

Civil Engineering Support for Telemetered Traffic Monitoring Sites

Final Report

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16. Abstract This project was aimed at providing various civil engineering support services for the telemetered traffic monitoring sites operated by the Statistics Office of the Florida Department of Transportation. This was a companion project to the one that provided electrical engineering support services for the same sites. The results of two major tasks undertaken in this project are reported herein. The first main task was aimed at conducting field evaluation of loop sealants and piezo grouts at Site 352 on Interstate 10 and Site 112 on Interstate 75. The evaluation will continue for another one year but preliminary results are discussed herein. The secondary task of this project was to evaluate the traffic data collection accuracy of two classifiers installed at Site 352. This task has been completed and the results show that there is no significant difference between the two classifiers in daily traffic volume data collection.			
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EXECUTIVE SUMMARY

Background

Monitoring traffic through extensive collection and efficient storage of traffic data is crucial for improving safety and efficiency of Florida highways. To this end, the Florida Department of Transportation operates temporary and permanent count stations strategically placed at various locations on the state highway system. The data collected by electronic equipment installed at these stations include individual vehicle records composed of number of axles per vehicle, axle spacing, overall vehicle length, and operating speed. The Florida Department of Transportation operates other sites categorized as weigh-in-motion (WIM) sites that are set up to additionally collect individual axle weights and overall gross vehicle weight. In general, the traffic count program managed by the FDOT Statistics Office is operating very well and serves a vital purpose of supporting federal, state, and private user needs. Nevertheless, the FDOT Statistics Office continues to experience a number of challenges in operating the count sites, in assuring the quality of data collected by these sites, and in complying with continually changing federal reporting requirements.

One of the major challenges faced by the FDOT traffic counting program is the durability of loop and piezoelectric axle sensor installations. The problem can be traced to the type of sealant used, method of installation, and quality control during installation of the loop and piezo sensors. Previous studies have determined that some grouts were not appropriate for Florida conditions and were thus excluded from the approved product list. However, long term performance review of the bonding material used to install loops and piezos at Telemetered Traffic Monitoring Sites (TTMS) has not been conducted. In addition, the influence on sensor durability by the methods of installation and quality control during installation has not been thoroughly studied. Thus, there was a need to conduct longitudinal research study of the factors that affect performance and durability of loop and piezo sealants.

In addition, the Florida Department of Transportation was interested in determining the performance of classifiers used at Site 352 on Interstate 10, which is a telemetered traffic monitoring site. The classifiers collect data on vehicular volumes, speeds, and vehicle classification. Of interest to FDOT, was whether the performance of the classifiers was influenced by the type of bonding material used to install sensors at two sensor array configuration.

Objectives

This project had two objectives. The first objective was to conduct field evaluation of the loop sealants and piezo grouts installed at TTMS Site 352 on Interstate 10 and TTMS Site 112 on Interstate 75. The evaluation involved conducting periodic physical observation of the bonding materials and recording electrical readings on inductance of the loop wires, ground resistance of the loop wires, and voltage amplitude of the piezos. The second objective was to evaluate two types of classifiers used at TTMS Site 352 for the purpose of determining if there

was a significant difference between the two classifiers in collecting volume, speed, and class data.

Findings and Conclusions

The results of the performance evaluation of loop sealants and piezo grouts are considered preliminary since the evaluation will continue for one year past this project period. The preliminary results showed that there were unequal deterioration rates of loop sealants of different formulation. The electrical readings showed that the ground resistance of some loop detectors was very low particularly when the readings were taken during wet pavement conditions. However, despite low ground resistance, these loops showed reasonable inductance readings which enabled the loops to continue collecting volume, speed, and class data accurately. As for the classifiers at TTMS Site 352, the results showed that there wasn't significant difference on the reporting of daily volumes by the two classifiers although it was found that the two sensor arrays had a slight difference in the traffic volume data that were collected during the study period.

Benefits

The results of this study were beneficial to the FDOT Statistics Office as it did build confidence in the performance of the two types of classifiers of interest. Although the field evaluation of loop sealants and piezo grouts is still continuing, the preliminary results have assured FDOT Statistics Office that traffic data can still be collected by loops that are showing significantly low ground resistance.

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PART ONE—COMPARISON OF IRD AND ADR CLASSIFIERS

1.1 Background

The Florida Department of Transportation, Statistics Office, was interested in determining the performance of the International Road Dynamics (IRD) continuous classifier. The approach used to accomplish this goal was first to compare the accuracy of a pair of count stations installed on the same lane and then compare that accuracy to similar data obtained using an Automatic Data Recorder (ADR) Model 3000 continuous counter which FDOT has been using satisfactorily for the last ten years. Site 352 on Interstate 10 was chosen for this experiment. The IRD classifier was installed at this site on August 26, 2008 and collected data until September 28, 2008. On September 29, 2008, the IRD classifier was disconnected and replaced with the ADR unit which in turn collected data from September 30, 2008 onwards. Parallel to this study, the Statistics Office was also interested in evaluating the performance of loop and piezo sealants. To this end, two arrays of sensors comprised of piezo-loop combination with different types of sealants were installed at this count station as shown in Figure 1.1. Both IRD and ADR units were connected to the two count sites consecutively and data were recorded by the two arrays of sensors simultaneously. The analysis of performance of the two classifiers involved conducting statistical analyses of the data collected by the two classifiers from the two stations labeled E and W shown in Figure 1.1. The speed, volume, and classification data were downloaded from the two sites for a period of 30 days each.

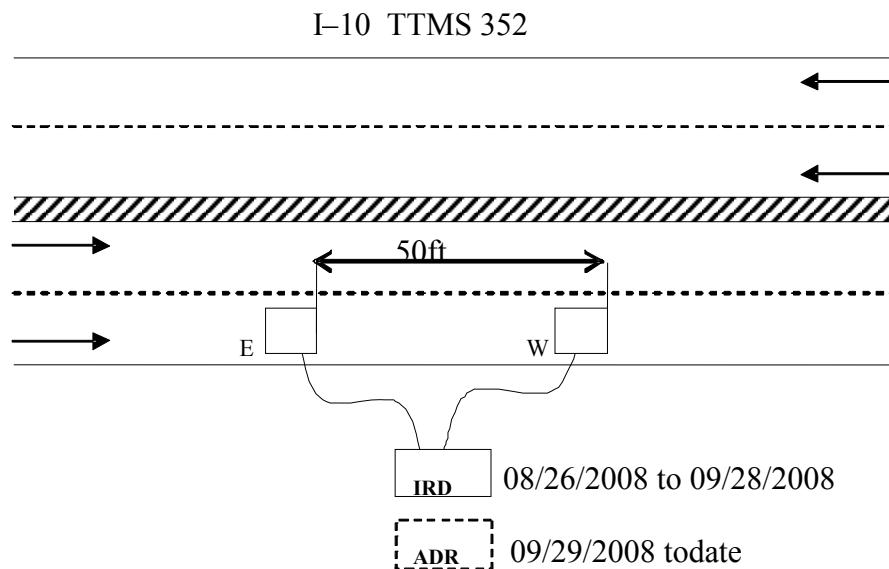


Figure 1.1 Field setup of the experiment

1.2 Graphical Overview of the Data

Figure 1.2 shows the frequency distribution of the daily total volume reported by the two classifiers from the two E and W count stations. The class frequencies add up to 30 days given that the daily volumes were summarized for 30 days. Figure 1.2 shows that data collected by the ADR display a positive skew while the IRD data skew is not as pronounced or as well defined. The data recorded from the W count station shown in green have been superimposed on the data collected from the E station shown in red. The results in Figure 1.2 show that the daily total volumes do not match up entirely but the significance of the difference will be analyzed further in the following subsections.

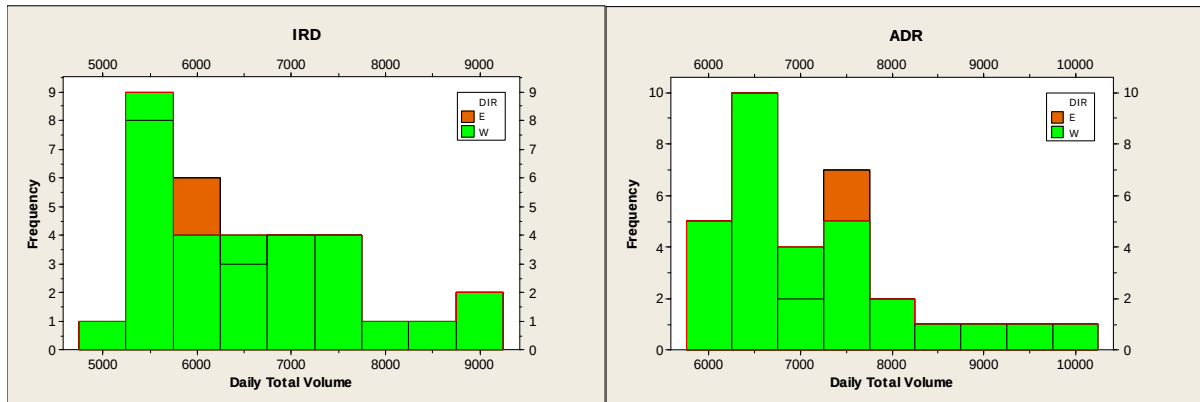


Figure 1.2 Histogram of the daily total volume

In addition to the histogram graphical display, a dotplot was constructed as shown in Figure 1.3. The data collected by the ADR is shown on the top of Figure 1.3 and the IRD data are shown at the bottom of Figure 1.3. Again, the positive skew of the data collected by the ADR classifier is apparent. Based on these graphical results, it was important to determine whether there were outliers in the data using boxplot technique.

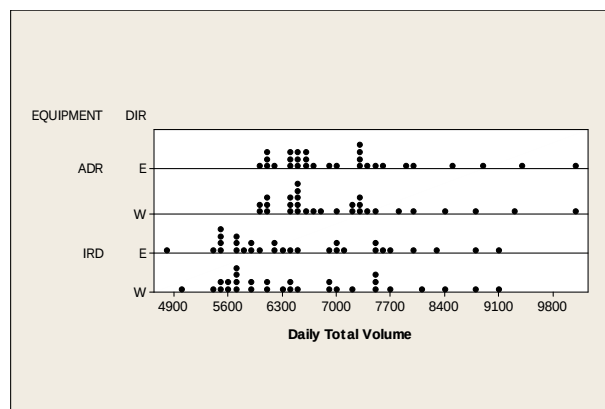


Figure 1.3 Dotplot of daily total volume

Figure 1.4 shows the boxplot¹ of the difference between the daily volume data collected at the E and W count stations. The plot represents E data subtract W data. Adjacent to the boxplot is the raw data of the difference between E and W data. The boxplot shows that the distribution of ADR data is more compact than the distribution of IRD data. However, both boxplots show the presence of possible outliers. The suspected outlier in the IRD data set is the “-209” difference as shown in the table. Closer look at the raw data revealed that this difference was recorded on 09/17/2008. The outlier in the ADR data set is the “62” difference shown in the same table. The raw data showed that it was recorded on 10/17/2008. Subsequent analyses will use data for 29 days with the suspected outliers removed from the IRD and ADR data sets.

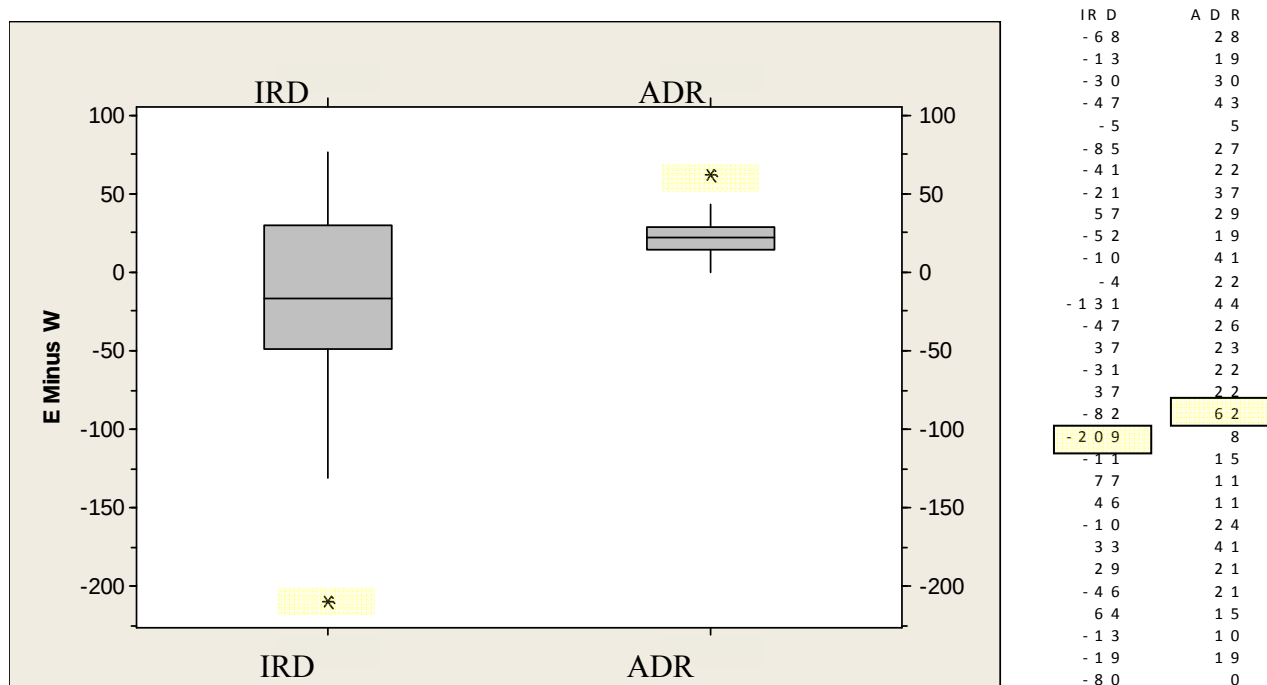


Figure 1.4 Boxplot of daily volume difference

1.3 Descriptive Statistics

The MINITAB software was used to generate the relevant descriptive statistics of the daily volume data collected by the two classifiers. The data were categorized by the count stations in order to later determine if there is a significant difference between the daily volumes collected from the two stations. The descriptive statistics of interest were the average daily volume, the standard deviation of the volume, coefficient of variation, skewness, and kurtosis. Table 1.1 shows the descriptive statistics of the daily total volume collected by IRD classifier stratified according to the count station, i.e., E or W. Table 1.2 shows the ADR descriptive statistics.

¹ A boxplot (also known as a box-and-whisker diagram) is a convenient way of graphically depicting groups of numerical data through their five-number summaries (the smallest observation, lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation).

Table 1.1 IRD descriptive statistics

DIR	Count	Mean	StDev	CoefVar	Minimum	Maximum	Skewness	Kurtosis
E	29	6622	1066	16.11	5366	9100	0.78	-0.35
W	29	6638	1065	16.05	5371	9113	0.78	-0.34

Table 1.2. ADR descriptive statistics

DIR	Count	Mean	StDev	CoefVar	Minimum	Maximum	Skewness	Kurtosis
E	29	7061	976	13.83	6017	10094	1.59	2.72
W	29	7038	973	13.83	5980	10079	1.60	2.72

The statistics displayed in Table 1.1 and Table 1.2 confirms that the ADR data reveal a positive skew that is higher than IRD data. Since the skew is consistent for both count stations, the cause of this skew might be attributed to the difference in data collected in different time frames—that is, different months. It seems that the month of October may have had some days with more traffic than the month of September given that the ADR data collected in October had higher minimums and higher maximums compared to IRD data collected in September. The coefficient of variation – the ratio of standard deviation to the mean ($\sigma/\bar{x}$) – indicates that the IRD data had more variation than the ADR data. The significance of the difference in the variability of data collection will be tested using inferential statistical methods discussed below.

1.4 Inferential Statistics

There are two aspects of the study that required conducting statistical significance tests. First, the analyst was interested in determining whether there was a significant difference between the data collected by the two count stations, E and W. Second, the analyst was interested in determining whether there was a significant difference between the data collected by the IRD and ADR classifiers.

1.4.1 Test of the Difference Between E and W Count Stations

Statistical procedures require that prior to testing the significance of the difference between the averages of two sample data (i.e., E and W), the analyst first test the equality of variance between the two samples. Table 1.3 shows the results of equality of variance test.

Table 1.3 Test of equality of variance between E and W

IRD Classifier

DIR	N	Lower	StDev	Upper	F-value	p-value
E	29	819.9	1066.5	1510.64	1.00	0.966
W	29	819.1	1065.5	1509.19		

ADR Classifier

DIR	N	Lower	StDev	Upper	F-value	p-value
E	29	750.6	976.3	1382.9	1.01	0.987
W	29	748.2	973.2	1378.5		

The results in Table 1.3 show that for both IRD and ADR classifiers, there is an overlap in the 95 percent confidence interval of the standard deviation, i.e., $P(Lower \leq \sigma \leq Upper)$. Both p-values are more than 95 percent suggesting that the analyst is more than 95 percent confident that the variances of the daily volume data collected from the E and W count stations are equal. The analyst can now proceed with analyzing the difference in daily volumes reported

from E and W count stations using a statistical procedure that assumes equal variance. In this case, a paired *t*-test was chosen given that both E and W count stations reported daily volumes in pairs. The results of the *t*-test are shown in Table 1.4.

Table 1.4 Test of equality of means between E and W

IRD Classifier

	N	Mean	StDev	SE Mean
E	29	6622	1066	198
W	29	6638	1065	198
Difference	29	-16.1	49.6	9.22
95% CI for mean difference: (-34.95, 2.81)				
t-test of mean difference = 0 (vs not = 0): t-value = -1.74 p-value = 0.092				

ADR Classifier

	N	Mean	StDev	SE Mean
E	29	7061	976	181
W	29	7038	973	181
Difference	29	22.6	11.2	2.09
95% CI for mean difference: (18.31, 26.86)				
t-test of mean difference = 0 (vs not = 0): t-value = 10.82 p-value = 0.000				

The results in Table 1.4 can be summarized as follows. For the IRD classifier, the analyst is 95 percent confident that the difference between E and W daily volume counts is not significant since the interval -34.95 and 2.81 contains 0. However, the *p*-value of 0.092 suggest that the difference between E and W data is significant with a confidence level of 91 percent [100(1-*p*)]. Similarly, for ADR classifier, the analyst is 95 percent confident that the E count station reports an average daily volume that is consistently between 18 and 27 vehicles higher than the W count station. This is also confirmed by the hypothesis test that resulted in a *p*-value of 0.00 which basically indicates that the confidence of the difference is close to 100 percent. In a nutshell, it is reasonable to conclude that the data collected by the E and W stations were significantly different at 90 percent confidence level when both IRD and ADR classifiers were in place.

1.4.2 Test of the Difference Between IRD and ADR Classifiers

The proper statistical procedure for testing the difference between the two means reported by the two classifiers is the test in the difference in means of two normal distributions assuming the variances between the two equipment are equal but unknown. The 100(1- α) confidence level is determined by the following equation:

$$\bar{X}_1 - \bar{X}_2 - t_{\alpha/2, n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \leq \mu_1 - \mu_2 \leq \bar{X}_1 - \bar{X}_2 + t_{\alpha/2, n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

where $S_p = \sqrt{\frac{(n_1-1)S_1^2 + (n_2-1)S_2^2}{n_1+n_2-2}}$

Since in Section 1.4, it was found that there was a significant difference between E and W data; consequently, the difference in IRD and ADR performance has to be analyzed using E and W data separately. Table 1.5 shows the statistical results for the E count station and Table 1.6 shows the statistical results for the W count station.

Table 1.5 E count station

	N	Mean	StDev	SE Mean
IRD	29	6622	1066	198
ADR	29	7061	976	181

Difference = $\mu_{\text{IRD}} - \mu_{\text{ADR}}$

Estimate for difference: -439

95% CI for difference: (-977, 99)

t-test of difference = 0 (vs not =): t-value = -1.63 p-value = 0.108 DF = 56

Both use Pooled StDev = 1022.4037

Table 1.6 W count station

	N	Mean	StDev	SE Mean
IRD	29	6638	1065	198
ADR	29	7038	973	181

Difference = $\mu_{\text{IRD}} - \mu_{\text{ADR}}$

Estimate for difference: -400

95% CI for difference: (-937, 137)

t-test of difference = 0 (vs not =): t-value = -1.49 p-value = 0.141 DF = 56

Both use Pooled StDev = 1020.3933

Both results in Table 1.5 and Table 1.6 indicate that the 95 percent confidence interval of the difference contains 0 suggesting that the difference is not significant at that level. However, the difference would be significant if the analyst was to construct a ≤ 89.2 confidence interval on E data and a ≤ 85.9 confidence interval on the W data.

1.5 Conclusions and Recommendations

Based on the results of the statistical analyses, it is reasonable to conclude that the IRD classifier reported daily volumes that are not significantly different from those reported by the ADR classifier. This inference is reached by considering the E and W data separately thus reinforcing this belief. However, the same data showed that if the analyst was to use an 85 percent confidence limit on the difference, the difference would be significant. Generally, confidence limits used in engineering applications are 90, 95, and 99 percent. The lack of definitive clarity on the difference of IRD and ADR performance may be attributable to the difference of calibration of the E and W sensors. The statistical analysis showed that, at 90 percent confidence level, when the IRD classifier was installed, the E sensors were reporting daily volumes that were significantly less than W sensors but when the ADR classifier was installed, the E sensors were reporting daily volumes that were significantly higher than W sensors. Concerns can be raised regarding possible outliers in the data. Although the statistical procedures showed that a daily volume difference of -209 for the IRD classifier and +62 for the ADR classifier were unusual, the analyst is not sure if these differences were legitimate. Because of these two caveats, it is the analyst's recommendation that further investigation might be warranted to determine why E and W sensors report different daily volumes and what the sources of outliers in the data sets are.

PART TWO—EVALUATION OF LOOP SEALANTS AND PIEZO GROUTS

2.1 Introduction

Monitoring traffic through extensive collection and efficient storage of traffic data is crucial for improving safety and efficiency of Florida highways. To this end, the Florida Department of Transportation operates temporary and permanent count stations strategically placed at various locations on the state highway system. The data collected by electronic equipment installed at these stations include individual vehicle records composed of number of axles per vehicle, axle spacing, overall vehicle length, and operating speed. The Florida Department of Transportation operates other sites categorized as weigh-in-motion (WIM) sites that are set up to additionally collect individual axle weights and overall gross vehicle weight. In general, the traffic count program managed by the FDOT Statistics Office is operating very well and serves a vital purpose of supporting federal, state, and private user needs. Nevertheless, the FDOT Statistics Office continues to experience a number of challenges in operating the count sites, in assuring the quality of data collected by these sites, and in complying with continually changing federal reporting requirements.

One of the major challenges faced by the FDOT traffic counting program is the durability of loop and piezoelectric axle sensor installations. The problem can be traced to the type of sealant and grout used, method of installation, and quality control during installation of the loop or piezo sensors. Previous studies have determined that some sealants and grouts were not appropriate for Florida conditions and were thus excluded from approved product list. However, long term performance review of the bonding materials used to install loops and piezos at Telemetered Traffic Monitoring Sites (TTMS) has not been conducted. In addition, the influence on durability by the methods of installation and quality control during installation have not been thoroughly studied. Thus, there is a need to conduct longitudinal study of the factors that affect performance and durability of loop and piezo bonding materials.

The objective of Part II of this project was to extend the evaluation of loop sealants and piezo grouts beyond laboratory evaluation to field performance evaluation. Two sites were picked for field evaluation of loop sealants and piezo grouts – that is, TTMS Site 352 on Interstate 10, and TTMS Site 112 on Interstate 75. The evaluation involved periodic observation of the rate of deterioration by taking photographs and videos of how the bonding materials appear over time. In addition, electrical readings were recorded. The electrical readings included inductance of the loop wires, ground resistance of the loop wires, and voltage amplitude of the piezos. The readings were taken during both dry and wet weather conditions to determine whether there was any moisture effect on the readings.

2.2 Literature Review

The study of loop sealants and piezo grouts involved first reviewing literature on what materials are available in the market and what are their properties. Fortunately, the Florida

Department of Transportation, through a research grant to the FAMU-FSU College of Engineering, sponsored the laboratory evaluation of piezo grouts. An extensive literature review was conducted as part of this study, the results of which are still relevant to the current study. The results of the extensive literature review on piezo grouts – focusing on grouts in the FDOT approved product list – is included below.

2.2.1 Overview

A polymer is a compound formed by the reaction of simple molecules having functional groups that permit their combination to proceed to high molecular weights under suitable conditions. Polymeric materials usually have high strength, possess a glass transition temperature, exhibit rubber elasticity, and have high viscosity as melts and solutions (Kumar & Gupta, 1998). It is due to these unique properties that they have found multifarious application to mankind in our modern society. Polymers that are commonly used for construction and highway installation include acrylics, epoxies and polyurethanes.

The installation of piezoelectric sensors for vehicle axle classification requires a better understanding of the composition and performance of three components—that is, the pavement, the sensor, and the bonding material. The bonding material (i.e., grout, adhesive, or sealant) is a substance that is capable of holding materials together by surface attachment.

2.2.2 Previous Evaluation of Bonding Materials for Piezo Installation

The literature review showed that little research has been done in adhesives used in installation of piezoelectric sensors. One study that reported on the bonding materials for piezoelectric sensors was conducted by Ueber *et al.* (1994). The study reported on the physical characteristics of the bonding agents including epoxies and acrylics. The studied materials included Flexibond #11, Flexolith and Transpo T46 (Flexible epoxies), Schul and TXDOT G-100 (rigid epoxies) and P5G and IRD (acrylics). Other materials tested were (HMMUP) High Molecular-weight Methacrylate and recycled Unsaturated Polyester and Masterfill, which are neither acrylics nor epoxies.

The study tested the bonding materials for different mechanical, physical and compatibility tests. The mechanical properties tests included bond strength, flexural bond test, shear bond test, tension bond test and freeze/thaw tension while physical tests performed were gel time, shrinkage, thermal expansion, vicat set time and viscosity. Compatibility tests performed included bond strength, flexural bond test, shear bond test, tension bond test and freeze/thaw tension. Since the objective of the study was to determine the best bonding materials, the study recommended some tests for the selection criteria while some of the mentioned tests were not recommended. The recommended tests and values are summarized in Table 2.1.

The same study conducted field evaluation of the materials. The results showed that at all three test sites both ECM P5G manufactured by Electronic Control Measurements (ECM) and IRD AS475 manufactured by International Road Dynamics (IRD) had good workability, smooth flow that encapsulates the sensor, and fast curing time. However, the study shows that both

ECM P5G and IRD AS475 showed signs of deterioration during the winter at the Amarillo site due to prolonged cold temperatures. Although a different criterion was used for evaluation of binder materials in the Texas study, ECM P5G and IRD AS475 were found to be among the materials with low glass transition temperature. However, it should be noted that some materials that were ranked low also had low glass transition temperature.

Table 2.1 Recommended selection criteria according to Ueber *et al.* (1994)

Recommended Test	Required Result (1 psi = 6.9 kPa)
Compressive Strength	$\geq 1,000$ psi
Complex Shear Modulus – Storage Modulus G'	2,000 – 10,000 psi at 25o C (77o F) Decrease with increasing temperature
Gel Time	5 to 15 minutes
Shrinkage	-1.0% to 0.5%
Vicat Set Time	≤ 30 minutes
Viscosity	20 to 40 Pa-s
Bond Flexural Strength	≥ 100 psi (to asphalt) ≥ 300 psi (to concrete) Failure at least 50% in paving material
Field Trial (ease of use)	

Another study that evaluated adhesive materials similar to the ones approved by FDOT was conducted by Alavi *et al.* (2000). This study was designed to evaluate, among others, the effect of adhesive material on stress transfer and signal output of weigh-in-motion sensors. The results found that temperature had an effect on signal output since the increase in temperature caused a decrease in the stiffness of the pavement and adhesive; consequently, the amplitude of the raw signal increased. However, the most significant result of this study was that the four adhesives that were used with BL Class I sensor (ECM P5G, PU 200, E-Bond 1261 and IRD AS475), did not show any significant difference in signal output with the increase in temperature.

The literature search also revealed another study that evaluated Bondo 7084 adhesive. This study, sponsored by the Florida Department of Transportation and conducted by the Florida Institute of Technology was designed to evaluate the performance of fiber optic sensors buried in pavements. The study evaluated various adhesives for use as bonding agents. Only one of the adhesives that were evaluated as part of this study—that is Bondo 7084—was approved for use by the FDOT Planning Office through its approved product list. The study indicated that Bondo 7084 performed poorly at two sites where it was evaluated. The material became so soft that it stuck on vehicles' wheels as they passed on the groove causing the material to peel off from the sensors (Criss 1998).

2.2.3 Types of Bonding Materials

All five adhesives discussed above are polymer materials that fall into three major groups: (a) epoxies (i.e. *G100* and *7084*), (b) acrylics (i.e., *AS475* and *P5G*), and (c) polyurethane (*PU200*). The general chemistry of epoxy, acrylic, and polyurethane polymers are briefly summarized below in relation to material constituents and known performance

characteristics of these materials as adhesives and sealants.

Epoxies

Epoxy adhesives consist of an epoxy resin (binder) and a hardener. The resin, usually in semisolid state, is the principle component and a hardener is a substance added to the adhesive to promote the curing reaction. The curing temperature strongly influences the ultimate cross-link density. The supply of heat during curing increases molecular mobility resulting in higher cross-link density.

Epoxies have found a particularly wide use in the construction industry. Amstock (2001) indicated that epoxies have high resistance to corrosion and chemicals. However, epoxies tend to be very rigid and generally exhibit low peel strength. These characteristics can become a problem in the bonding of materials to flexible substrates such as asphalt pavements. Toughening agents can be compounded into the epoxies to improve peel strength to some extent. Epoxies usually produce large amounts of heat upon curing, causing problems with heat-sensitive materials or substrates, particularly if large volumes of epoxy are used.

Acrylics

Acrylics are thermoplastic materials manufactured from methylacrylate monomers found in products of petroleum, agricultural, and synthesis industries. Acrylics adhesives cure by addition of polymerizing agents. The formation of free radicals initiates a very rapid chain reaction that results in the cure of the adhesive. This cure chemistry is significantly more rapid than a typical cure for condensation polymers such as those in epoxy and urethane adhesives

Acrylics challenge epoxies in shear strength and offer flexible bonds with good peel strength. Acrylics are known for their high impact resistance, good low temperature characteristics, excellent long-term resistance to weathering and sunlight, low water absorption and excellent resistance to most chemicals. While acrylics respond well to heat, they are not affected by cold, and they do not become brittle in cold weather.

Polyurethanes

Like epoxies, polyurethane reactive adhesives include systems that are available as 100 percent solids or solvent based on one or two part formulations. Polyurethane adhesives are made with isocyanate resins as building blocks. The pot lives of two-component polyurethane adhesives such as PU200 can vary from as little as 15 seconds to as long as 16 hours, depending on the type of reactant (or hardener) used. Polyurethane-based adhesives form tough bonds with high peel strength. They have better low temperature strength than other adhesives but do not have high temperature resistance. They also have good flexibility, abrasion resistance, and toughness. They have good chemical resistance although not generally as good as epoxies or acrylics. Some polyurethane adhesives degrade substantially when exposed to high humidity and high temperature environments. This moisture sensitivity occurs with both the cured adhesive and the uncured components. Kumar & Gupta (1998) pointed out that usually the curing is slow and the adhesive joint tend to have low modulus of elasticity.

Table 2.2 summarizes important properties of epoxies, acrylics, and polyurethanes. The table lists some of the major advantages and shortcomings of each type of adhesive as it relates to workability and long term performance of the adhesive when used outdoors as a bonding agent or sealant.

Table 2.2 Advantages and limitations of epoxies, acrylics, and polyurethanes

Type of adhesive	Advantages	Limitations
Epoxy	• High chemical resistance • Outstanding adhesion to various substrates • Water resistant • Low shrinkage upon cure • Good electrical properties • High strength	• Exact proportions needed for optimum strength • Limited pot life • Rigid
Acrylic	• Excellent impact resistance and flexibility • Excellent peel and shear strength • Substrate versatility	• Shorter working time
Polyurethane	• Excellent toughness and flexibility • Fair to good chemical resistance • Excellent UV resistance • Fast cure	• Poor temperature resistant • Sensitive to moisture both in cured and uncured state • Short pot life • Slow curing • Low modulus • Poor water immersion resistance • Variety of formulations can cause wide differences in performance

2.2.4 Characteristics of Adhesives Approved by FDOT Planning Office

The information obtained from the Florida Department of Transportation indicates that there are five adhesives that were approved for use in the State of Florida. These adhesives are G100 by E-Bond Epoxies, 7084 by Dynatron/Bondo Corporation, P5G by Electric Control Measurements, AS475 by International Road Dynamics Inc., and PU200 by Global Resins Limited.

G100 by E-Bond Epoxies

G100 is an epoxy-based material that has variably been used in Florida for approximately 18 years for piezo installation and other purposes such as patching and placement of anchor bolts, dowels and pins in concrete surfaces. It is usually supplied in two parts, a resin and a hardener. The material is supplied in 11½, 26, or 46-pound containers. The resin and the hardener are mixed in 25 to 1 ratio by weight. The manufacturer technical data sheet indicates that the resin and hardener should be mixed within three to five minutes of opening the containers and poured immediately after mixing. The manufacturer recommends the curing time of one hour to 14 hours depending on the substrate temperature. Lower substrate temperature

requires longer curing period while higher substrate temperature requires shorter curing time, thus allowing faster opening of the road to traffic. It should be noted that originally G100 was formulated for installation of heavy WIM frames in portland cement concrete pavements in Texas.

7084 by Dynatron/Bondo Corporation

This is also an epoxy-based adhesive that is supplied in two parts—resin and hardener. Both the resin and a hardener are supplied in 12.6 pounds. The material is mixed in 1:1 ratio. The mixing time is not indicated in the technical data sheet. The data sheet does not indicate the mix cure time but indicates the gel time at 77°F to be between 17 to 25 minutes.

ECM P5G by Electronic Control Measurement

This is an acrylic-based adhesive supplied in two parts—resin and hardener. The hardener is peroxide. ECM P5G is also mixed with fine filler material intended to improve bonding. The filler material commonly used is dry sand. The adhesive is supplied in 13.5 pounds containers. The manufacturer recommends that the resin should be premixed (without hardener) for four minutes or until the resin has a smooth/even texture. The hardener is then added and mixed for not more than one minute after which the binder is immediately used. The data sheet indicates that the expected cure times range from 20 minutes for 75°F to 100°F temperatures to 40 minutes for 40°F to 50°F temperatures.

AS475 by International Road Dynamics (IRD) Inc.

This adhesive is also acrylic-based and supplied in two parts—resin and hardener. The hardener is composed of benzyl peroxide organic (PBO) powder. The resin is supplied already pre-mixed with fine filler material that, according to the manufacturer, provides strength and consistency to the adhesive mixture. The filler material is made of fine aggregate and prevents the resin from cracking by serving as a heat sink for the significant heat created during the curing of the resin. The material is supplied in 39.6-pound pails for 12-foot sensors and 22-pound pails for 6-foot sensors. The manufacturer recommends thorough mixing of resin and filler material prior to adding the hardener. The hardener is added in an amount that is dependent upon the ambient temperature and mixed with resin and filler for approximately two minutes. The manufacturers indicate that the mixture cures fully in 30 to 40 minutes.

PU200 by Global Resins Limited

This is a polyurethane-based adhesive that is also supplied in two parts consisting of resin and hardener. In addition, the adhesive is supplied in two versions—one for winter installation when outside temperature is below 40°F and another for summer installations when outside temperature is above 40°F. The resin and the hardener are supplied separately in cans. The resin and hardener are premeasured so that there is no need of calculating the mix ratio. The manufacturer data sheet indicates that the material should be left to cure for approximately one hour before opening the site to traffic.

Table 2.3 compares pertinent material characteristics for the five adhesive types. The information in Table 2.3 was obtained from the technical data sheets provided by the manufacturers where available. It is noteworthy that information on two adhesives—that is P5G and AS475—are adaptation from a study conducted by Euber *et al.* (1994) since the technical data sheets from these manufacturers lacked the relevant information. Through a telephone conversation with manufacturer’s representatives, it was indicated that the material composition has not changed much since Euber *et al.* study was conducted in 1994.

Table 2.3 Comparison of physical characteristics of the adhesives

Property	Adhesive type				
	G100	7084	P5G	AS475	PU200
Hardness	85-88	80±5			85
Shrinkage	0%	0%	0%	0.04%	
Water Absorption	0.03%	0%			
Compressive Strength	8000 psi		3583 psi	1024 psi	5173 psi
Tensile Strength		2500±200 psi	2564 psi	2529 psi	18811psi
Viscosity		500 poise	25 Pa-s	21 Pa-s	110 poise
Set time		45 min	11 min at 0°C	30 to 40 min	20 min
Gel Time	17-25 min. @ 77°F	17 to 25 min.	13 min. @ 25°C	17 min. @ 25°C	10 min. @ 20°C

2.2.5 Forces Applied to Binders

There are varied forces that act on the binder that binds the piezo with the pavement. These forces can contribute to the degradation of the bonding. The forces are discussed in the following sections.

Cyclic loading

The binder material is subjected to cycling loading caused by the action of tires on the road. The environmental factors such as temperature also cause cyclic loading to the binder. Ashcroff *et al.* (2001) reported that the mode of failure in composite joints is heavily dependent on environmental conditions, with temperature variation having a significant effect. The moisture is also known to contribute to the deterioration of the mechanical properties of bonded joints with time (Ashcroft *et al.*, 2001).

Compression

As it is to the pavement, the binder is subjected to the induced compression stresses mainly caused by the action of tires. However, because of repeated dynamic loading from the traffic the failure is expected to ultimately yield below the normal ultimate compression strength.

The binder also experiences compression due to contraction and expansion that occur due to sudden changes of weather.

Tension

Several factors such as expansion and contraction of the binder material may lead to tensile stresses in the binder material and bond interface. Sufficient bond tensile strength is therefore required in order to overcome tensile stresses that may be induced to the binder.

2.2.6 Possible Modes of Failure and Their Causes

The bonding material can fail in various modes due to static and dynamic stresses caused by loading and environmental factors discussed above. The following sections discuss modes of failure that can happen and the mechanistic reasons for the failures.

Bond failure

One of the most important parameters affecting the bonding effect of the binder is the adhesion of the binder to the substrate surface. Lack of compatibility is one of the factors that cause bond failure. Compatibility is the ability of two or more substances combined with one another to form a homogeneous mix having useful binding properties. Other factors that may cause bond failure include shrinkage and poor workmanship during installation and water intrusion. As far as bonding between the binder and metals is concerned, water is known to be the substance that causes the greatest problems in the environmental stability of adhesive joints (Knox and Cowling, 2000). Water entry may cause weakening by one or a combination of the following actions:

- (a) altering the adhesive properties in a reversible manner, such as by plasticization,
- (b) altering the adhesive properties in an irreversible manner either by causing it to hydrolyse, crack or craze, and
- (c) attacking the interface, either by displacing the adhesive or hydrating the metal or metal oxide.

Fatigue failure

More than 75 percent of failures in engineering components are attributed to fatigue failure (Timings, 1999). A material which is subjected to a stress which is alternatively applied and removed a very large number of times, or which varies between limiting values, will fracture at a very much lower value of stress than in a normal tensile stress. Alternate wheel loading, temperature variations, strong sunlight (UV radiation), ageing, expansion and contraction may attribute to fatigue failure of the binder.

Failure due to Compression

This mode of failure occurs when the applied stress exceeds the ultimate compression strength of the binder. However, the design of the pavement is not based on the single impact

load but rather accumulation of the effect of the long term axle loading. The understanding of the compression characteristics of the material is therefore not sufficient to describe long term performance of the binder in the pavement.

Failure due to brittleness

Brittleness occurs mainly in low temperature conditions. This is a property of the material that shows little or no plastic deformation before fracture when a force is applied. This type of failure is likely to occur if the temperatures are low.

Surface wearing

The binder surface is exposed to friction of tires that may lead to wearing of the binder layer hence exposing the sensor. The binder is also subjected to abrasion, a process where hard particles are forced against and moved along a solid surface. Hard particles may include sand, loose aggregates, metal chipping, etc.

2.3 Field Evaluation of Loop Sealants and Piezo Grouts

The Florida Department of Transportation tasked the research team to evaluate loop sealants and piezo grouts in the field for the purpose of determining the long the performance characteristics of these materials. Fortunately, the telemetered traffic monitoring site 352 (TTMS Site 352) on Interstate 10 already had these materials installed in August 2008. A number of different sealants and piezo grouts were installed at TTMS Site 352 for the secondary objective of evaluating loop sealants and piezo grouts field performance. Figure 2.1 shows the layout of the site with the type of the bonding materials used to seal each sensor. For the loop sealants, three types were used: 3M #5000; Wabo #19420 2-part silicon; and Fabick 2:1. For the piezo grouts, four types were used: G-100; AS475; Fabick 2:1; and Fabick 1:1².

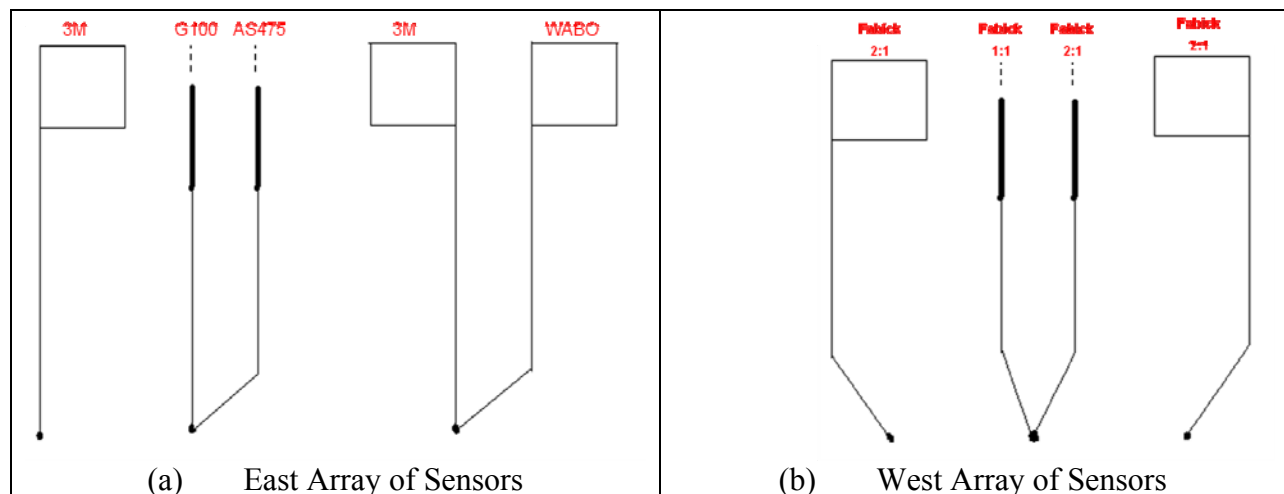


Figure 2.1 Layout of sensors at TTMS Site 352.

² Fabick 1:1 and 2:1 refers to the ratio of resin to hardener by volume.

It was the view of the FDOT Statistics Office that an additional site is needed for further evaluation of loop sealants and piezo grouts. At the progress meeting held in March 2009, a plan for sealing loops and piezos at Site 112 on Interstate 75 was discussed in detail. Present during the discussion were Joe Poole and Terry Robinson of Southern Traffic Systems which has the push-button contract with FDOT Planning Office. It was decided that Loop # 11 at that site will be completely replaced while all other loops and piezos will be resealed wherever deterioration is observed and the cracks are present. A design of experiments approach was adopted in which a number of loop sealants and grouts from the FDOT Planning Approved Product List (Section 741 through 747) were to be used. The sealing plan that was adopted is shown in Table 2.4.

On March 30, 2009, Southern Traffic Systems implemented the loop sealing and replacement plan discussed above. Dr. Ren Moses and Mr. Kip Jones attended the nighttime installation. Because the installation was conducted at night, it was difficult to take photographs of the installation to document the appearance of the sealants and grouts soon after the installation. Thus, Ren Moses, Doreen Kobelo, and Onyekachi Acholem travelled to the site again on April 6, 2009 to take photographs and to measure the resistance and inductance of all loops including Loop #11 which was replaced. The final loop repair plan is shown in Figure 2.2 and Figure 2.3.

Table 2.4 Loop repair plan at site 112.

Loop No.	Condition	Ground Resistance (Ω)	Inductance (μ H)	Recommended action	Type of sealant
1	- Noticeable pavement distress in the outside lane - Loop sealant cracking mostly along the wheel path	∞	143.0	Seal the cracks around the loop and the lead in cables	3M
2	- Exposed wires in the lead in cable - Pavement unraveling around the loop	12.5	142.5	Replace the loop and the lead in cables	Fabick 2:1 topped with G100
3	- Exposed wires in the loop - Moderate bonding failure around the loop	∞	145.6	Seal the cracks around the loop and the lead in cables	3M
4	Minor bonding failure around the loop	∞	142.7	Seal the cracks around the loop and the lead in cables	Fabick 2:1
5	- Minor bonding failure around the loop - Sever bonding failure around the lead in cables	∞	140.2	Seal the cracks around the loop and the lead in cables	3M
6	- Minor bonding failure around the loop - Severe longitudinal cracking in the lead in cable sealant	∞	137.5	Seal the cracks around the loop and the lead in cables	Fabick 2:1
7	- Minor bonding failure around the loop - Severe longitudinal cracking in the lead in cable sealant	∞	137.2	Seal the cracks around the loop and the lead in cables	Bondo
8	- Minor bonding failure around the loop - Severe longitudinal cracking in the lead in cable sealant	46.4	136.2	Seal the cracks around the loop and the lead in cables	Stat-a-flex
9	- Exposed wires in the loop and in the lead in cable - Moderate bonding failure around the loop	∞	137.9	Seal the cracks around the loop and the lead in cables	Bondo
10	- Minor bonding failure around the loop - Exposed wires in the lead in cable	∞	136.8	Seal the cracks around the loop and the lead in cables	Stat-a-flex
11	- Severe bonding failure around the loop - Severe cracking of bonding in the lead in cables	12.5	132.2	Seal the cracks around the loop and the lead in cables	Bondo
12	- Severe bonding failure around the loop - Severe bonding cracking around the lead in cables	∞	131.5	Seal the cracks around the loop and the lead in cables	Stat-a-flex

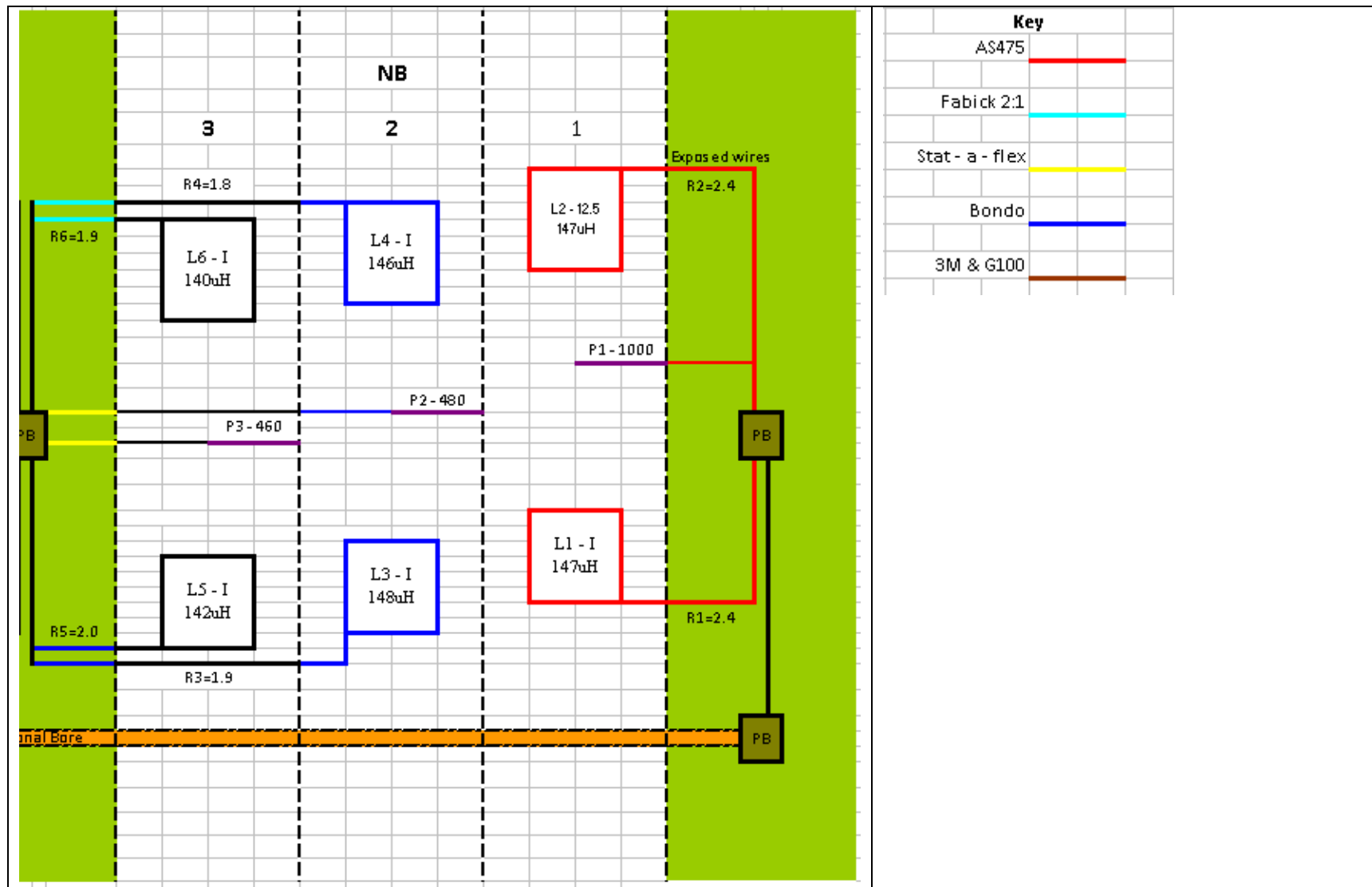


Figure 2.2. Site 112 loop repair installation in the northbound direction

2.4 Continuous Monitoring of Sites 352 and Site 112

The project team monitored the performance of loop sealants and piezo grouts at both Site 352 on Interstate 10 and Site 112 on Interstate 75. The records show that the project team travelled to these sites eight times at regular intervals to observe the physical attributes of the bonding materials and to measure electrical outputs. The travel dates were February 18, 2009; April 6, 2009; June 4, 2009; July 8, 2009; August 13, 2009; August 18, 2009; October 20, 2009; and December 10, 2009. The performance review involved taking photographs and videos of how the loop sealants and piezo grouts appear as well as measuring inductance of loop wires, measuring ground resistance of loop wires, and measuring voltage output of piezos at Site 352. The latest photographs taken are shown in Appendix A and the electrical readings are shown in Appendix B.

2.5 Preliminary Results and Summary

The performance evaluation of the loop sealants and piezo grouts at TTMS Site 352 on Interstate 10 and TTMS Site 112 on Interstate 75 is supposed to continue for another one year past this project period. The continued evaluation of loop sealants and piezo grouts at these two sites will be funded by the Florida Department of Transportation Statistics Office through a different work task order. Therefore, the summary of the results discussed herein should be considered preliminary. The results show that the resealing of some loops had slowed the deterioration of the installation. In addition, although the ground resistance of some loops was below the acceptable level, the inductance was not too negatively affected thus enabling the continuing extraction of vehicle data from TTMS Site 112 on Interstate 75.

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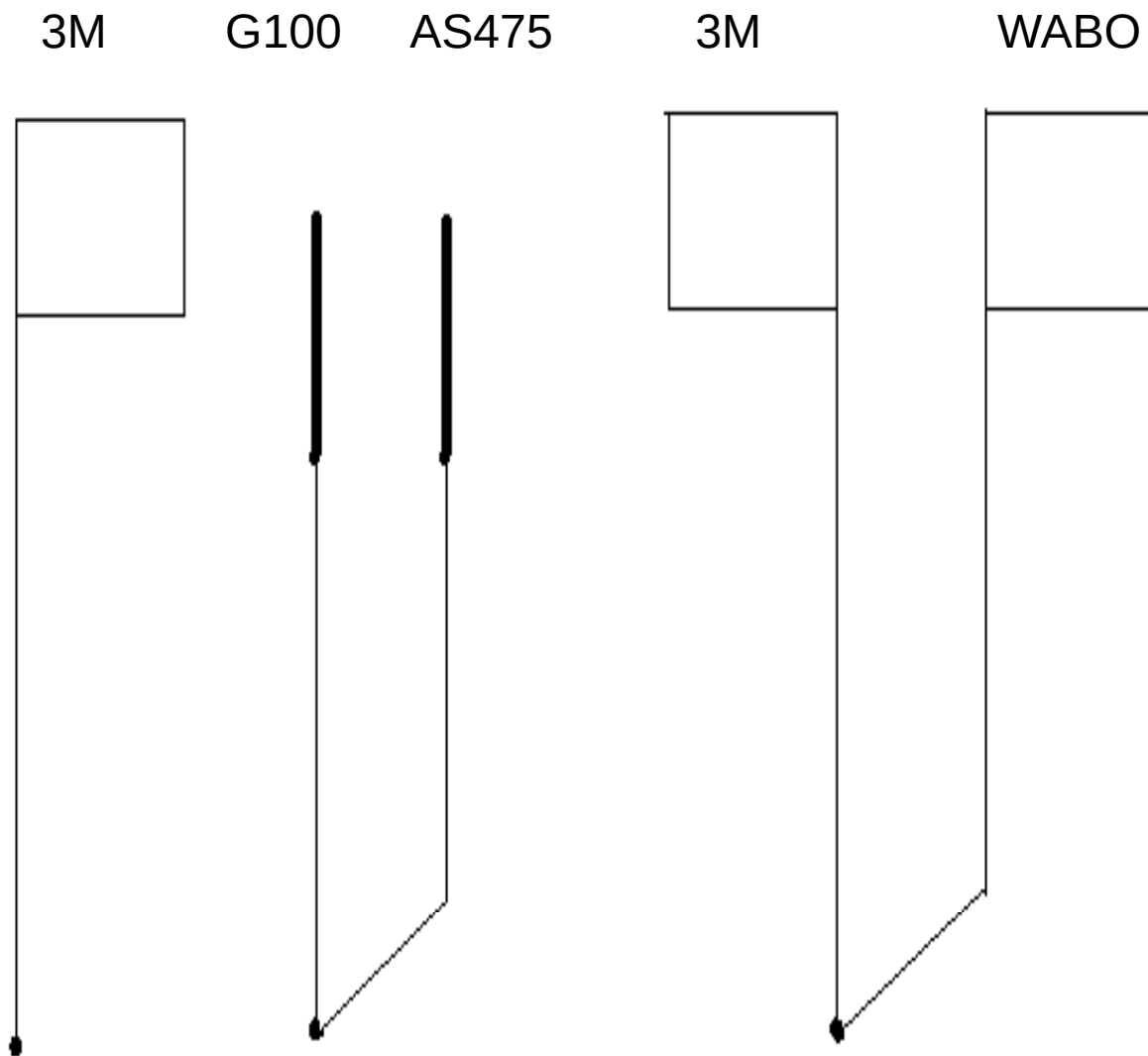
Appendix A -- Physical Evaluation at Site 352 and 112

Purpose

- To review the performance of loop sealants and piezo grouts at Site 352 and 112
- To measure inductance and ground resistance of loop wires at Site 112 and Site 352
- To measure piezo amplitude readings at Site 352 to assess piezo sensing performance in relation to the deterioration of grout

PHYSICAL OBSERVATIONS AT TTMS SITE 352

Sensor Layout – West Array



Sensor Layout – East Array

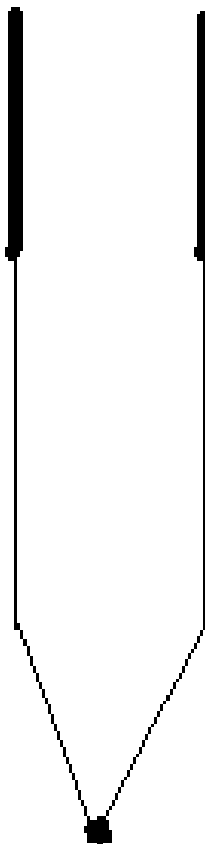
Fabick

2:1



Fabick

1:1



Fabick

2:1



Fabick

2:1

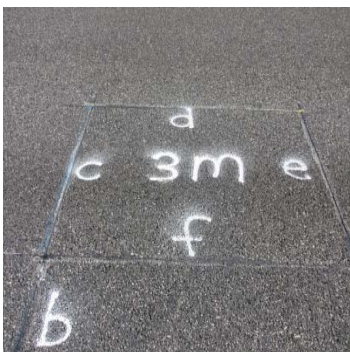
3M Loop sealant (1)



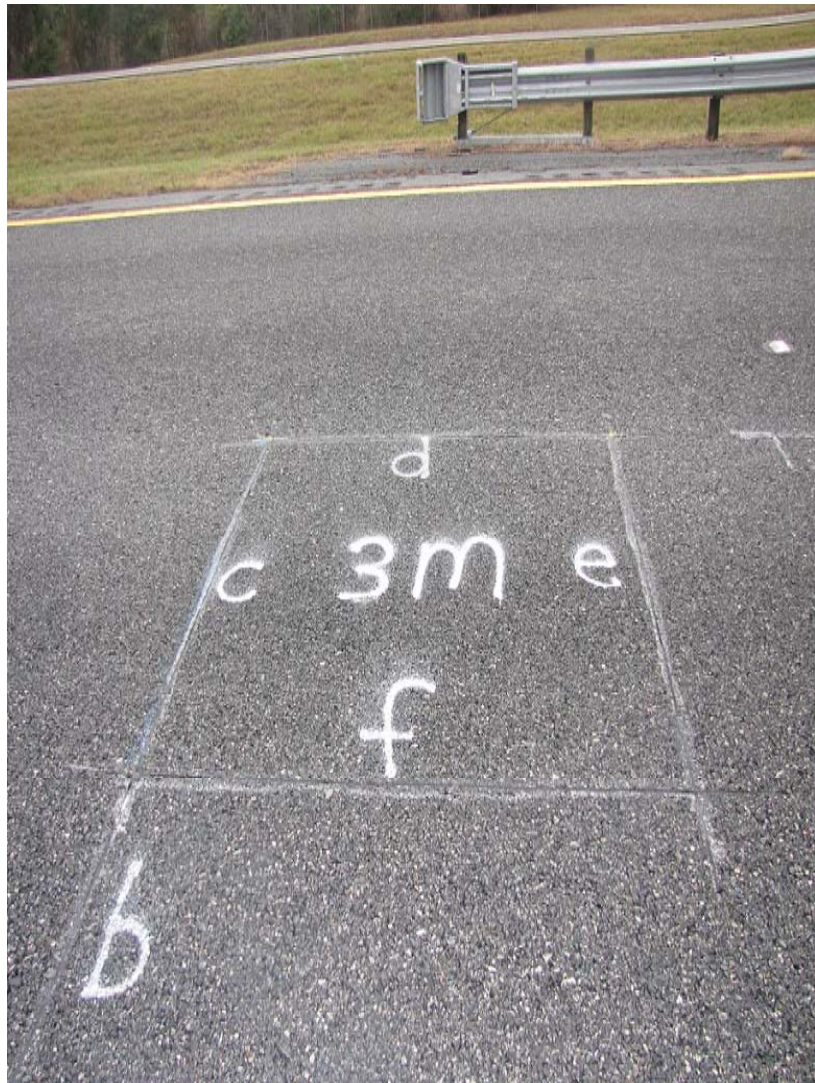
07/08/09



08/13/09



10/20/09



12/10/09

3M Loop sealant (1)



07/08/09



08/13/09



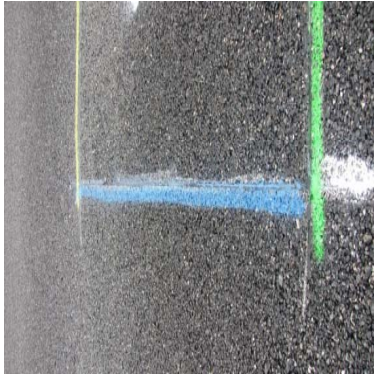
10/20/09



12/10/09

Side closer to the outside shoulder

3M Loop sealant (1)



07/08/09



08/13/09



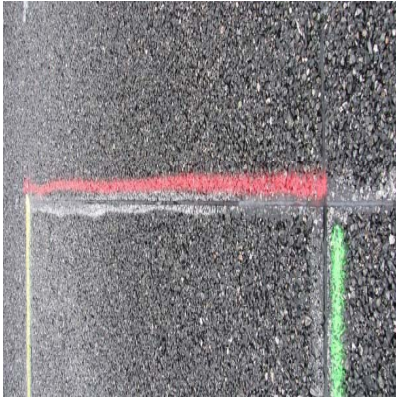
10/20/09



12/10/09

First side hit traveling east

3M Loop sealant (1)



07/08/09



08/13/09



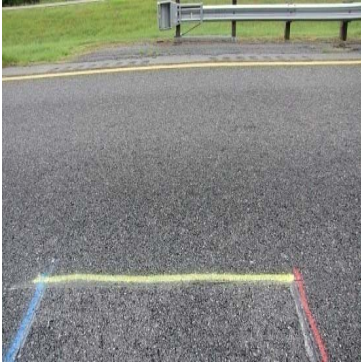
10/20/09



12/10/09

Second side hit traveling east

3M Loop sealant (1)



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

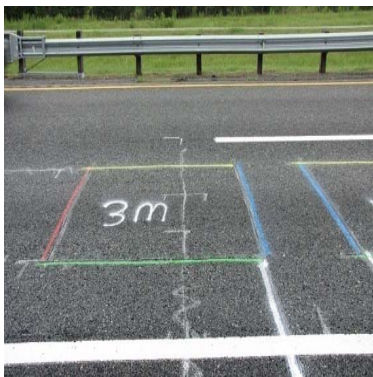
3M Loop sealant (2)



04/06/09



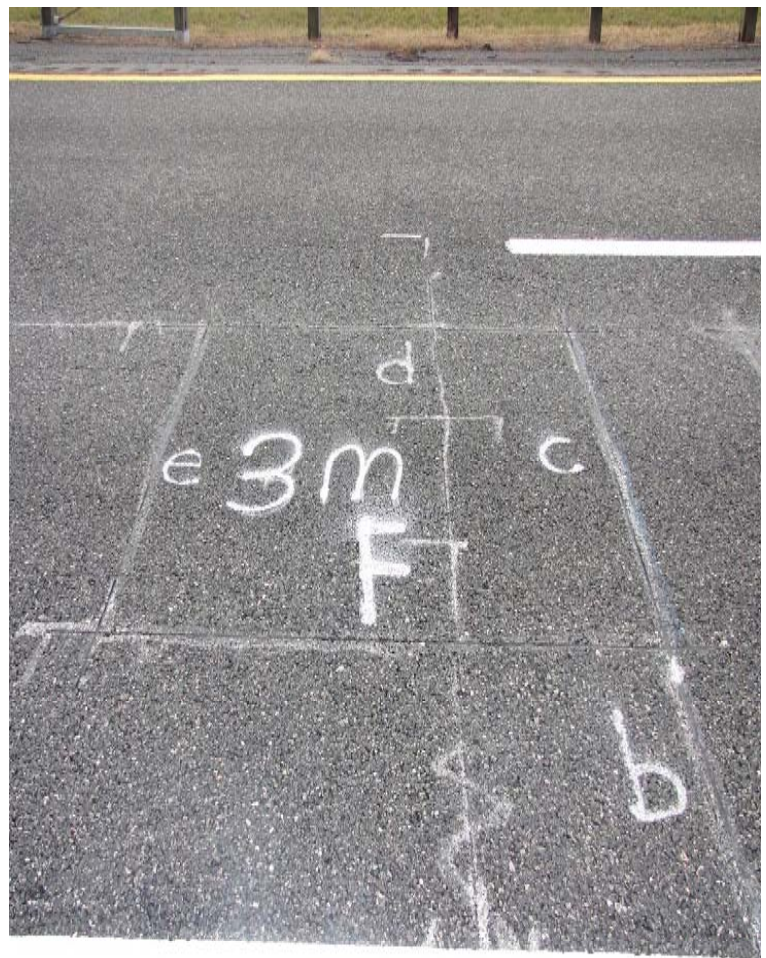
10/20/09



07/08/09



08/13/09



12/10/09

3M Loop sealant (2)



07/08/09



08/13/09



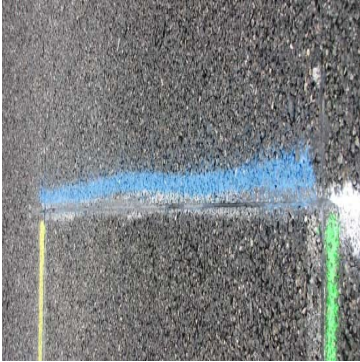
10/20/09



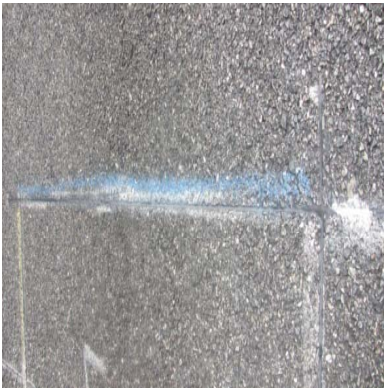
12/10/09

Side closer to the outside shoulder

3M Loop sealant (2)



07/08/09



08/13/09



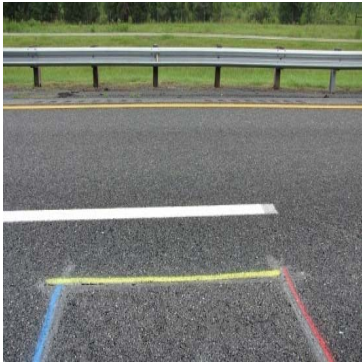
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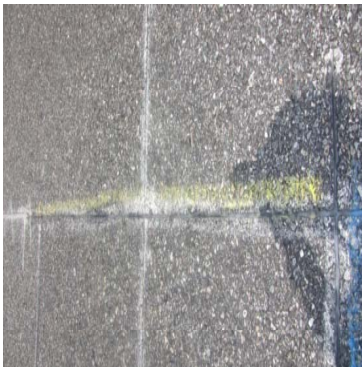
12/10/09

Second side hit traveling east

3M Loop sealant (2)



07/08/09



08/13/09



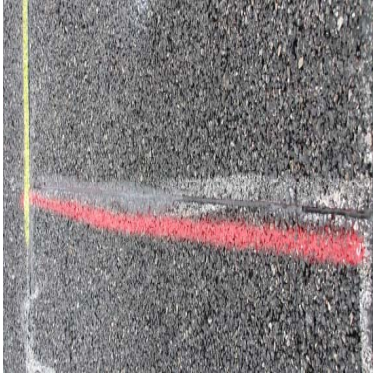
10/20/09



12/10/09

Side closer to the inside lane

3M Loop sealant (2)



07/08/09



08/13/09



10/20/09



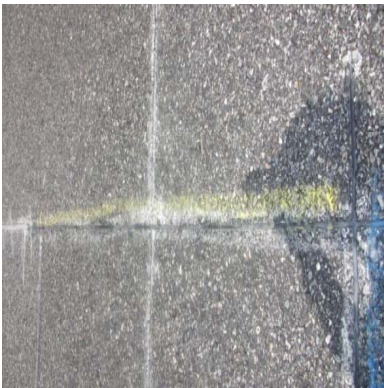
12/10/09

First side hit traveling east

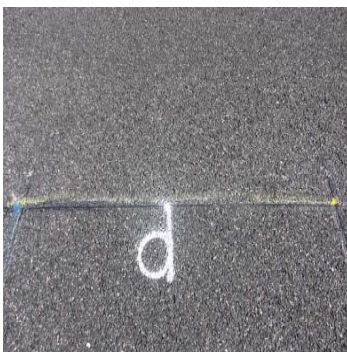
3M Loop sealant (2)



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

WABO Loop Sealant



07/08/09



08/13/09



10/20/09



12/10/09

WABO Loop Sealant



07/08/09



08/13/09



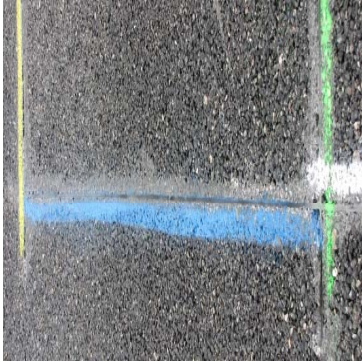
10/20/09



12/10/09

Side closer to the outside shoulder

WABO Loop Sealant



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling east

WABO Loop Sealant



07/08/09



08/13/09



10/20/09



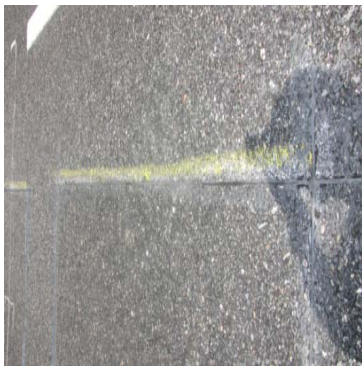
12/10/09

Second side hit traveling east

WABO Loop Sealant



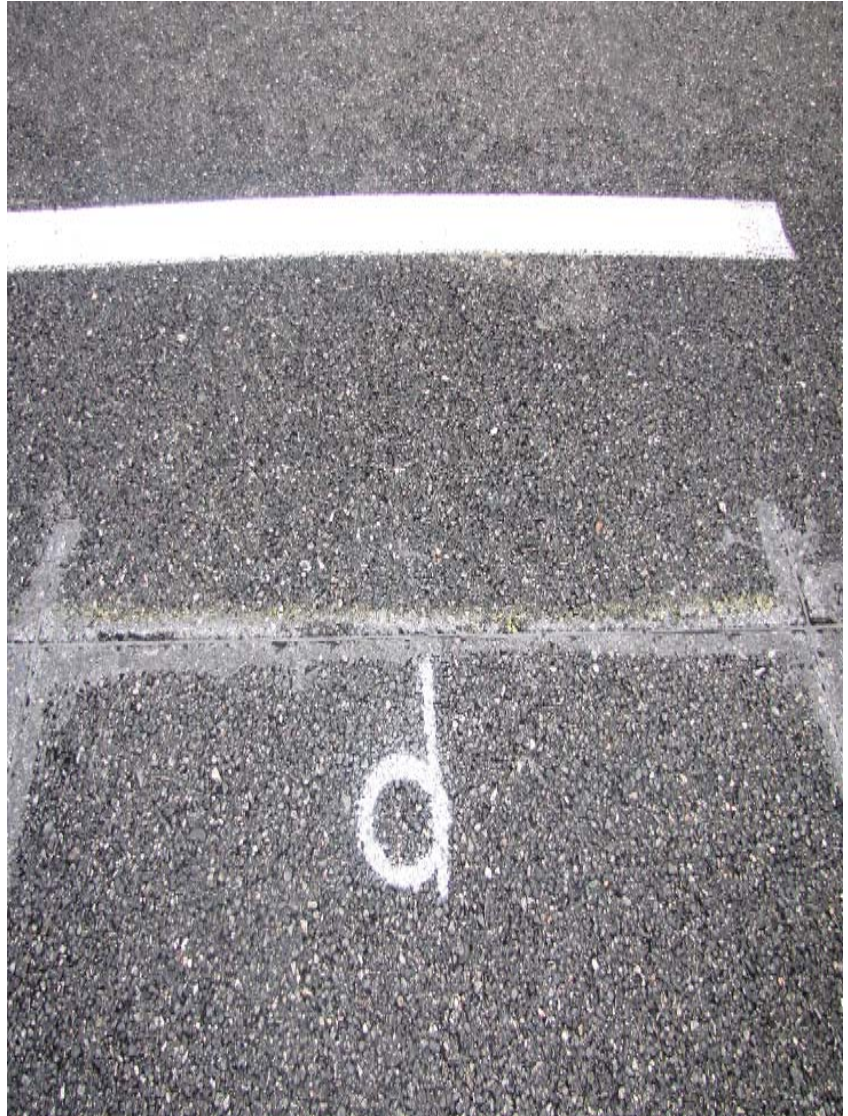
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

FABICK 2:1 Loop Sealant (1)



07/08/09



10/20/09



04/06/09



08/13/09



12/10/09

FABICK 2:1 Loop Sealant (1)



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

FABICK 2:1 Loop Sealant (1)



07/08/09



08/13/09



10/20/09



12/10/09

Exposed wire

First side hit traveling east

FABICK 2:1 Loop Sealant (1)



07/08/09



08/13/09



10/20/09



12/10/09

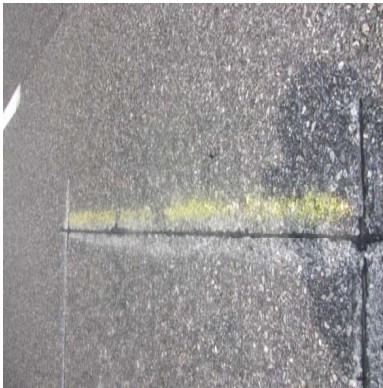
Exposed
wire

Second side hit traveling east

FABICK 2:1 Loop Sealant (1)



07/08/09



08/13/09



10/20/09



Unraveling pavement

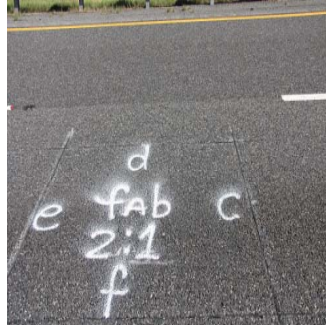
12/10/09

Side closer to the inside shoulder

FABICK 2:1 Loop Sealant (2)



04/06/09



10/20/09



07/08/09



08/13/09



12/10/09

FABICK 2:1 Loop Sealant (2)



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

FABICK 2:1 Loop Sealant (2)



07/08/09



08/13/09



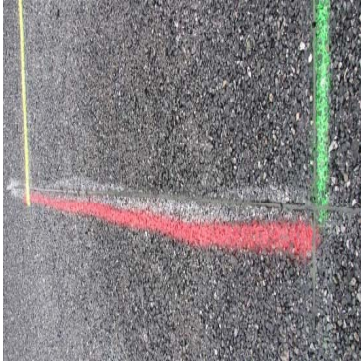
10/20/09



12/10/09

Second side hit traveling east

FABICK 2:1 Loop Sealant (2)



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling east

FABICK 2:1 Loop Sealant (2)



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

East Array Piezos

FABICK 1:1 & FABICK 2:1 GROUTS



02/18/09



07/08/09



10/20/09



12/10/09



04/06/09



08/13/09

Worn out grout

West Array Piezos

G100 & AS 475 GROUTS



02/18/09



07/08/09



10/20/09



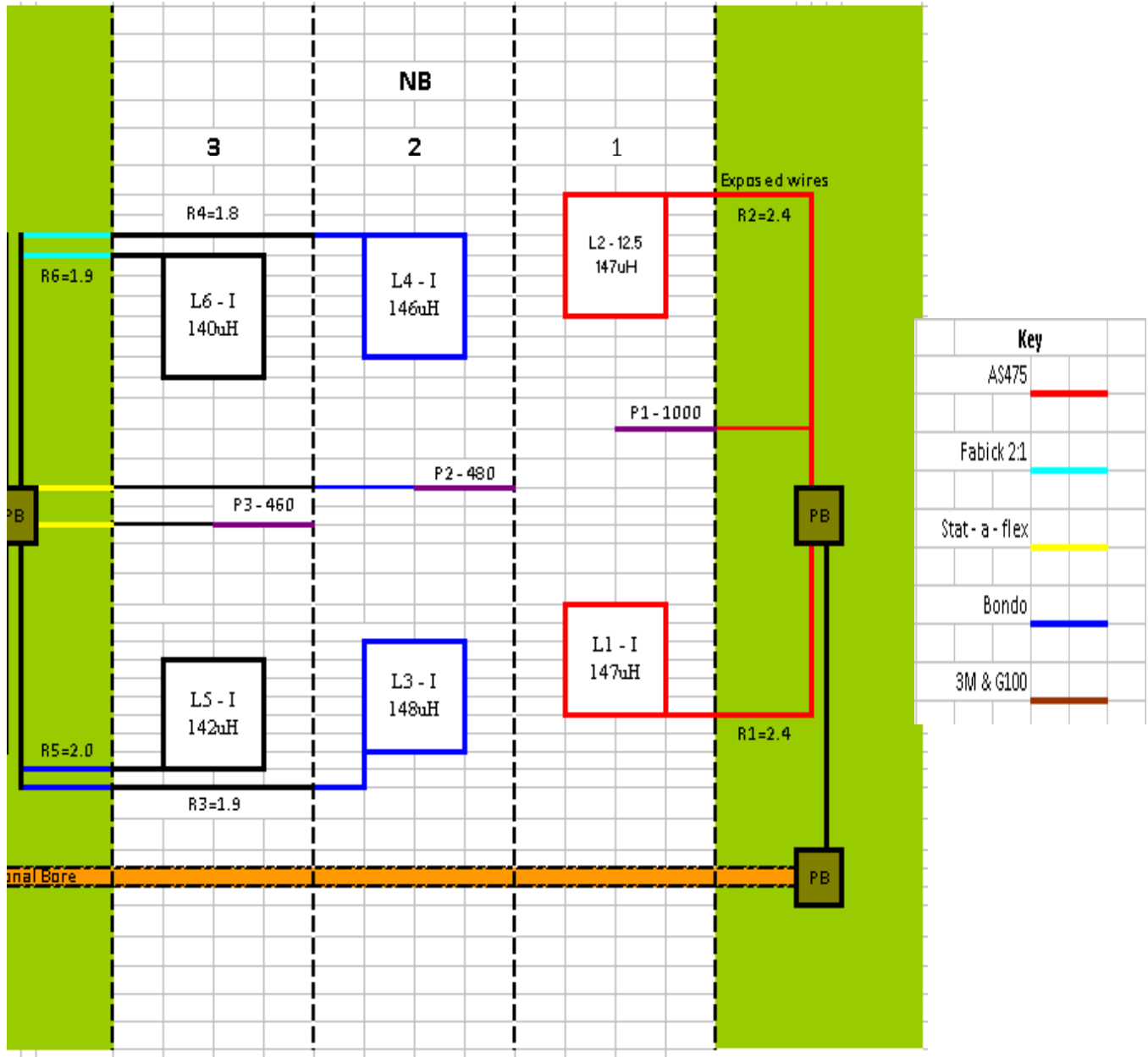
04/06/09



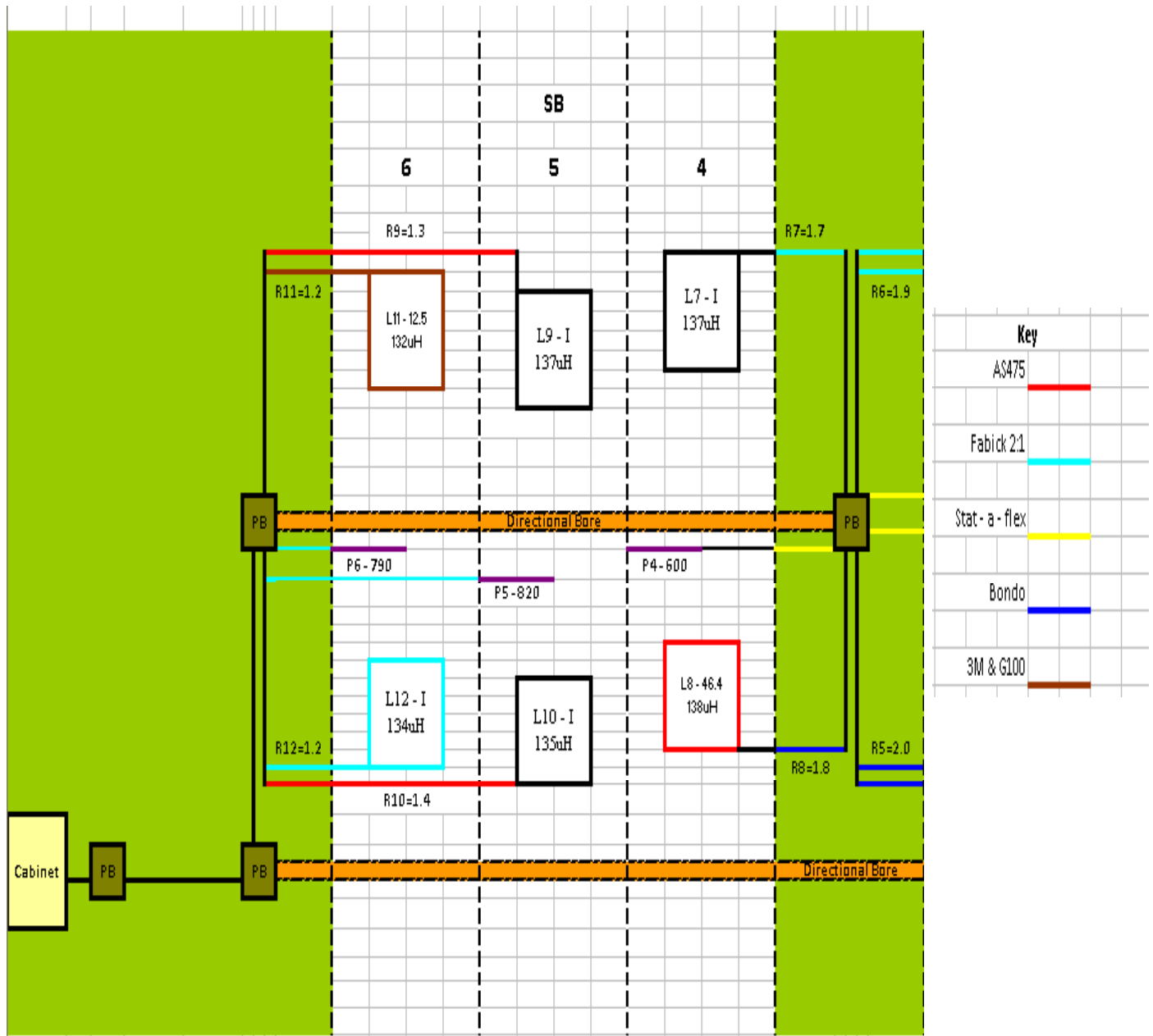
08/13/09

PHYSICAL OBSERVATIONS AT SITE 112

Northbound



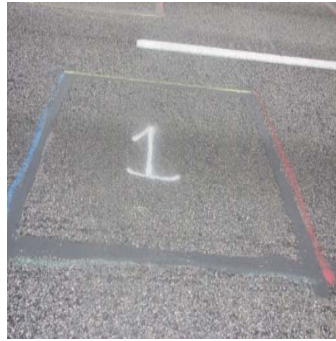
Southbound



Loop #1 – Resealed using AS 475



02/18/09



08/13/09



10/20/09



04/06/09



07/08/09



12/10/09

Loop #1 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



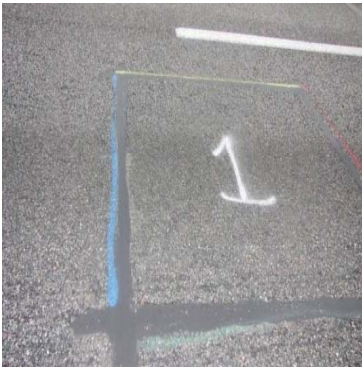
12/10/09

Side closer to the outside shoulder

Loop #1 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling north

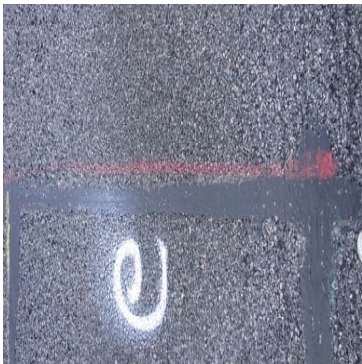
Loop #1 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling north

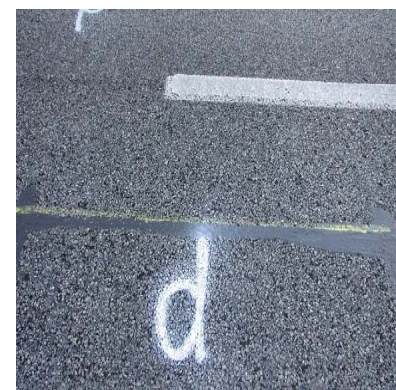
Loop #1 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #1 – Resealed using AS 475



04/06/09



10/20/09



08/13/09

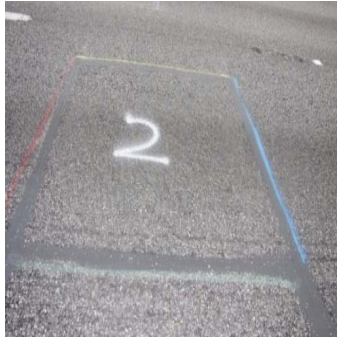


12/10/09

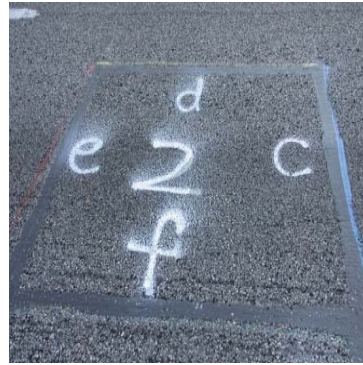
Loop #2 – Resealed using AS 475



02/18/09



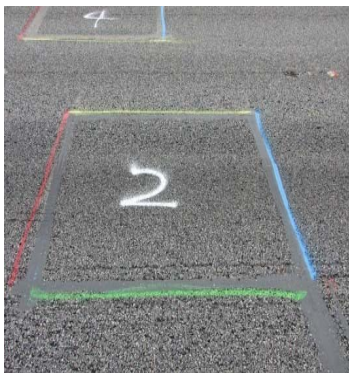
08/13/09



10/20/09



04/06/09

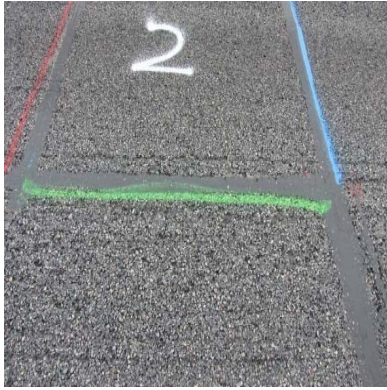


07/08/09



12/10/09

Loop #2 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #2 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling north

Loop #2 – Resealed using AS 475



04/06/09



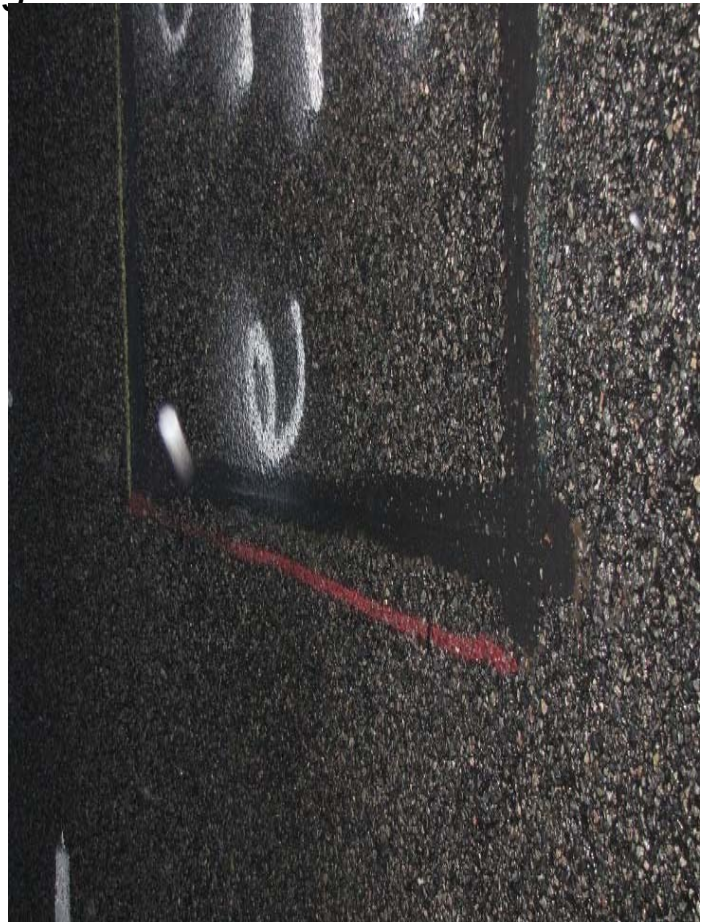
10/20/09



07/08/09



08/13/09



12/10/09

First side hit traveling north

Loop #2 – Resealed using AS 475



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #2 – Resealed using AS 475



04/06/09



08/13/09



10/20/09



12/10/09

Loop #3 – Resealed using BONDO



04/06/09



10/20/09



07/08/09



08/13/09



Worn out
pavement

12/10/09

Loop #3 – Resealed using BONDO



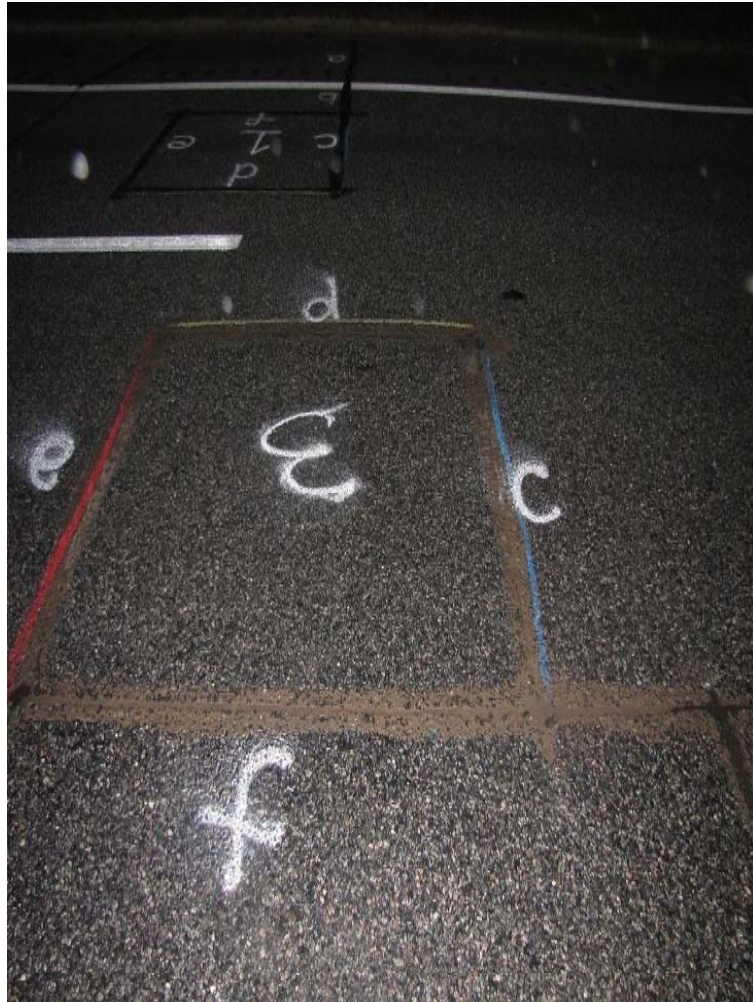
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #3 – Resealed using BONDO



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling North

Loop #3 – Resealed using BONDO



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling north

Loop #3 – Resealed using BONDO



04/06/09



10/20/09



07/08/09



08/13/09



12/10/09

Side closer to the inside shoulder

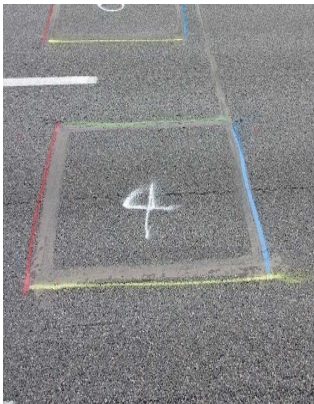
Loop #4 – Resealed using BONDO



04/06/09



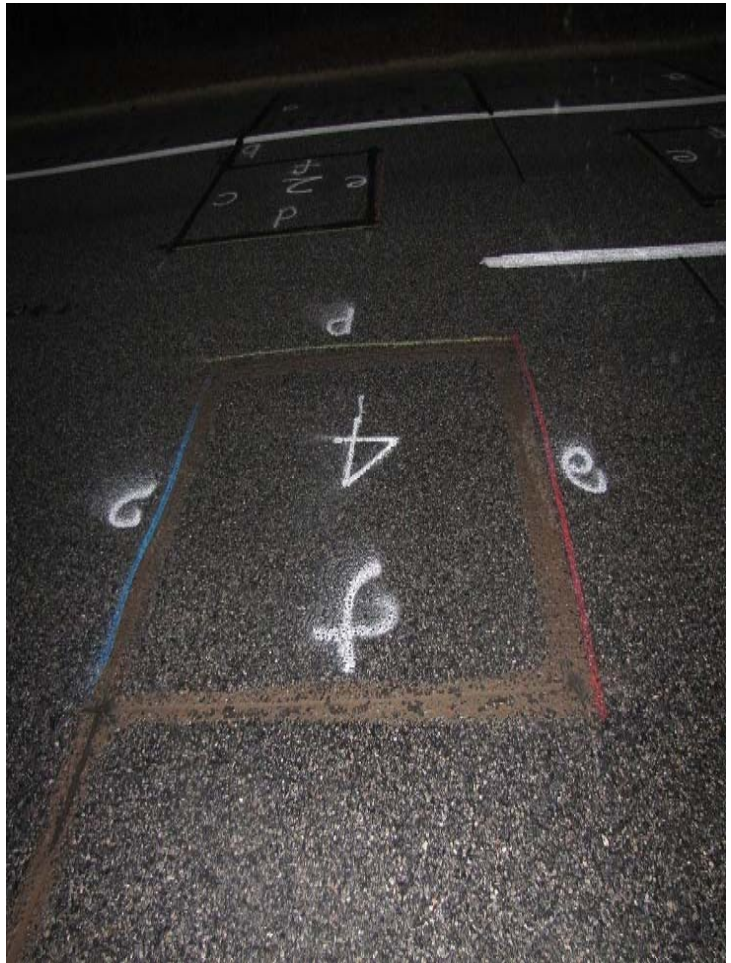
10/20/09



07/08/09



08/13/09



12/10/09

Loop #4 – Resealed using BONDO



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #4 – Resealed using BONDO



07/08/09



08/13/09



10/20/09

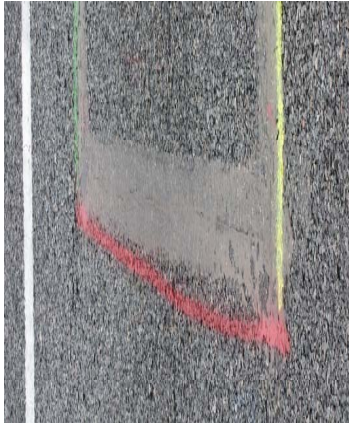


12/10/09

Sealant de-
bonding

Second side hit traveling north

Loop #4 – Resealed using BONDO



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling north

Loop #4 – Resealed using BONDO



04/06/09



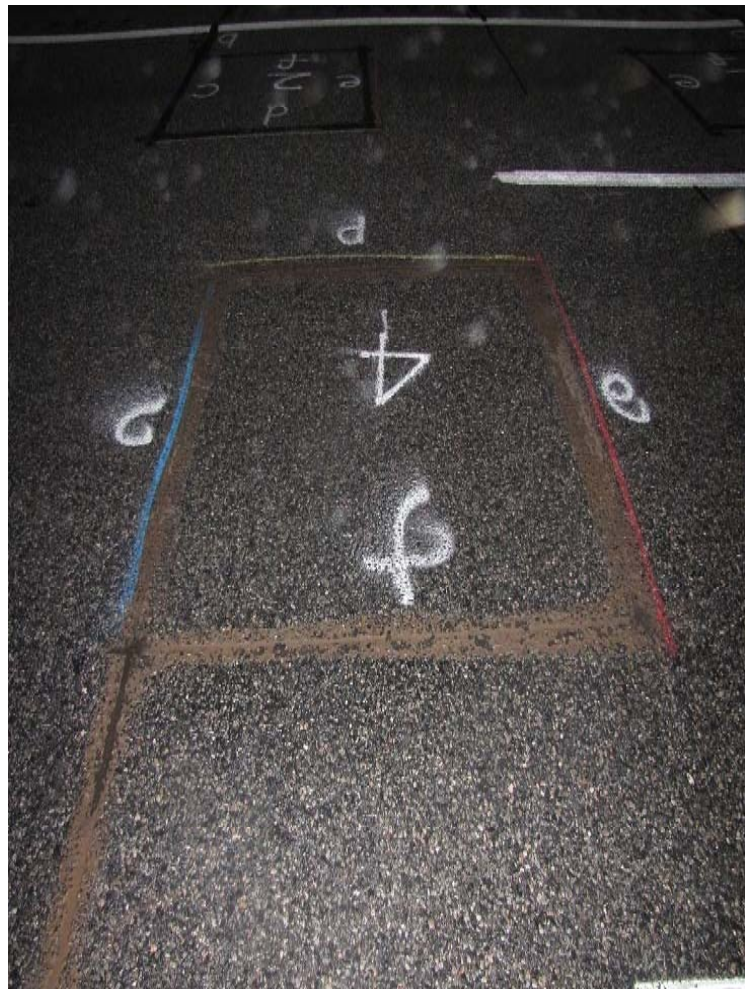
10/20/09



07/08/09



08/13/09



12/10/09

Side closer to the inside shoulder

Loop #5 – No Action on the Loop



07/08/09



08/13/09



10/20/09



12/10/09

Loop #5 – No Action



07/08/09



08/13/09



10/20/09



Unraveling
pavement

12/10/09

Side closer to the outside shoulder

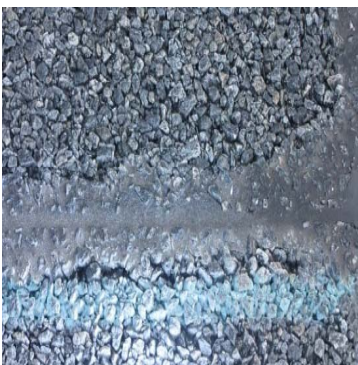
Loop #5 – No Action



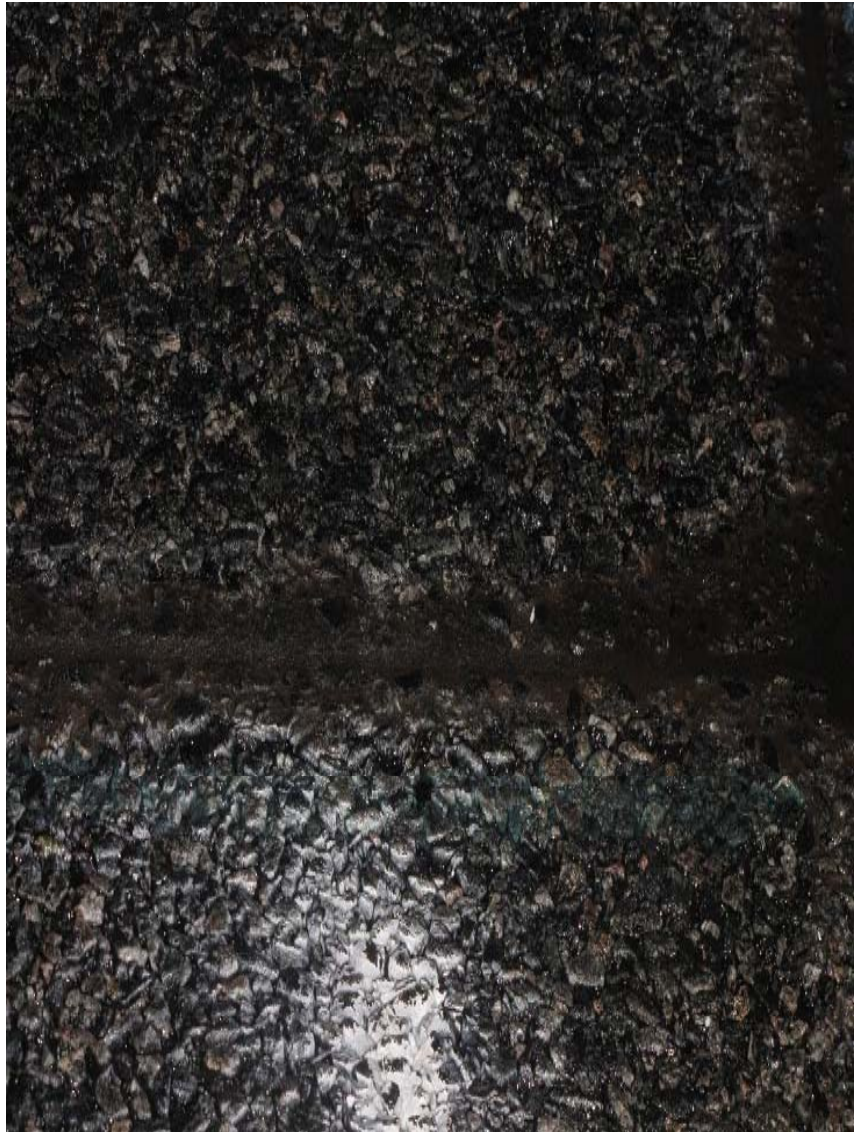
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #5 – No Action



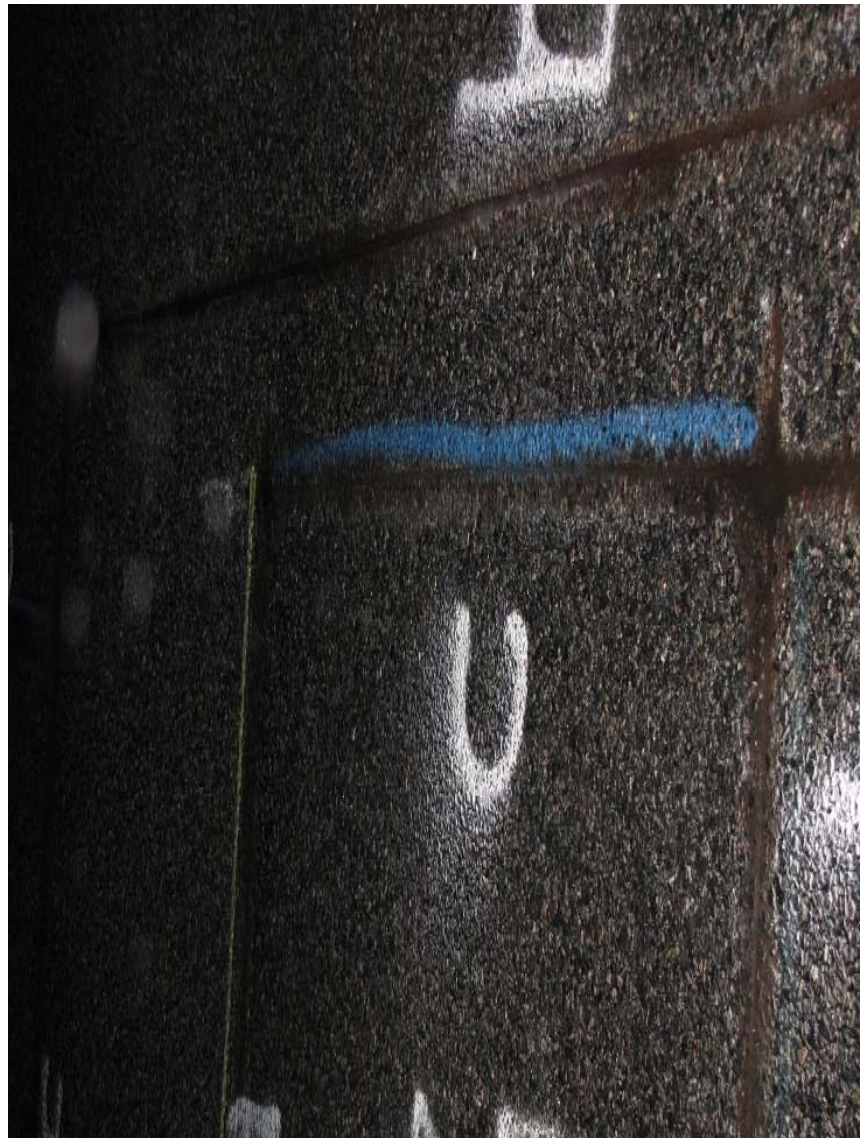
07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling north

Loop #5 – No Action



07/08/09



08/13/09



10/20/09



Unraveling pavement

12/10/09

Second side hit traveling north

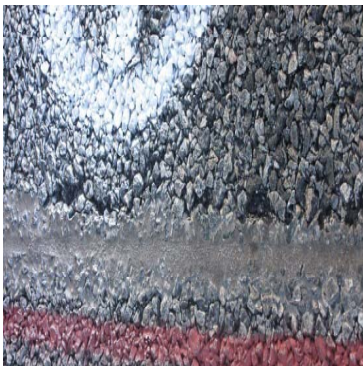
Loop #5 – No Action



07/08/09



08/13/09



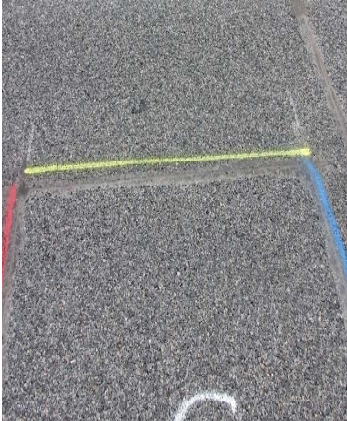
10/20/09



12/10/09

Second side hit traveling north

Loop #5 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #5 – Shoulder Resealed using BOND-O



07/08/09



10/20/09



12/10/09

Loop #6 – No Action on the Loop



07/08/09



08/13/09



10/20/09



12/10/09

Loop #6 – No Action



07/08/09



08/13/09



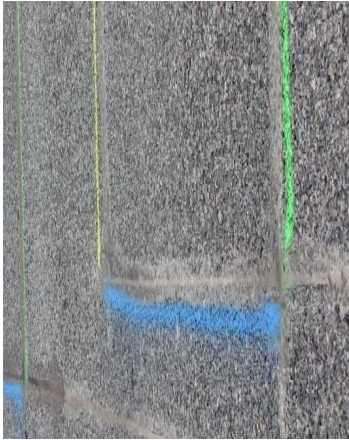
10/20/09



12/10/09

Side closer to the outside shoulder

Loop #6 – No Action



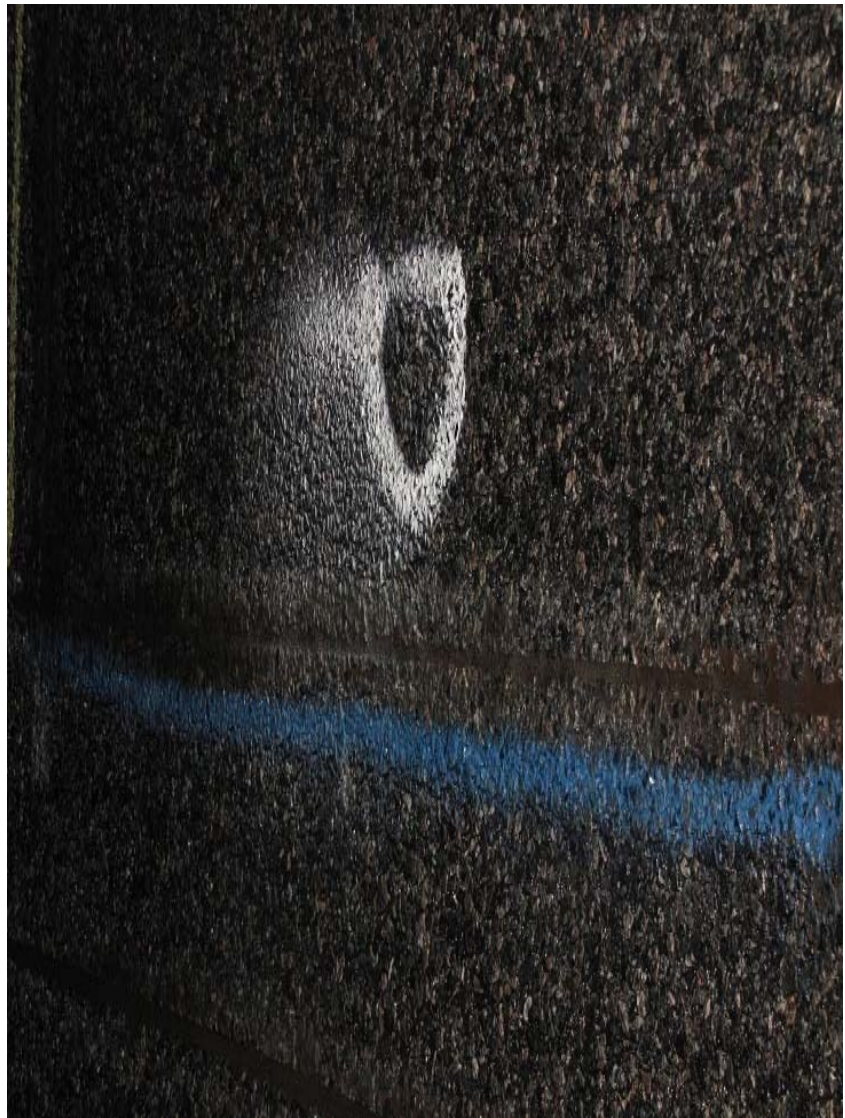
07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling north

Loop #6 – No Action



07/08/09



08/13/09



10/20/09

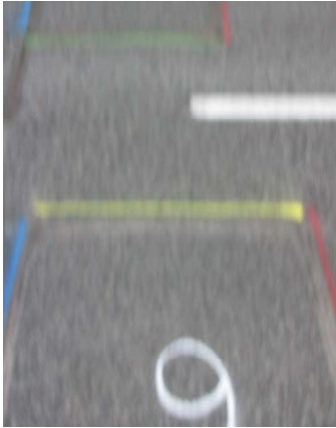


12/10/09

First side hit traveling north

100

Loop #6 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

101

Loop #6 – Shoulder Resealed using FABICK 2:1



04/06/09



07/08/09



10/20/09



12/10/09

Loop #7 – No Action on the Loop



07/08/09



08/13/09



10/20/09



12/10/09

Loop #7 – No Action



07/08/09



08/13/09



10/20/09



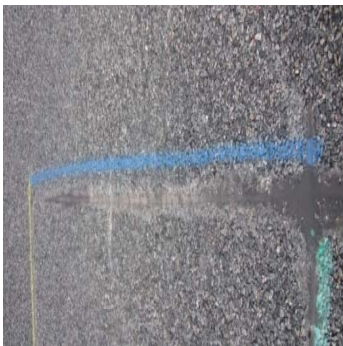
12/10/09

Side closer to the outside shoulder

Loop #7 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling south

Loop #7 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling south

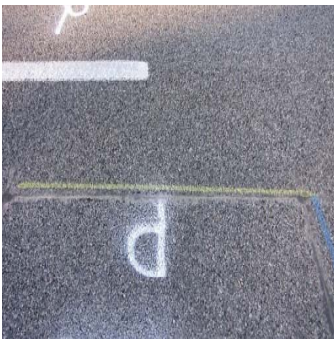
Loop #7 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

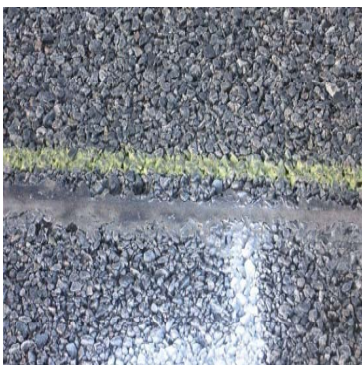
Loop #7 – No Action



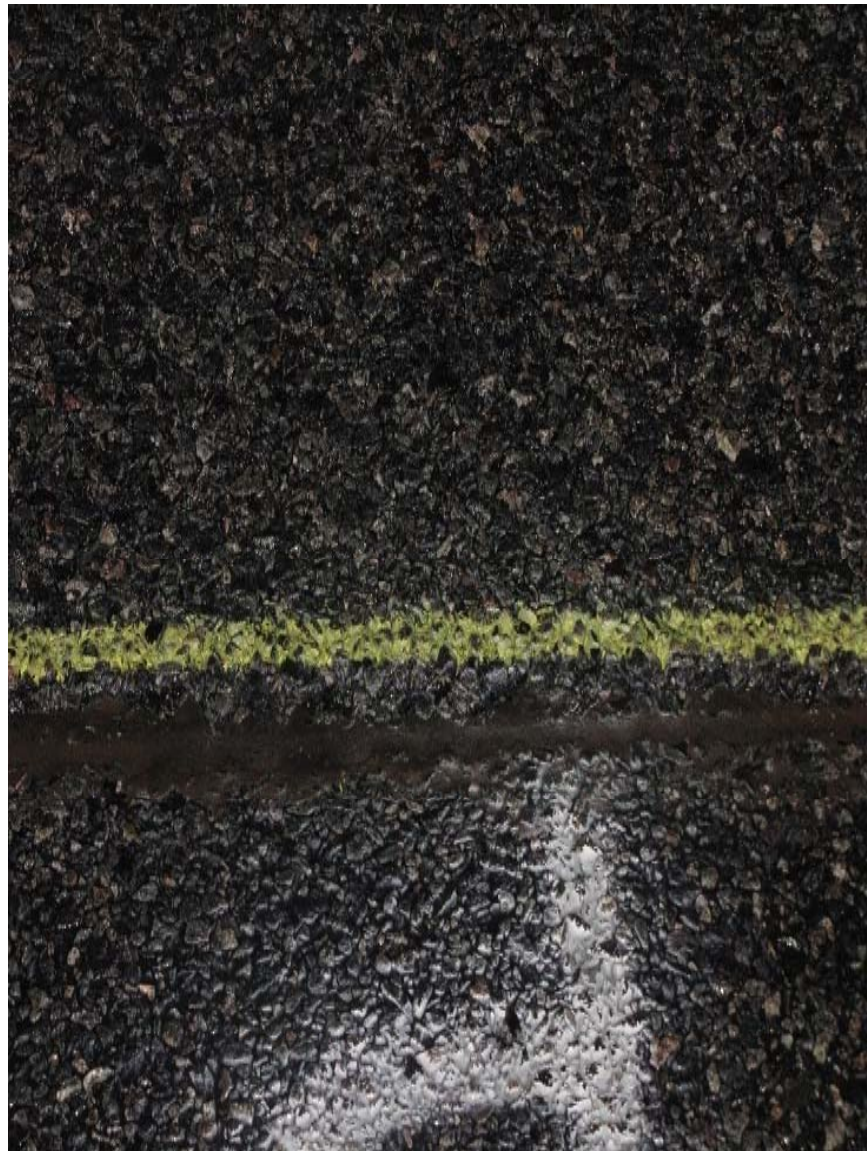
07/08/09



08/13/09



10/20/09



10/20/09

Side closer to the inside shoulder

Loop #7 – Shoulder resealed using FABICK 2:1



04/06/09



10/20/09



12/10/09

Loop #8 – No Action on the Loop



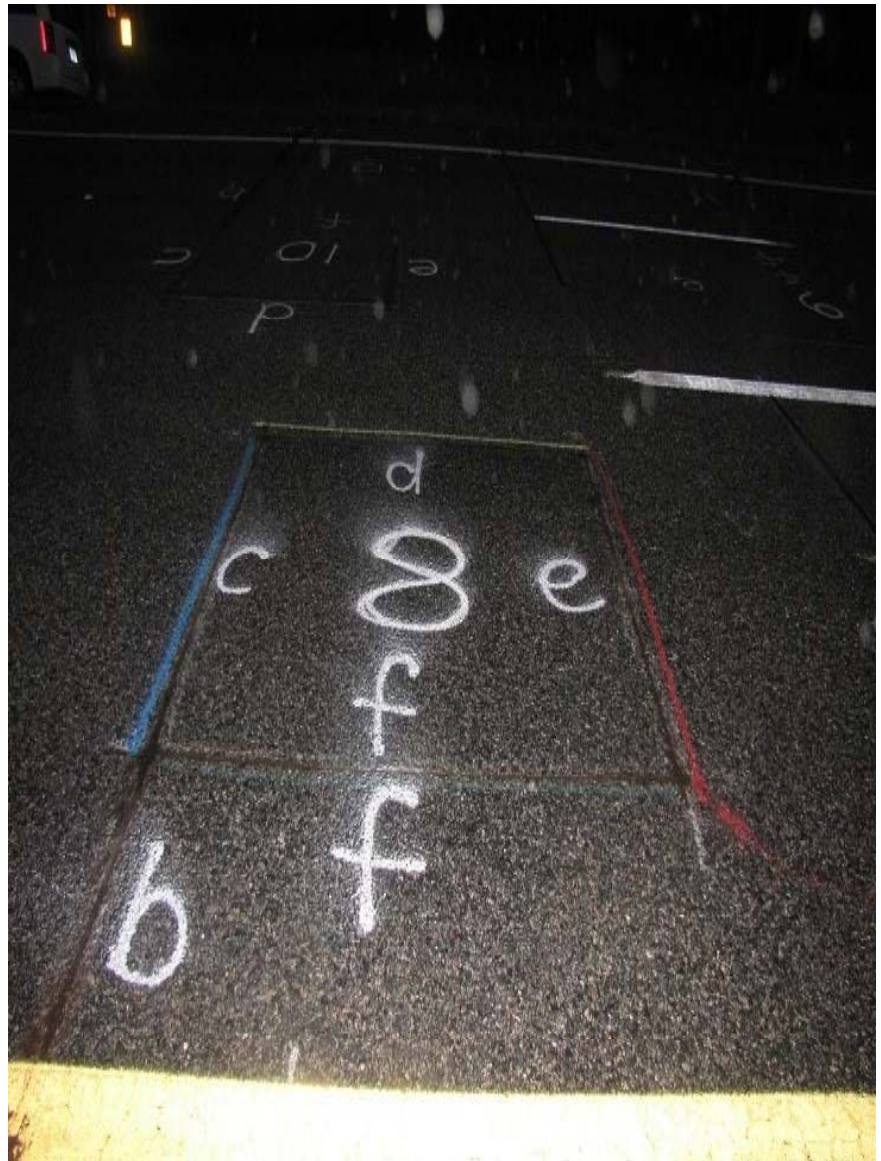
07/08/09



08/13/09



10/20/09



12/10/09

Loop #8 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #8 – No Action



07/08/09



08/13/09



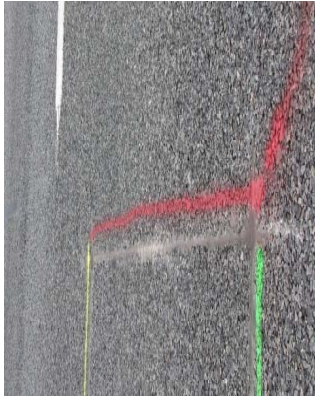
10/20/09



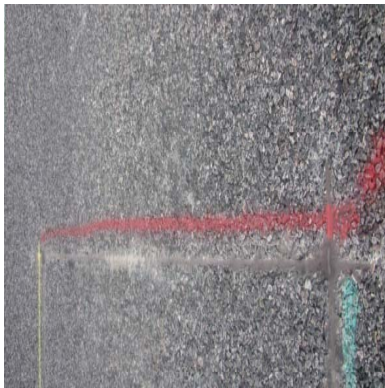
12/10/09

Second side hit traveling south

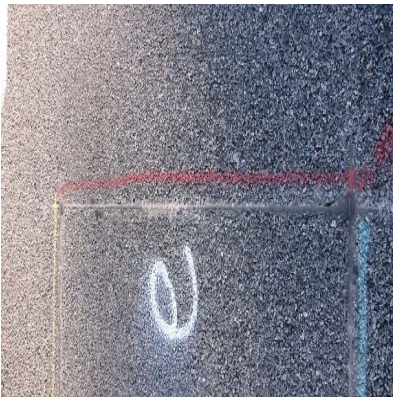
Loop #8 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling south

113

Loop #8 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #8 – Shoulder resealed using BONDO



04/06/09



10/20/09



12/10/09

Loop #8 – Shoulder resealed using BONDO



04/06/09



07/08/09



10/20/09



Shoulder cracking

12/10/09

Loop #9 – No Action on the Loop



07/08/09



08/13/09



10/20/09



12/10/09

Loop #9 – No Action



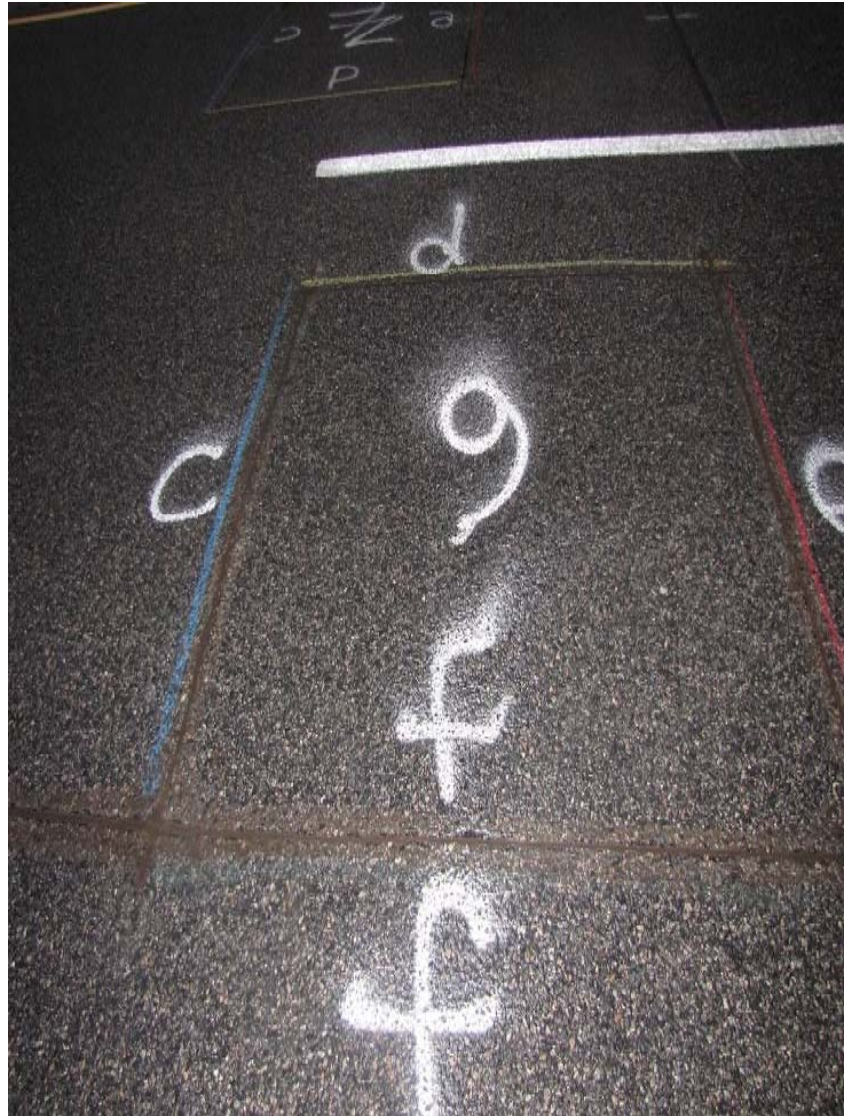
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #9 – No Action



07/08/09



08/13/09



10/20/09



Loop sealant de-bonding

12/10/09

First side hit traveling south

Loop #9 – No Action



07/08/09



08/13/09



10/20/09



Loop sealant de-bonding

12/10/09

Second side hit traveling south

120

Loop #9 – No Action



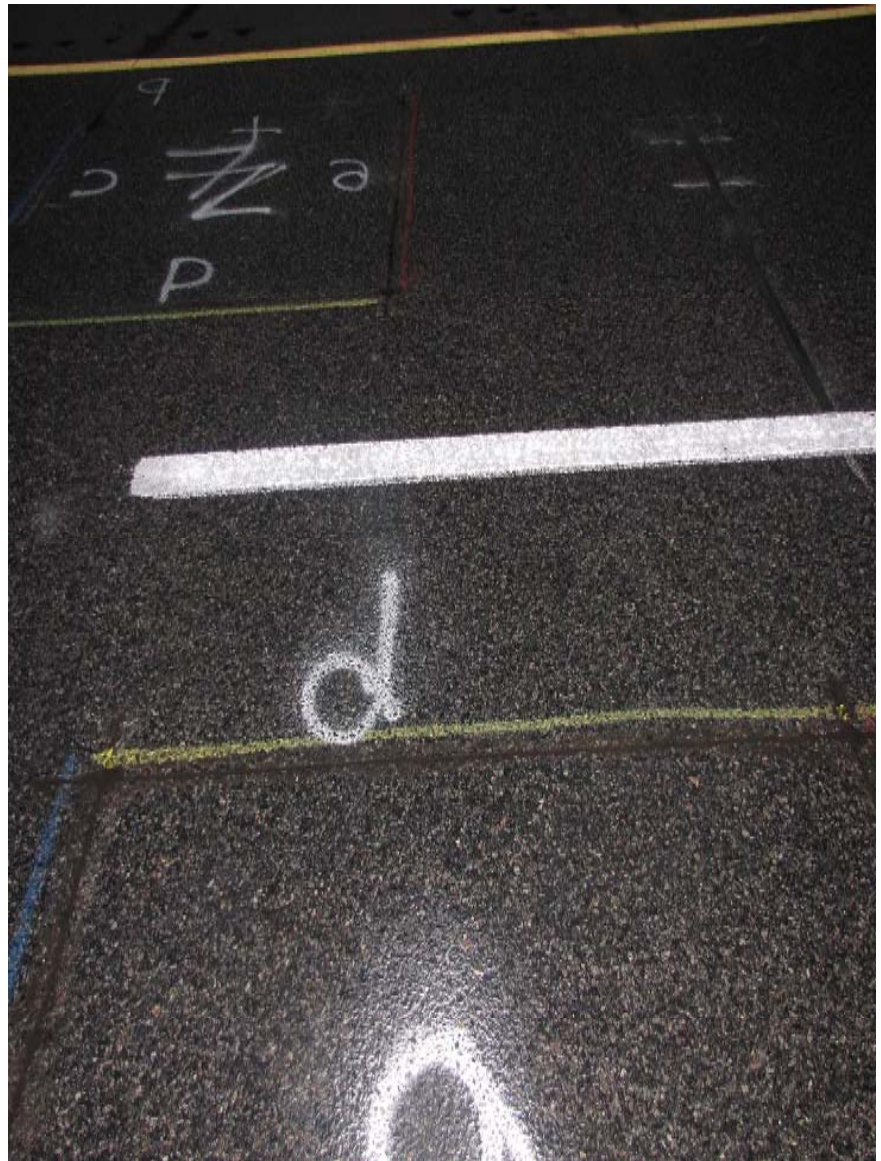
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #9 – Shoulder resealed using AS 475



04/06/09

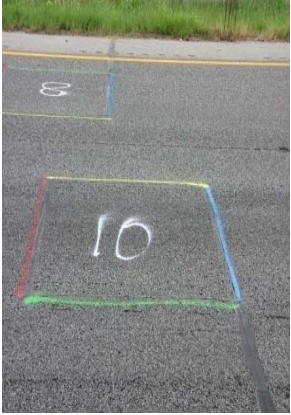


10/20/09



12/10/09

Loop #10 – No Action on the Loop



07/08/09



08/13/09



10/20/09



12/10/09

Loop #10 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #10 – No Action



07/08/09



08/13/09



10/20/09



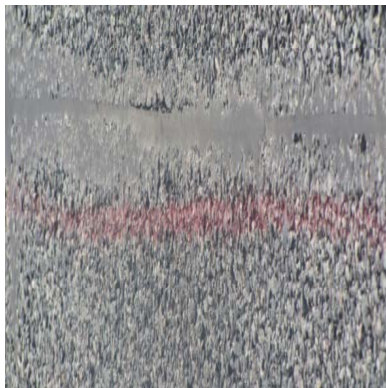
12/10/09

Second side hit traveling south

Loop #10 – No Action



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling south

126

Loop #10 – No Action



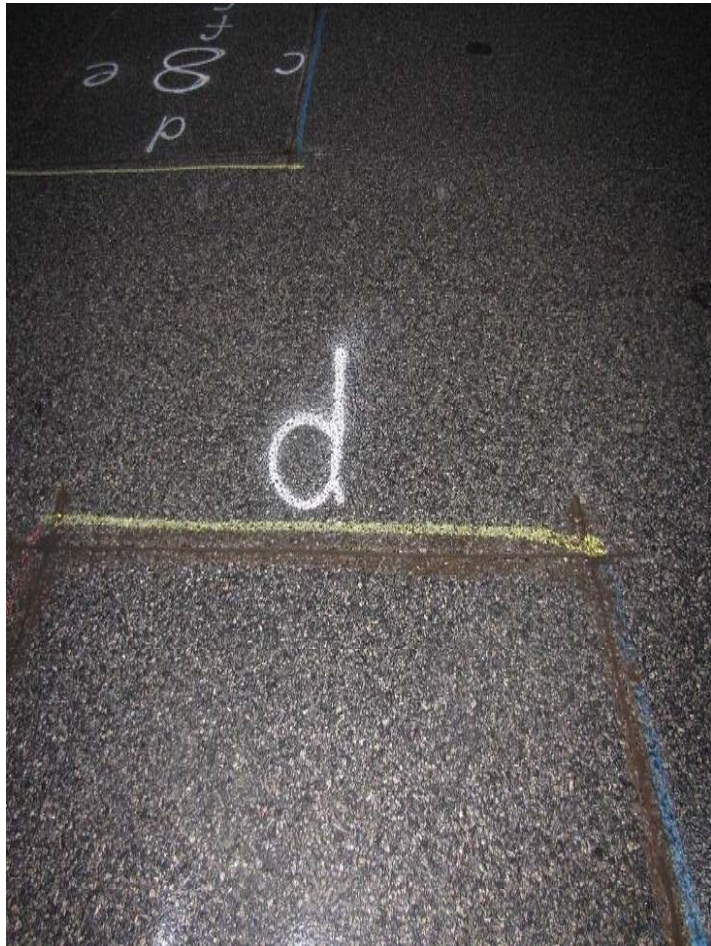
07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #10 – Shoulder resealed using AS 475



02/18/09



04/06/09



10/20/09



12/10/09

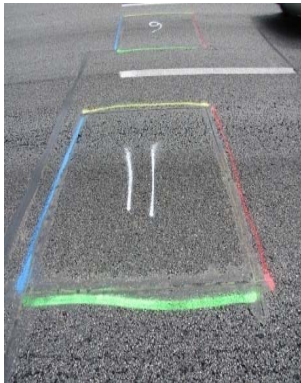
Loop #11 – Replaced Loop and sealed using 3M topped with G100



04/06/09



10/20/09



07/08/09



08/13/09



12/10/09

Loop #11 – Replaced Loop and sealed using 3M topped with G100



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #11 – Replaced Loop and sealed using 3M topped with G100



07/08/09



08/13/09



10/20/09



Unraveling pavement

12/10/09

First side hit traveling south

Loop #11 – Replaced Loop and sealed using 3M topped with G100



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling south

Loop #11 – Replaced Loop and sealed using 3M topped with G100



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Loop #12 – Resealed using FABICK 2:1



04/06/09



10/20/09



07/08/09



08/13/09



12/10/09

Loop #12 – Resealed using FABICK 2:1



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the outside shoulder

Loop #12 – Resealed using FABICK 2:1



07/08/09



08/13/09



10/20/09



12/10/09

Second side hit traveling south

Loop #12 – Resealed using FABICK 2:1



07/08/09



08/13/09



10/20/09



12/10/09

First side hit traveling south

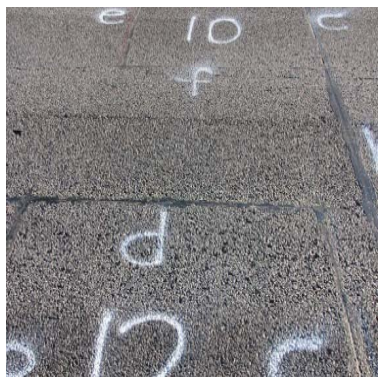
Loop #12 – Resealed using FABICK 2:1



07/08/09



08/13/09



10/20/09



12/10/09

Side closer to the inside shoulder

Piezo #5 & #6 – Shoulder resealed using FABICK 2:1



04/06/09



10/20/09



07/08/09



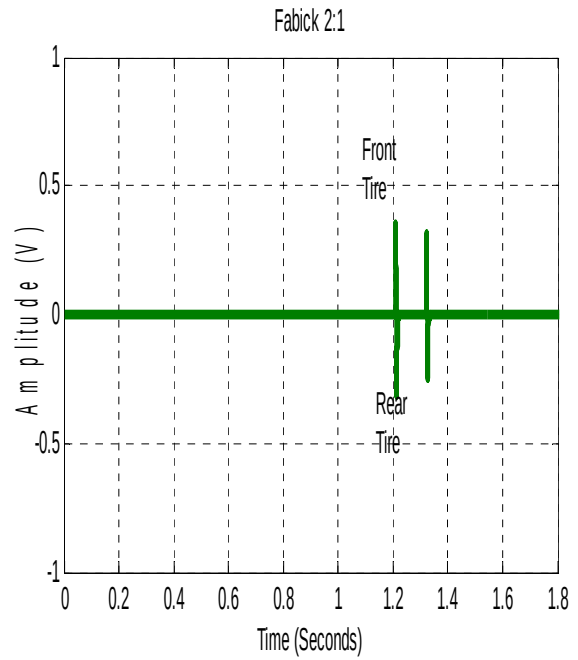
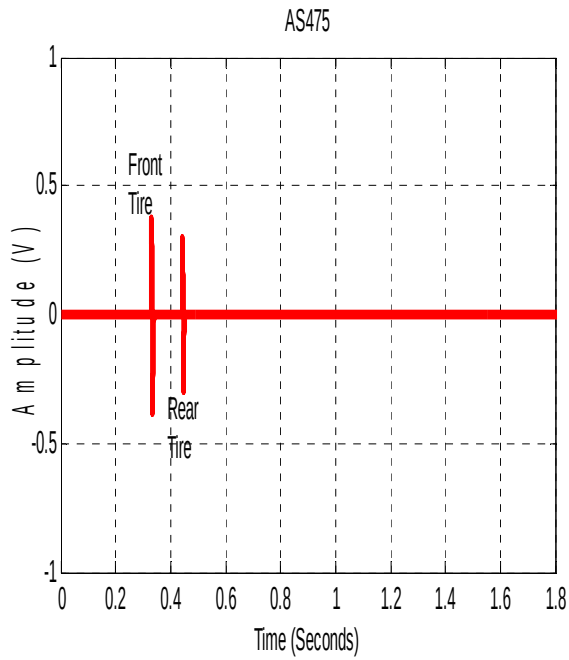
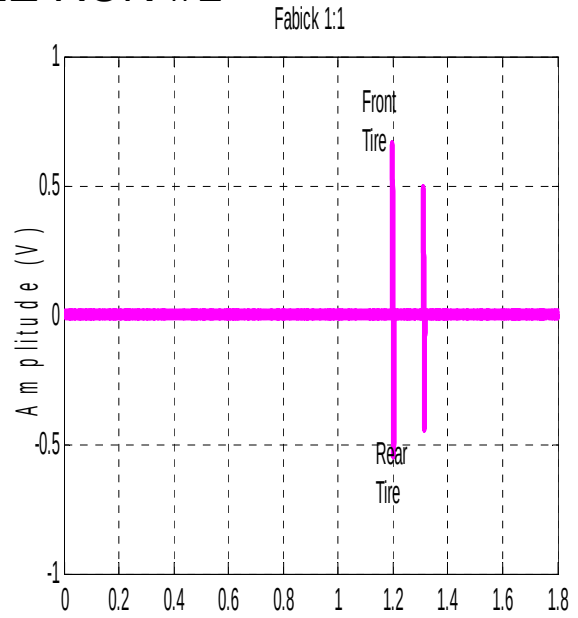
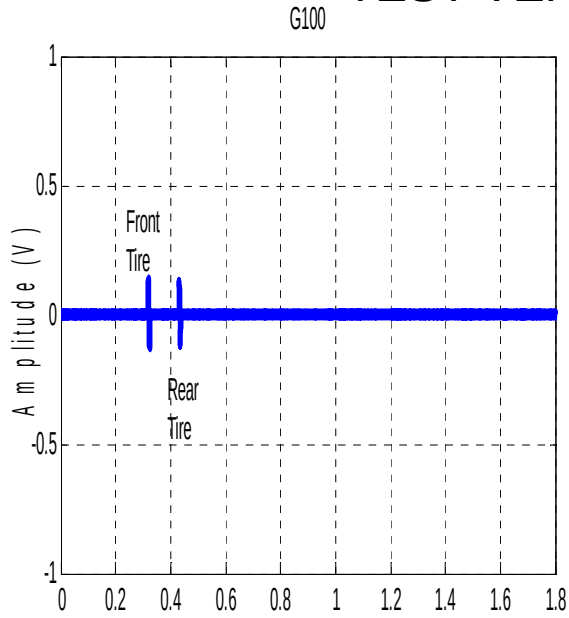
12/10/09

Appendix B – Electrical Measurements at Site 352 and 112

Site 352: Piezo Voltage Measurements

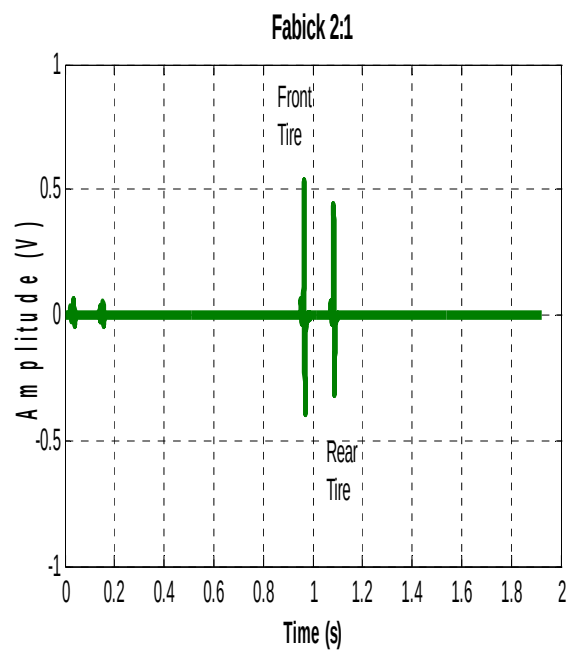
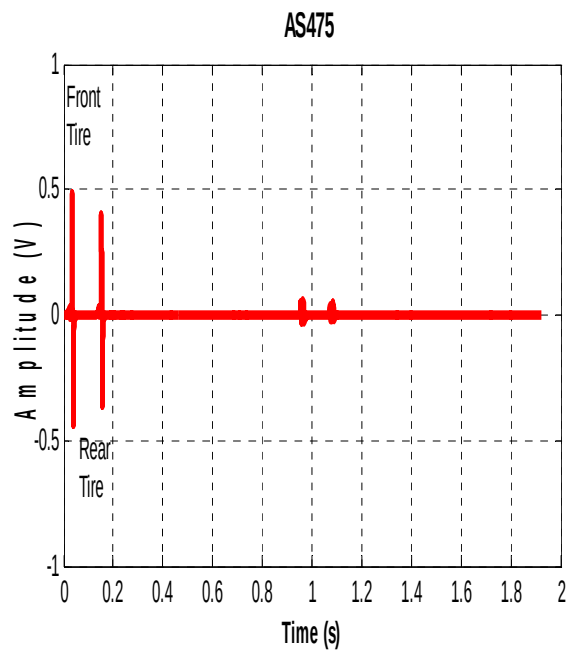
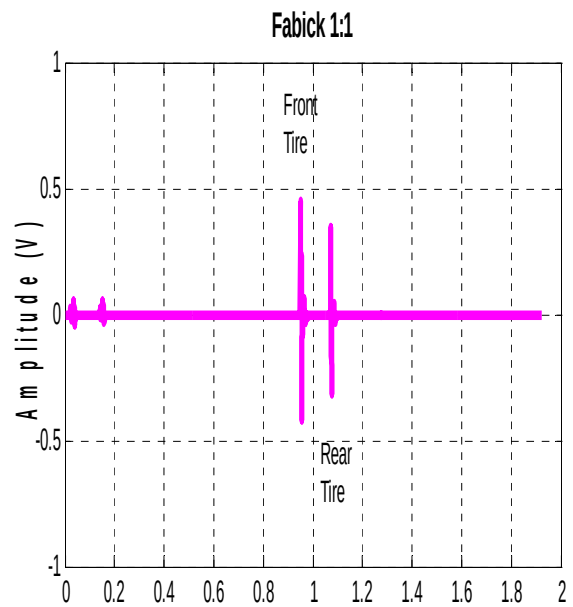
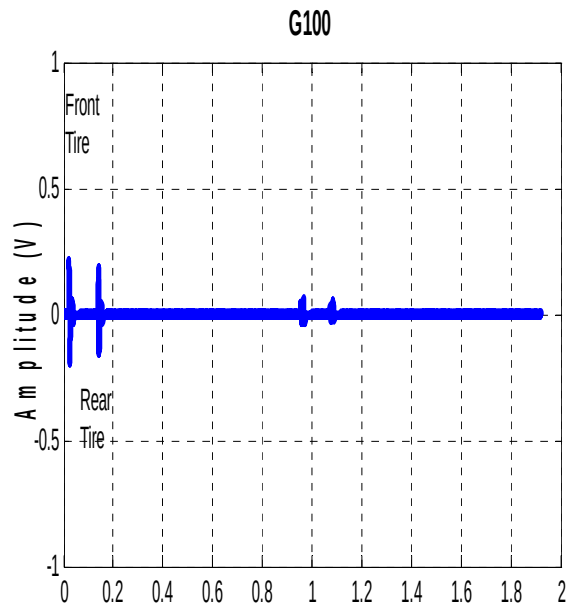
- 5 runs using a Test Vehicle
 - Chrysler Town & Country Minivan
- Other vehicles recorded:
 - Three Class 9
 - Random Bus with Dual Tires
 - U-Haul Truck with dual rear tires
 - Pick Up Van with dual tires

TEST VEHICLE RUN #1



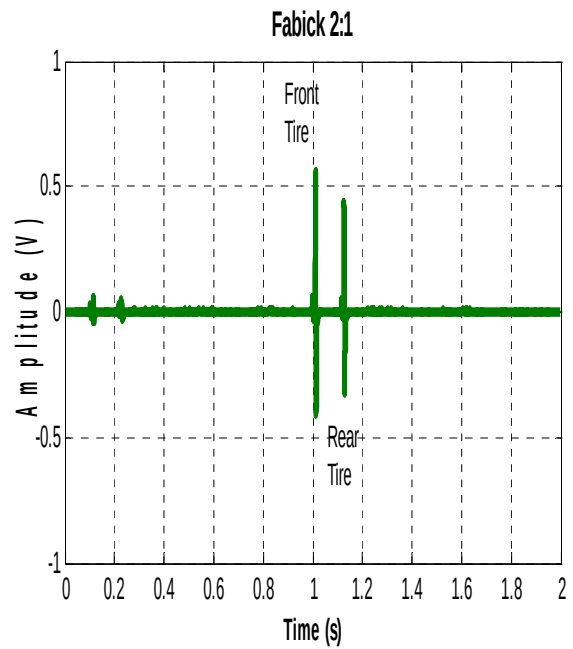
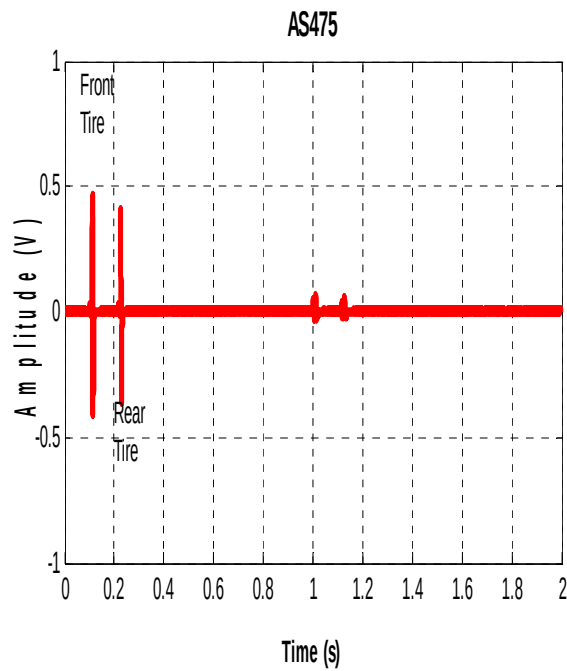
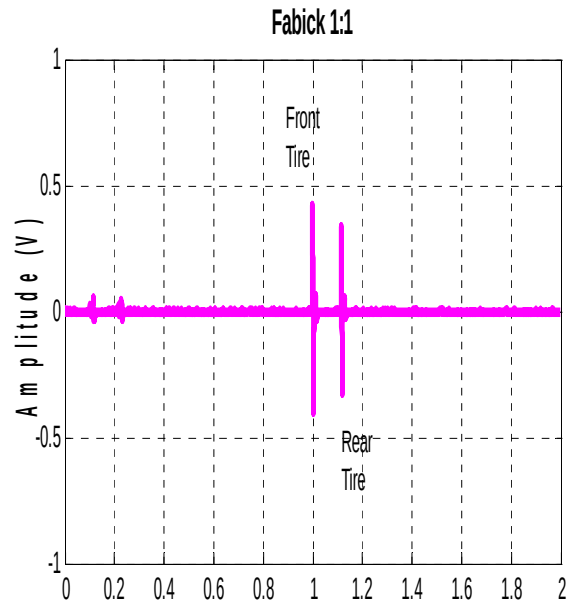
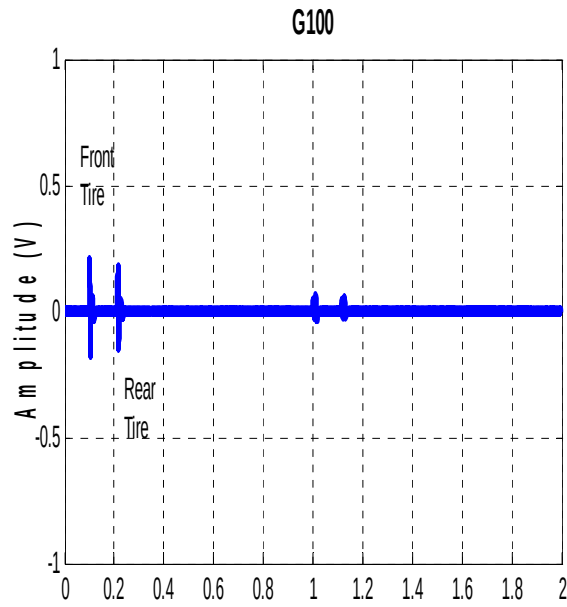
	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.1351	0.1236	0.3705	0.2934	0.6588	0.4879	0.3537	0.3142

TEST VEHICLE RUN # 2



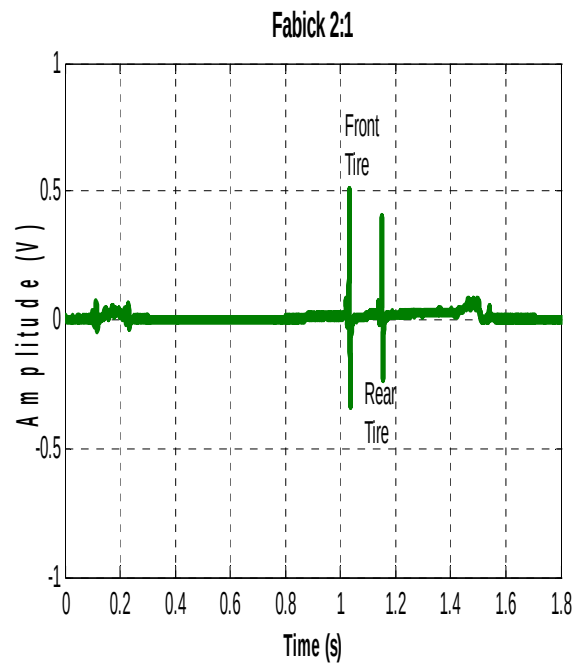
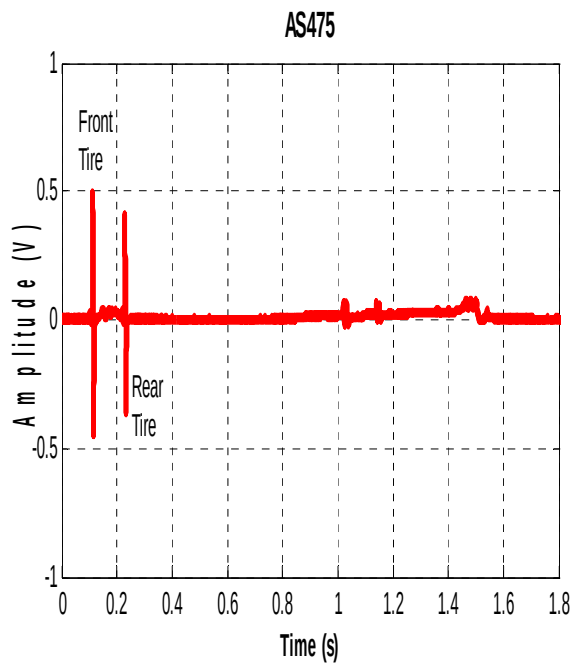
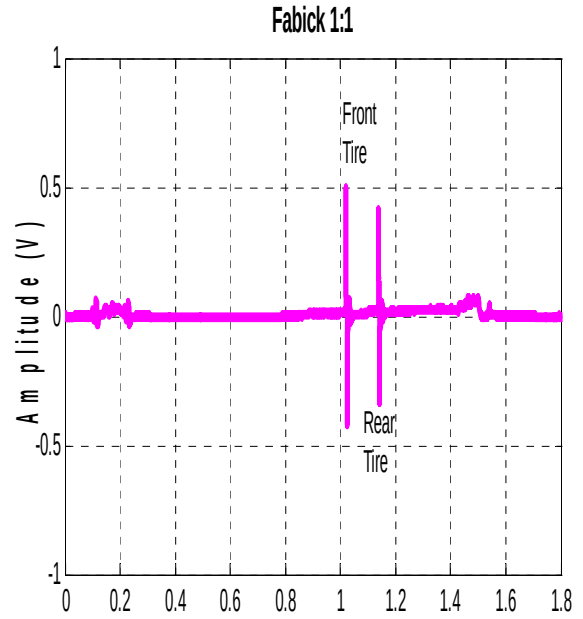
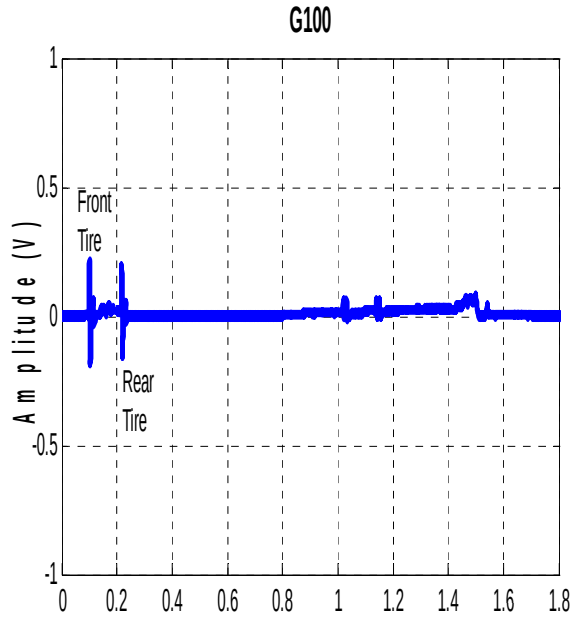
	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.2160	0.2030	0.4615	0.3985	0.4988	0.4879	0.5137	0.4142

TEST VEHICLE RUN # 3



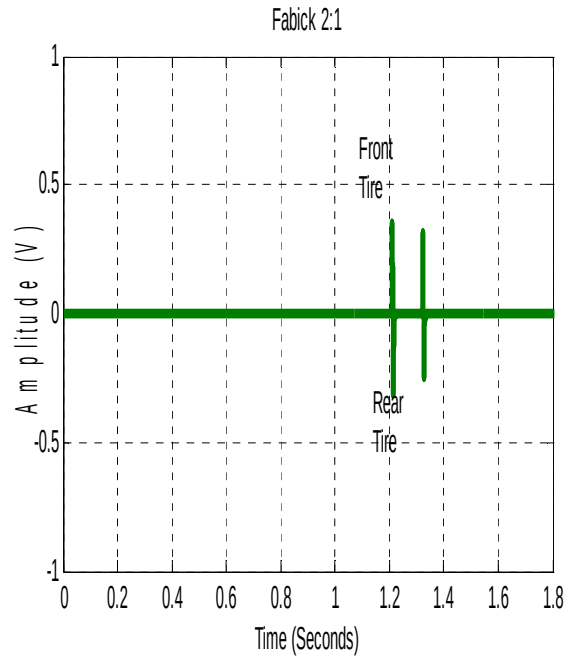
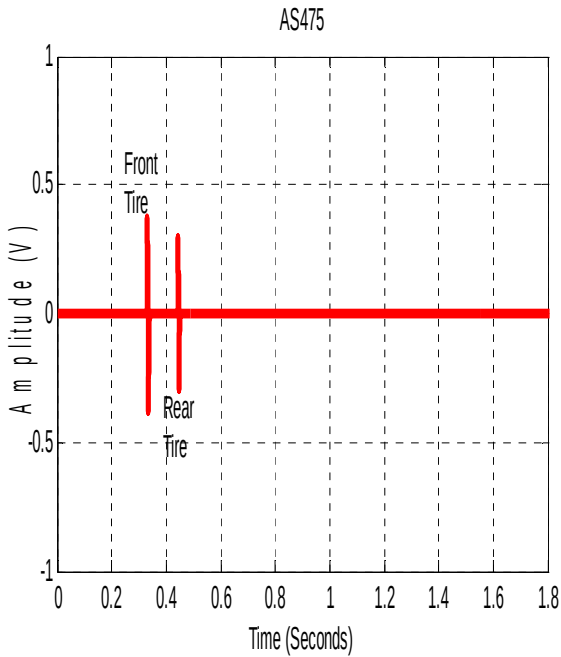
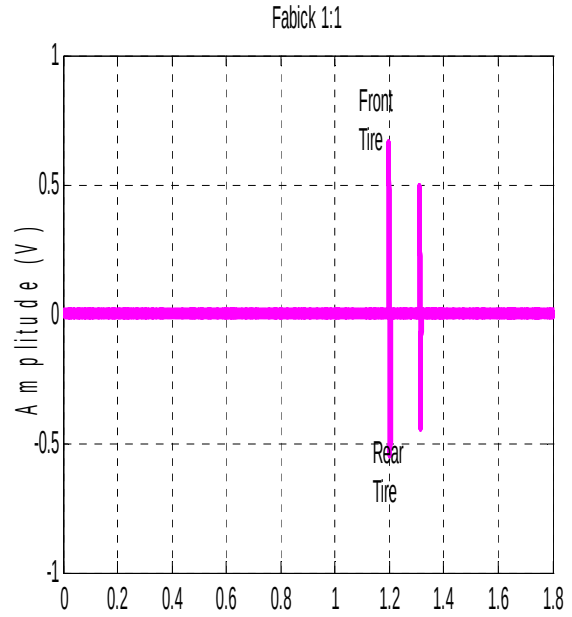
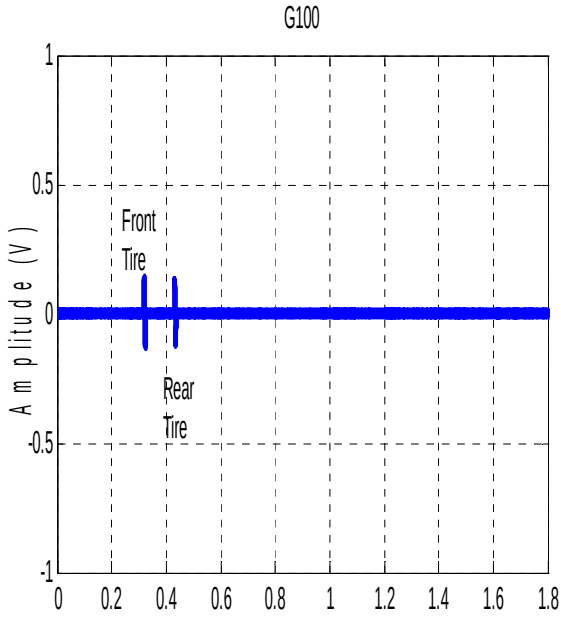
	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.2351	0.1536	0.4705	0.3934	0.4816	0.4345	0.5244	0.4443

TEST VEHICLE RUN # 4



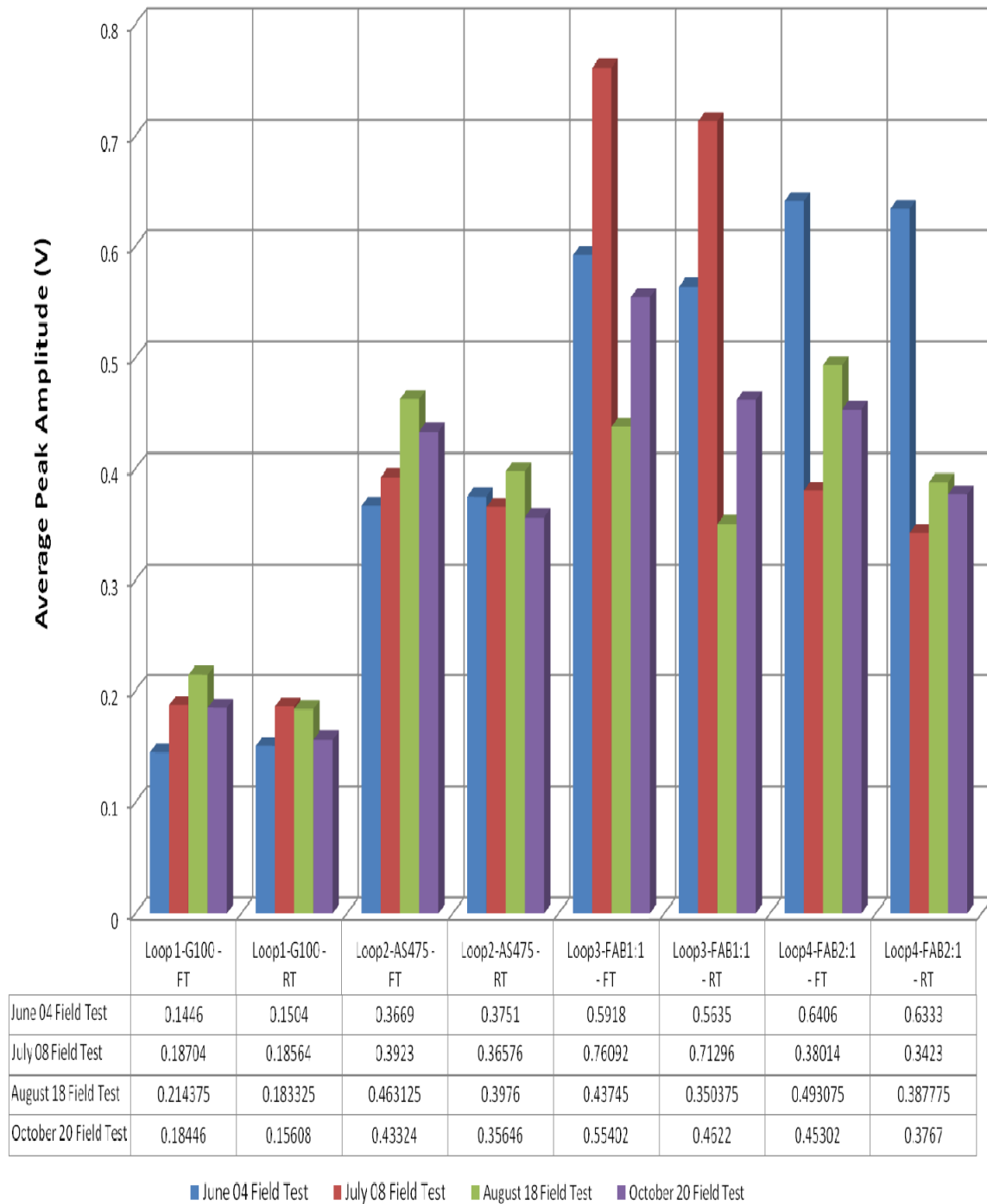
	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.1985	0.1836	0.4946	0.3934	0.4901	0.4018	0.4996	0.3683

TEST VEHICLE RUN #5



	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.1376	0.1166	0.3691	0.3036	0.6408	0.4989	0.3737	0.3425

Comparison of Average Peak Outputs of the Piezo Sensors for Test Vehicle

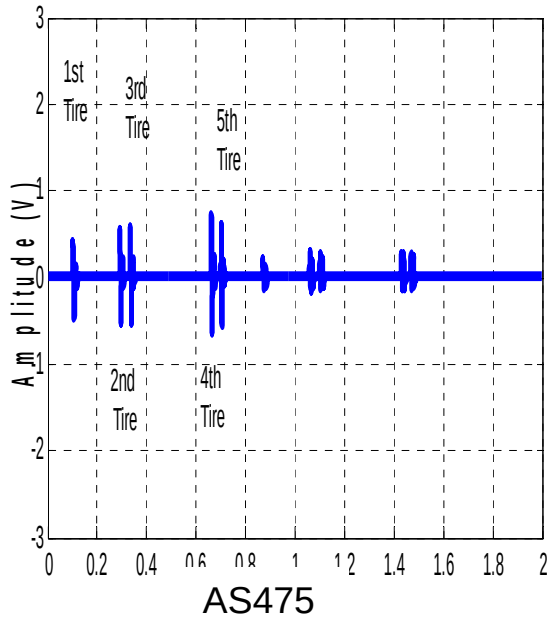


FT: Front Tire RT: Rear Tire

1st Random Class 9 (5-Axle Truck)

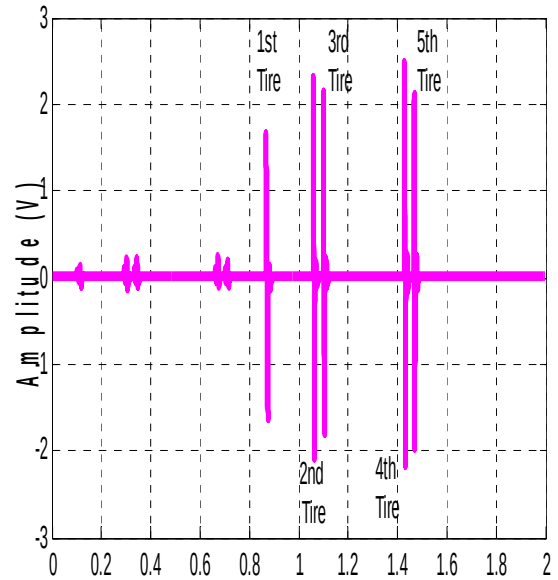
G100

Piezo Sensor 1



Fabick 1:1

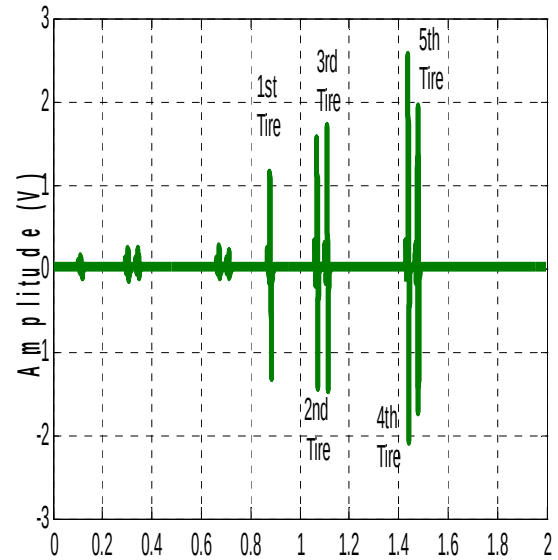
Piezo Sensor 3



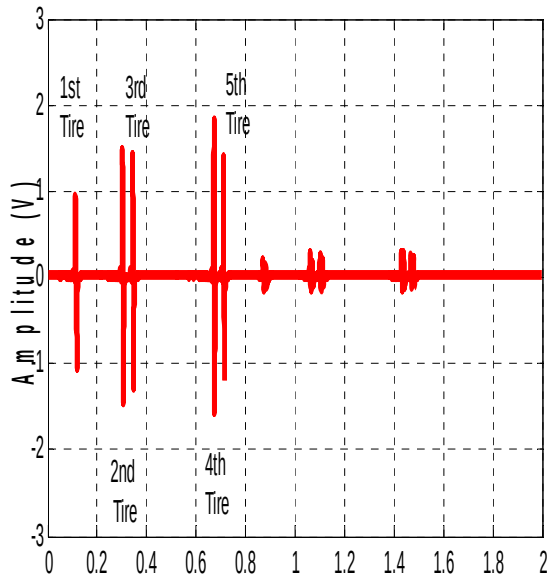
Fabick

2:1

Piezo Sensor 4

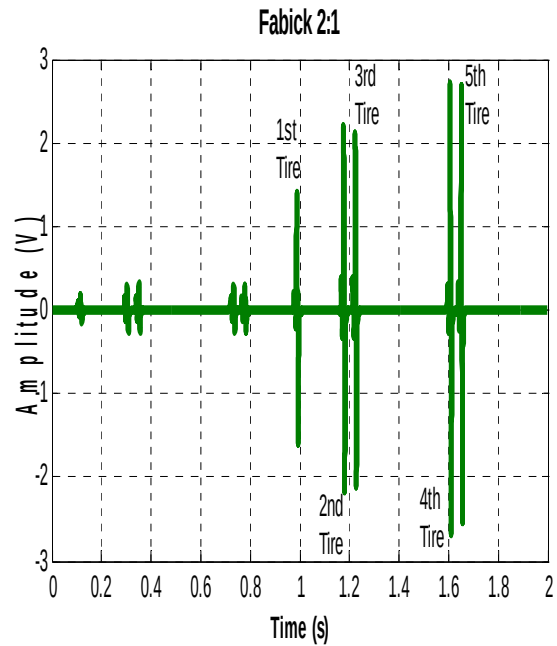
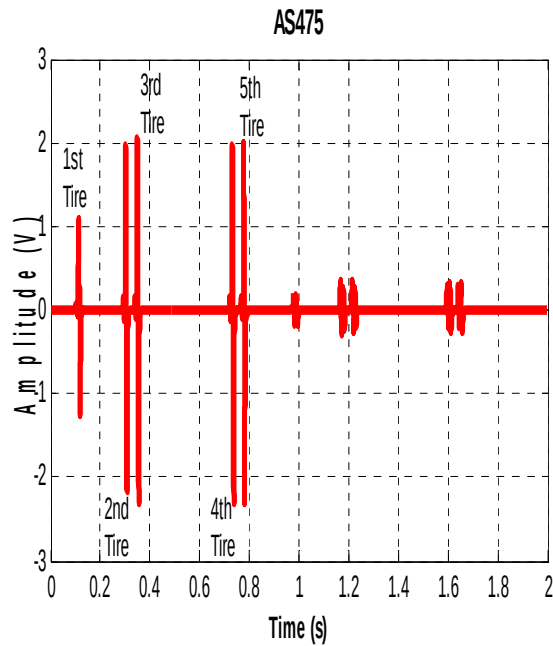
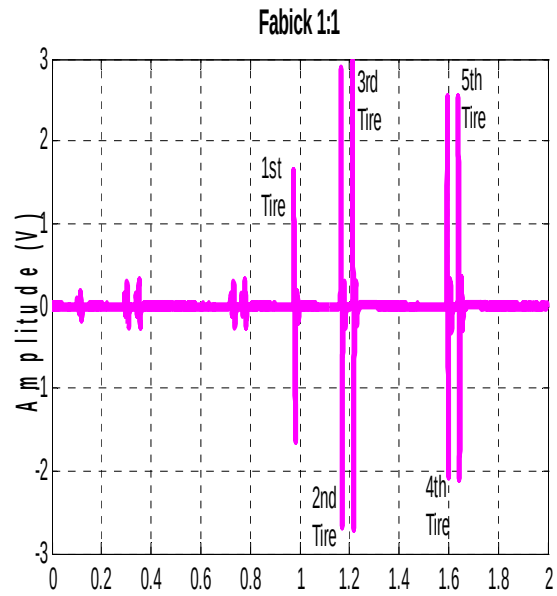
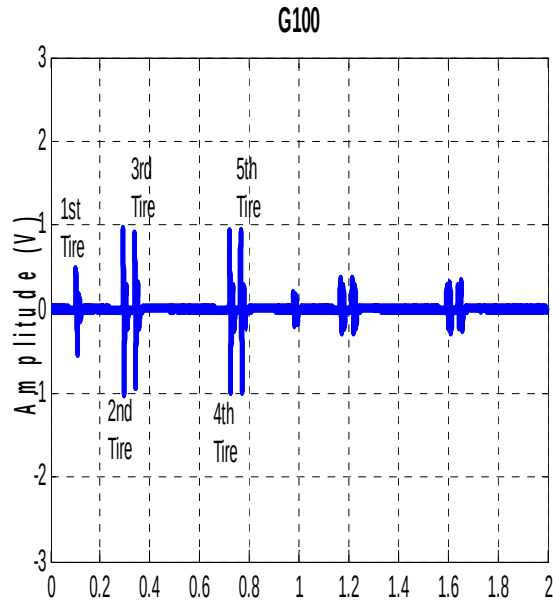


Piezo Sensor 2



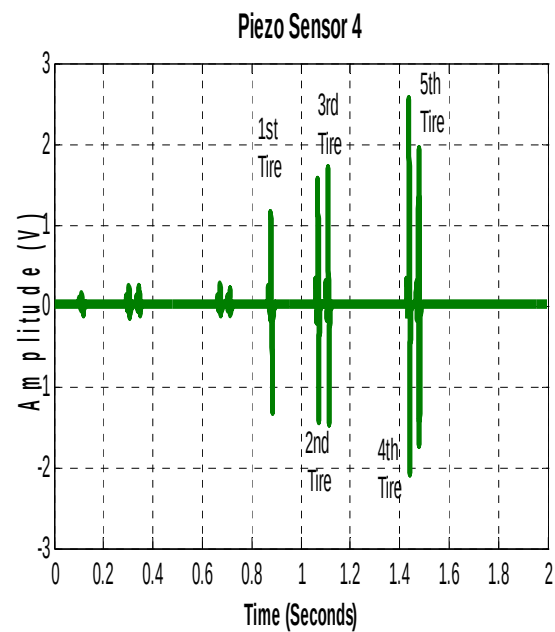
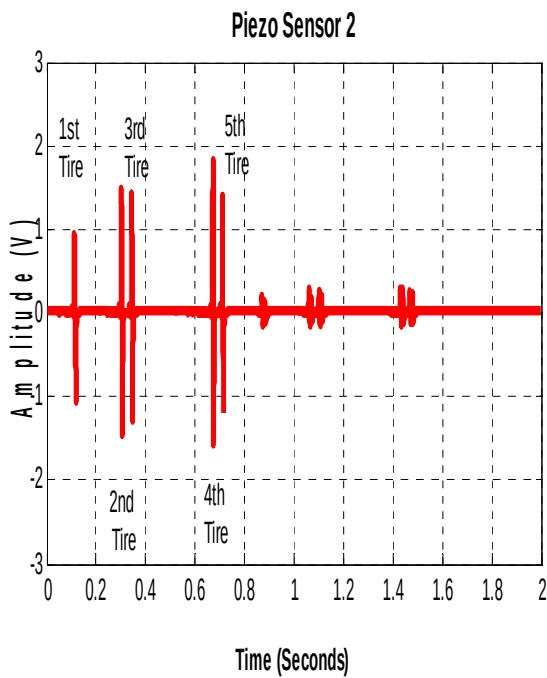
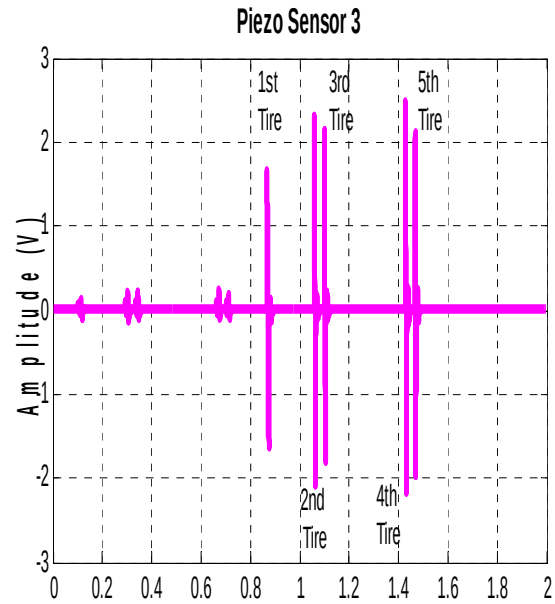
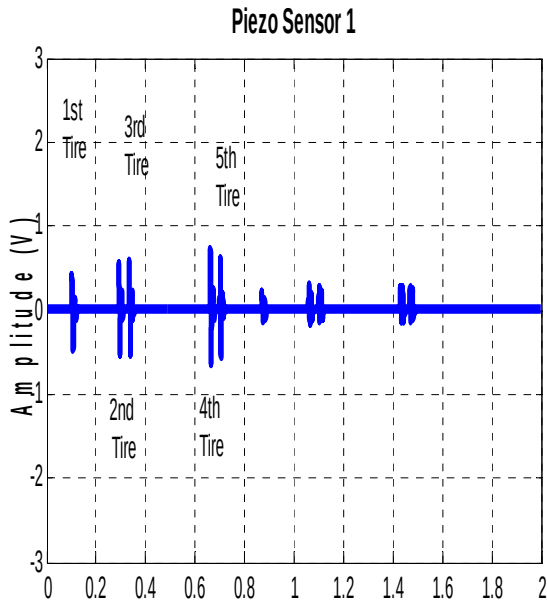
	G100 Time (Seconds)					AS 475					Time (Seconds)					Fabick 1:1					Fabick 2:1				
Tire	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th
Peak Values (V)	0.4080	0.5550	0.5520	0.5517	0.4613	0.895	1.3840	1.3120	1.7220	1.5030	1.7600	2.4150	2.0240	2.3620	2.2150	1.0420	1.4540	1.798	2.6430	1.8290					

2nd Random Class 9 (5-Axle Truck)

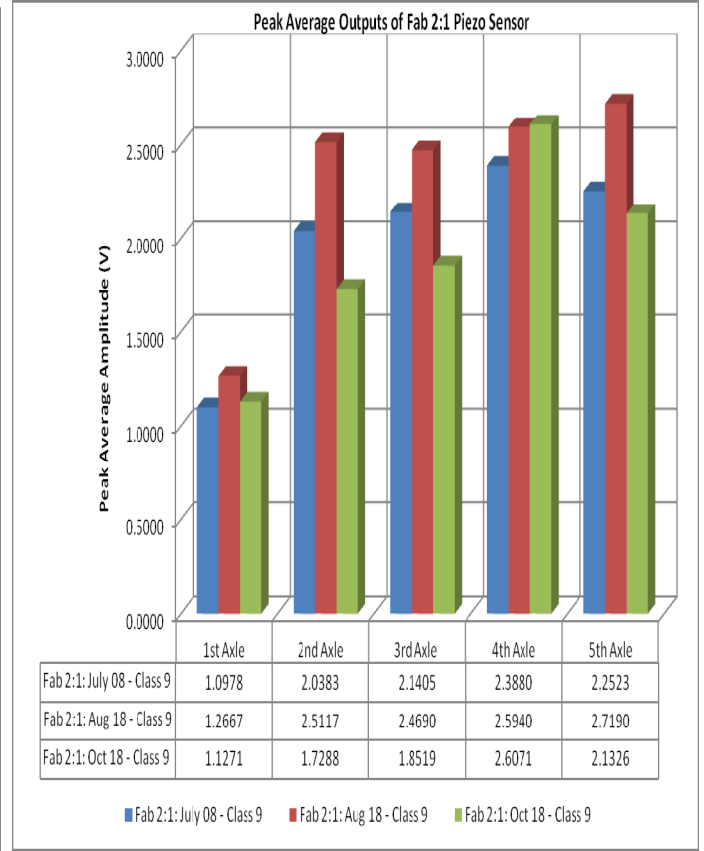
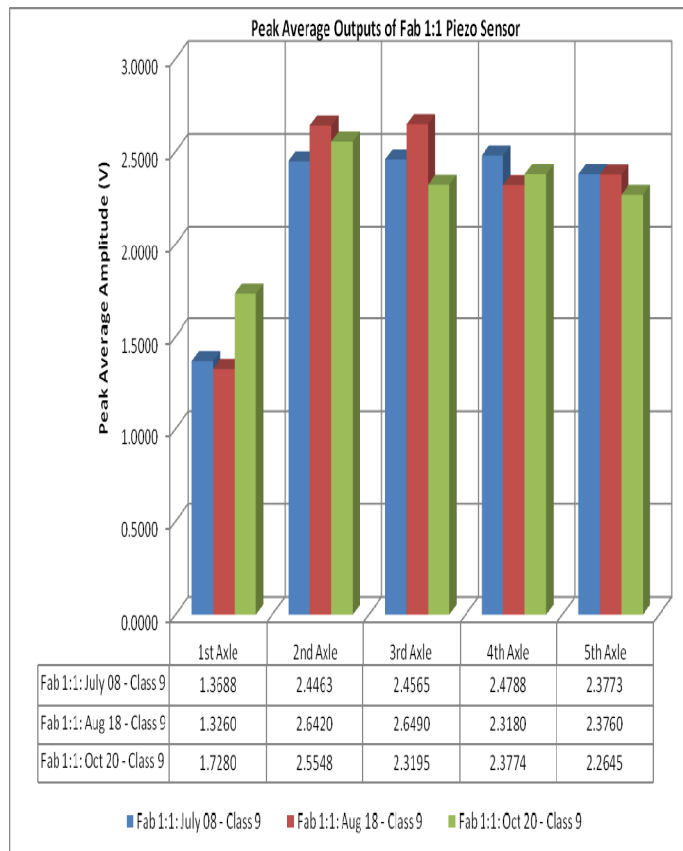
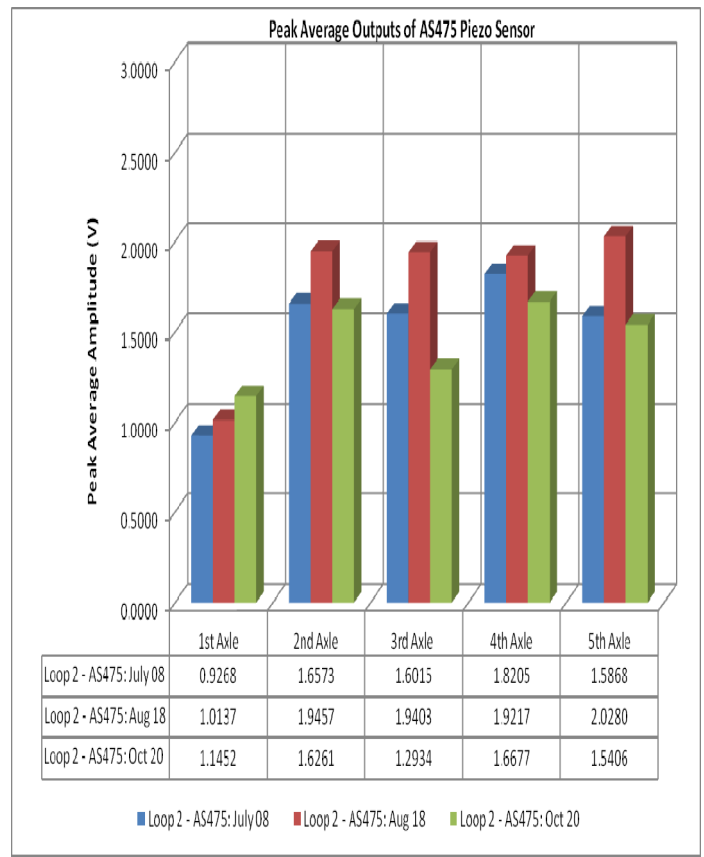
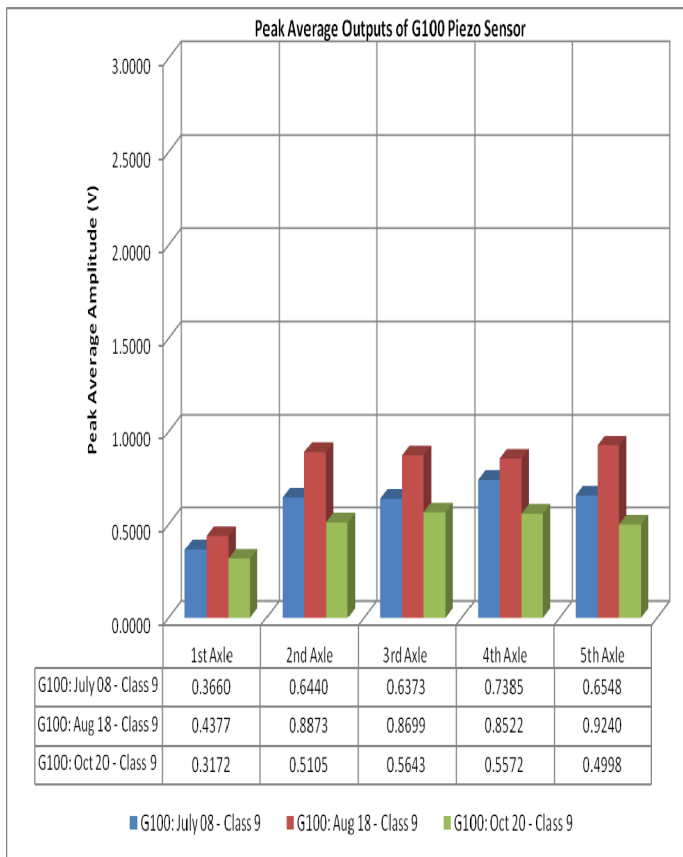


	G100					AS 475					Fabick 1:1					Fabick 2:1				
Tire	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th
Peak Values (V)	0.2351	0.5244	0.4682	0.4805	0.4977	1.6471	1.9860	1.2170	1.4990	1.6150	1.6880	2.8280	2.9320	2.4040	2.5470	1.2290	2.2670	2.2280	2.7340	2.6660

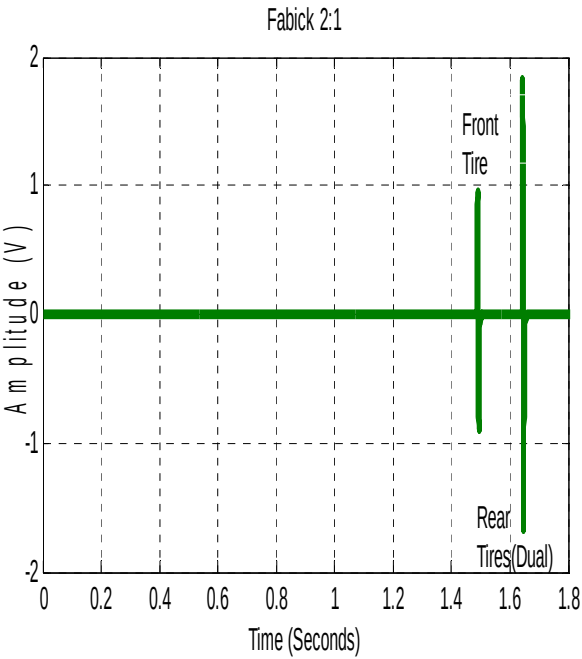
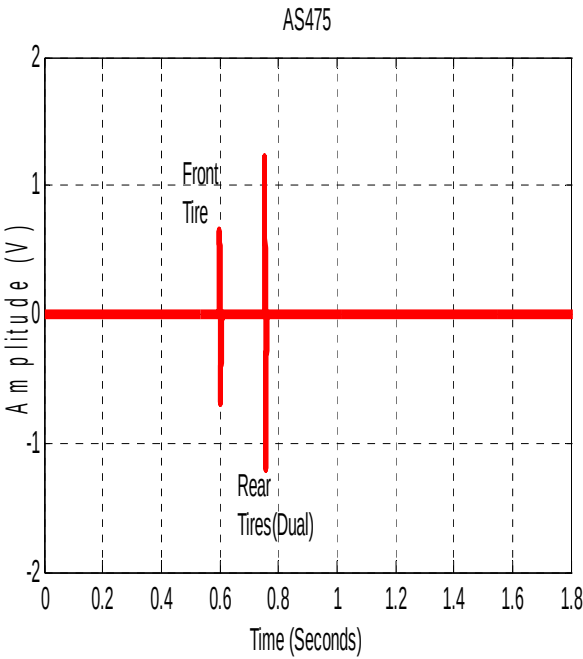
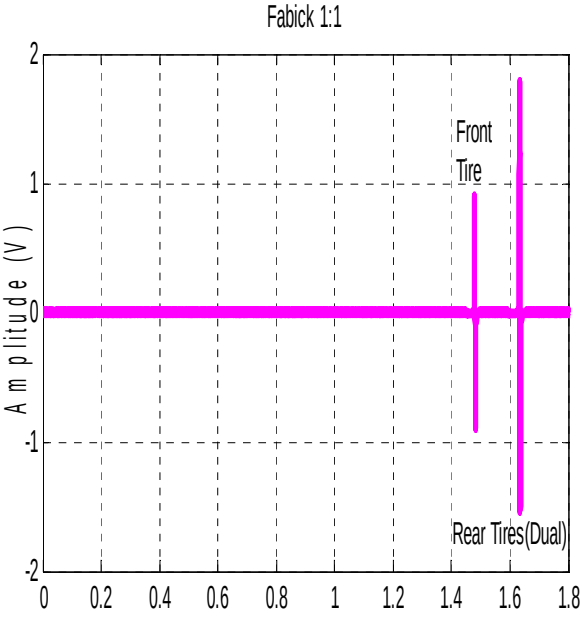
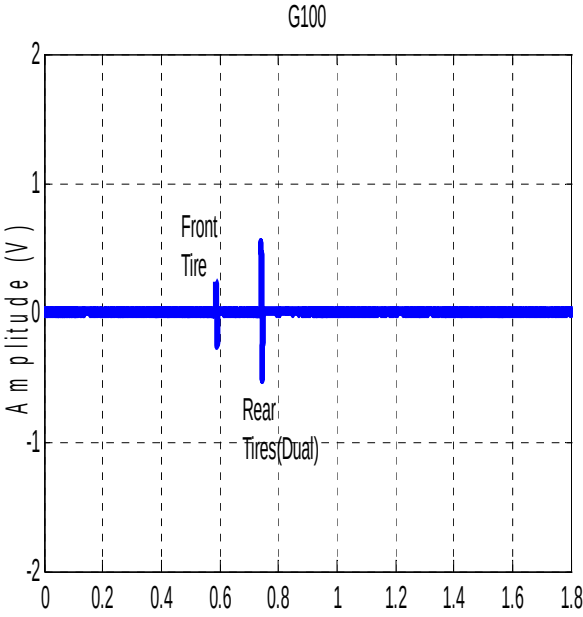
3rd Random Class 9 (5-Axle Truck)



	Piezo Sensor 1					Piezo Sensor 2					Piezo Sensor 3					Piezo Sensor 4				
Tire	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd	3 rd	4 th	5 th
Peak Values (V)	0.3084	0.4521	0.6728	0.6395	0.5405	0.8935	1.5084	1.3512	1.7822	1.5038	1.7360	2.4215	2.0024	2.3662	2.0315	1.1102	1.4654	1.5298	2.4443	1.9029

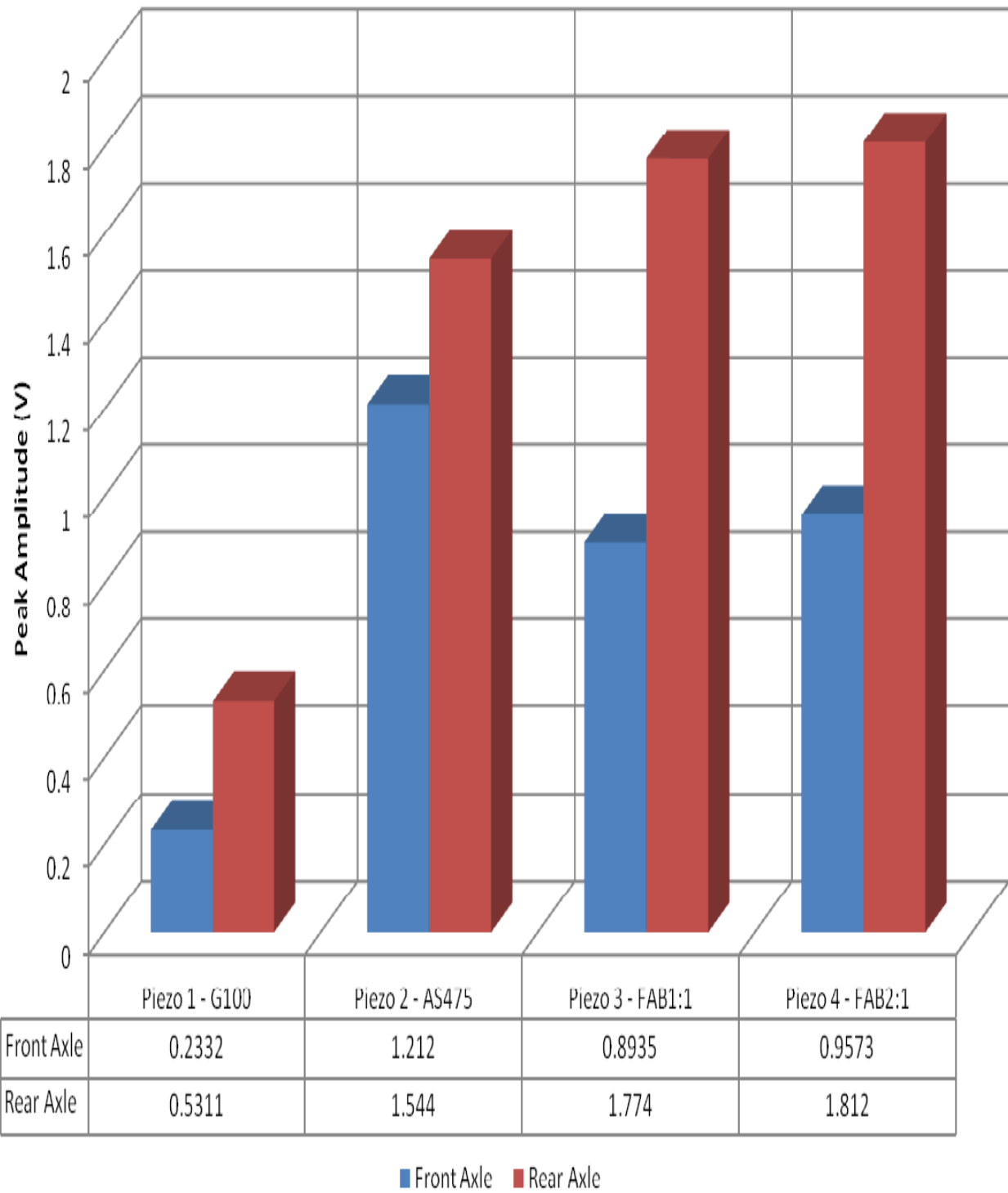


Random Bus with Dual Tires

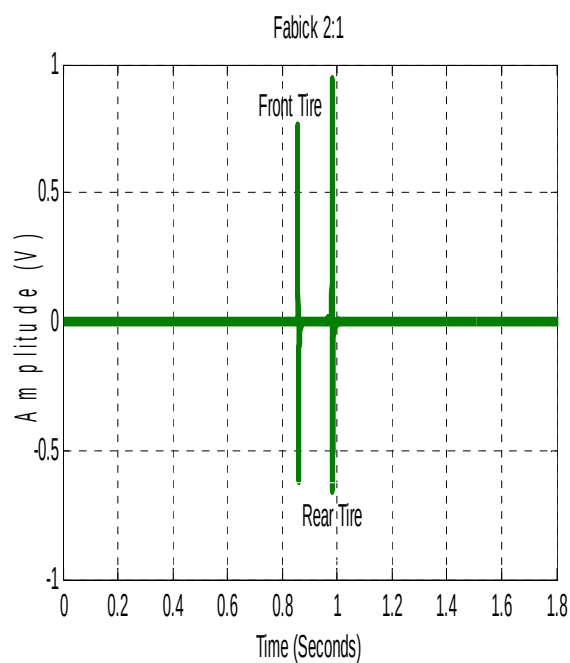
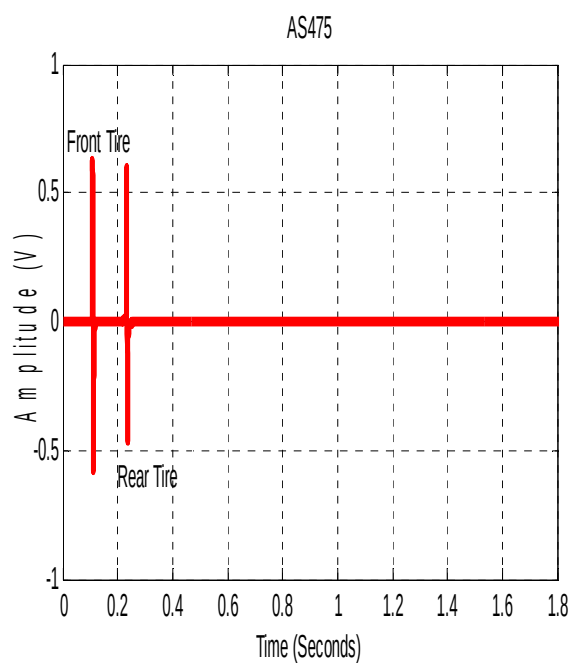
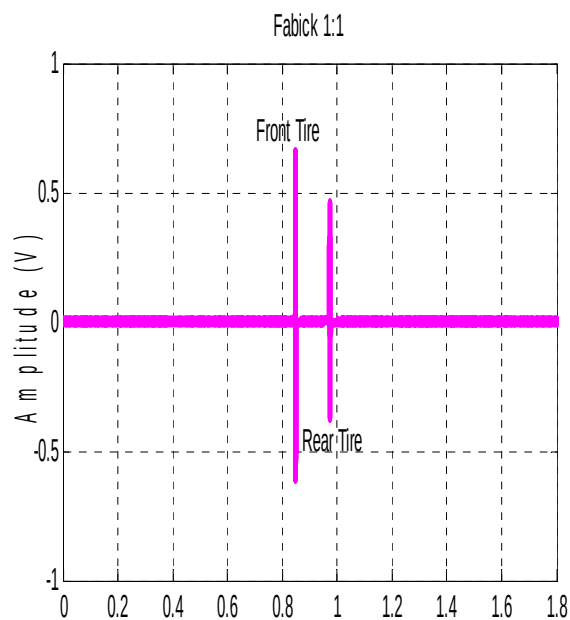
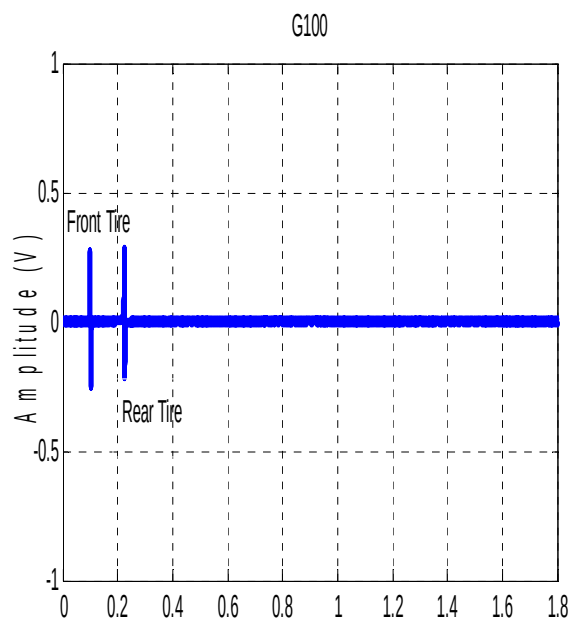


	G 100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.2332	0.5311	1.2120	1.5440	0.8935	1.7740	0.9573	1.8120

Peak Outputs for Piezo Sensors for Random Bus with Dual Tires

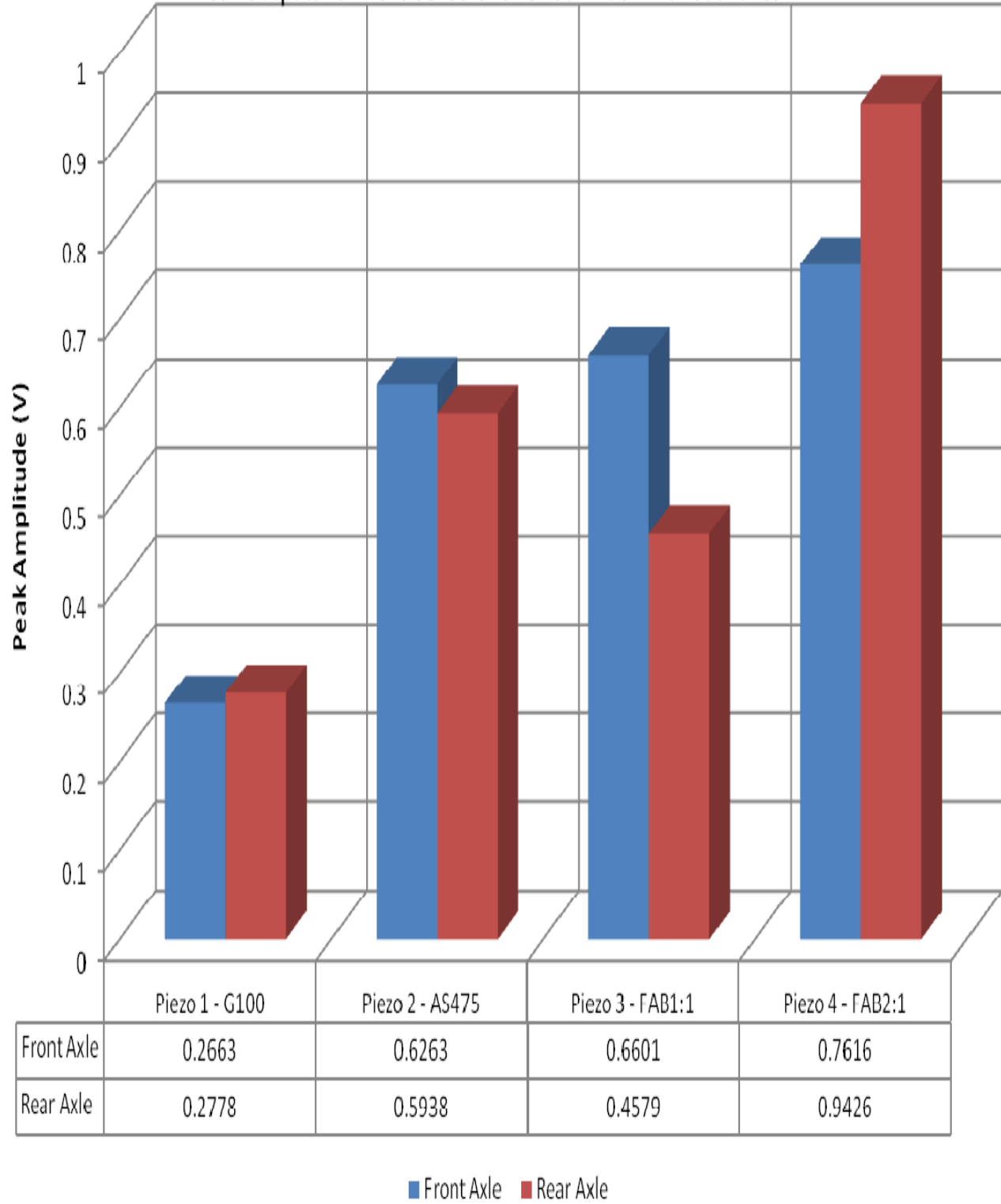


U-Haul Truck with dual rear tires

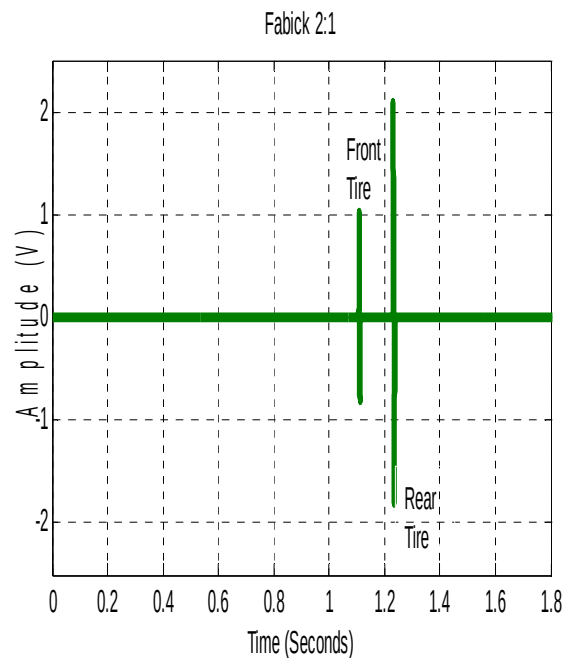
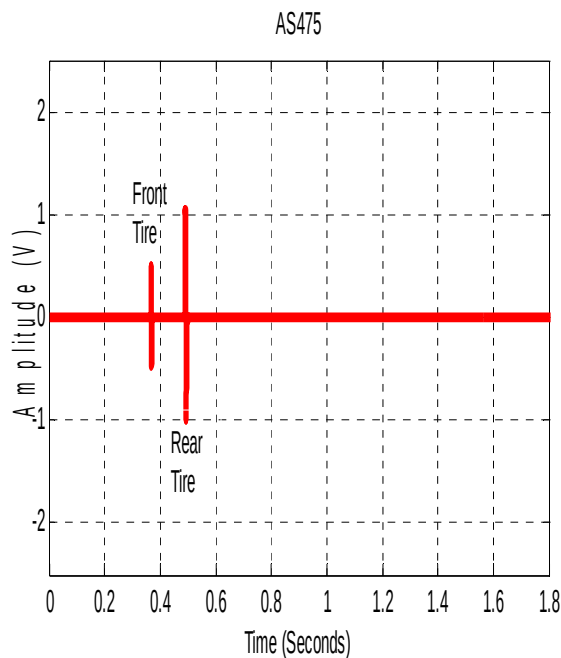
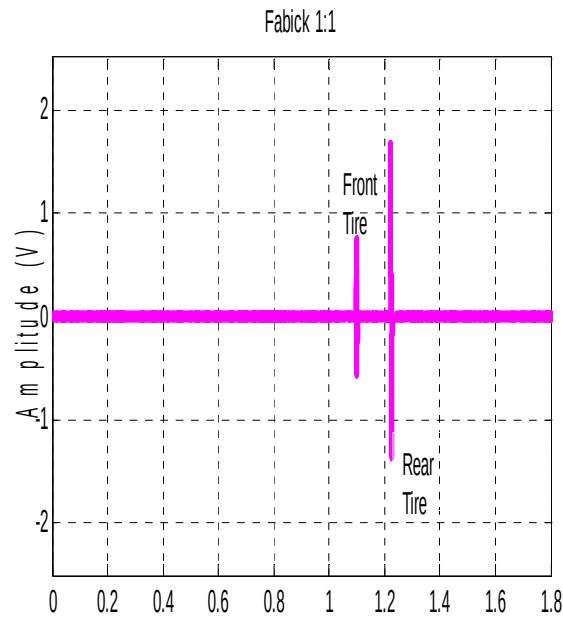
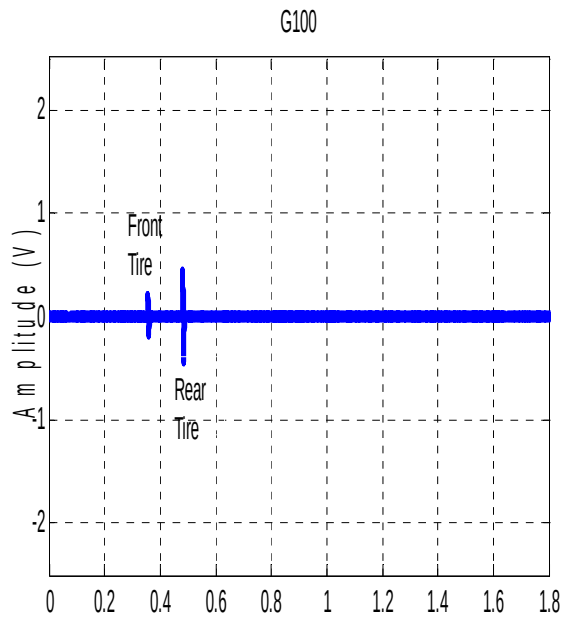


	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.2663	0.2778	0.6263	0.5938	0.6601	0.4579	0.7616	0.9426

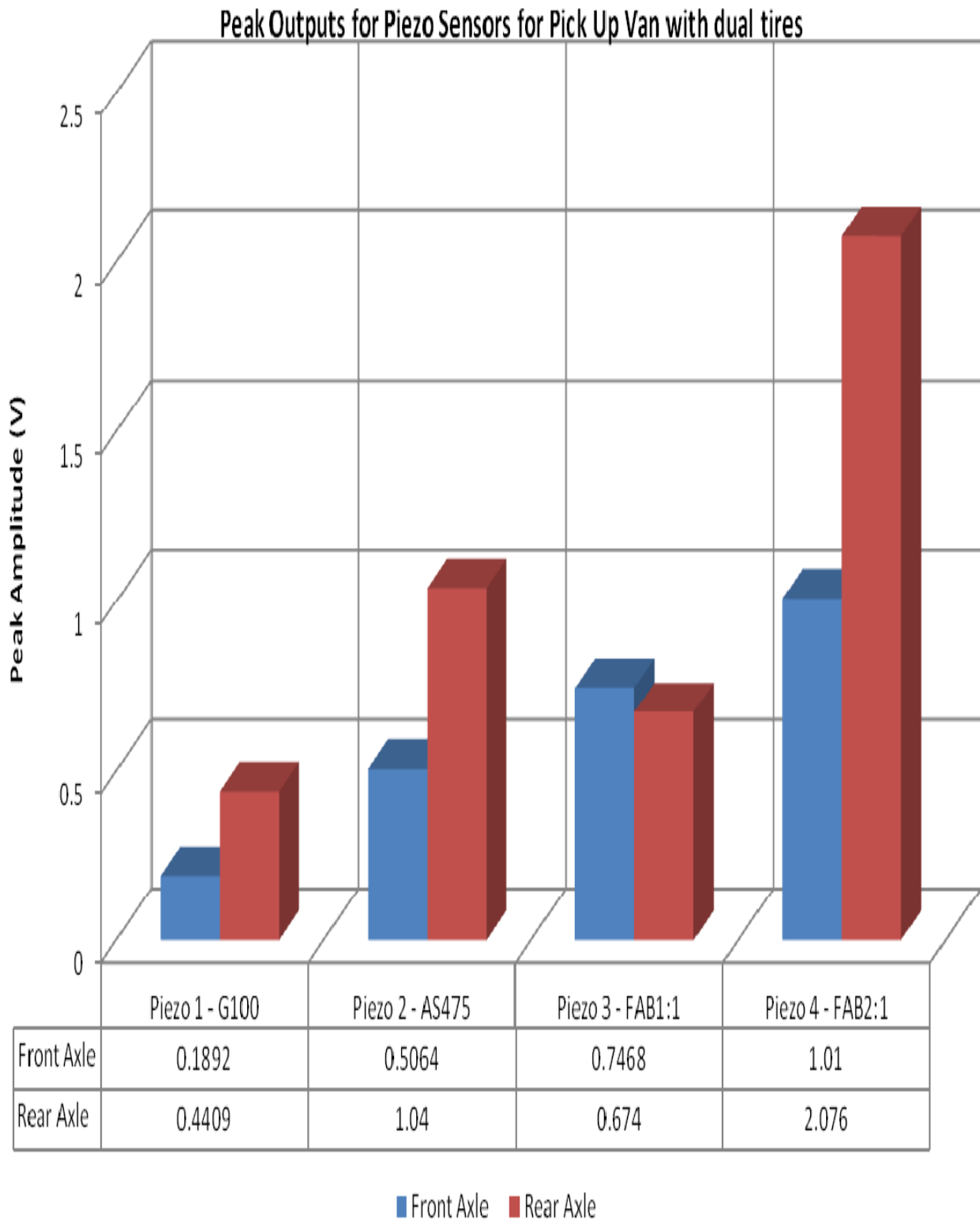
Peak Outputs for Piezo Sensors for UHaul Truck with dual tires



Pick Up Van with dual tires



	G100		AS 475		Fabick 1:1		Fabick 2:1	
Tire	Front	Rear	Front	Rear	Front	Rear	Front	Rear
Peak Values (V)	0.1892	0.4409	0.5064	1.0400	0.7468	0.6740	1.0100	2.076



Site 112 & 352: Loop Measurements Updated

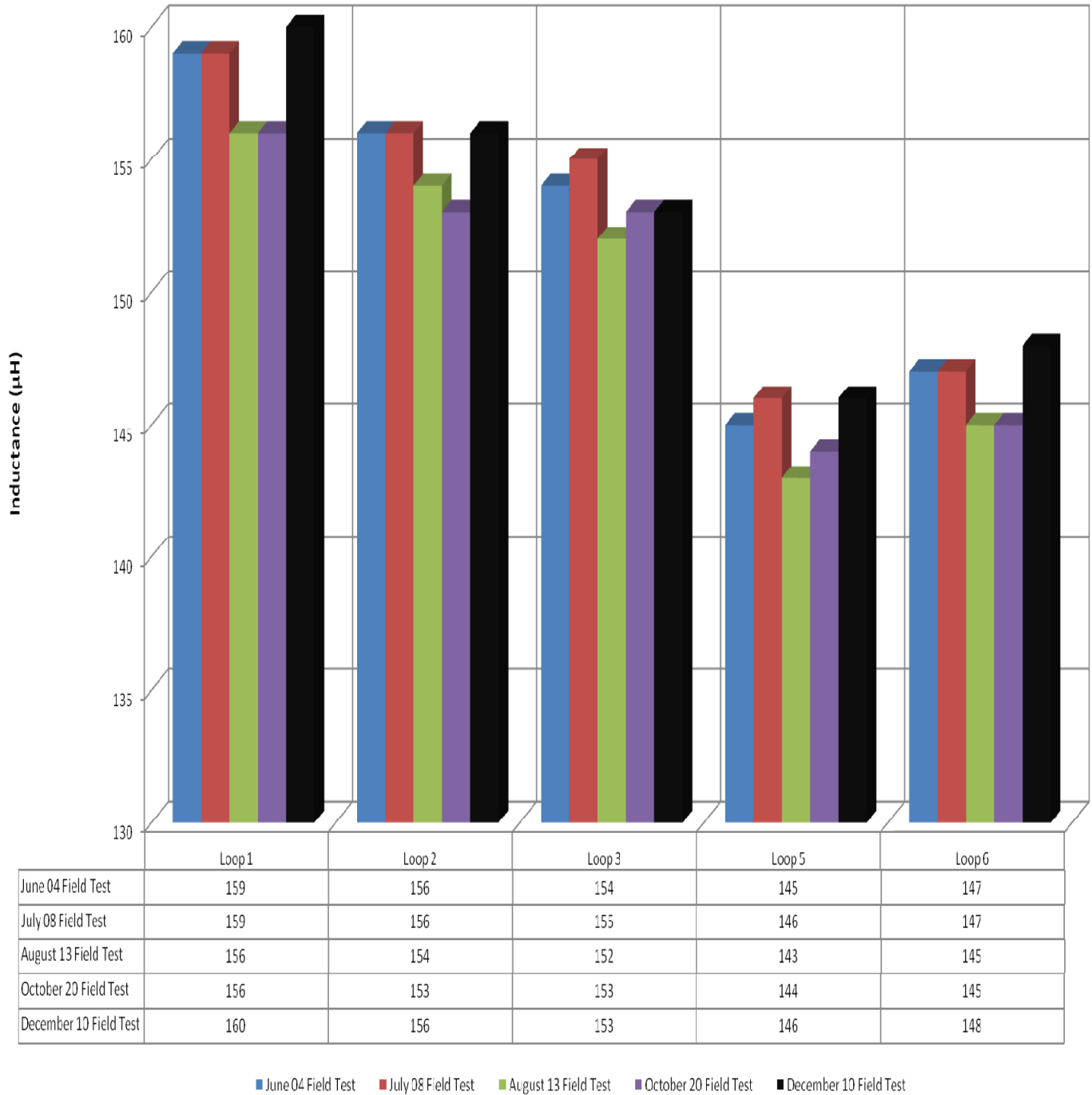
- Ground Resistance & Inductance Measurements
- Site 352:
 - Loops 1, 2, 3, 5, 6
- Site 112:
 - Loops 1 - 12

Site 352: Loop Measurements

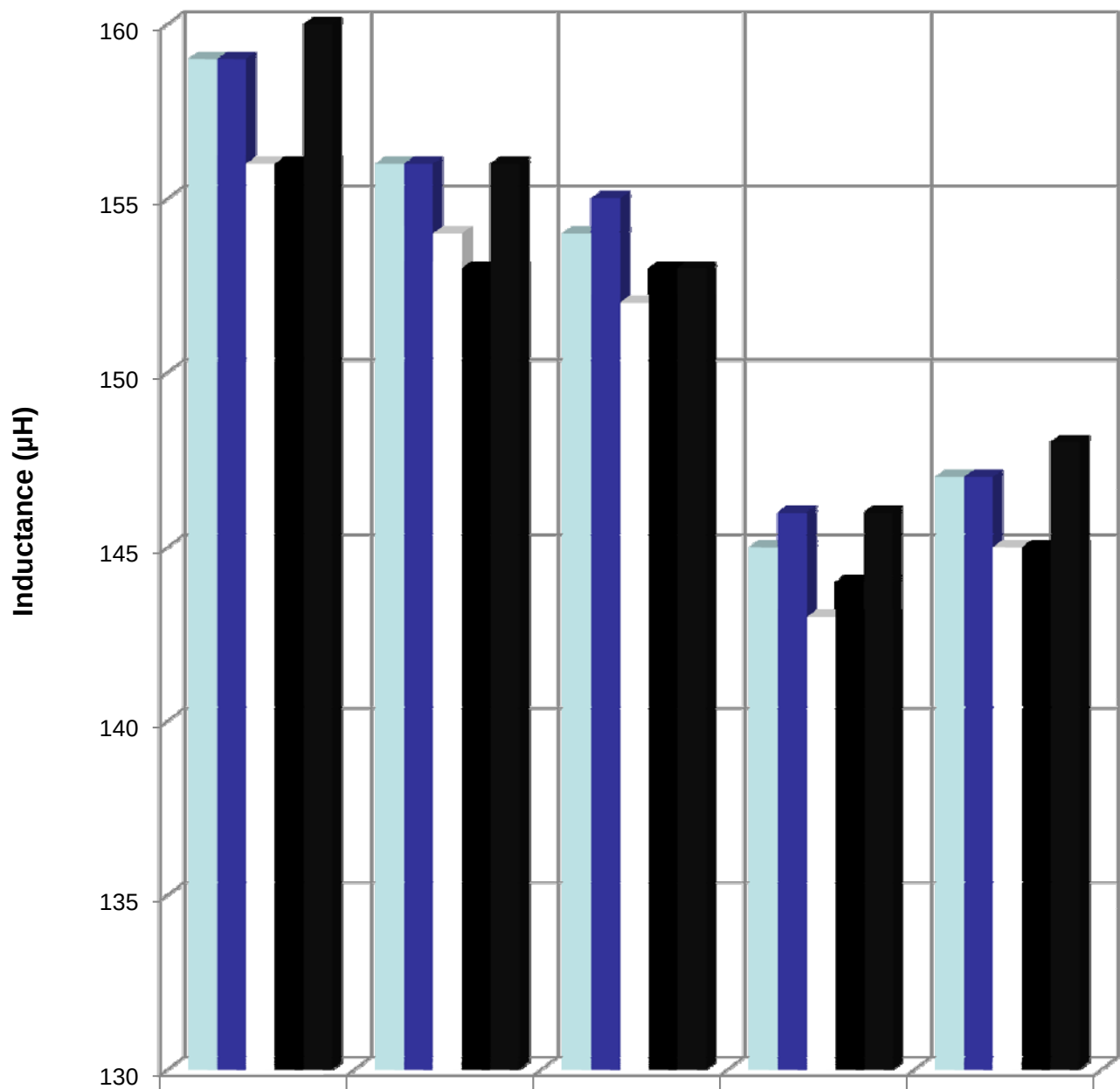
December 10, 2009 Field Test

Loop	Inductance (μH)	Resistance ($\text{M}\Omega$)
1	160	Infinite
2	156	Infinite
3	153	Infinite
5	146	0.84
6	148	Infinite

Comparison Chart for Inductance of Loop Sensors: Site 352



Comparison Chart for Inductance of Loop Sensors: Site 352



	Loop 1	Loop 2	Loop 3	Loop 5	Loop 6
June 04 Field Test	159	156	154	145	147
July 08 Field Test	159	156	155	146	147
August 13 Field Test	156	154	152	143	145
October 20 Field Test	156	153	153	144	145
December 10 Field Test	160	156	153	146	148

■ June 04 Field Test

■ July 08 Field Test

■ August 13 Field Test

■ October 20 Field Test

■ December 10 Field Test

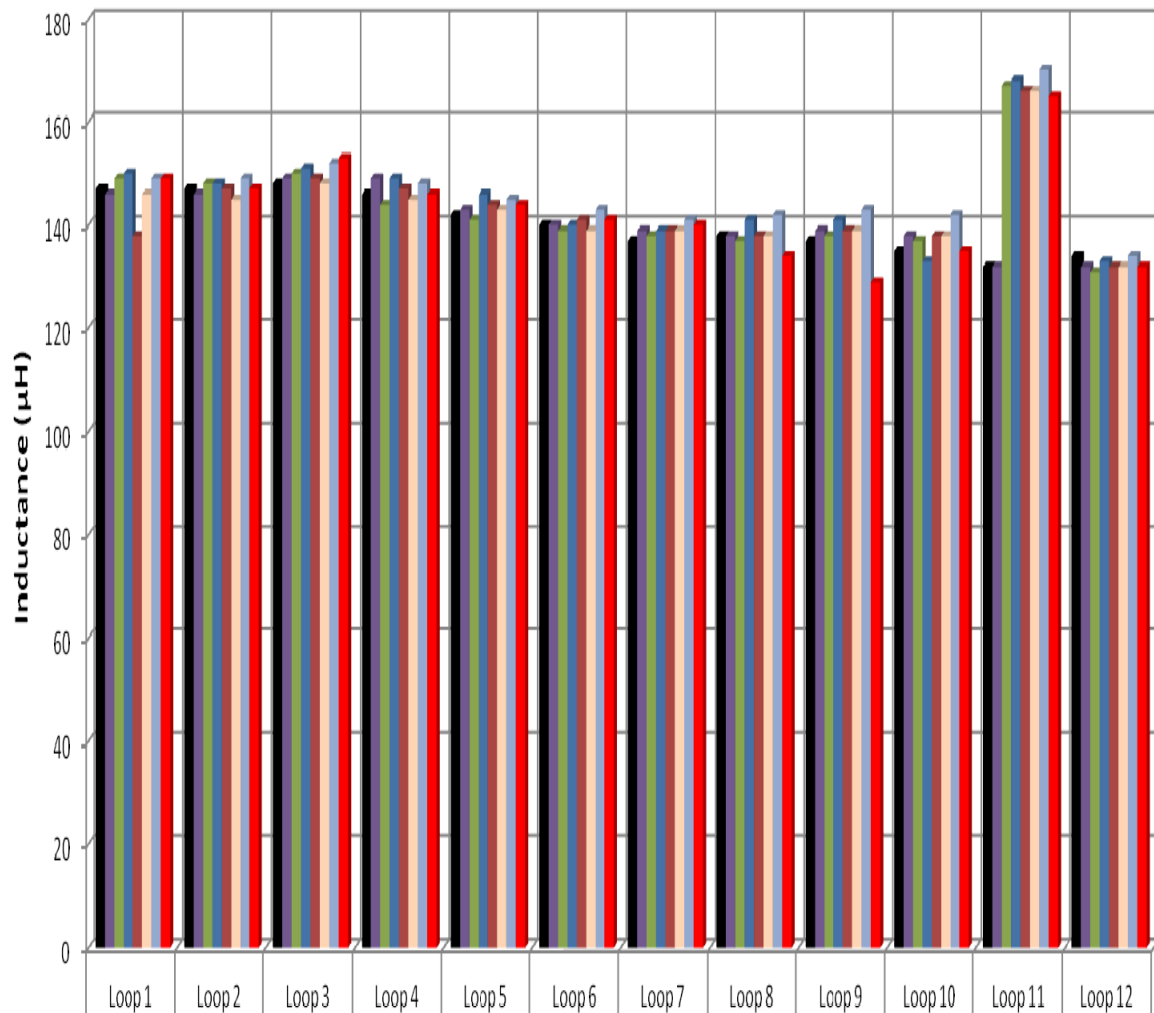
Comparison Table for Ground Resistance Tests for Site 352

Loop	Sealant used	06:04:09 (MΩ):	07:08:09 (MΩ):	08:04:09 (MΩ):	10:20:09 (MΩ):	12:10:09 (MΩ): Wet Day
<u>1</u>	3M	Infinite	Infinite	Infinite	Infinite	Infinite
<u>2</u>	3M	Infinite	Infinite	Infinite	Infinite	Infinite
<u>3</u>	WABO	Infinite	Infinite	Infinite	Infinite	Infinite
<u>4</u>	FABICK 2:1	1.45	0.466	2.35	2.2	0.84
<u>5</u>	FABICK 2:1	Infinite	Infinite	Infinite	Infinite	Infinite

**Inductance Measurements (Site 112): December
10, 2009 Field Test (Wet day)**

Loop	Inductance (μH)	Resistance ($\text{M}\Omega$)
1	149	0.41
2	147	0.36
3	153	Infinite
4	146	22.8
5	144	Infinite
6	141	Infinite
7	140	10.54
8	134	16.6
9	129	Infinite
10	142	0.98
11	165	Infinite
12	132	8.5

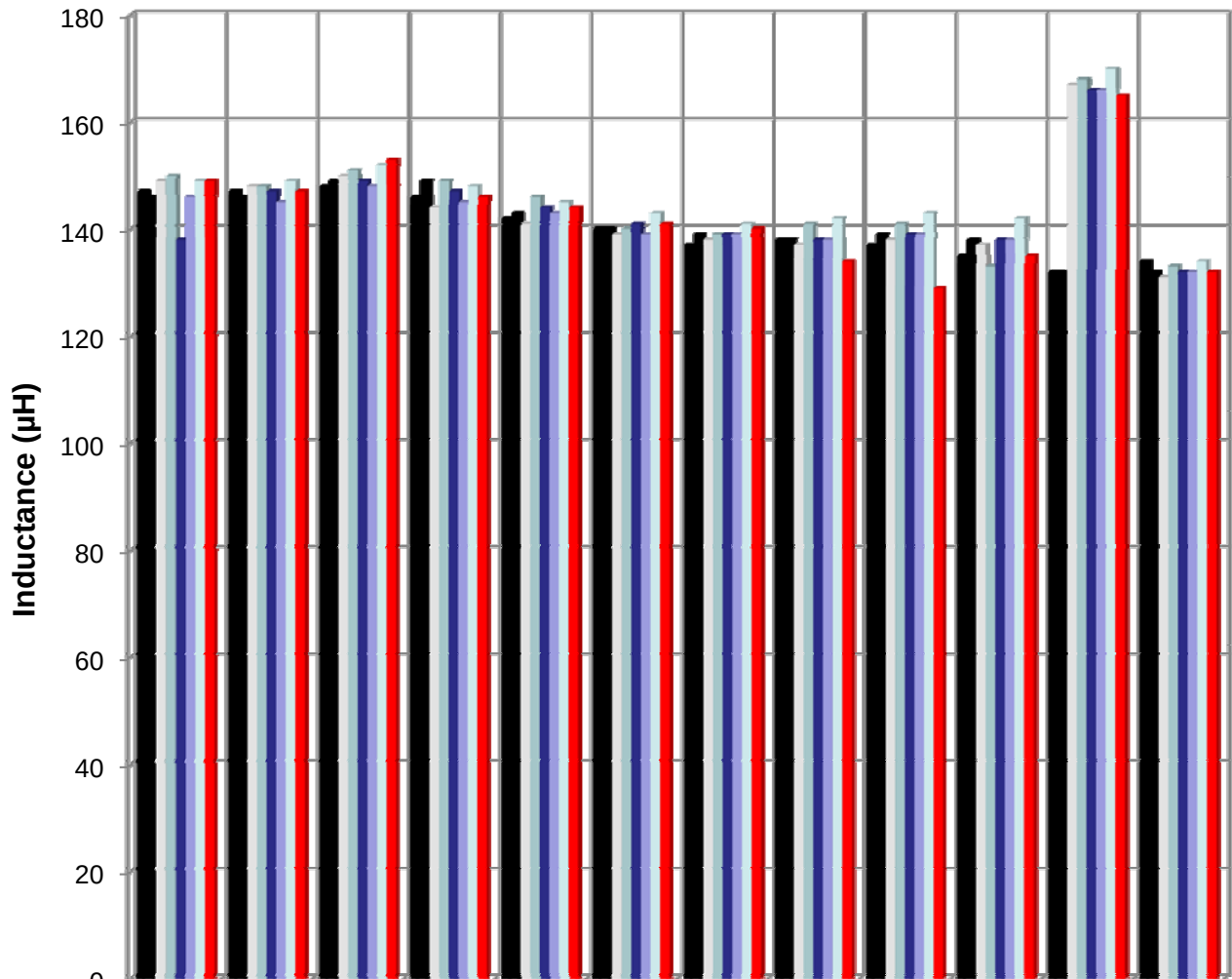
Comparison Chart for Inductance of Loop Sensors: Site 112



	Loop 1	Loop 2	Loop 3	Loop 4	Loop 5	Loop 6	Loop 7	Loop 8	Loop 9	Loop 10	Loop 11	Loop 12
Before Feb 18	147	147	148	146	142	140	137	138	137	135	132	134
Feb. 18 Field Test	146	146	149	149	143	140	139	138	139	138	132	132
April 06 Field test	149	148	150	144	141	139	138	137	138	137	167	131
June 04 field Test	150	148	151	149	146	140	139	141	141	133	168	133
July 08 Field Test	138	147	149	147	144	141	139	138	139	138	166	132
Aug. 13 Field Test	146	145	148	145	143	139	139	138	139	138	166	132
Oct. 20 Field Test	149	149	152	148	145	143	141	142	143	142	170	134
Dec. 10 Field Test	149	147	153	146	144	141	140	134	129	135	165	132

■ Before Feb 18
 ■ Feb. 18 Field Test
 ■ April 06 Field test
 ■ June 04 field Test
 ■ July 08 Field Test
 ■ Aug. 13 Field Test
 ■ Oct. 20 Field Test
 ■ Dec. 10 Field Test

Comparison Chart for Inductance of Loop Sensors: Site 112



	Loop 1	Loop 2	Loop 3	Loop 4	Loop 5	Loop 6	Loop 7	Loop 8	Loop 9	Loop 10	Loop 11	Loop 12
Before Feb 18	147	147	148	146	142	140	137	138	137	135	132	134
Feb. 18 Field Test	146	146	149	149	143	140	139	138	139	138	132	132
April 06 Field test	149	148	150	144	141	139	138	137	138	137	167	131
June 04 field Test	150	148	151	149	146	140	139	141	141	133	168	133
July 08 Field Test	138	147	149	147	144	141	139	138	139	138	166	132
Aug. 13 Field Test	146	145	148	145	143	139	139	138	139	138	166	132
Oct. 20 Field Test	149	149	152	148	145	143	141	142	143	142	170	134
Dec. 10 Field Test	149	147	153	146	144	141	140	134	129	135	165	132

■ Before Feb 18 ■ Feb. 18 Field Test ■ April 06 Field test ■ June 04 field Test
 ■ July 08 Field Test ■ Aug. 13 Field Test ■ Oct. 20 Field Test ■ Dec. 10 Field Test

Comparison Table for Resistance Tests for Site 112

Loop	B/4. 02:18:09 (Wet Day) (MΩ):	02:18:09 (MΩ):	03:23:09	04:06:09 (MΩ):	06:04:09 (Wet Day) (MΩ):	07:08:09 (MΩ):	08:13:09 (MΩ):	10:20:09 (MΩ):	12:10:09 (Wet Day) (MΩ):
1	Infinite	Infinite	Resealed using AS475	Infinite	Infinite	<u>6.90 – 10.98</u>	5.8	8.31	0.41
2	Infinite	Infinite	Resealed using AS475	Infinite	Infinite	<u>0.298 – 1.5</u>	5.35	4.81	0.36
3	Infinite	Infinite	Resealed using Bondo	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	Infinite
4	Infinite	Infinite	Resealed using Bondo & shoulder using Fabcik 2:1	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	22.8
5	Infinite	Infinite	Shoulder resealed using Bondo	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	Infinite
6	Infinite	Infinite	Shoulder resealed using Fabick 2:1	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	Infinite
7	Infinite	Infinite	Shoulder resealed using Fabick 2:1	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	10.54
8	46.4	Infinite	Shoulder resealed using Bondo	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	16.6
9	Infinite	Infinite	Shoulder resealed using AS475	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	Infinite
10	Infinite	Infinite	Shoulder resealed using AS475	Infinite	-4 (faulty) Other direction gives infinite	<u>2.68</u>	2.72	0.96	0.98
11	12.5	Infinite	Replaced using 3M and topped by G100	Infinite	Infinite	<u>Infinite</u>	Infinite	Infinite	Infinite
12	Infinite	Infinite	Resealed using Fabick 2:1	Infinite	1 st Reading: 10-17 2 nd Reading: 11.6	<u>21.4 – 24.6</u>	5.13	13.55	8.5