FHWA/IN/JTRP-2005/13

Final Report

STATEWIDE WIRELESS COMMUNICATIONS PROJECT

Volume 3: Data Collection and Signal Processing for Improvement of Road Profiling and Proof of Concept of a Vehicle-Infrastructure Based Road Surface Monitoring Appliation

James V. Krogmeier
Darcy M. Bullock

July 2008

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Volume 3: Data Collection and Signal Processing for Improvement of Road Profiling and Proof of Concept of a Vehicle Infrastructure-Based Road Surface Monitoring Application

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Joint Transportation Research Program
Project No. C-36-75O
File No. 8-9-15
SPR-2852

Conducted in Cooperation with the
Indiana Department of Transportation
and the U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
July 2008

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2005/13	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Statewide Wireless Communications Project	**5. Report Date** July 2008
	6. Performing Organization Code
7. Author(s) J. V. Krogmeier and D. M. Bullock	**8. Performing Organization Report No.** FHWA/IN/JTRP-2005/13
9. Performing Organization Name and Address Joint Transportation Research Program 1284 Civil Engineering Building Purdue University West Lafayette, IN 47907-1284	**10. Work Unit No.**
	11. Contract or Grant No. SPR-2852
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

The Statewide Wireless Communications Project was an umbrella project intended to support various INDOT activities in the area of wireless communications. As these activities were conducted independently the report for the project is organized into three volumes. Volume 1 contains the results of satellite and cellular communications field testing undertaken in support of INDOT's SiteManager application. Volume 1 also contains the results of an evaluation of spread spectrum radios for long-range communications. Volume 2 contains the results of detection zone evaluation for loop detection of bicycles and the results of testing algorithms for travel time estimation using vehicle re-identification based on inductive and micro-loop signatures. Finally, Volume 3 contains the results of preliminary testing of a vehicle-infrastructure integration application in road condition monitoring. In Volume 1 we found that SiteManager could not be adequately run over a satellite link because the long round trip delay of the communication link negatively interacted with SiteManager's internal client-server communications protocol to severely reduce overall throughput. A solution to the problem was to use terminal emulation in the field with the client software running on a computer connected to the server via a high bandwidth, low delay link. The downside to the terminal emulation approach is that it requires that the field engineer have a communication link wherever the application is run. In Volume 1 we also found that current generation spread spectrum radio ranges in Indiana topography with antenna heights corresponding to signal arm mounting were on the order of 3 miles. This was too short by a factor of 3 to support a multihop network for traffic signal control and telemetry. In Volume 2 we developed a numerical technique for mapping the bicycle detection zones of loop detectors. A number of recommendations were made concerning loop geometry, depth, detector sensitivity, and pavement markings for purposes of improving bicycle detection. We also developed algorithms for travel time estimation based on vehicle signatures captured from commercially available inductive and micro-loop detector cards. The travel time estimation algorithms were field tested and show promise. In Volume 3 a prototype road condition monitoring system was built upon a passenger van platform and preliminary field testing and data analysis was done. Algorithms were developed to address positional uncertainties present in GPS measurements in order to allow the averaging of data taken in multiple independent runs. The results were also field tested using INDOT's Laser Profiling vehicle.

17. Key Words satellite communications, TCP/IP, spread spectrum radios, inductive and micro-loop detection, vehicle-infrastructure integration.	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** Vol 1 – 42 Vol 2 – 37 Vol 3 - 31	**22. Price**

Form DOT F 1700.7 (8-69)

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1. Introduction

1.1. The Vehicle-Infrastructure Integration (VII) Concept

Pavement smoothness is typically characterized during construction in the process of contract payment approval. In addition, road surfaces are periodically, but infrequently, evaluated by transportation departments either using specialized instruments or by visual inspection. Pavement failures are often reported by motorists' phone calls when they are not detected by official inspection. The quality of public reports varies, especially regarding the precise location of the problem. A more efficient, cost-effective means of scheduling road maintenance is desirable and would be a great asset for maintenance scheduling in municipalities. In this report we investigate the possibility of a semi-automated system for road surface monitoring, which could be enabled with the planned deployment of the U.S. Department of Transportation (USDOT) vehicle-infrastructure integration (VII) program [VII 2005].

Vehicle-infrastructure integration ideas began to be seriously considered by federal and state transportation departments in the early 1990s as the national ITS architecture was being developed. An exploratory workshop on VII was held at the 2003 ITS America Conference leading to the formation of a VII Working Group. VII is included in the US DOT's "major inititatives" program approach with a decision on nationwide rollout scheduled for 2008 [ITS America 2005].

There have been a number of field trials of VII technology around the nation. Most of these efforts have focused on the dedicated short-range (DSRC) communications and networking problems underlying VII applications [Redmill 2003, Zhu 2003], on safety applications of VII in the areas of intersection collision warning and pedestrian detection and warning for busses [Misener 2005], and on travel information systems enabled by DSRC [Wang 2002]. It is expected that a number of additional applications areas will benefit. Research has already begun on using the data that will be collected by VII for other purposes, such as traffic monitoring [Tanikella 2007] and road weather measurement [Petty 2007]. This report describes a vision for future use of VII sensors for pavement and ride quality monitoring. We imagine vehicles already equipped with accelerometers for air bags and GPS receivers to log data related to pavement smoothness and location as illustrated in Figure 1. The individual data logs from a large fleet of such sensor-networked vehicles would be processed appropriately to produce GIS maps flagged with locations of emerging pavement failures. The processed data could then be used to create a prioritized task list for pavement maintenance crews, with precise geographic location of problem areas. In addition, the spatially local information can be combined to provide a network-level monitoring of the road infrastructure, giving decision makers valuable information on where to spend limited funds.

Prioritized Work List
1. I-465 SB near mm 27.15
2. I-65 NB near mm 121.82
3. I-70 WB near mm 87.44
4. I-74 EB near mm 4.07

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Figure 1: Envisioned System integrated with VII.

1.2. Concepts of Road Roughness and Its Measurement

Work on the development of qualitative and quantitative measures of road roughness goes back to various roads tests conducted by AASHTO starting from the 1950s [AASHTO 1986]. These tests defined the Present Serviceability Rating (PSR), a subjective measure of road roughness, and the Present Serviceability Index (PSI), an objective measure of road roughness, which could be used to compute the PSR [Carey 1960, Moore 1986, Gulen 1994, Al-Omari 1994, Hall 1999, Paterson 1986, Garber 2002]. More recently, the International Roughness Index (IRI) [Sayers 1998] has been identified as the most common metric used to determine road roughness [Khaled 1999]. Two families of pavement roughness measuring devices have evolved over the years: 1) profilometers, which directly measure the road profile (a plot of relative road elevation versus distance in the direction of travel), and 2) vehicle response meters, which directly measure the ride. Extensive research on the most appropriate measuring procedures and indexes has taken place over the years and profilometers are the most frequently used by agencies [Khaled 1999].

1.2.1. Profilometers

A longitudinal road surface profile is a measure of road surface height relative to some reference elevation as a function of longitudinal distance in the direction of travel. The road profile depends on the actual track followed along the lane and therefore variations in profile are to be expected in repeated measurements. A road profile can be captured by rod-and-level survey or by a profilograph, which is a wheeled instrument capable of recording the elevation angle as it is moved along the road at low speed. Rod-and-level surveys and profilographs are primarily used in quality control assessment on new construction or repaving jobs. The most common instrument in use today is the so-called inertial profiler, which operates at highway speeds. An inertial profiler uses a non-contact distance sensor (laser, infrared, ultrasonic) to measure distance from a point on the host vehicle body to the road surface below. Measurements from a vertical axis accelerometer are processed to create an inertial reference frame and the distance measurements are expressed relative to it. Longitudinal distance along the road is measured using a precision odometer. The first inertial profiler design goes back to the 1960s [Sayers 1998] and, while great advances have been made in inertial reference systems since then, a modern reliable instrument, such as the Ames Engineering profilometer as in Figure 2 still costs about $70,000. Some effort has been made in the design of lower cost, non-contact light weight profiling devices [Mondal 2000] although they typically require a low operating speed (between 8 and 25 miles per hour).

Figure 2: INDOT Laser Profiling Vehicle.

1.2.2. Vehicle Response Meters

A large amount of network pavement smoothness data has been gathered using vehicles equipped with a so-called road meter. These devices are known as Response Type Road Roughness Measuring Systems (RTRRMS). They do not measure the road profile but rather they measure the response of the vehicle to the road profile. Devices in this category include all instruments that measure relative axle-body motion, or body and axle acceleration, or a combination. The most prevalent RTRRMS instrument is the Mays Ride Meter, which computes an integrated displacement between the body and the axle and uses that to characterize road roughness (integrated inches of relative vertical displacement over the distance traveled in miles). RTRRMS are inexpensive, rugged, easy to use, and can operate at highway speeds. However, RTRRMS measurements depend on the dynamic response of the host vehicle, and consequently, roughness measurements from RTRRMS are not stable over time and their portability is often in question. Nevertheless, RTRRMS devices have been used for more than 50 years by engineers due to the usefulness of the data they generate in assessing road ride quality. It has been suggested that the interest in profiling devices would significantly decrease once RTRRMS data could be made reproducible and portable [Khaled 1999].

1.3. Issues in Using VII Data to Augment Existing Road Roughness Measurements

Although profilometer type devices are well suited to precise contract acceptance procedures, it is not clear what the most cost-effective distributed sensing might be for an architecture that receives reports from a large number of vehicle probes of different makes, models, and maintenance histories. In fact, determining the quality of information on roadway infrastructure and hazards that can be mined from existing and planned vehicle sensors is one of the first tasks that needs to be performed to justify advancing the planned vehicle infrastructure integration efforts.

Several issues must be addressed to demonstrate and evaluate the feasibility of such a distributed pavement monitoring sensor network. Many of the sensors that would be needed for collecting road roughness measurements already exist on a growing number of vehicles today – vertical axis accelerometers (as part of a roll-over protection system), suspension position sensors, and GPS – although they may not be optimized and calibrated for this purpose. Cost often limits these sensors to be of lower accuracy than those found in a typical class 1 profiler. The sensor data collected from each vehicle would be different because the dynamical response of each vehicle would depend on the handling package (suspension parameters), weight, tuning and driver behavior. Lastly, the sensors would report data at different sampling rates and their geographical position will be acquired through affordable GPS devices with their attendant positional uncertainty.

2. Problem Statement

FHWA's VII initiative has the potential to vastly change the way that transportation systems are managed yet most state DOTs have limited experience in this area. With a few exceptions VII applications have been more focused on the vehicle side of the problem, particularly in the area of safety. VII also has the potential to change transportation management on the infrastructure side although there have been few case studies to date. The research reported here was intended to examine a particular application of interest to INDOT, namely road condition monitoring and how a VII enabled network of vehicles could serve the purpose and complement existing road profiling capabilities.

3. Objectives or Purpose

The objective of this research was to build a prototype VII system and to design signal processing tools to enable road condition estimation via a distributed network of sensor equipped vehicles. A secondary object was to examine how such a system could complement existing INDOT road profiling efforts.

4. Work Plan

The work described in this report has been organized into four tasks as outlined below.

4.1. Task A: Design of Prototype of a Vehicle-Infrastructure Integration System

The major focus of the work here was on the design of a mobile sensing, data logging, and communications device that:

- Integrates measurements from vehicle-mounted accelerometers and GPS.
- Creates a standardized log of the data.
- Has the capability to wirelessly upload the logged data.

In addition, the project developed some of the infrastructure-side equipment and software needed to communicate with the mobile sensor-logger and to process the data to produce maps of ride quality and estimated locations of pavement failures. The system is only a first generation prototype, intended as a proof of concept and to gain practical experience with VII applications.

The scope of work for this task involved the following steps:

1. Identification of Required Sensing, Computer Equipment, and Test Vehicle.
2. Design of Mobile Sensor-Logger-Communications Device.
3. Design of Infrastructure-Side Communications and Computing.
4. Installation of Mobile Sensor-Logger-Communicators in Test Vehicle.

4.2. Task B: Preliminary System Shakedown and Data Collection/Processing

Initial tests were performed in order to verify that the data collection system was working properly. Rudimentary data processing algorithms were applied to the data to illustrate the feasibility of using the system for approximately locating areas of pavement failure. More sophisticated signal processing needed to average the results of multiple runs of the system were developed later.

4.3. Task C: Design of Signal Processing for Multiple Runs Data Fusion

In order to fuse the data from multiple runs of the system signal processing is required in order to remove the effect of GPS and odometer position errors. Simply averaging the data without accounting for these errors has a tendency to wash out the effect we are looking for, especially in the case of pavement disturbances of limited extent (e.g., emerging potholes, etc.). These issues with positional uncertainty also cause problems for INDOT's laser profiling vehicle, hence related algorithms were derived to allow the fusing of multiple profiler runs.

4.4. Task D: Experiments and Data Processing

The signal processing algorithms developed in the previous task were fully tested using field data logged in the West Lafayette vicinity.

5. Analysis of Data

5.1. Task A: Design of Prototype of a Vehicle-Infrastructure Integration System

Inexpensive three-axis accelerometers from Crossbow were identified as suitable for the project. The required acceleration dynamic range was determined by taking some preliminary measurements in rented vehicles. It was noted that accelerations of plus or minus 3 g were commonly encountered over rough roads and therefore we settled on a plus or minus 4 g sensor. It should be noted that some current vehicles already incorporate vertical acceleration sensors for rollover protection but that these are intended for measuring large accelerations (on the order of 50 g) and are therefore unsuitable for our purposes.

A data acquisition system was identified from National Instruments. It has the advantage of communicating with a host via USB. Additional equipment identified included a headless PC, a power inverter, an uninterruptible power supply (UPS), a distance measuring instrument (DMI), a GPS receiver and antennas for GPS and wireless LAN connectivity.

The accelerometer used was a ± 4 g three axis Crossbow model CXL-LP [Crossbow 2007]. The accelerometer signal was sampled at 200 Hz by a National Instruments USB 6009 A/D card. The A/D card was then connected to a laptop computer via a USB port. A Garmin OEM 18 PC GPS receiver was connected to the laptop via a Serial Cable, sampled at 1.0 Hz [Garmin 2005]. The software used for data collection was National Instruments Labview 7.1, a versatile graphical programming environment often used for data acquisition and real-time control. The data from each device was linked by a timestamp from the local machine, which was synchronized to Coordinated Universal Time (UTC) time from the GPS receiver on startup. A block diagram of the prototype system is shown in Figure 3.

The portable data collection system was used in four vehicles: the INDOT profiling vehicle of Figure 2, a Purdue Joint Transportation Research Program (JTRP) 1998 Dodge Ram passenger van (Figure 4), a 1999 Mercury Mystique and a 2007 Chevrolet Impala. The vertical axis accelerometer was mounted on the body of all four vehicles:

- INDOT profiling vehicle: on a rack behind driver seat
- JTRP Dodge Ram: directly below rear bench seat
- Mercury Mystique: directly below passenger seat
- Chevrolet Impala: directly below passenger seat

Some of the in-vehicle equipment is shown in Figure 5.

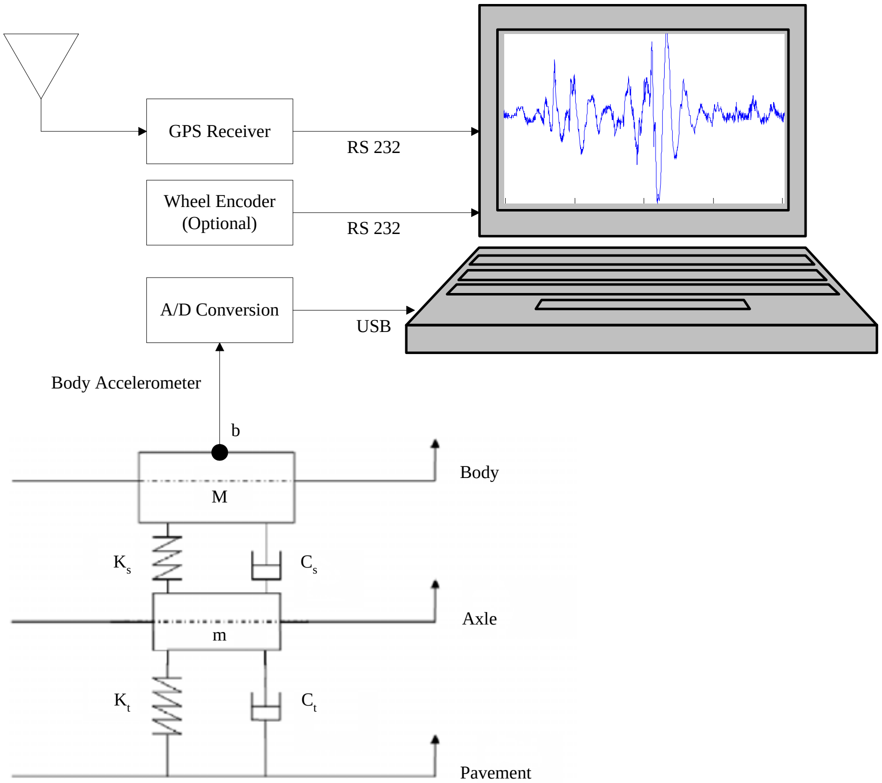
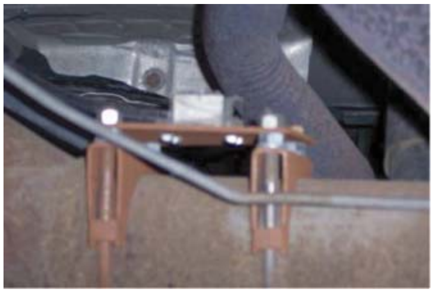


Figure 3: Portable data collection system.

Figure 4: JTRP passenger van used to carry instrumentation.

(b) Three axis accelerometer.



(a) Van equipment rack containing network switch, server, and UPS.

(c) Accelerometer mounted on van axel.

(d) Distance measuring instrument.

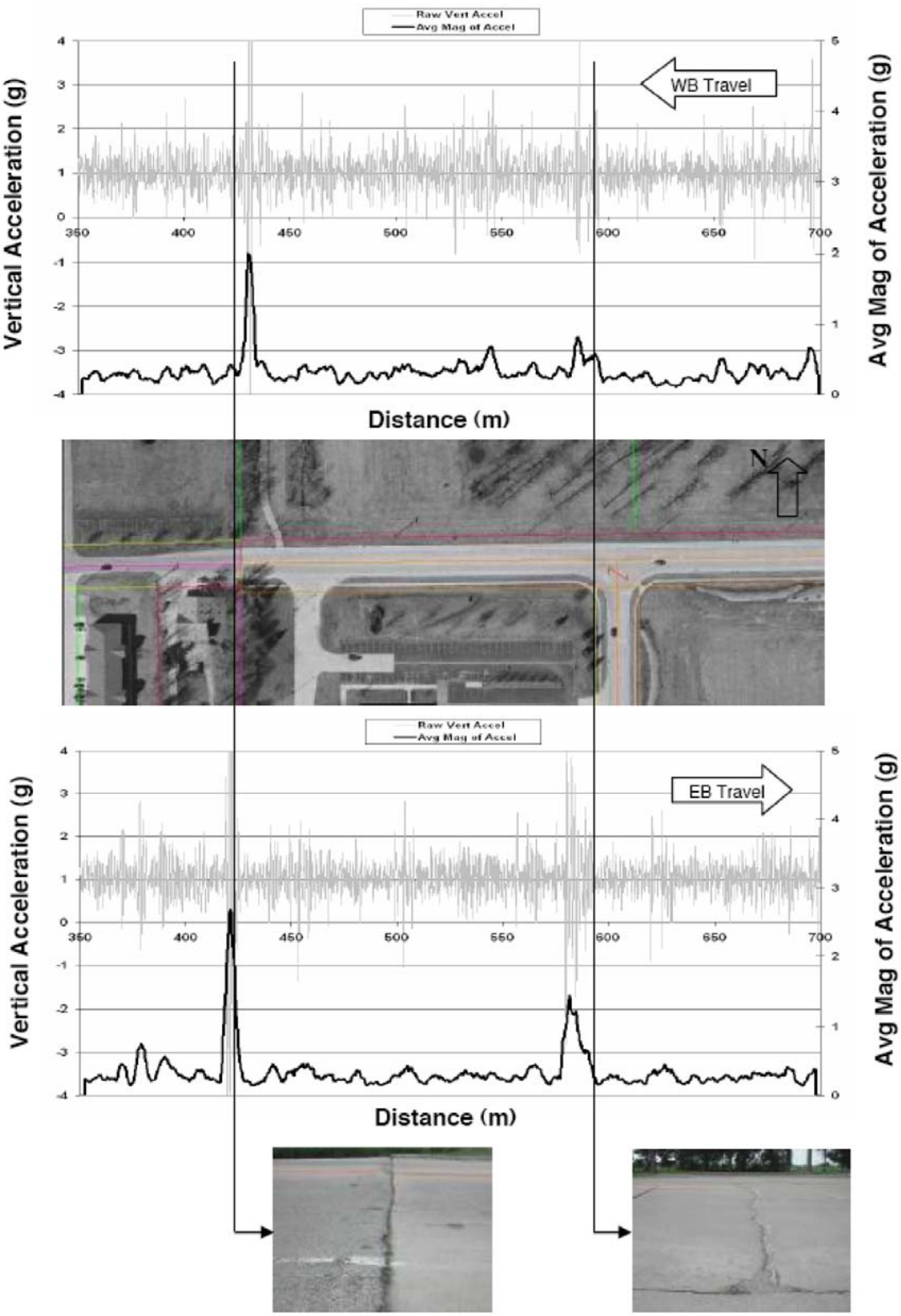
(e) GPS antenna mounted on van roof.

Figure 5: Instrumentation mounted in JTRP van as part of VII test vehicle.

5.2. Task B: Preliminary System Shakedown and Data Collection/Processing

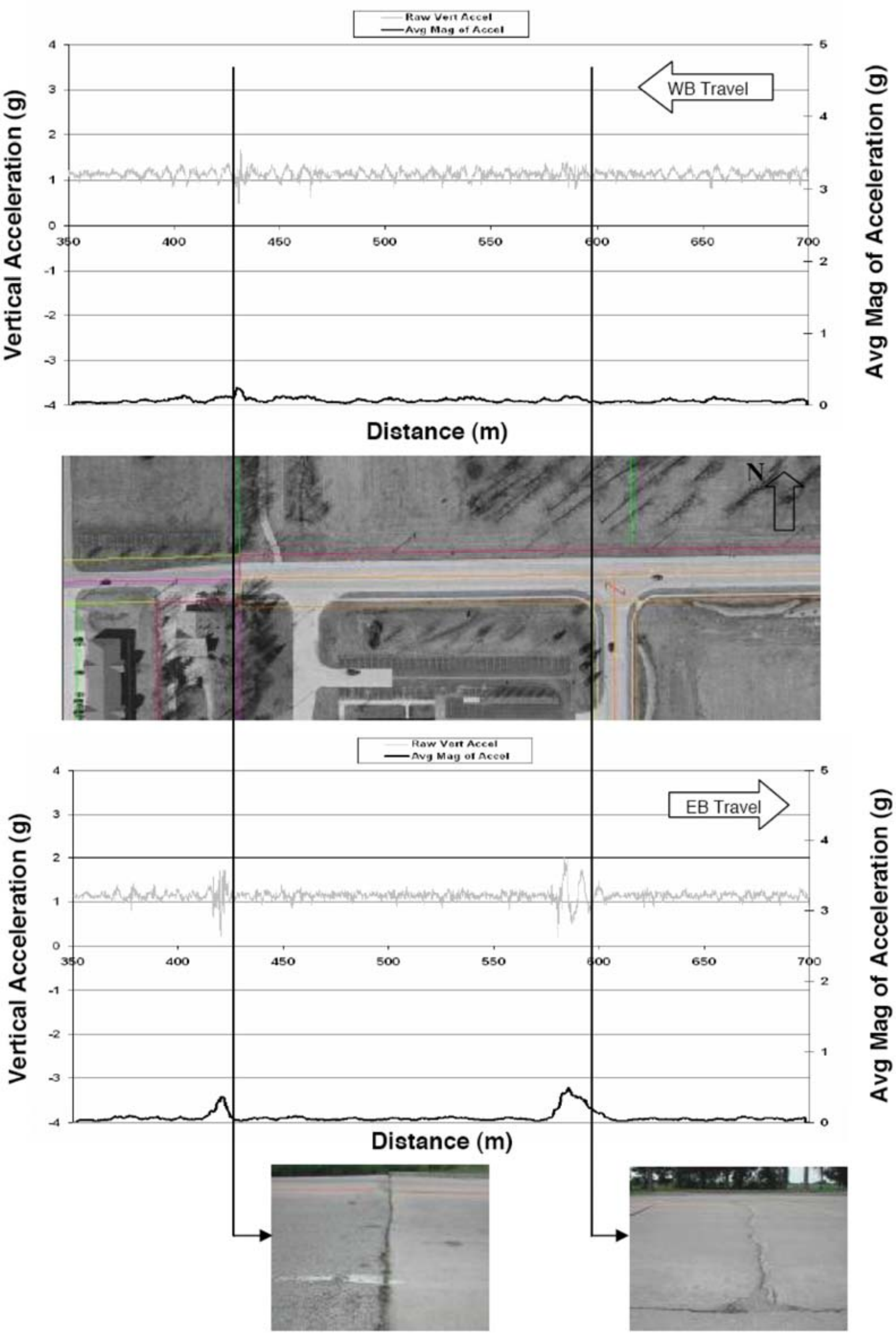
A variety of tests of the sensor data collection have been completed in the West Lafayette, IN vicinity. The JTRP van was equipped with two rear-axel mounted accelerometers and one body-mounted accelerometer. The first test was run on county road 350 N in West Lafayette where two pavement disturbances were located. The first was at an asphalt to concrete transition (Figure 6(a)) and the second was at a transverse crack in concrete at a sunken area (Figure 6(b)).

The data from the accelerometer mounted on the axle is shown in Figure 6 and the data from the accelerometer mounted on the floor of the van is shown in Figure 7. The vertical acceleration in both graphs is the thinner and lighter line centered about 1g and is a relatively noisy signal that makes it difficult to perceive any roadway defects. By comparing the raw vertical acceleration in Figures 6 and 7, it is clear the vehicle suspension filters a great deal of both noise and information. The thicker black line is a plot of the moving average of the absolute magnitude of the vertical acceleration. This moving average value has much clearer peaks in the vicinity of the roadway defect, particularly for the accelerometer mounted on the axle (Figure 6), where the suspension does not filter out any of the vertical acceleration.



a). Asphalt-Concrete Transition b). Transverse crack in concrete

Figure 6: Example Road Defects on 350N in West Lafayette, IN (vertical acceleration on axle).



a). Asphalt-Concrete Transition b). Transverse crack in concrete

Figure 7: Example Road Defects on 350N in West Lafayette, IN (vertical acceleration on frame).

A number of additional tests of the road condition monitoring system were run and additional development of the data processing algorithm was completed. In particular, a modestly more sophisticated acceleration filtering algorithm was developed, which takes account of vehicle speed in designing the length of the moving average window applied. The new algorithm was applied to data gathered during a run down Ferry Street in Lafayette where the pavement disturbances were caused by manhole covers in the traffic lanes. An aerial photo of Ferry Street is shown in Figure 8 and the moving average filtered acceleration data is shown in Figure 9.

Figure 8: Ferry Street in Lafayette, IN.

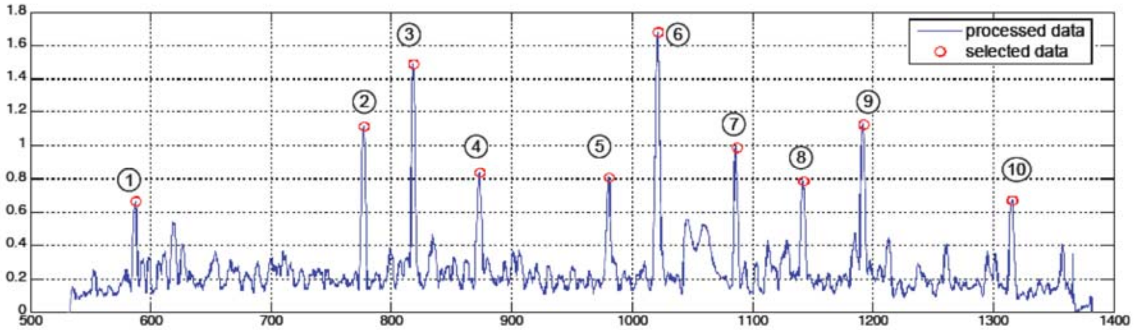


Figure 9: Filtered vertical acceleration data from rear axle versus distance along Ferry Street.

A very simple algorithm was applied to the filtered acceleration data in order to select acceleration peaks as the locations of possible defects. The algorithm merely selects the top N peaks and logs the GPS location associated in the data file. When this algorithm is applied to the data in Figure 9, the estimate of disturbance locations in Figure 10 results.

Figure 10: Pavement disturbance location estimate from Ferry Street run. Note that there are both false positives and missed detections.

5.3. Task C: Design of Signal Processing for Multiple Runs Data Fusion

5.3.1. Combining Sensor Data

Acceleration and position data are logged along with synchronized time stamps and a re-indexing and interpolation performed to express the acceleration data on a uniform sampling grid (10 samples per foot in this experiment) in traveled distance from a fixed reference point. The GPS position measurements in latitude, longitude, and geodetic height were projected to a UTM grid (Up, Northings, Eastings) using the WGS-84 geographic datum. In this new Cartesian coordinate, the distance traveled by the vehicle can be easily computed. Alternatively, a wheel encoder or odometer-like instrument may be used instead of a GPS receiver to create the distance scale. This latter approach to computing the distance traveled would provide a more precise and accurate distance scale. However, acquiring data from wheel encoders is more difficult and less portable than using GPS. Since GPS data is not collected continuously, an assumption made in creating the distance scale with GPS data is that the vehicle is traveling at constant speed between GPS samples, collected at approximately 1Hz. We note that in the resulting accelerometer signals displayed in this paper the typical ~1 g offset that is due to the earth's gravitational field is subtracted to allow easier statistical analysis.

5.3.2. Correlate-Average Algorithm

Figure 11 illustrates the problem encountered due to slight inaccuracies of a typical inexpensive GPS receiver; those used in this research had an accuracy specification of < 15 m [Garmin 2005]. Both signals are measuring the same physical disturbance, but are slightly out of synch with each other. It is widely accepted that the process of averaging a large number of measurements of the same quantity is a typical approach to obtain better data by removing the effects of noise. However in the above situation, each measurement of the same entity is acquired with an offset. Clearly, the proper methodology needs to incorporate a procedure to properly align the signals prior to averaging.

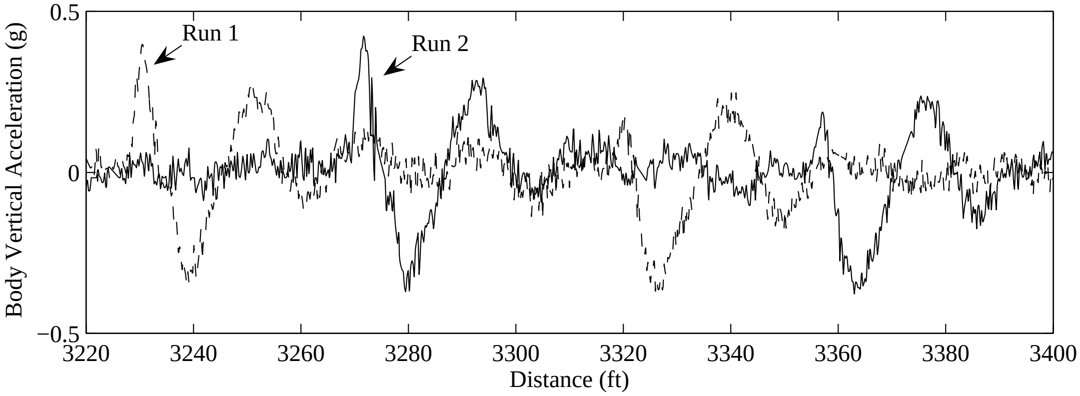


Figure 11: Offset due to spatial uncertainty of consumer grade GPS during two different runs.

Correlation is a well-known signal processing technique often used to compare similarity between signals. A historically persistent example is in radar, where a signal is transmitted, it bounces off an object a certain distance away, and then received back at the source (with noise added). Cross-correlation between the sent and received signal determines how much the received signal is shifted in time, and therefore how far away the object that reflected the signal is. The same principle illustrated above can be used to correct the offsets experienced by the acquired signals.

In the present application, one can view the acceleration vs. distance signal created by each run with the same vehicle as the same response signal process which is slightly shifted in the spatial domain due to standard GPS inaccuracies, and slightly different in shape due to the effects of electronic and vibration noises, driver variation, etc.

Let X be a random process representing the values of one data collection run, and Y be a random process representing the values of a separate data collection run. If X and Y are jointly WSS random processes, the cross-correlation is defined by

$$c_{XY}(m) = E[X_n Y_{n+m}] \qquad m = \ldots -1, 0, 1, \ldots \qquad (1)$$

where E is the expectation operator, n is the index of random processes X and Y, and m is the lag between them. The sample cross-correlation between two finite random sequences X_n and Y_n is defined as

$$c'_{XY}(m) = \frac{1}{N-m} \sum_{n=0}^{N-m-1} X(n)Y(n+m) \qquad 0 \le m \le N-1 \qquad (2)$$

$$c'_{XY}(m) = \frac{1}{N-|m|} \sum_{n=|m|}^{N-1} X(n)Y(n+m) \qquad 1-N \le m \le 0 \qquad (3)$$

where N is the number of samples in each sequence. The maximum value of $c'_{XY}(m)$ shows which shifting of m best aligns the two signals. The best shift is called α.

For M runs, the cross-correlation is computed between all combinations of two runs, and the resulting distance offset is used to populate a M x M matrix of distance offsets

$$\begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,M} \\ \alpha_{2,1} & \alpha_{2,2} & \cdots & \alpha_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M,1} & \alpha_{M,2} & \cdots & \alpha_{M,M} \end{bmatrix}$$

This is a skew matrix and can be simplified further because a single run does not need to be shifted to align with itself to

$$\begin{bmatrix} 0 & \alpha_{1,2} & \cdots & \alpha_{1,M} \\ -\alpha_{1,2} & 0 & \cdots & \alpha_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ -\alpha_{1,M} & -\alpha_{2,M} & \cdots & 0 \end{bmatrix}$$

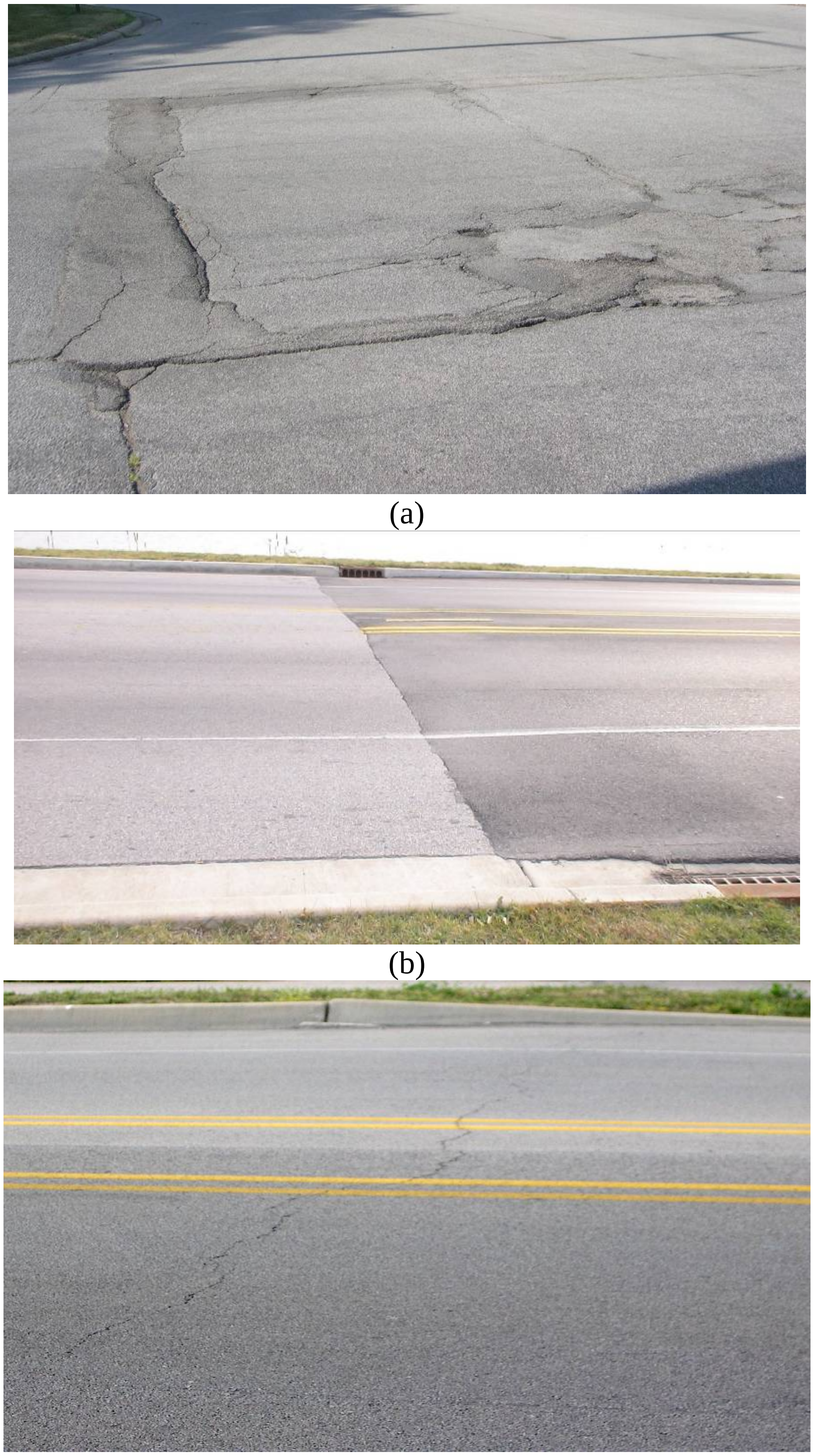
Run #1 was shifted by the average of α's in row 1, Run #2 was shifted by the average of α's in row 2, Run #M was shifted by the average of α's in row M, etc. After all runs have been aligned by their respective shifts, they are then averaged to produce a composite signal. More information about cross-correlation can be found in [Lathi 1998] and [Leon-Garcia 1994].

5.4. Task D: Experiments and Data Processing

5.4.1. Procedure

In general, the data collection program was started with the vehicle stationary and aligned with a particular landmark, such as a road sign, stop bar, etc. A similar alignment technique was used for terminating the data runs. These consistent start/stop mechanisms helped with troubleshooting and created very similar distance scales. In a future implementation, starting and stopping locations would not need to be synchronized, because road sections can be extracted by GPS coordinates.

Two test sites were chosen to collect data. The first site featured a large disturbance, shown in Figure 12(a), roughly 8100' (2469 m) from the starting reference. The INDOT profiling vehicle made five runs over the route, and the JTRP Dodge Ram made 30 runs over the route, all in the same lane. An accelerometer and GPS receiver acquired data simultaneously with the INDOT laser profiler. A second test site was chosen, with two large disturbances, one at 3240’ (988 m) and another at 3330’ (1015 m) from the starting reference. The JTRP Dodge Ram, Mercury Mystique, and Chevrolet Impala each made 10 runs on this route, all in the same lane.



(a)

(b)

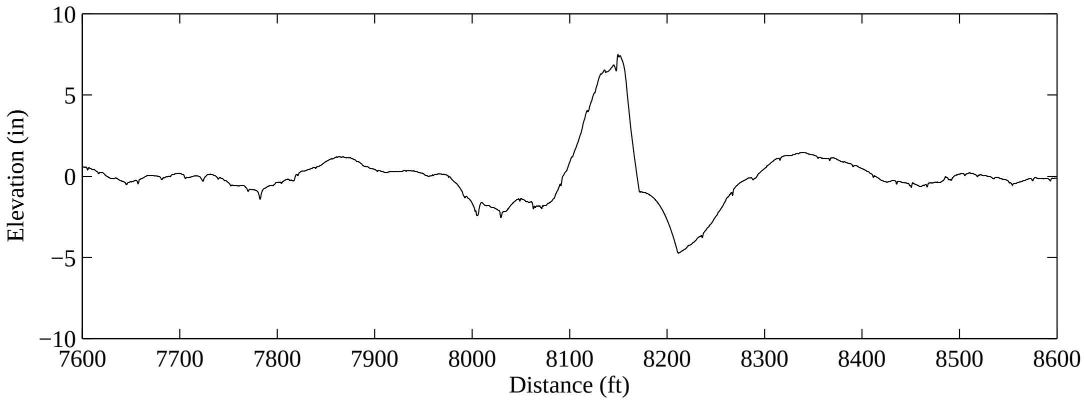
(c)

Figure 12: Road disturbances analyzed in this research. (a) Test site #1 at approximately 8100 feet. (b) Test site #2 at approximately 3240 feet. (c) Test site #2 at approximately 3320 feet.

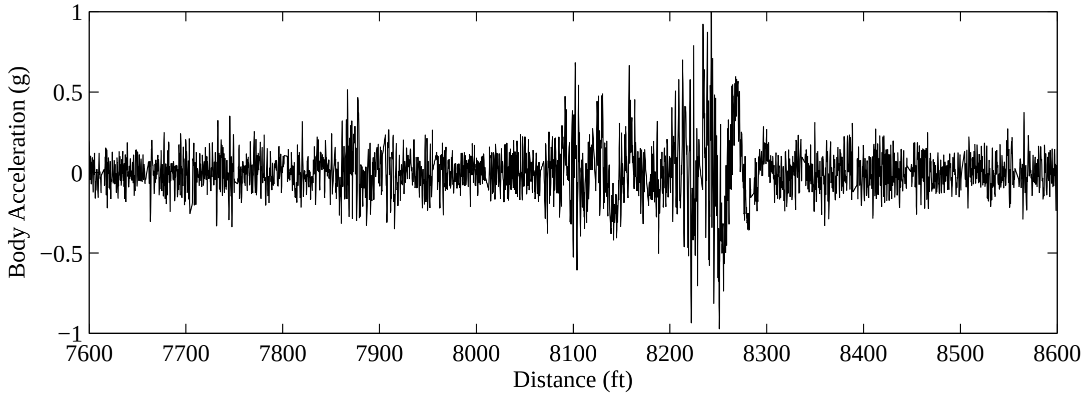
5.4.2. Test Site #1: Verification with INDOT Profiler

Figure 13(a) shows a section of the filtered profile created by the INDOT profiling vehicle. The resulting acceleration vs. distance plot is shown in Figure 13(b). The JTRP Dodge Ram with the same equipment traversed the same route, and the corresponding signature is shown in Figure 13(c). Clearly, the accelerometer data and actual profile agree that a disturbance is present around 8100’ (2469 m) from the starting reference.

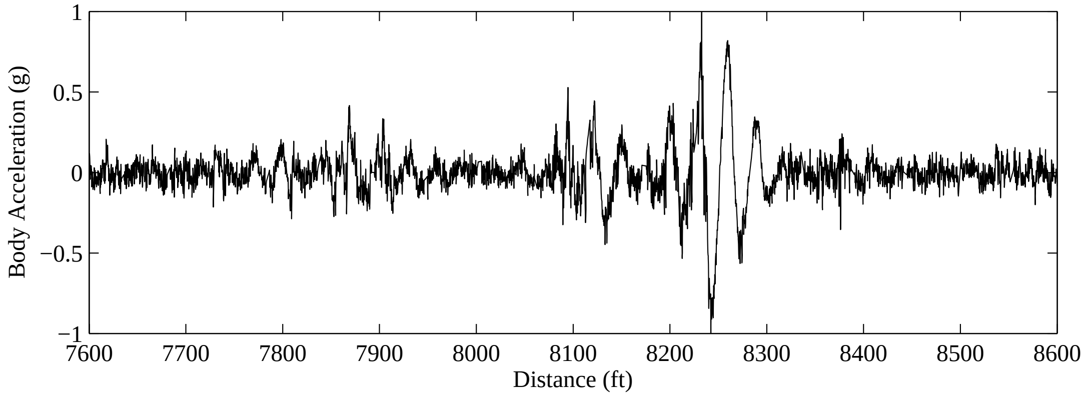
Figure 14 illustrates the benefit of using a correlation algorithm. Figure 14(a) is, once again, the result from a single run over the disturbance of Figure 6(a). The plot in Figure 14(b) shows the result of averaging 30 runs, illustrating that the signal averages to zero because of small GPS inaccuracies. After being properly aligned using the algorithm in Section 5.3.2 and then averaged, a smoother, more accurately located signal appears in Figure 14(c). It was observed that the signal to noise ratio (SNR) and distance location improved as the number of runs used in the algorithm increased. Starting with one run, adding more runs to the algorithm improved the signal quickly but the improvement eventually tapered off so the addition of more runs to the algorithm did not make as significant improvement. For example, for 2-12 runs the signal was visually smoother with the addition of each run, but did not appear to improve using additional runs. The standard deviation of acceleration values, an indirect measure of SNR, of 3, 12, and 30 runs resulted in an 11.4, 38.6, and 39.2 percent decrease from the standard deviation of one run, respectively.



a) Filtered profile created by INDOT laser profiler

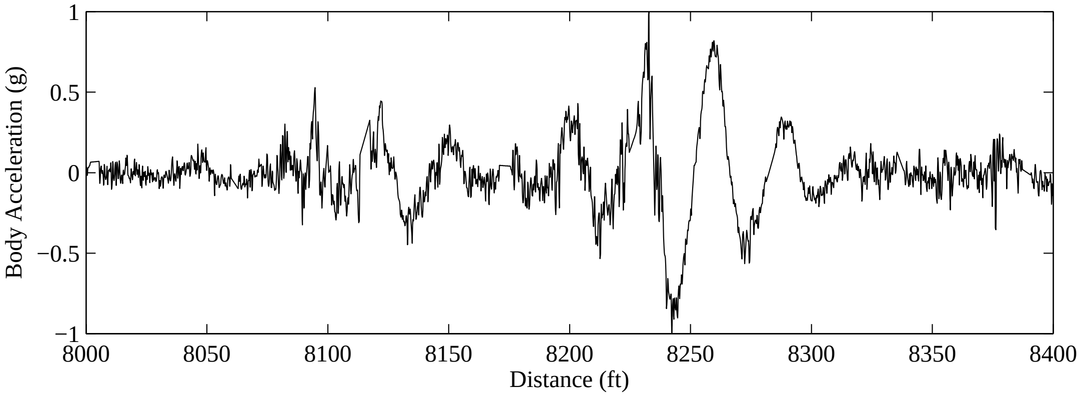


b) Signal from accelerometer mounted on body of INDOT laser profiler

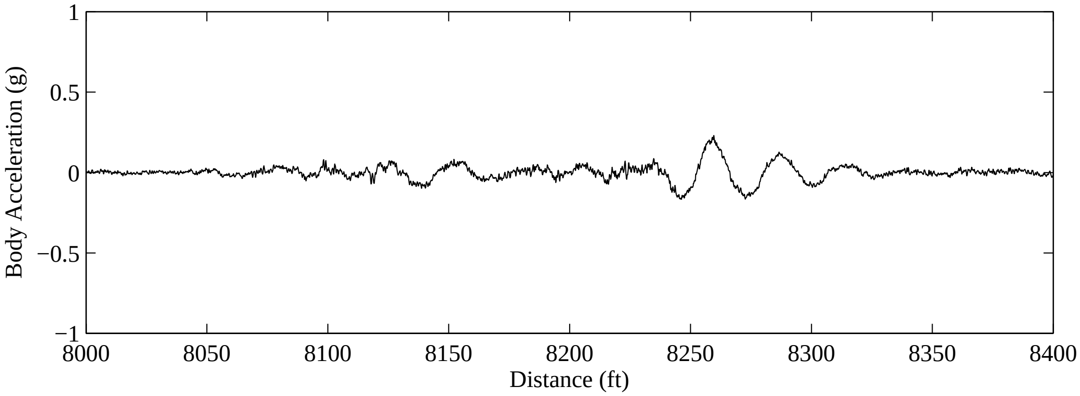


c) Signal from accelerometer mounted on body of JTRP Dodge Ram

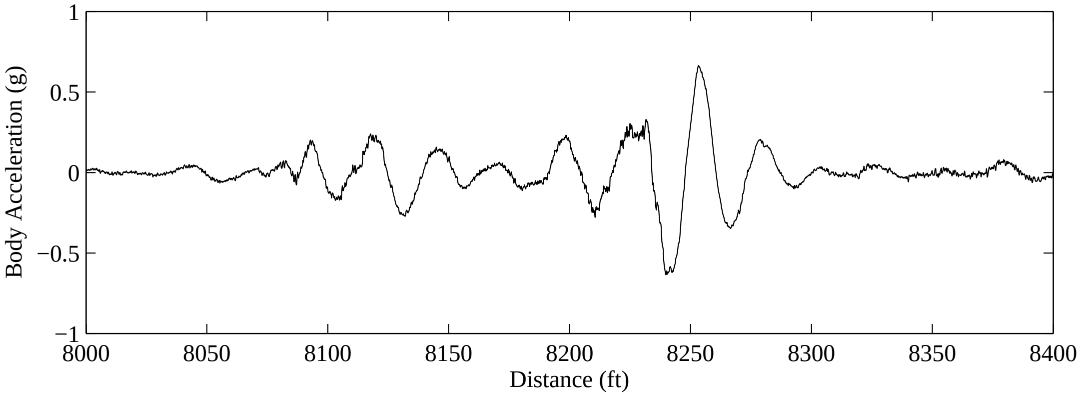
Figure 13: Test Site #1: Verification of road disturbance by comparing with INDOT profile.



a) One body acceleration from JTRP Dodge Ram



b) Result of averaging 30 independent body accelerations from JTRP Dodge Ram



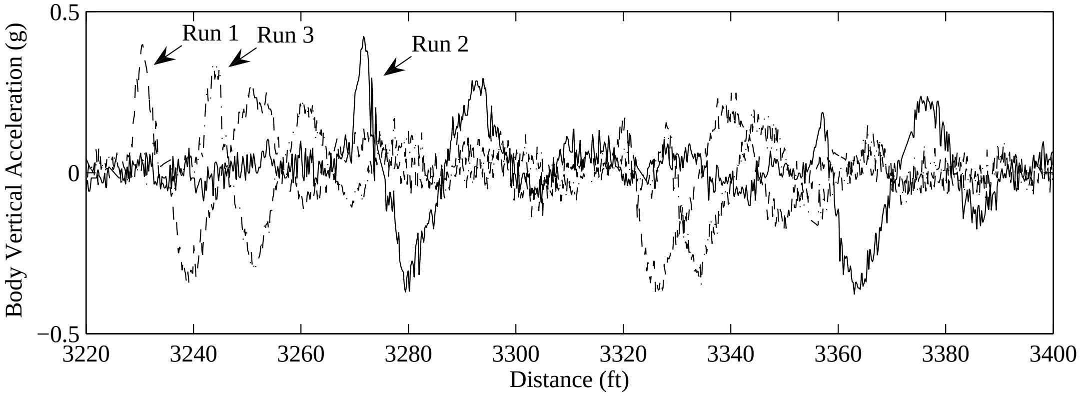
c) Result of correlating, shifting, and averaging 30 body accelerations from JTRP Dodge Ram

Figure 14: Test Site #1: Analysis of multiple data collection runs through the same road section (zoomed in).

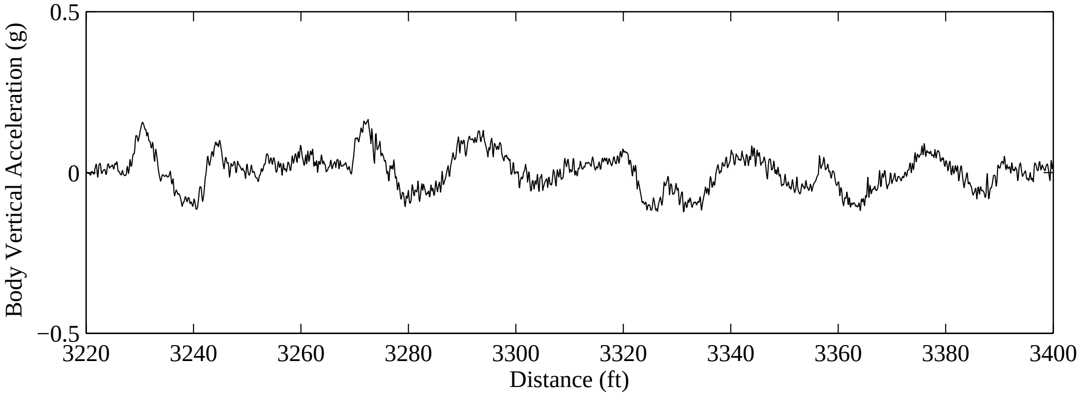
5.4.3. Test Site #2: Combining Data from Multiple Vehicles

Figure 12 illustrates the successful ground-truth with the INDOT profiler from Test Site #1 and Figure 14 illustrates the impact of correlating and averaging multiple runs. An additional test site was chosen for testing multiple vehicles (see Figure 12(b) and Figure 12(c) for photos of the first and second major disturbance, respectively). An analysis of three runs of the JTRP Dodge Ram is shown in Figure 15. Figure 15(a) shows 3 unprocessed accelerations, and illustrates that each run appears very similar, only shifted in distance due to GPS errors. Similar to Figure 14, Figure 15(b) shows signal loss if the three runs are only averaged without correlating and then shifting. Figure 15(c) shows both an improvement in SNR (an 18.3 % decrease in standard deviation compared to one run) and location after applying the Correlate-Average Algorithm presented above.

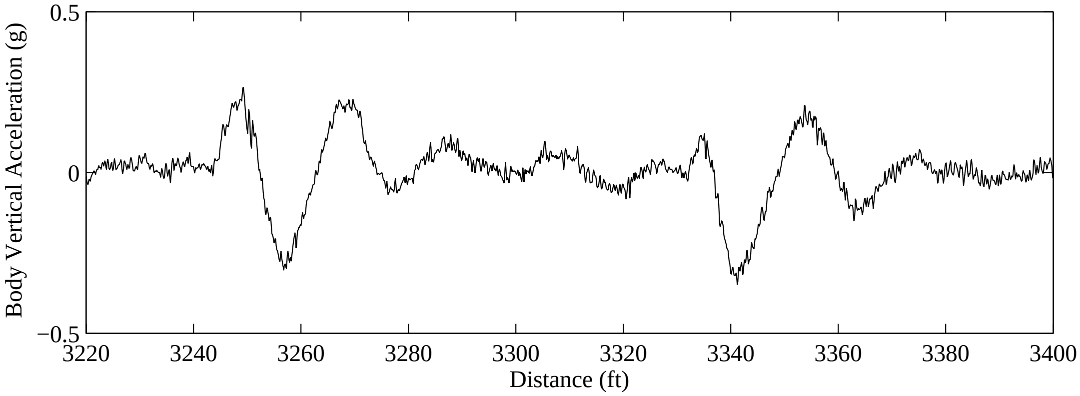
A total of ten runs were made with the JTRP Dodge Ram, Mercury Mystique and Chevrolet Impala, and the resulting composite signals appear in Figure 16. As one can see, all three vehicles indicate a disturbance at approximately 3240’ (988 m) and 3330’ (1015 m) from the starting reference. The waveforms in Figure 16 show that the response to the road disturbances of the two cars is quite similar. Figure 17(a) shows the composite of ten runs from both the Mercury Mystique and Chevrolet Impala, whereas Figure 17(b) show the composite of ten runs from all three vehicles. This suggests vehicle data may be grouped by vehicle class. Figure 17(b) shows a bump at the expected location, but the waveform does not preserve the “shape” that any of the three composites from an individual vehicle. Due to the variation in dynamics between vehicles, our hypothesis is that the composite from many vehicles will not approach a representation from any particular make or model, but converge to a value that is more representative of the physical reality.



a) Three (3) body accelerations from JTRP Dodge Ram

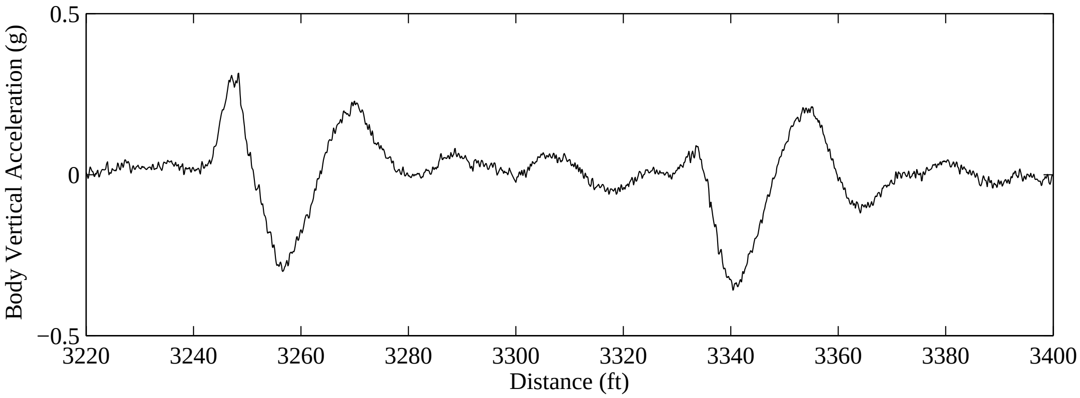


b) Result of averaging 3 independent body accelerations from JTRP Dodge Ram

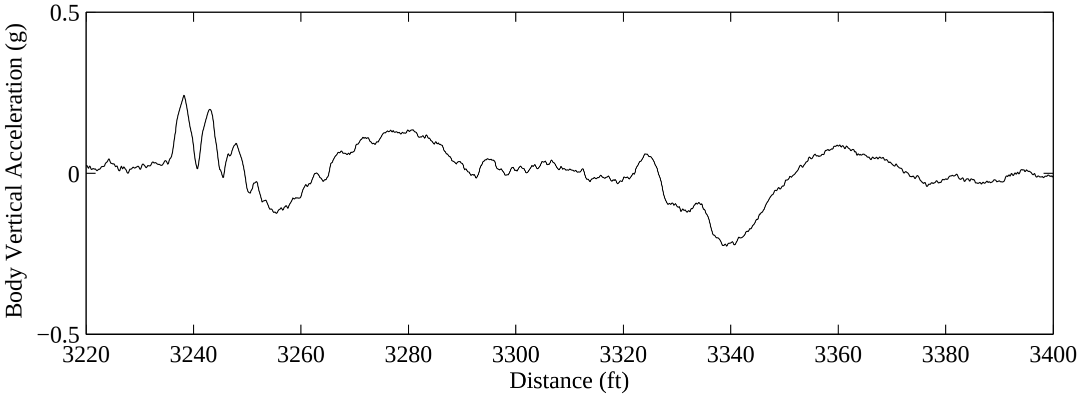


c) Result of correlating, shifting, and averaging 3 body accelerations from JTRP Dodge Ram

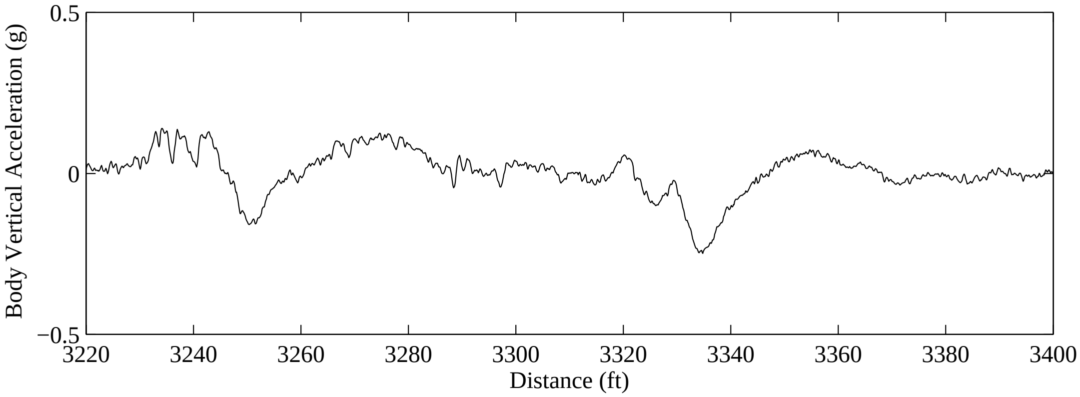
Figure 15: Test Site #2: Analysis of multiple data collection runs through the same road section.



a) Composite using 10 runs of JTRP Dodge Ram accelerations

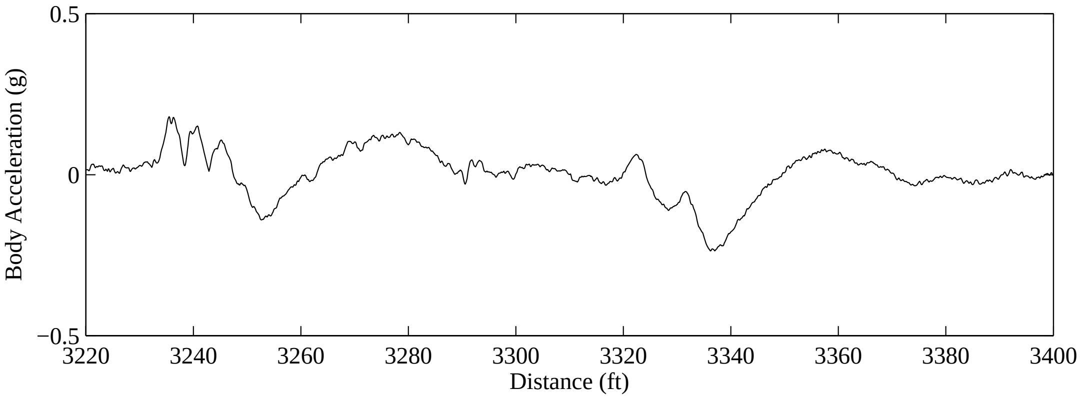


b) Composite using 10 runs of Chevrolet Impala accelerations

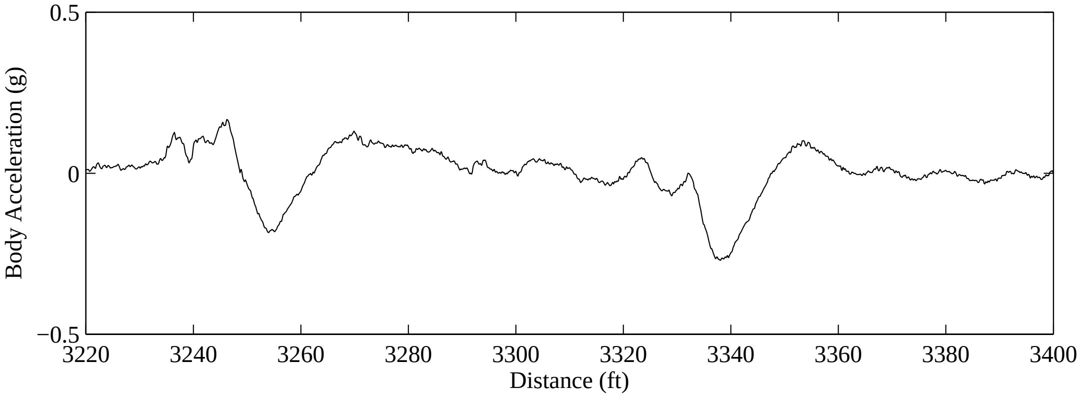


c) Composite using 10 runs of Mercury Mystique accelerations

Figure 16: Test Site #2: Analysis of multiple data collection runs through the same road section.



a) Composite using 10 runs from both Impala and Mystique



b) Composite using 10 runs from each of the three vehicles

Figure 17: Test Site #2: Analysis of multiple data collection runs through the same road section.

6. Conclusions

Automotive electronics make continual advances every year, and an assortment of sensors is incorporated into each system. New safety and performance features are initially introduced in low volume on luxury and high-performance models. They mature, come down in price, gain market penetration, and become commonplace. It is prudent to reuse these existing, calibrated vehicular sensors. A robust VII system for detecting road defects can be realized by keeping costs low and reusing current sensors. This task presented some preliminary analysis of some candidate sensors and demonstrated that there are opportunities for detecting roadway defects and potential safety problems using accelerometers. Further work is required on both the VII system architecture and the VII sensor systems to realize a functioning system, but recent advances in automotive electronics and telecommunication make this a promising area for further study.

A real-time, distributed, portable road-roughness measuring system was proposed and a prototype demonstrated. A method of properly aligning data from multiple vehicles was introduced and the importance of first correlating, shifting, and then averaging the data to improve the quality of data was documented. These methods have been compared to the actual profile produced by an INDOT profiling vehicle, and analysis of multiple vehicles demonstrated the feasibility of the idea. Further discussion and collaborating with the various stakeholders is recommended to develop a shared vision leveraging VII to provide an up-to-date status of potholes and other roadway defects, as well as the condition of links in a networked road infrastructure.

7. Recommendations and Implementation Suggestions

Vehicle-Infrastructure Integration is included in the US DOT's "major inititatives" program approach with a decision on nationwide rollout scheduled for 2008. The work of this subtask represents one of the first field tests of VII technology in Indiana although a number of more extensive tests have been conducted around the country. The focus of the test done here, unlike the focus of other tests around the United States, was on the use of VII to improve DOT operations in the area of road condition monitoring.

The limited test done in Task D is sufficient to prove concept but is insufficient to determine the overall utility of the idea. More algorithm development and testing should be done and Indiana should strive to maintain its visibility in the national VII effort by continuing work in VII over the next few years.

Several areas of transportation systems can be improved by a pavement condition monitoring system introduced in the previous sections. First, this system would be useful in routine pavement maintenance, where incoming data would populate work schedules for field crews. Second, the real-time capabilities would be of use in risk management, where dangerous road conditions could be identified and resolved in minimal time. Finally, data can be combined to monitor the overall condition of longer road segments, which would aid in determining the priority of repaving existing roads.

Several technical factors must be studied further before such a system can be implemented. Due to the variation between vehicle dynamics, experiments must be performed using many vehicles on a variety of road surfaces to determine repeatability. An appropriate and efficient method of combining spatially local data from multiple vehicles is needed due to the sheer volume of potential data. Lastly, the area of graphical information systems (GIS) is needed to efficiently display information to decision-makers.

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