database server at Marquette. However, data access speeds were relatively slow due to the limited amount of bandwidth and there was no off-site backup of the data (however, back-up data are stored on a redundant set of hard disks with RAID 5). A remote server in the western part of the nation was chosen to store a redundant set of data and actually provided better bandwidth. This remote server acted as both the data server for outside data requests and as a backup for the collected field data.

At some point, the remote server encountered technical difficulties and failed to function properly. These difficulties continued and it was decided to create a second server at Marquette to house a redundant set of data and help handle outside requests.

A new computer was built in-house and set up at a location away from the main server. This computer serves as a mirror of the main database, meaning that the database software constantly monitors the main database and updates data as needed to create an identical copy. In addition, backup files of the entire database have been created on a regular basis.

Since the remote server host is not in use anymore, it was necessary to find a server to host the project web service. This required a web server that supported PHP, a scripting language used here to query the database. Since Marquette does not have this service running on the university web servers, a web server was launched on the main database server.

This computer now runs web server software along with the PHP scripting client. The webpage and its components were updated to follow the new web service. The web based data viewer utility is up and running along with the project website.

In addition to the above work, a watchdog program was developed to monitor the database and send email and text message alerts to the system managers. The watchdog program checks the row count of the active database table at a set time interval (currently, 30 minutes). If the row count does not increase within the intervals, an alert is sent so that problems/errors can be corrected.

The data acquisition software has undergone continual maintenance as needed. As problems were identified or improvements were realized, adjustments were made to the code. The evolution of this program is truly the heart of project and has become many times more robust and efficient since the project inception.

Chapter 2 - Data Analysis Software

Due to the large amount of data being received from the project, it would be nearly impossible to analyze all of the data by hand. Because of this reality, computer programs were developed to automate the process. Of particular interest for this research project, and asphalt pavement research in general, is the maximum tensile strain induced in the pavement by a passing wheel load. The first task was to create a method by which the maximum tensile strain could be taken from the raw strain signals and then matched accordingly with the appropriate wheel loading. At first glance, this seems quite simple for the idealized case, but "real" data contain many differences from an idealized case. Figure 2-1 provides a flow-chart of the general process used for event matching.

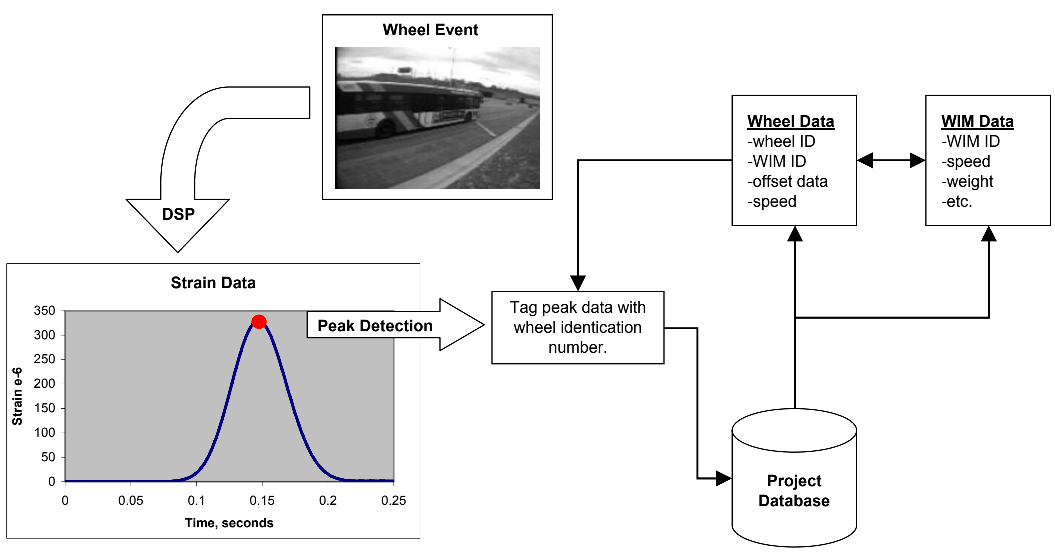


Figure 2-1 – Data collection process

The difficulties in analyzing the data can be viewed at two different levels - the first level consisting of the strain signal as a complete entity. One aspect that is different from the idealized situation is the fact that there may be more than one peak in each recorded strain signal. For instance, a tandem axle group creates two peaks that are closely spaced together, especially at high speeds. Another concern is instances where the strain signal was recorded improperly, and the peak may be missing – not to mention instances where the wheel event is missing entirely. In general, it is not surprising to find anomalies within the data every so often and each of these issues must be dealt with in the programming code. The causes of the error can be related to numerous things such as the vehicle merging into another lane, moving too slow or fast, vehicle bounce, and so on.

The second level is viewed on a smaller scale, as individual data points. An example of this sort of complication is signal noise, and how to distinguish noise from peak strains occurring for very light wheel loads. The data analysis process for sorting out these peak events can be described in various components. This is done to keep the coding understandable, manageable and easier to follow than one single file containing all of the code. Even with this, some parts of the program are quite long and complicated, and will be difficult to understand for a non-experienced reader. However, the fundamental explanation of each routine should seem quite simple and understandable by anyone. Each individual method used is simple at is source, but becomes complicated when used in conjunction with many other routines.

2.1 - Phase I Strain Measurement

The first phase of this project dealt with the design and construction of the system for recording data. Within phase, experiments were carried out on individual instruments to check that they were functioning properly and to either check or create calibration data.

The accuracy of these instruments is crucial in order to provide good data used for research. The strain gauges were of particular importance as they are the focus of this project. It was found that the noise levels in the strain gauges was about 0.2 με for the CTL brand sensors and about 1.0 με for the Dynatest brand sensors (4). After careful inspection of the experimental calibration data, is was decided to use the experimental calibration factors rather than the manufacturer's factors. This would provide the greatest amount of accuracy for each individual instrument.

Overall the CTL strain sensors are accurate to about ± 0.5 με while the Dynatest sensors are accurate to about ± 1.0 με, conservatively speaking. Although the gauges are readable to more significant figures, the amount of signal noise present causes the actual precision to decrease slightly.

For more information see the report preceding this report titled *Marquette Interchange Perpetual Pavement Instrumentation Project: Phase I Final Report* (4). The report covers information regarding the design and construction of the pavement experiment.

2.2 - Database Architecture and Program Flow

The database contains four general tables which consist of the wheel data, WIM data, strain and pressure data, and finally environmental data. Each row of the WIM table represents one vehicle while each row of the wheel table represents an individual wheel load. Each row of the strain and pressure table represents one output data point from each of the 29 sensors (25 strain and 4 pressure), which are currently sampled at a rate of 1 kHz. The number of data rows for each wheel event is dependent on the travel speed of the wheel. For each wheel load, a data selection window is opened to include strain readings while the load is positioned anywhere within a sixteen foot measurement space, beginning at a point 8 feet before the sensor to a point 8 feet after the sensor location. For a wheel travel speed of 60 mph (88 fps), the wheel would be within this 16 foot measurement window for a period of 16/88 = 0.1818 seconds. Thus, for the 1 kHz sample rate, a total of 182 samples would be stored. As travels speeds diminish, the within-window time period increases as do the number of stored data rows, and vice-versa as the travel speed increases above 60 mph.

The environmental table consists of rows of data taken every fifteen minutes and has no correlation to individual wheel/vehicle events other than the time at which they were taken. A graphical relationship of the data is shown in Figure 2-2 (excluding environmental data).

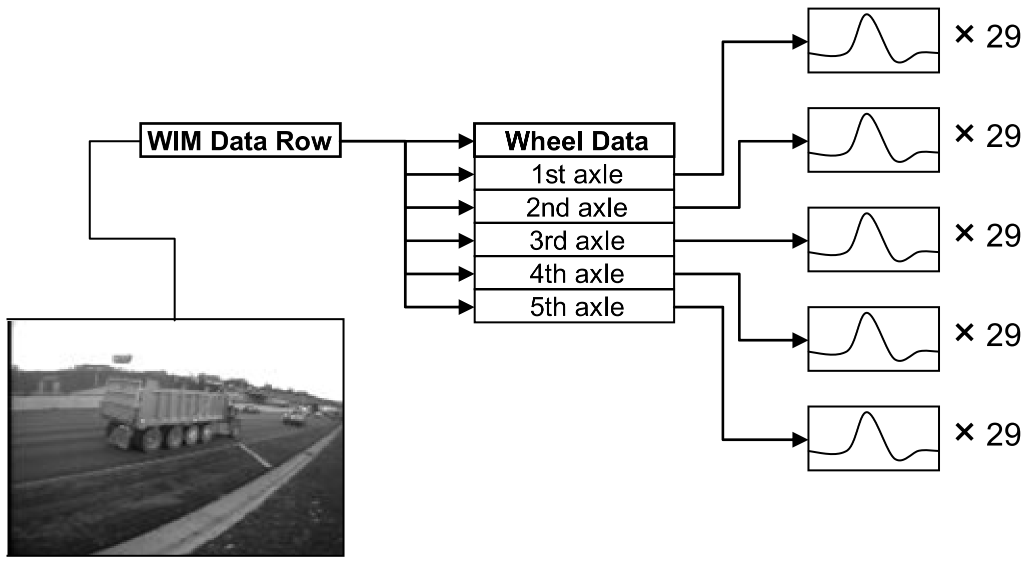


Figure 2-2 - Data relationship.

The most logical procedure to analyze the data based on this architecture is as follows and corresponds to Figure 2-2 above. Begin with a row (one particular vehicle) of the WIM table and cache the data row into memory. Next use a key (WIM ID) unique to the WIM table and query the wheel table, selecting all rows that posses the same key – of which the returned rows consist of the specific wheels for that particular vehicle. Finally the unique wheel identifications for individual wheels are used to query the appropriate strain and pressure data and then analyzed. The results of the analysis algorithms are then stored into yet another database for future use. This 'ahead-of-time' processing and storing of results was done to save time for future applications.

2.3 - Analysis Modules

As stated before, the analysis package has been designed in separate modules. Considering the programming language used in this case, C#, they are often referred to as ‘classes’ which contain the methods to carry out the work.

The significant modules or classes used here are for

- Peak detection in signals
- Aggregation of the peaks amongst all of the sensors
- Matching the correct peak with each associated wheel event
- Calculation of the load times
- Calculation of the area under the signal trace.

In addition to this another module was developed to rebuild strain signals for axle groups which were closely spaced together, essentially taking the short recordings and ‘splicing’ them together to form one continuous signal.

There are many other incidental modules which had to be created in order for the program to operate, however they are not essential to this report and information on these classes are not provided here. These classes are responsible for operations such as opening database connections and other various actions.

2.3.1 - Signal Regeneration

The function of the signal regeneration module is to take strain data for closely spaced axle groups and combine them into one long data stream. The development of this module actually came after difficulties arose while trying to match peak tensile strains with specific wheel events. The following explains why this module is necessary.

When the axle of a vehicle enters the test section, the data acquisition system sets off a flurry of events which is triggered by the wheel wander piezo sensors. When a wheel is detected, the data acquisition system enters the data stream being generated and grabs data from the strain and pressure sensors for a window of time which is determined at the instance of the event. The size of this window is based on the calculated speed; a slow moving vehicle will occupy the test section longer and thus the system will store a much longer sample of strain and pressure data. A fast moving vehicle will cause the system to store a rather short amount of strain data.

These differences are illustrated below in Figure 2-3 for two FHWA class 4 vehicles recorded only a few hours apart and with similar offsets. The wheel weights for the slow and fast vehicles are 5.45 and 4.1 kips, respectively. Although the axle loads (or wheel loads rather) are somewhat similar, the strain induced in the pavement are drastically different, demonstrating the effect that speed has on pavement strain.

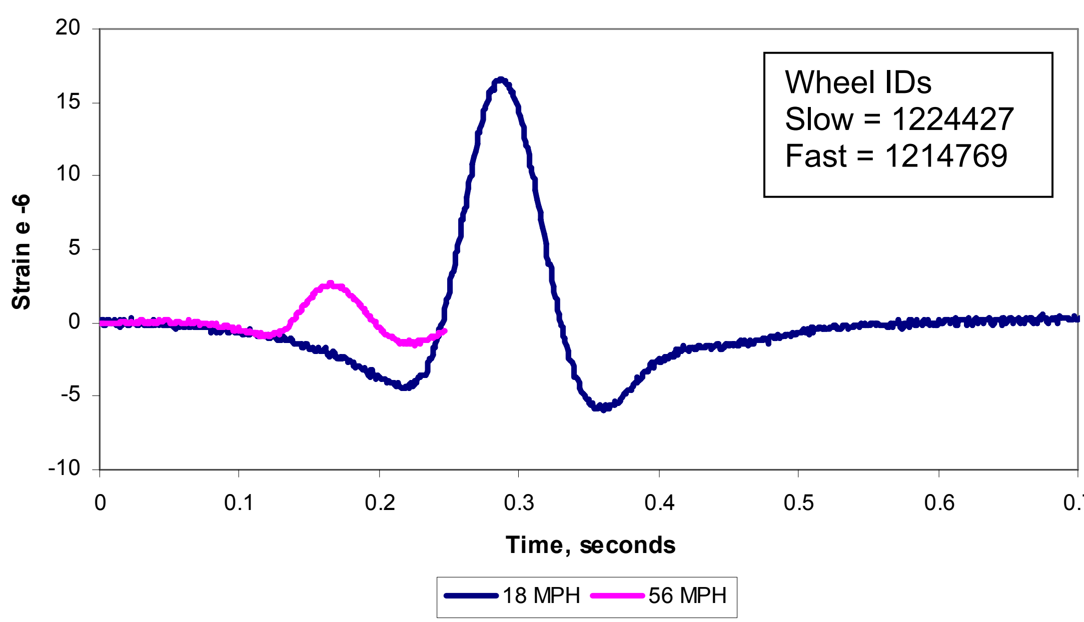


Figure 2-3 - Strain versus vehicle speed.

The data being sampled by the acquisition system are constantly being measured and stored in a small block of memory, constantly disposing the oldest data point at the top and adding the newest data point to the end.

If the particular vehicle has relatively short axle spacings (say a tandem or tridem axle group), it is possible that the windows of this data collection for the axles may overlap, as shown in the strain signals in Figure 2-4 for a quad axle dump truck. Note that in Figure 2-4 the 3rd and 4th axle recordings are nearly identical and that the 4th recording actually contains data earlier than the 3rd recording.

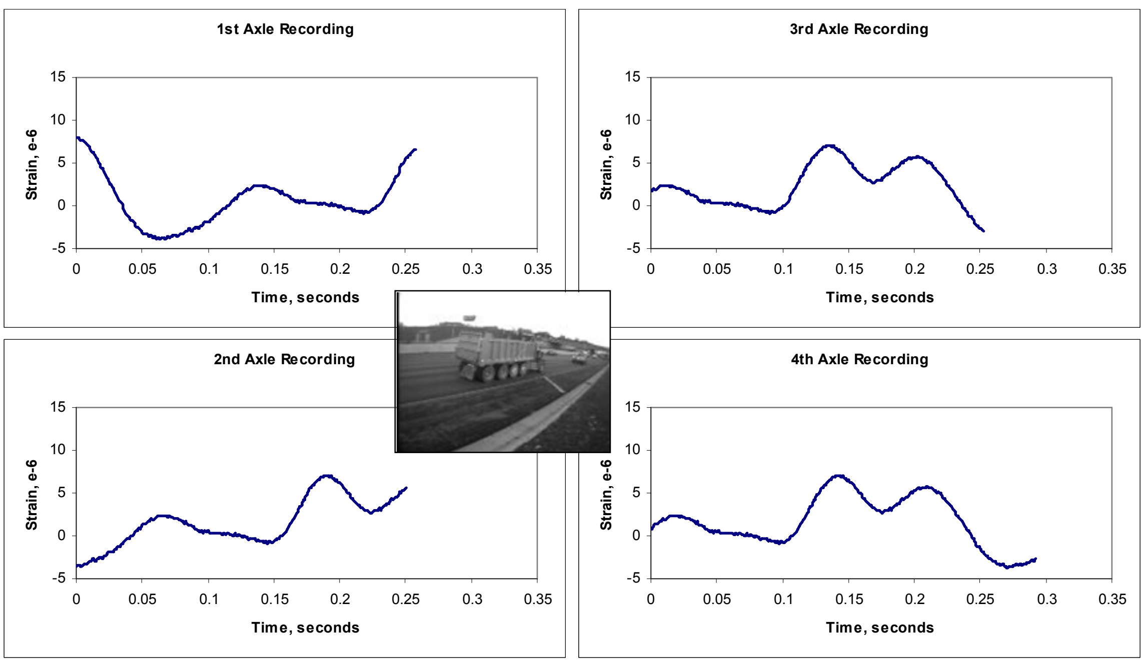


Figure 2-4 - Quad axle strain signals.

Depending on the type of vehicle and the axle configuration, it is possible to have nearly identical strain recordings for two or more wheel events. This presents an issue for analysis because there may be two peak tensile/pressure values in one data recording, thus making a row-by-row analysis of the data not possible. If it were to be done, it would be too difficult to differentiate which peak strain/pressure value corresponded to which axle.

In addition to this fact, there is the possibility of shadowing the change in strain/pressure caused by the wheel event. The strain gauges and pressure cells were calibrated in the lab and the data were entered into the system so that all of the sensors were reading a value of 0.00 μstrain or 0.00 psi. Upon installation the gauges became loaded and thus the values did not read zero any longer. Temperature also affects some of the gauges, causing the measured value to drift, not to mention the strains induced in the pavement due to contraction and expansion (it should be noted that this drift has little effect on the accuracy or precision of the sensor).

Since we are looking for the change in strain in the sensors an average of the first few data points is taken and subtracted from the rest of the data. For the purpose here, this subtracted value is referred to as the baseline. The 'shadowing' problem that occurs is that for strain recordings that contain multiple axles, it is possible that the axle event just before the current may cause a peak in the beginning of the data trace. If the first few data points are averaged to try to obtain a baseline value, it will compute a much higher (or lower) value than it should, thus possibly providing peak strains that are erroneous.

Because of the aforementioned reasons, an algorithm was developed to select the proper consecutive strain/pressure signals and splice them together into one large signal. The algorithm then hands the rebuilt signal back to the analysis program for further processing. The process used to rebuild the signals in quite simple.

Because the acquisition system is simply storing data from a memory buffer, the same data points can exist in multiple strain/pressure signals. In the event that there are large overlaps in the signal traces, there may be a large number of data points which are identical. The chaotic nature of the signal due to the noise and from the wheel event itself causes a large enough series of data points to be considered unique. This unique sequence can then be used to search consecutive data traces for a sequence which is exactly the same.

The algorithm used only five data points from only one gauge to do this with almost perfect accuracy. The first five data points from a signal are subtracted from a moving array of data points from the previous signal. If the subtraction of the two arrays equals an array of zeros, then the data points from the newer signal are added to the older signal. This process is carried out for each wheel. However, since the timing for each strain gauge is identical, the remaining 28 instrument signals are added together based on the location found from the first gauge.

The final result of this module is a complete set of strain/pressure signals comprised of signals generated by multiple wheels. Depending on the nature of the recordings, this process may yield no results. In this event the rest of the program handles the analysis in a separate manner.

2.3.2 - Peak Detection

The main function of the peak detection process is to search each strain/pressure signal recording and select the peak tensile strains. A very simple process was used to accomplish this goal. This module essentially returns a table with two columns - time and a value (either strain or pressure). Each row of the table represents one peak detected in the signal recording and the number of peaks is limitless.

A very common method for finding peaks in data signals is to perform a linear regression of a set of points and subsequently analyze the slope. When the slope equals zero, it is assumed there is a peak at that location. This process was assumed to be slightly too complicated and might consume too many computing resources. In addition, another software package which contained such an analysis tool was found to be quite accurate but was no better then the simplified process developed here.

The peak detection module for this project operates in a very simple manner. The strain/pressure signals are comprised of data points recorded every 0.001 seconds. First a submitted strain trace is normalized by subtracting the average of the first 20 points from the entire signal. Next, beginning at the first data point a group of points is averaged. Then another group of points is averaged at a specified distance away. These two averaged values are then subtracted. If the difference is within a specified threshold, then the data point is stored as a peak.

There are different properties which can be set in the algorithm to maximize accuracy. The number of data points to use in the averaged values and the spacing between them can be set as well as the threshold for the difference between them. A thorough analysis has been conducted to obtain the best values. In addition to these an overall threshold has been applied to filter out signal noise, thus anything smaller then about +1 με (tension) is not recorded as a peak. A time spacing threshold has also been implemented, otherwise it might be possible that multiple points meet the search criteria within the same peak pulse.

It should be noted that the signal is manipulated after the signal is normalized but before the actual peak detection. Each data point is multiplied by a factor of 5 to increase the effects of values greater than plus or minus one. This helps to eliminate the effects of the noise and make actual peaks more pronounced. Also, only the absolute value is used when comparing the difference in the average values, thus a 'valley' is processed as a 'peak', but stored as its original value.

2.3.3 - Load Time and Area Integration

Two other important pieces of information that could be found from the strain traces was the time of loading and the area underneath the tensile portion of the strain trace. Both of these processes are contained in one analysis module because they are closely related.

For a particular strain signal this algorithm requires the location of the peak data point of interest which could have been generated by the peak detection module. To calculate the load time, the program enters the normalized strain/pressure signal and moves backwards through the data until the strain value reaches a value of less then zero and records the location (or time). It then re-starts at the peak value, moving forward through each data point looking for the first data point to drop below zero, storing the location of the point. The load time is the product of 0.001 seconds and the number of data points between the two stored values (assuming a sample rate of 1000 Hz). Using the two values found for the load time, the program than iterates through the data points and calculates each individual area using the trapezoid rule.

It should be noted that for certain axle configurations, namely tandems and tridems, it is possible that the area and load time calculated for the axles in the group will be exactly the same. These particular values will represent the load time and area for all three axles because the strain signals might not return to a base value. An example of such a signal is shown below in Figure 2-5 – the strain signal represents the tandem axle group on the class 6 vehicle. The method, if any, by which the load time and area would be split into representative quantities for each wheel is outside the scope of the project because there exist no known way of doing so.

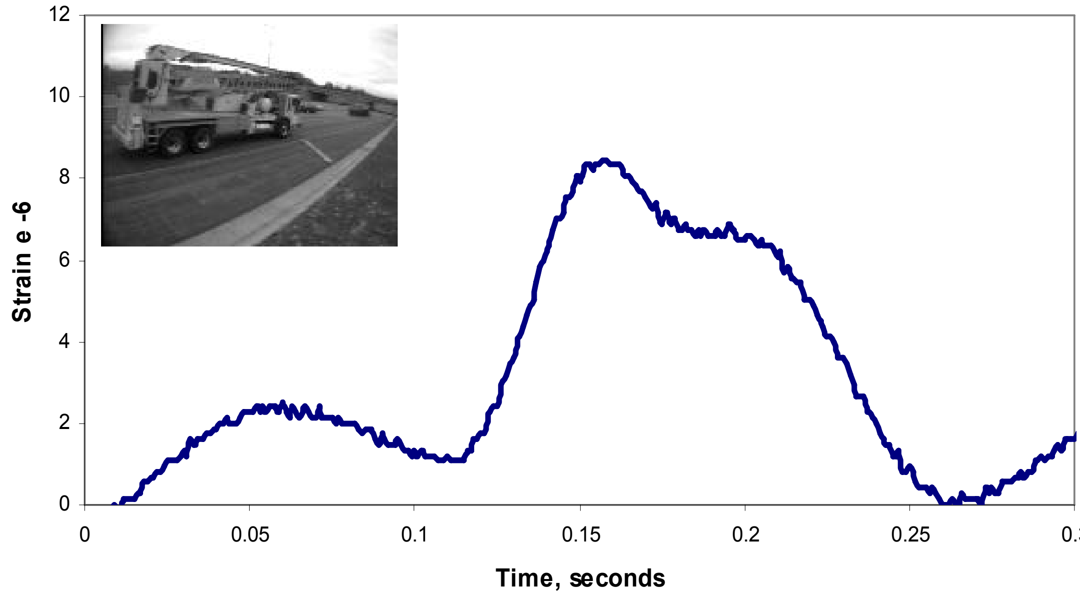


Figure 2-5 - Tandem axle strain signal.

When this module finishes, it returns two tables – one containing load time data and the other area data, each row in the tables representing an individual wheel. The two tables each contain 30 columns; the first column is the unique wheel ID, and the other 29 represent data for each of the 25 strain gauges and 4 pressure cells.

2.3.4 - Matching Peak Strains and Pressures to Wheel Events

The previous three modules must be tied together in some fashion to make meaningful data. This fourth and final module is responsible for this and also institutes the previous three modules. This final module ultimately returns three tables of data which contain the peak strain/pressure, area, and load time data – each row associated with wheel identifications that match those in the original data tables. These three tables are then stored in a new database which can be queried at a later time.

This module has three main routines contained within itself. The first routine (represented by steps 1 and 2 in Figure 2-6 below) gathers all of the wheel and WIM data for a particular vehicle which typically consists of one row of WIM data and numerous rows of wheel data (corresponding to each axle on the vehicle that was recorded). As stated before, the easiest path for analysis is to begin with a row of WIM data containing a unique WIM identification and subsequently querying the wheel database table using that unique ID.

The second routine is responsible for taking data from the peak detection program and sorting them into logical groups based on time (step 3 in Figure 2-6 below). The peak detection module simply takes a signal, which could be from anywhere, and detects and records peaks within a signal. Since there are 25 strain sensors and 4 pressure cells, the peaks that are detected do not occur at exactly the same time, but still need to be sorted accordingly. This particular routine runs the peak detection on a signal (which may or may not be a regenerated signal) and then organizes the results into a table where each row represents a relative instance of time. The result is a table of strain/pressure peak values where each row represents a time instance.

Lastly, the third routine analyzes time signatures, matches the peak data with corresponding wheel events, and institutes the time of loading and area routines (step 4 in Figure 2-6 below). There are several different analysis methods the program uses based upon the class of the vehicle, each tailored to the specific type of vehicle.

From the WIM data the relative time spacing between axles is calculated based on speed and axle spacing. The program then runs through the sorted and organized peak data looking for the same time signature and subsequently stores those particular values tagging them with the appropriate wheel identification. In the event that the program fails at finding a proper match, there are separate routines to employ a different method to accomplish the same goal.

When this module finishes it returns three data tables containing the area, time of loading, and peak strain/pressure data. From here another set of code handles saving the data to a database for use at a later time (step 5 in Figure 2-6).

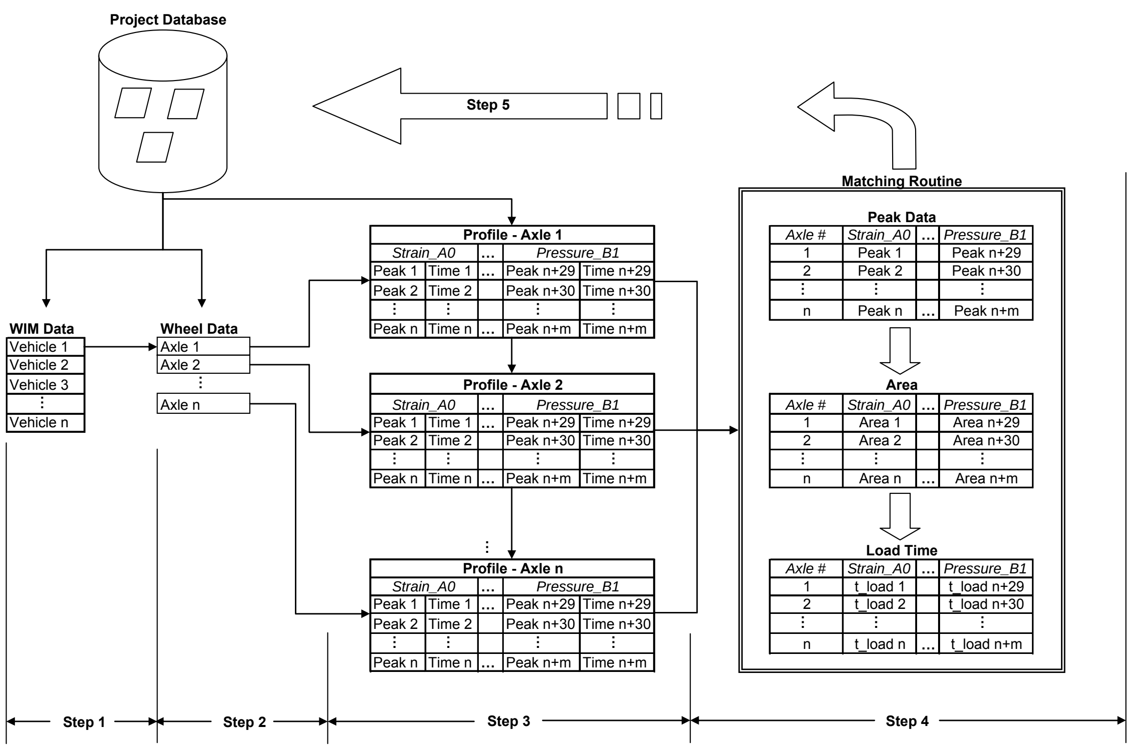


Figure 2-6 - Data analysis program flow

With these modules working together, a completely automated system can be set up to iterate through every row of WIM data and store the analysis data. The program is setup to analyze the data one week at a time. Depending on the number of wheel events that cause significant strain measurements, the analysis may take up to several hours to complete one week of data.

2.4 - Analysis Performance

The tools developed to analyze the data and generate meaningful information needed to be checked to ensure adequate results were being obtained. To do this, a series of vehicles were randomly selected from the database and the peak values, area under the curve, and load times were measured by hand. Then the values generated by the analysis program were compared against these actual values to see how well they compared.

The randomly selected vehicles were chosen from different vehicle classes ranging from class 4 up to class 10 vehicles. This was thought to represent the most common and the most important vehicles in terms of pavement research. All of the axles for the selected vehicle were included in the comparison. Additionally, one random strain gauge was selected for the comparison to include any local effects due to gauge calibration factors and wheel offset.

It should also be noted that one week of data was used to pull the vehicles and that this week represented a time where ambient temperatures were moderately warmer and tensile strains were moderately higher. This was done because during colder temperatures strains are considerably smaller, limiting the number of applicable strain measurements for analysis.

Four vehicles were selected from each class (from class 4 to class 10) which comprised 90 individual axles. In some cases axles were missed by the data acquisition system. However no preferential treatment was given to vehicles with omitted axles. Furthermore, nothing was done to account for these missed axles in terms of checking the performance of the analysis program. The performance of the data acquisition process and the analysis process is completely independent.

From these 90 axles, a random strain gauge from the first 5 gauges in the first sensor array (the 'A' array) was selected to be included in the evaluation. (This was done because during the development of the software, a limited set of strain gauges was used to simplify preliminary coding. The first four gauges consisted of longitudinal gauges which present a greater challenge for analysis due to the common compression-tension-compression pavement behavior.) The actual peak strain value was picked by hand for each of the 90 strain traces. For the case of axle groups containing successive peaks, the value of interest was matched with the proper corresponding axle based on judgment. Any strain below the threshold of +1 με (tension) was recorded as zero to be consistent with the analysis program.

Figure 2-7 below is a plot of actual peak tensile strain versus the detected peak strain for each sampled strain trace. Note that most of the sampled strains were lower than 12 με and the results are quite reasonable. In general the detected and recorded peak values (both strain and pressure) will be slightly lower than the actual value. This is simply due to the fact that a moving average is applied to the signal before analysis.

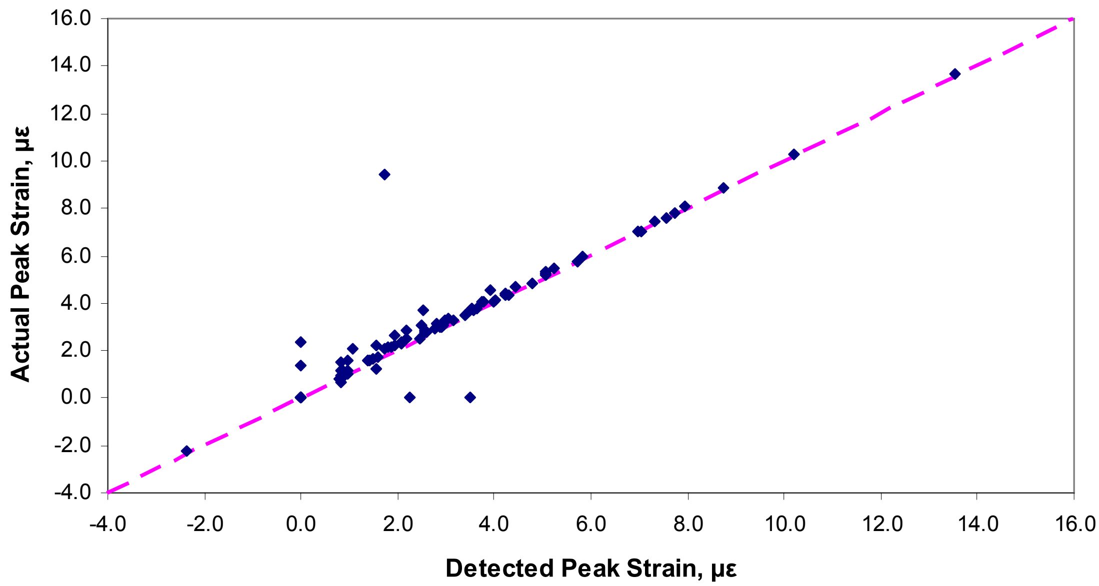


Figure 2-7 - Actual versus detected peak tensile strains.

Accuracy at these relatively low strain values provides some comfort in future analyses were strains become substantially larger. The algorithm used will become increasingly more accurate due to the inherent balancing of the simplified slope analysis used for peak detection. With low strain values signal noise can sometimes become as large as the strain peak, possibly causing misinterpretation of the signal and hence the need to set a lower bound threshold of 1 με.

As described in the earlier discussion of the peak detection process, strains smaller then +1 με (tension) are filtered out. However, the plot in Figure 2-7 above shows values below this threshold. This is possible because the peak detection process analyzes the absolute values of the signals so all extremes, valleys and peaks, are detected. Because of this it is possible that a negative (compressive) strain peak can added to the result set. For example, a wheel load traveling down the center of the wheel-path may induces tensile strains directly under the load, however at some lateral distance away from the load, their may be peak compressive strains occurring at the same instant of time. In some cases there may not be a peak at all, tensile or compressive.

The algorithm for selecting peaks from the strain has also been applied to the pressure data. No formal check has been made, but close inspection shows that the algorithm operates in similar manner in regard to the strain pulses. In general the excursions in the measured values of the pressure cells are vastly greater than the signal noise and hence the peak detection algorithm operates more efficiently due to this, similar to the explanation above for the strain data.

The area under the curve and load time calculations are based directly off of the raw or regenerated signals and the peak strain/pressure data as stated above in the discussion of the module. Due to this fact the accuracy of these values are directly dependent on the performance of the peak detection. Random checks of these calculations show that the algorithms perform as designed; any inherent errors in calculations are related to the peak detection process.

Chapter 3 - Data Packages

The third task for this second phase was to develop data packages and make the data available to the public. This has been accomplished and three outlets exist for users to access the data – the web data-viewer, downloadable pre-packaged data files, and direct database access comprise these three outlets.

3.1 - Web Data-Viewer

The web data view utility was developed to provide the general public a look at real time data being recorded by the data acquisition system. Figure 3-1 below shows the thumbnail index page for the utility.

Users can click on the individual thumbnail images which takes them to the snap-shot page. During this time, the database is queried for the pertinent information regarding the particular wheel event. This snap-shot page (Figure 3-2 shown below) allows the user to view specific data such as WIM and strain data for the particular vehicle – environmental data are also provided. A button near the bottom of the page allows the user to download the data in a simple comma separated text file.

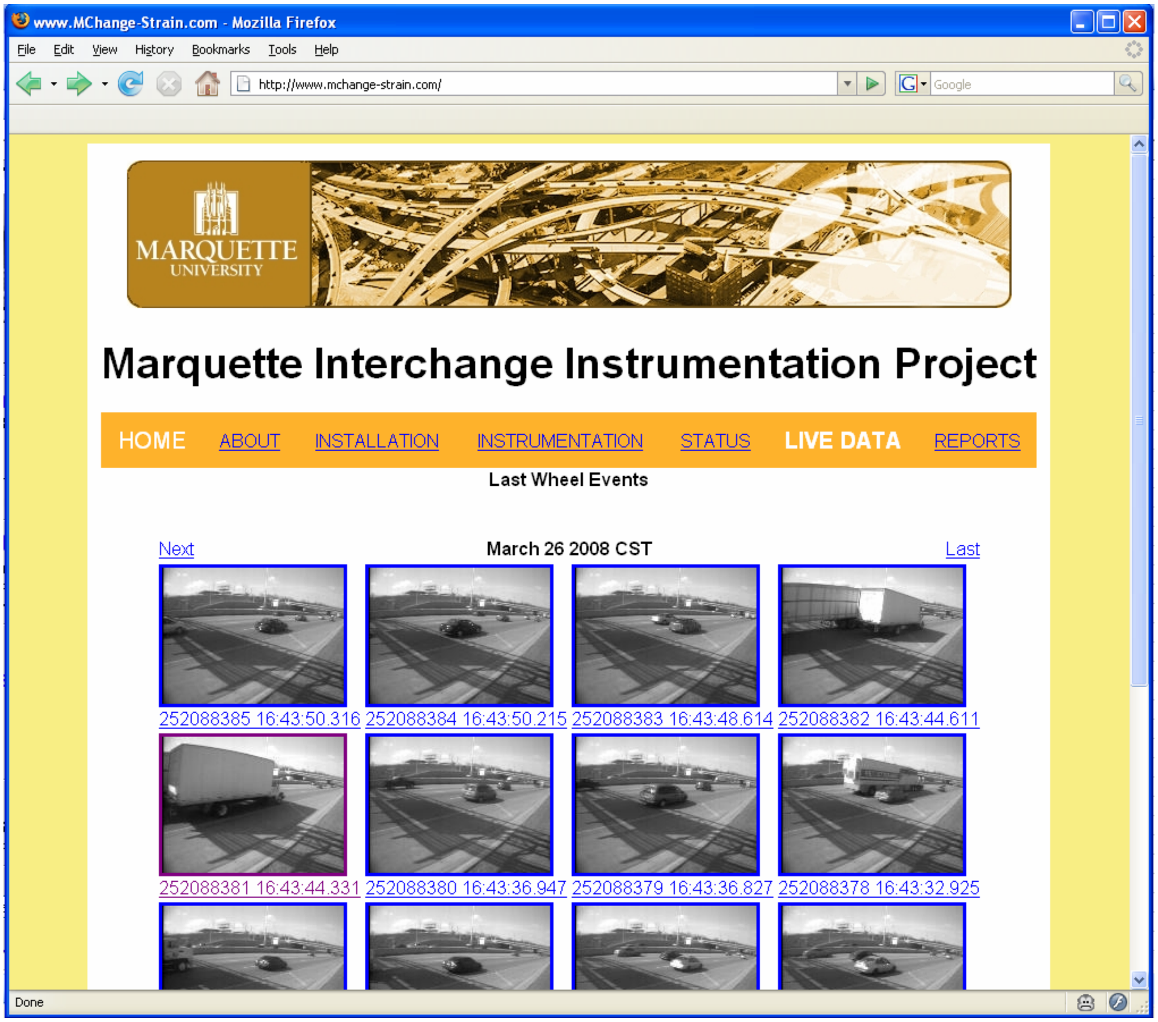


Figure 3-1 - Data viewer index screen.

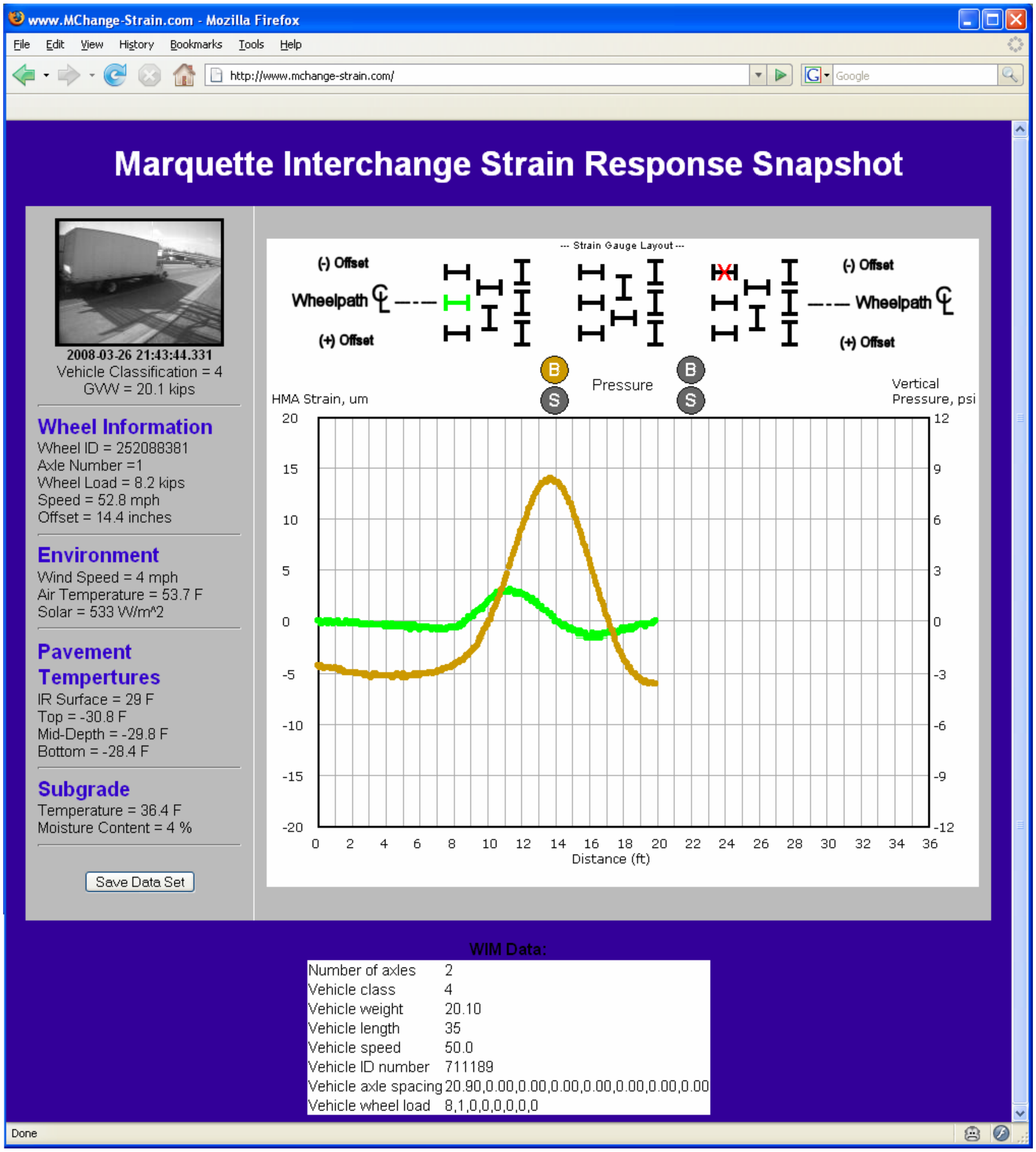


Figure 3-2 - Data snapshot page.

3.2 - Data Packages

In order to freely distribute the data for the general public, the data have been sorted into distinct packets that can be downloaded from the web server. Specifically, each week of data (one data table) has been exported to a comma separated values text file (*.CSV). This format was chosen due to its simplicity, size, and versatility. This file format is easily imported into most database programs and spreadsheets. The individual text files were then compressed into *.ZIP files, bringing down the file sizes drastically (about 5 – 10 % of original size).

However, some data tables were quite small and others (such as the strain and pressure data) were very large. The environmental, WIM, and wheel data have been combined into a handful of files. It should be noted that the exported wheel data table does not contain the images because of the difficulty of exporting the image to binary in CSV format.

The strain and pressure data tables, on the other hand, are quite large and were broken down into multiple parts based on wheel_ids. One week of profile data typically constituted gigabytes of data; however the ZIP file format only supports a total uncompressed file size of 2.0 gigabytes. Because of this, the profile was broken down into multiple pieces based on the wheel identifications – meaning that rows of data with the same wheel identification are all contained within one file.

These files were then simply posted to a webpage on the project website. There are plans to add a user registration page that is required for downloading of the files. Figure 3-3 below is an image of the actual data page as it exists now.

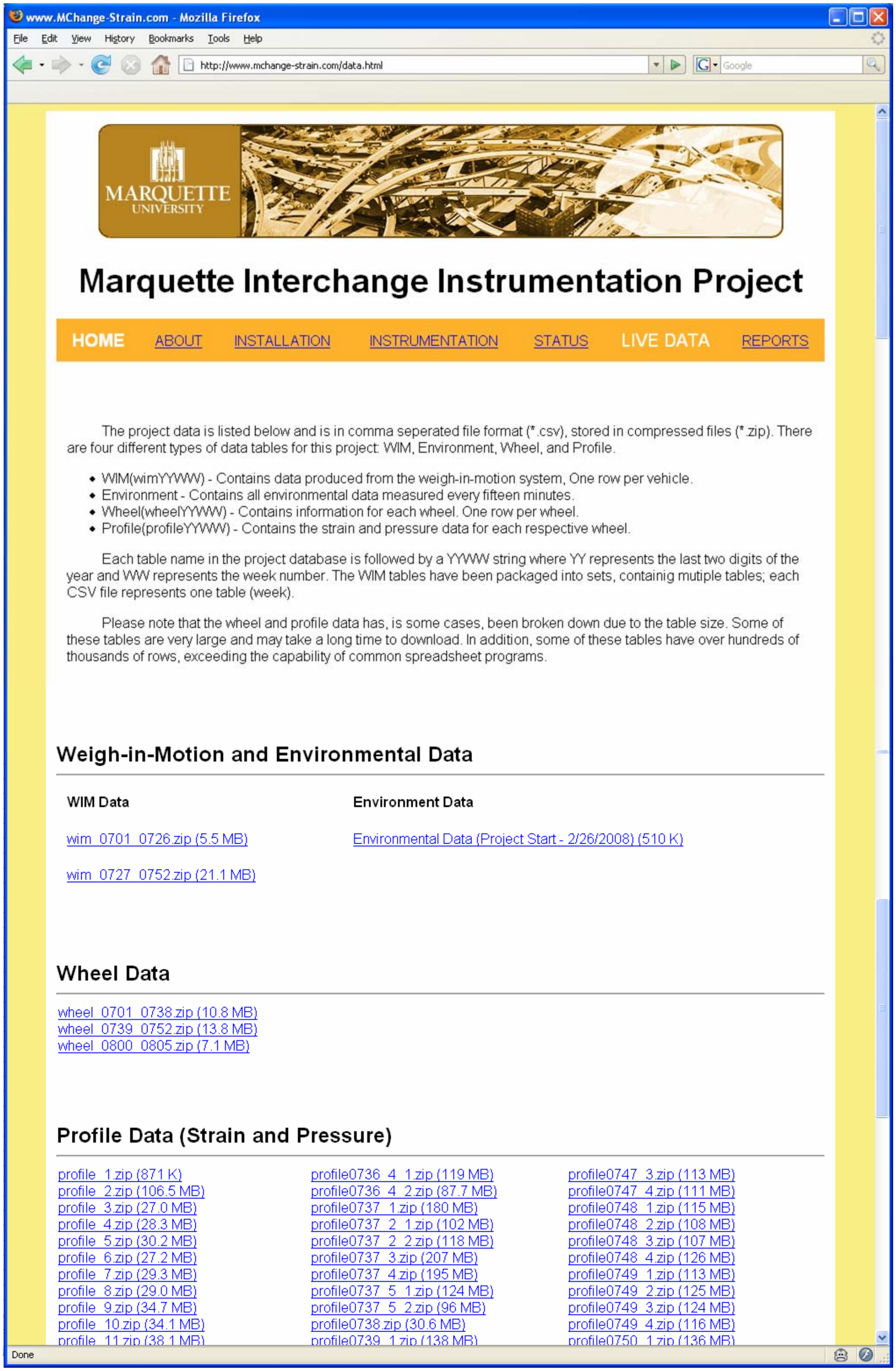


Figure 3-3 – Data page.

3.3 - Database Access

For users needing advanced access to the data, read-only accounts can be generated as needed on the MySQL database. Users needing this access must communicate with the administrators directly to acquire this. Users having this direct access have a variety of tools at their disposal for running queries against the database. The MySQL community develops and releases software on a regular basis and anyone can download and use these utilities by visiting www.mysql.com and navigating to the "downloads" section of the developer's zone.

The most useful tool for the average user will be the MySQL Query Browser, which is contained in the utilities package under the name "GUI Tools" on the downloads section of their web page. This tool will run any query and allows the user to export the data to multiple file formats (XML, CSV, etc).

Other database programs can also be used to import data when direct access is granted. The details of how to accomplish this are not within the scope of this report, but individuals with experience using databases should have little problem accomplishing this.

In addition to this, many (if not all but a few) programming languages have the ability to transact with MySQL databases. This allows users to create programs to accomplish specific tasks automatically and vastly speed up analyses. This ability is crucial to analyzing the vast amount of data contained here. A few MySQL compatible programming languages that may be known to civil engineers are the following: MATLAB, C#, Visual Basic, NI LabVIEW, Java, Python, and many, many more.

In order to demonstrate the ease of MySQL, a few example queries are in order. For the first example, the user is looking for all wheels/axles from week 0817 with speeds equal to and greater than 65 mph. The MySQL command would be…

```
SELECT * FROM wheel0817 WHERE speed > 65;
```

The letters in blue (if viewing this report in color) are the MySQL keywords, wheel0817 is the table name, and speed is a field in the table. Next, the user wants all class 5 vehicles with GVW between 3.0 and 8.0 kips from week 0817 and sorted by date and time…

```
SELECT * FROM wim0817 WHERE weight > 3.0 AND weight <= 8.0
ORDER BY date_time ASC;
```

The user now needs 200 rows of WIM data and the corresponding wheel data from week 0736…

```
SELECT * FROM wheel0736 JOIN wim0736 ON wim_id =
vehicle_number LIMIT 200;
```

In this example, the JOIN keyword is used to combine data from two different tables. The data is combined based on the condition following the ON keyword. In this instance, the two tables are related by two unique identifications, wim_id and vehicle_number. The LIMIT keyword limits the result to 200 rows of data – this can be useful from preventing an overly large result which can slow down both the client and server machines.

For the last example, the user wants the number of WIM entries with speed = 44 mph from week 0736…

SELECT COUNT(*) FROM wim0736 WHERE speed = 44.3;

This final example will return only one result which will be the number of rows in the table with speeds = 44.3 mph. This query can be useful to quickly determine the size of the table or to retrieve the number of trucks.

Chapter 4 - Conclusions and Recommendations

The project has been successful and continues to collect valuable pavement response data. The overall health of the system is excellent and the data acquisition process has evolved to a state that little user input is needed to operate the recordation process. As evidenced in this report, there are a handful of maintenance items that needed to be taken care of, but as the research team gained experience, the amount of time and effort required for each decreased.

The research team has found that certain instruments such as the temperature gradient probes and infrared temperature probes have a difficult time withstanding the harsh environment along a typical Wisconsin highway, particularly due to the effects of winter maintenance operations which include heavy deicing treatments. However, more innovative ways to 'bulletproof' the system can be developed in time. Valuable data have already been produced and will continue in the future, provided the acquisition system is maintained. Real-time, full scale pavement responses are being recorded at a level of completeness and accuracy far exceeding initial expectation. This project, and future projects, show huge potential for pavement and other engineering disciplines alike.

The pavement response and environmental data collected during Phase I and II activities have been posted on the project website at www.mchangestrain.com and are available for download by pavement researchers worldwide. These data are expected to generate significant research ideas and allow for the validation of pavement design models currently in use.

At the time of sensor installation, it was unclear how long the sensors would survive, particularly the strain sensors installed at the bottom of the HMA layer. At the time of this report, nearly all of the strain sensors are still functioning and collecting valuable data. It is recommended that continued efforts and resources be dedicated to continue the data collection process for as long as the sensors remain active. Efforts should also be undertaken to develop, fabricate and install retro-fit strain sensors that could be installed after construction to extend the life of data collection efforts on this project and/or on in-place HMA pavement systems throughout the State of Wisconsin, effectively expanding our body of knowledge on the structural performance of these pavements.

References

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Appendix A - Verification Data

Vehicle Class	Trial Number	Wheel Identification	Strain Gauge	Detected Peak, με	Actual Peak, με	Δε
Class 4	1	250182284	A0	1.0	1.6	-0.6
	2	250182425	B4	0.8	1.0	-0.2
	3	250182426	B4	0.8	1.5	-0.7
	4	250182738	A3	0.0	0.0	0.0
	5	250182739	A2	7.1	7.1	0.0
	6	250182784	A1	1.6	2.2	-0.6
	7	250182785	A0	3.5	3.8	-0.2
Class 5	8	250182041	B4	0.9	1.2	-0.3
	9	250182360	A0	0.8	0.8	0.0
	10	250182361	B4	1.0	1.2	-0.2
	11	250182431	A3	2.2	2.5	-0.3
	12	250182432	A1	3.4	3.5	-0.1
	13	250182526	A3	1.7	9.5	-7.7
Class 6	14	250182044	A0	2.5	3.1	-0.6
	15	250182045	A3	5.7	5.8	-0.1
	16	250182046	A2	2.8	3.1	-0.3
	17	250182131	A1	2.9	3.0	-0.1
	18	250182132	A2	0.8	0.8	0.0
	19	250182133	A1	2.5	2.8	-0.3
	20	250182895	A3	7.0	7.1	-0.1
	21	250182896	B4	0.0	0.0	0.0
	22	250182897	A2	0.0	0.0	0.0
	23	250184432	A2	0.0	2.4	-2.4
	24	250184433	A1	3.8	4.1	-0.3
	25	250184434	A1	3.1	3.3	-0.3
Class 7	26	250196981	A3	4.0	4.1	-0.1
	27	250196982	A1	0.8	0.7	0.2
	28	250196984	A2	2.1	2.4	-0.3
	29	250196985	A2	1.8	2.2	-0.4
	30	250197003	A0	3.7	4.1	-0.3
	31	250197004	B4	0.8	1.1	-0.3
	32	250197005	A3	4.4	4.7	-0.3
	33	250197006	A0	1.9	2.2	-0.3
	34	250197007	A3	5.3	5.5	-0.2
	35	250197156	A1	7.3	7.5	-0.1
	36	250197157	A2	1.6	1.7	-0.1
	37	250197159	A0	3.5	3.7	-0.2
	38	250197160	A0	2.6	2.8	-0.2
	39	250197236	A3	8.8	8.9	-0.1
	40	250197237	A2	0.0	0.0	0.0
	41	250197239	A3	7.7	7.8	-0.1
	42	250197240	A0	5.1	5.2	-0.2

Vehicle Class	Trial Number	Wheel Identification	Strain Gauge	Detected Peak, με	Actual Peak, με	Δε
Class 8	43	250198009	A3	1.4	1.6	-0.2
	44	250198010	B4	2.5	2.5	0.0
	45	250198011	B4	2.1	2.3	-0.2
	46	250198046	A3	2.8	2.9	-0.2
	47	250198047	A2	5.1	5.2	-0.1
	48	250198048	B4	2.9	3.0	-0.1
	49	250198418	A1	3.0	3.1	-0.1
	50	250198419	A1	5.1	5.3	-0.3
	51	250198420	B4	0.0	0.0	0.0
	52	250198421	A2	1.5	1.7	-0.2
	53	250199426	A2	0.0	0.0	0.0
	54	250199427	A1	2.2	2.9	-0.7
	55	250199428	A2	0.0	0.0	0.0
	56	250199429	A1	1.4	1.6	-0.2
Class 9	57	250194350	A3	7.9	8.1	-0.1
	58	250194351	A3	10.2	10.3	-0.1
	59	250194352	B4	1.0	1.0	0.0
	60	250194353	A1	5.8	6.0	-0.2
	61	250194354	A2	1.9	2.2	-0.3
	62	250194677	A1	1.7	2.1	-0.4
	63	250194678	B4	0.0	0.0	0.0
	64	250194679	A1	0.0	0.0	0.0
	65	250194759	A3	3.6	3.7	-0.1
	66	250194760	A2	3.5	0.0	3.5
	67	250194761	A0	2.2	0.0	2.2
	68	250194762	A1	4.0	4.1	-0.1
	69	250194763	A3	3.6	3.8	-0.1
	70	250195004	A3	4.2	4.4	-0.2
	71	250195005	B4	1.6	1.2	0.4
	72	250195006	A2	0.9	1.1	-0.2
Class 10	73	250195734	A1	3.0	3.3	-0.3
	74	250195735	A2	0.0	0.0	0.0
	75	250195736	B4	0.0	0.0	0.0
	76	250197070	A3	4.2	4.3	-0.1
	77	250197071	A3	4.8	4.8	0.0
	78	250197072	A3	3.9	4.5	-0.6
	79	250197073	A2	0.0	1.4	-1.4
	80	250197074	A0	1.4	1.6	-0.2
	81	250197075	B4	0.8	0.9	-0.1
	82	250197303	A0	3.2	3.3	-0.1
	83	250197304	A0	7.6	7.6	-0.1
	84	250197305	A2	2.5	3.7	-1.2
	85	250197306	A3	13.6	13.7	-0.1
	86	250197307	A0	2.6	2.8	-0.2
	87	250197308	A2	1.9	2.6	-0.7
	88	250218257	A0	1.1	2.1	-1.0
	89	250218258	A1	4.3	4.3	0.0
	90	250218259	A3	-2.4	-2.2	-0.2

Wisconsin Highway Research Program
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706
608/262-2013
www.whrp.org