Civil Engineering Support for the Traffic Monitoring Program (June 2017 – November 2017)

Final Report

Project No. BDV30-977-20

by

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METRIC CONVERSION FACTORS

1 inch = 2.54 cm
1 mph = 1.609 km/h
1 pound = 0.4536 kg
Fahrenheit degrees = 9/5 x Celsius + 32
1 kip = 4.4482216 kN

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16. Abstract

The Transportation Data and Analytics Office of the Florida Department of Transportation operates traffic monitoring sites scattered throughout the state of Florida. Consequently, the Office is faced with the continuing challenge of maintenance, sustainability, modernization of processes and equipment, and assurance of the quality of data collected from these sites. This project was aimed at providing civil engineering support for the operation of the traffic monitoring sites by undertaking four major tasks: (1) evaluation of the performance of the Florida vehicle classification table implemented at these sites through various vendor equipment; (2) surveying State highway officials in the United States to solicit their experience with the operation of traffic monitoring sites and their experience with traffic data quality and assurance; (3) evaluation of weight data collected by weigh-in-motion (WIM) systems installed at the test site to determine the effect of the frequency of calibration on the quality of the collected WIM data; and (4) evaluation of new sealants for the installation of loops and piezos at the traffic monitoring sites. The report is divided into four chapters detailing the task undertaken, the results obtained, and the recommendations made. A number of recommendations have either been implemented or are under consideration for deployment with the purpose of improving the performance of the traffic monitoring sites.

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1.1 Background

The backbone of the Florida Department of Transportation's traffic data collection program is a network of over 300 telemetered traffic monitoring sites (TTMS) distributed throughout the state highway system. The equipment installed at these sites continuously acquires traffic flow parameters in a variety of formats. Categories of macroscopic data that are collected include traffic volume, vehicle classification, speeds, and weights. With the exception of the weight data, the traffic information is aggregated by hour of the day. Data are retrieved nightly from the monitoring sites using polling software and modem connections. Another major traffic data collection activity is assigned to the individual FDOT districts. This consists of short term (i.e., 24- or 48-hour) traffic data collection sessions at approximately 1,000 sites in each district. Since many of these locations are located on high traffic volume facilities or are otherwise unsafe for the deployment of temporary traffic sensors on the pavement, permanent infrastructure has been installed. These locations are known as portable traffic monitoring sites (PTMS). The main difference between TTMS and PTMS locations is that PTMS do not include either a power source or a communication capability. Electronic data collection units are moved among sites as part of the temporary traffic data collection program. The PTMS data are downloaded directly into a personal computer.

The vehicle classification data from these sites are important for the Transportation Data and Analytics Office's clients, including consultants, researchers, designers, and planners who use the data to perform various analyses. To make conclusions derived from these analyses technically sound and accurate, it is important that the vehicle classification data should be as much error free as possible and should not be dependent upon vendor-supplied hardware and software.

1.2 Objective

Consistent with the overall goal of providing civil engineering support to the FDOT's Transportation Data and Analytics Office to enhance its traffic monitoring program, the objective of undertaking this task was to improve vehicle classification by examining the performance of the existing classification table across different data recorders, including ADR 3000 Plus Traffic Counter/Classifier by Peek Traffic Corporation, iSINC® ITS System Electronics by International Road Dynamics Inc., Kistler recorder by Kistler USA, and MetroCount Vehicle Classifier System by MetroCount.

1.3 Data Collection

The testbed located at the Capital Circle Highway was utilized in this study. The layout of the testbed is shown in Appendix A. Video data were collected at the site on March 30, 2016. The purpose of collecting video data was to establish ground truth. A high-definition Panasonic 4K video camera, Model # *HC-WX970*, was used. A high capacity memory card (Kingston 64 GB micro adapter) was used to store the video data. The timeframe of 10:00 a.m. to 2:00 p.m. was chosen for continuous recording of vehicles. It was thought that this off-peak period had the likelihood of having most heavy vehicles compared to peak hour traffic.

When the video data were being collected, the roadside data recorders were simultaneously set to collect per vehicle records (PVR) on each lane. The time-stamped PVR data were to be used later on for matching vehicles on video with vehicles recorded by the individual machines. Figure 1.1 below shows the set-up of the video camera in order to capture axle spacings of vehicles.

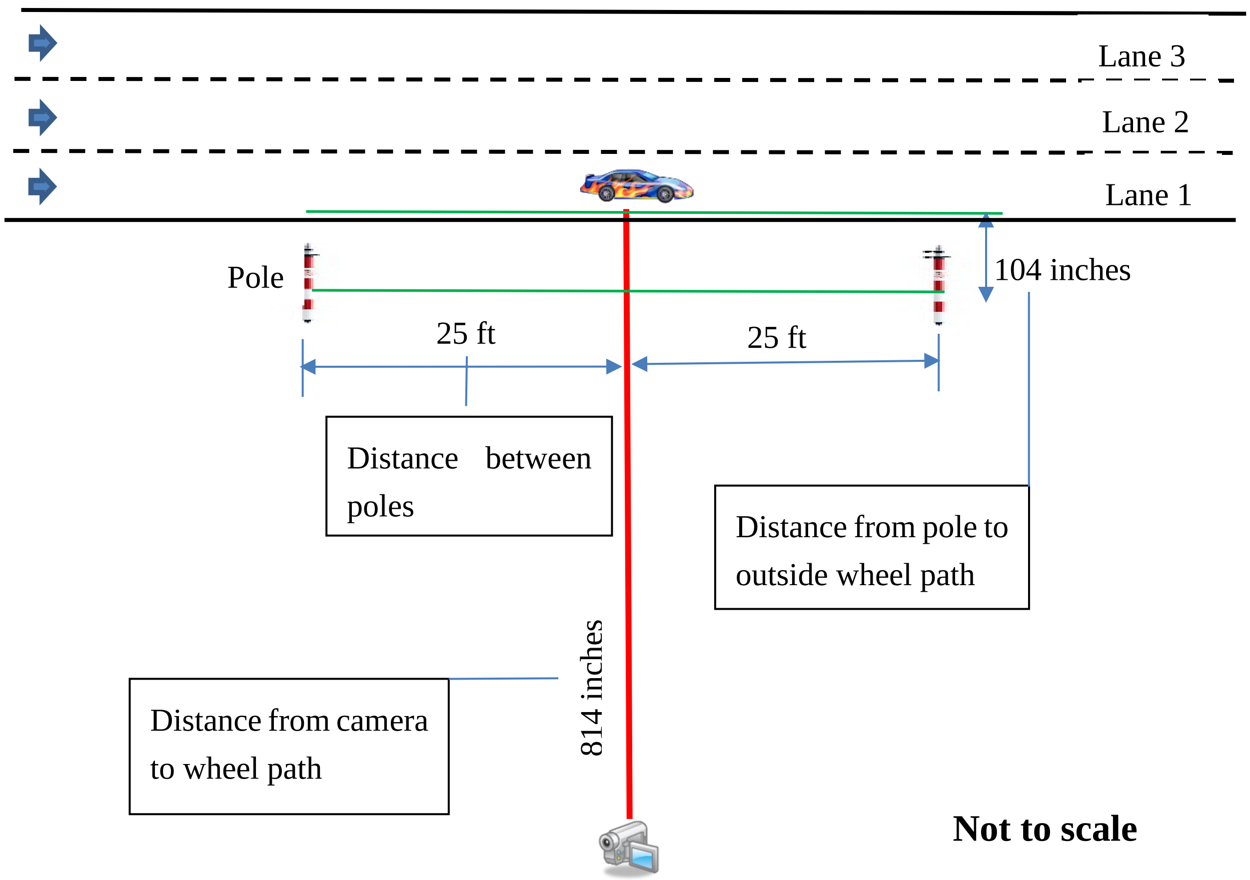


Figure 1.1 Setup of the Video Camera

1.4 Results and Discussion

Following collection of video data, the next major task was to match individual vehicles on video to vehicles recorded by the data recorders. This task was very time-consuming as it involved the following steps:

- calculate headways of individual vehicles from the PVR data,
- freeze a vehicle image on video as it passes the detector then determine time of passage,
- calculate the headways of individual vehicles extracted from the frozen video images,
- match the vehicles by comparing PVR time headway data to video time headway data, and
- observe class similarity or difference between the video and individual recorders.

The results of the ensuing analysis of each system are discussed in the following sections.

1.4.1 Analysis of MetroCount Vehicle Classifier System

Using headways and other information mentioned above, vehicles observed on video were compared to vehicles counted the MetroCount Vehicle Classifier System, the results of which are summarized by class as shown in Table 1.1. The vehicle classification table used by the MetroCount to classify vehicles is shown in Appendix Table B-1.

TABLE 1.1 MetroCount and Video Matched Vehicles

Vehicle Class	Total # of Vehicles Observed on Video	Total # of Vehicles Counted by MetroCount	Difference	Percent Difference
1	3	5	+2	+66.7%
2	338	357	+19	+5.6%
3	162	147	-15	-9.3%
4	0	7	+7	-
5	36	23	-13	-36.1%
6	19	18	-1	-5.3%
7	2	2	0	0.0%
8	0	8	+8	-
9	11	11	0	0.0%
10	3	3	0	0.0%
11	0	0	0	-
12	0	0	0	-
13	0	0	0	-
14	0	0	0	-
15	0	0	0	-
Total	574	581	+7	+1.2%

In looking at the column titled "Difference", it should be noted that positive (+) indicates that the data recorder (in this case MetroCount) recorded more vehicles than the ground truth in that particular class while negative (-) indicates that the machine recorded fewer vehicles than the ground truth. Overall, the total number of vehicles reported by MetroCount is fairly close to the total number of vehicles observed on video – i.e., there is a difference of only 7 vehicles (+1.2 percent). However, the results displayed in Table 1.1 does not distinguish between vehicles that were thrown in a wrong class from vehicles that were overcounted by MetroCount, i.e., ghost vehicles. Such distinction requires matching vehicles individual vehicles observed on video and observed by MetroCount. A detailed look at misclassified vehicles was conducted as shown in Table 1.2 and in Figure 1.2. It is worth noting that analysis of matched vehicles was limited to one lane only – that is, eastbound outside lane.

While Table 1.1 showed that MetroCount reported seven more vehicles than were actually observed on video, representing a +1.2% counting error, the results in Table 1.2 show that it misclassified 105 vehicles, representing 18.3% overall classification error rate. It is worth noting that the vehicles analyzed in Table 1.2 are the ones that were actually matched between the video and the MetroCount. Thus, for example, the 2 more vehicles that MetroCount said existed in Class 1 (i..e., ghost vehicles) are not included in Table 1.2

TABLE 1.2 Analysis of MetroCount Misclassified Vehicles

Vehicle Class	Number of Vehicles Observed on Video	Number of Matched Vehicles Correctly Reported by MetroCount	# of Vehicles Misclassified by MetroCount	Percent Misclassified
1	3	3	0	0.0%
2	338	307	31	29.5%
3	162	111	51	48.6%
4	0	0	0	0.0%
5	36	14	22	21.0%
6	19	18	1	1.0%
7	2	2	0	0.0%
8	0	0	0	0.0%
9	11	11	0	0.0%
10	3	3	0	0.0%
11	0	0	0	0.0%
12	0	0	0	0.0%
13	0	0	0	0.0%
14	0	0	0	0.0%
15	0	0	0	0.0%
Total	574	469	105	18.3%

The information displayed in both Table 1.2 and Figure 1.2 shows that most misclassified vehicles were in Class 2 and Class 3 involving a total of 71 vehicles between these two classes. The overall misclassification rate of 18.3% can mostly be attributed to misclassification in Class 2 and 3. If these vehicles are removed from the count, the misclassification rate drops to 5.9%.

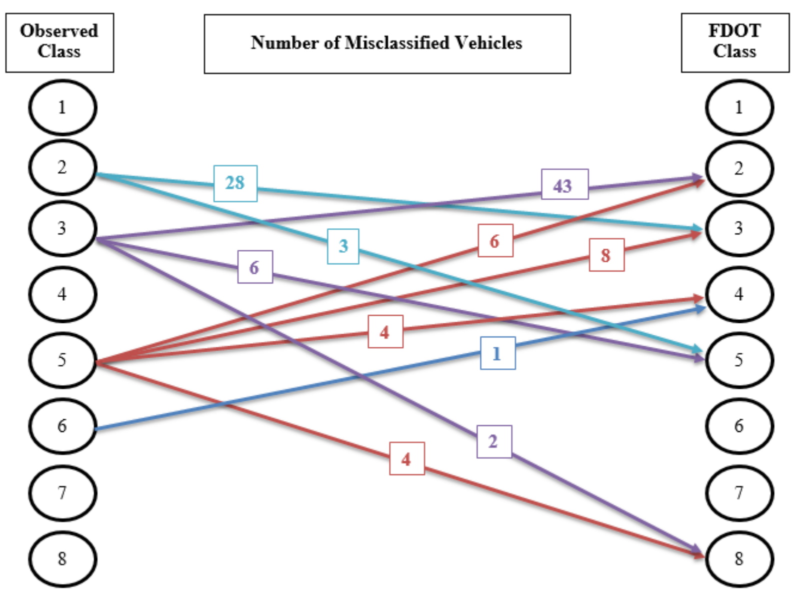


Figure 1.2 Detailed Look of Misclassified Vehicles by MetroCount

1.4.2 Analysis of iSINC Data Recorder

The results of analysis of data recorded by the iSINC data recorder are summarized in Table 1.3. The table shows that 574 vehicles were observed on video while 578 vehicles reported by iSINC representing a difference of only 4 vehicles (+0.7 percent). The misclassified vehicles were further examined as shown in Table 1.4 and in Figure 1.3 to determine their profile. The vehicle classification table used in the iSINC recorder to classify vehicles is shown in Appendix Table B-2.

TABLE 1.3 iSINC and Video Matched Vehicle

Vehicle Class	Total # of Vehicles Observed on Video	Total # of Vehicles Counted by iSINC	Difference	Percent Difference
1	3	0	-3	-100.0%
2	338	329	-9	-2.7%
3	162	180	+18	+11.1%
4	0	1	+1	-
5	36	20	-16	-44.4%
6	19	18	-1	-5.3%
7	2	2	0	0.0%
8	0	8	+8	-
9	11	11	0	0.0%
10	3	3	0	0.0%
11	0	0	0	-
12	0	0	0	-
13	0	0	0	-
14	0	0	0	-
15	0	6	+6	-
Total	574	578	+4	+0.7%

Both Table 1.4 and Figure 1.3 show that the biggest source of misclassification is in Class 2 and Class 3 involving a total of 61 vehicles between these two classes. The overall misclassification rate of 15.7% can mostly be attributed to misclassification in Class 2 and 3. If these vehicles misclassified in Class 2 and Class 3 are removed from the count, the misclassification rate drops to 5.0%.

TABLE 1.4 Analysis of iSINC Misclassified Vehicles

Vehicle Class	Number of Vehicles Observed on Video	Number of Vehicles Correctly Reported by iSINC	# of Vehicles Misclassified by iSINC	Percent Misclassified
1	3	0	3	3.3%
2	338	301	37	41.1%
3	162	132	30	33.3%
4	0	0	0	0.0%

TABLE 1.4 (Cont'd)

Vehicle Class	Number of Vehicles Observed on Video	Number of Vehicles Correctly Reported by iSINC	# of Vehicles Misclassified by iSINC	Percent Misclassified
5	36	17	19	21.1%
6	19	18	1	1.1%
7	2	2	0	0.0%
8	0	0	0	0.0%
9	11	11	0	0.0%
10	3	3	0	0.0%
11	0	0	0	0.0%
12	0	0	0	0.0%
13	0	0	0	0.0%
14	0	0	0	0.0%
15	0	0	0	0.0%
Total	574	484	90	15.7%

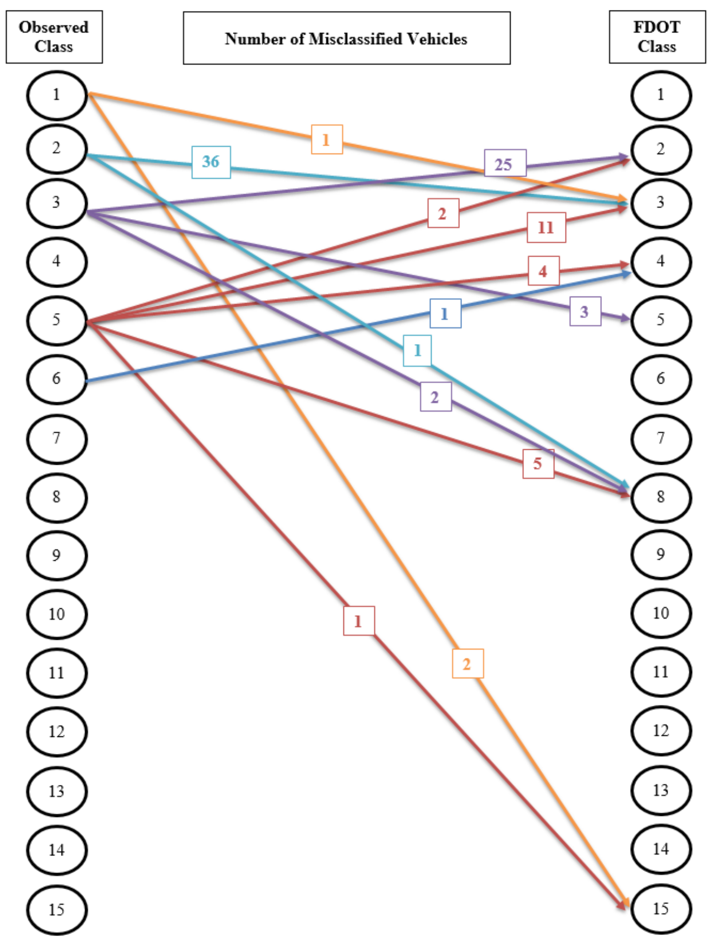


Figure 1.3 Detailed Look of Misclassified Vehicles by iSINC

1.4.3 Analysis of ADR 3000 Data Recorder

Table 1.5 shows the summary of vehicles that were counted by the ADR 3000 and matched with the vehicles extracted from the video. A total of 571 vehicles were counted on video during the analysis time frame while *ADR 3000* recorder recorded a total of 576 vehicles which is only 5 (0.9 percent) more vehicles. A detailed look at misclassified vehicles was subsequently conducted as shown in Table 1.6 and in Figure 1.4. The vehicle classification table used by the ADR 3000 to classify vehicles is shown in Appendix Table B-3.

TABLE 1.5 ADR and Video-Matched Vehicles

Vehicle Class	Total # of Vehicles Observed on Video	Total # of Vehicles Counted by ADR 3000	Difference	Percent Difference
1	3	10	+7	+233.3%
2	336	323	-13	-3.9%
3	161	133	-28	-17.4%
4	0	2	+2	-
5	36	41	+5	+13.9%
6	19	20	+1	+5.3%
7	2	2	0	0.0%
8	0	16	+16	-
9	11	8	-3	-27.3%
10	3	3	0	0.0%
11	0	0	0	-
12	0	0	0	-
13	0	0	0	-
14	0	0	0	-
15	0	18	+18	-
Total	571	576	+5	+0.9%

Similar trends of misclassification between Class 2 and Class 3 were observed as displayed in both Table 1.6 and Figure 1.4. A total of 78 vehicles were misclassified between these two classes. The overall misclassification rate is 27.1 percent. If the vehicles misclassified in Class 2 and Class 3 are removed from the count, the misclassification rate drops to 13.5%.

TABLE 1.6 Analysis of ADR Misclassified Vehicles

Vehicle Class	Number of Vehicles Observed on Video	Number of Vehicles Correctly Reported by ADR 3000	# of Vehicles Misclassified ADR 3000	Percent Misclassified
1	3	1	2	1.3%
2	336	279	57	36.8%
3	161	85	76	49.0%
4	0	0	0	0.0%
5	36	20	16	10.3%

TABLE 1.6 (Cont'd)

Vehicle Class	Number of Vehicles Observed on Video	Number of Vehicles Correctly Reported by ADR 3000	# of Vehicles Misclassified ADR 3000	Percent Misclassified
6	19	18	1	0.6%
7	2	2	0	0.0%
8	0	0	0	0.0%
6	19	18	1	0.6%
7	2	2	0	0.0%
8	0	0	0	0.0%
9	11	8	3	1.9%
10	3	3	0	0.0%
11	0	0	0	0.0%
12	0	0	0	0.0%
13	0	0	0	0.0%
14	0	0	0	0.0%
15	0	0	0	0.0%
Total	571	416	155	27.1%

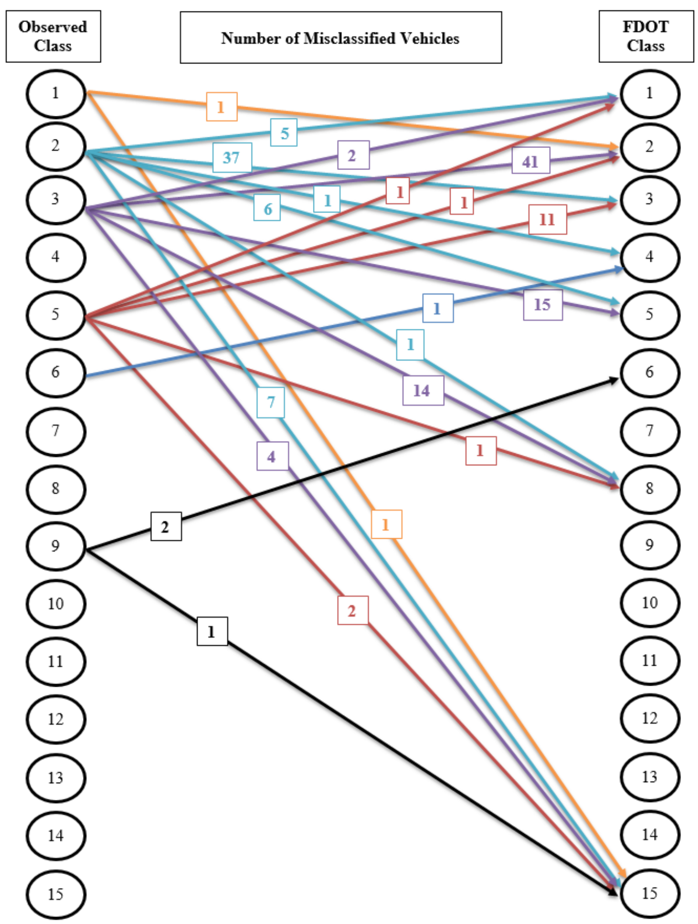


Figure 1.4 Detailed Look of Misclassified Vehicles by ADR

1.4.4 Comparative Analysis of MetroCount, iSINC, and ADR 3000

Figure 1.5 shows a comparative analysis of the three traffic recorders. It is worth noting that data from the Kistler recorder was collected but unfortunately it does not report class of a vehicle. Therefore, it was removed from the comparative analysis. The results in Figure1.5 shows that *iSINC* has the lowest overall misclassification rate. This result is consistent with previous studies which found that a recorder which additionally uses vehicle weights as an additional discriminating variable tends to perform better. Further observation of the results in Figure 1.5 shows that *MetroCount* performance in classification is close to both *iSINC* and *ADR 3000*. It is noteworthy that the total number of vehicles reported by the *MetroCount* data recorder were very close to the ground truth, i.e., a difference of only 1.2 percent. These results, however, need to be qualified as follows. This test site is predominantly characterized by passenger car vehicles throughout the day. As seen in the tables displayed above, the site lacks vehicles of Class 4 and higher. Thus, the difference in performance of the recorders in classifying vehicles of higher classes cannot be ascertained.

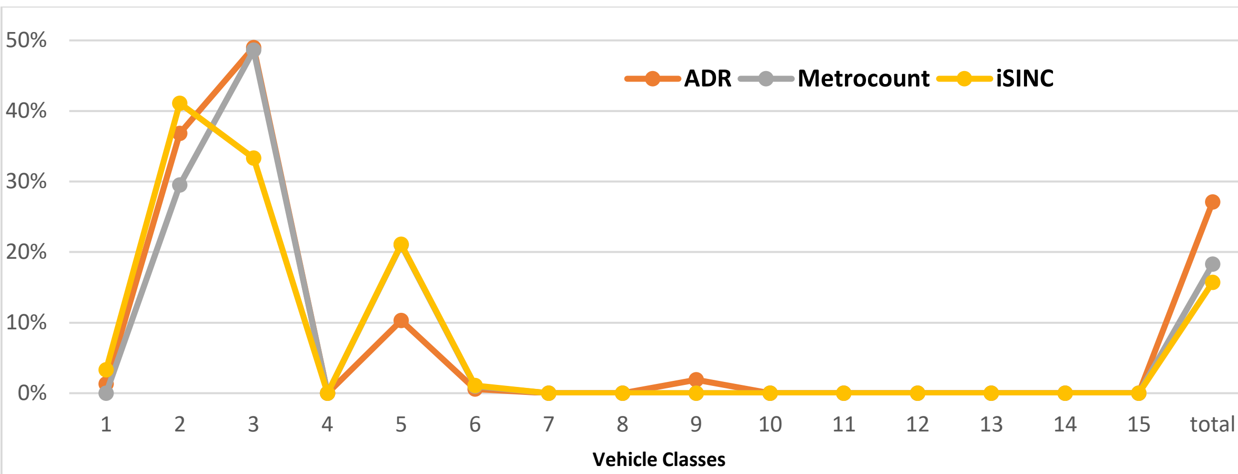


Figure 1.5. Percent Misclassification Rate for All Data Recorders

TASK 2: SURVEY RESULTS & IMPLEMENTATION RECOMMENDATIONS

2.1. Introduction

This report documents the responses of a detailed questionnaire that was sent to State highway agencies in the United States soliciting their experience with operation of traffic monitoring sites and their experience with traffic data quality and assurance. The questionnaire was divided into three parts: Part A – Installation of Traffic Monitoring Sites; Part B – Maintenance of Traffic Monitoring Sites; and Part C – Data Quality Control and Assurance. Appendix C shows the questionnaire. The survey targeted State Departments of Transportation officials who are directly involved with traffic data collection. Given that there are many aspects of traffic monitoring ranging from field data collection to office database management, in some states more than one person responded depending on the nature of their duties in the traffic monitoring work flow.

The survey was administered online using Google Forms. An email with a link to the website was sent to the targeted officials. Some DOT officials wrote back that their computer security policies do not allow access to such websites. For these officials, the survey was directly mailed to them in MS WORD file format. A total of 35 responses were received from 31 states. Appendix D lists State DOT officials that have so far responded to the questionnaire. The sections below discuss in detail the results of the survey based on responses received in the three parts of the survey.

2.2. Installation of Traffic Monitoring Sites

Like Florida, practically all states responding have installed automatic traffic recording devices on their highways to collect data for meeting federal reporting requirements. Most states responded that the data they collect for monthly reporting purposes are traffic volume, axle-based vehicle classification data, and weight data comprised of axle and gross vehicle weights for Class 4 through Class 13. Some states indicated that they additionally submit occupancy data, speed data, and length-based classification data. Some states reported that they submit on annual basis AADT data, truck AADT data, design hour factors, and VMT data. Interestingly, the State of Minnesota reported that they were expecting to start reporting bicyclist and pedestrian data from their continuous monitoring sites beginning Fall 2016.

Of interest in this survey was the types of vehicle sensing technologies used by different states to capture traffic data; what types of roadside data recorders are installed at the monitoring sites; and what factors influence choosing sites for installation of continuous monitoring devices. The sections below discuss responses related to these topics.

2.2.1 Sensors

The results show that, like Florida, loop-piezo-loop sensor combination is still the backbone of vehicle/axle counting at permanent traffic monitoring sites. In addition to loop-piezo-loop array, some states have been looking into (and implementing) non-intrusive traffic data collection technologies as detailed below.

- Some states (Nebraska, Ohio, Maryland, Michigan, Washington, Iowa, Arkansas, Wisconsin) report using side-fired/overhead-mounted radar technology (in particular, Wavetronix radar sensor) to collect speed, volume, and vehicle lengths. Some states have developed algorithms to convert vehicle length data into FHWA F-Scheme axle-based classification.
- The states of Indiana and South Carolina report having some success with Sensys sensors which are installed in holes cored in the roadway and thus have a smaller footprint compared to standard loops.
- The State of Virginia is using video imaging technology (using equipment manufactured by Miovision Technologies Inc.) to collect volume data only. However, they are evaluating the efficacy of this technology to collect class data as well.
- The State of North Carolina reports using the Infra-Red Traffic Logger (TIRTL) sensor manufactured by CEOS Pty Ltd of Australia to collect vehicle classification data.

Traditionally, load cells and bending plate technologies have reliably been used to collect weight data while a vehicle is in motion. A load cell is a transducer that creates an electrical signal proportional to the weight of the vehicle's axle being measured. The bending scale consists of two adjacently placed steel platforms instrumented with strain gauges, which measure tire load induced-strains that are subsequently converted to axle weight. Because of the intrusive nature and cost involved in installing load cells and bending plate WIM sensors, states are evaluating and/or implementing new technologies at their WIM sites. These technologies include:

- in-ground Quartz WIM sensing technology, and
- in-ground strip scale technology that utilizes strain gauges but with a smaller footprint compared to bending plate or load cell technologies.

2.2.2 Data Recorders

The results show that data recorders manufactured by Peek Traffic Corporation and Diamond Traffic Products Inc. are frequently mentioned for classification sites while International Road Dynamics Inc. *iSINC* data recorders are frequently mentioned for WIM sites. The State of Mississippi reported to also be using RAKTEL Universal Traffic Event Logger manufactured by Mikros Traffic Monitoring Ltd. of South Africa.

2.2.3 Factors Considered in Installing Traffic Monitoring Sites

Collection of traffic data of high quality for end-user purposes starts with careful consideration of where a permanent site should be located. There are many factors that play a role, and states reported some of those factors as follows:

Geographic locational characteristics – Proximity to state lines to capture profiles of vehicles entering or leaving a state; large presence of trucks in bypass routes and mountainous areas; proximity to enforcement scale (see Section 2.4.4 for further information).

Traffic characteristics – Ensuring roadways in all functional classifications are covered; satisfy statistical requirements for getting appropriate design factors; near new developments that generate significant traffic; new sites to fill gaps in traffic data following statewide review.

Site characteristics – pavement condition; flat and tangent section; availability and signal strength of cellular communication to enable telemetry polling; availability of electric power; overhead clearance for solar panels; avoidance of queue spillover to the site due to congestion, intersection, or railroad crossing. Additionally, if devices are side-fired/overhead-mounted care should be taken to choose a site that would provide interference-free operation of radar, video, and other electronic devices (e.g, from overhead electric wires) and sight to cover whole cross section of the roadway. *Safety characteristics* –optimal sight distance and space for crew to enter, work, and exit the site.

2.2.4 Loop/Piezo Sealants

The survey results show that there many other states using the loop sealants that were recently field-evaluated in Florida, specifically, *Bondo P-606 Loop Sealant* manufactured by the 3M Company, *Stat-A-Flex* manufactured by Durant Performance Coatings Inc., *Detector Loop Sealant Black 5000* by the 3M Company; *Pro-Seal 6006* by RAI Products; and *Q-Seal 290S* by Chemque Inc. The survey results revealed only one additional sealant that has not been field or lab-tested in Florida – that is, *BASF Master Seal SL 180* manufactured by BASF Corporation. Review of the manufacturer's technical data sheet shows that it is a polyester sealant supplied in two parts, i.e., resin and hardener.

In regard to piezo sealants, the survey results show that most states use the same grouts that are either already in the Florida DOT approved product list or were considered for approval at one time or another. The main grouts are *G-78* produced by E-Bond Epoxies Inc., *ECM P6G* manufactured by Electronic Control Measurement Inc., and *AS475* supplied by International Road Dynamics Inc. It is worth noting that International Road Dynamics Inc. recommends the use of *PU200* sealant for installation of their *RoadTrax BL* sensors; however, this sealant was removed from Florida DOT approved product list many years ago because laboratory testing and field evaluation revealed that it was not suitable for Florida conditions. Kistler Instrument Corporation recommends the use of Kistler grout in installing their *Lineas® quartz WIM* sensors. There are a number of Kistler sensors installed in Florida but the grout has not been subjected to laboratory evaluation or field monitoring on longitudinal basis.

Of the 31 states that responded to the survey, 16 reported using pushbutton contractors (outsourcing) while 13 states use in-house crews (insourcing) for installation and maintenance of their traffic monitoring sites. Two states did not respond to this question. Some states try to ensure quality installation by having a DOT inspector present at all installation and maintenance jobs. In addition, some states require a 12-month warranty on all installations including grout and sealants. A few innovative and different practices learned from the survey include:

- The State of Nebraska says "the evaluation process for new grout/sealant is to install a piezo and a loop at a medium volume automatic traffic recorder (ATR) site using the new sealant and evaluate the installation characteristics initially then monitor the durability over the course of the next year."
- The State of Virginia says "VDOT uses one contractor, not contractors plural. The VDOT business model is that the contractor is paid for quality data produced by sensors they install, and electronics they own and operate, after installation is complete. This ensures the contractor has vested interest in the quality of installation and the post installation performance. A contract quality control person from a separate company is on site during installation to monitor the installation and document (photographs and standard reports) each facet of installation.

Contract work is also videotaped on site using a site overview camera mounted on a truck and also close-up video as needed to monitor specific performance e.g, mixing or pouring grout. Videos are reviewed by contract administrators for compliance and 'performance drift' issues".

2.3. Maintenance of Traffic Monitoring Sites

Maintenance practices of permanent count sites differ State by State. Some states use the "when issues arise" method in which traffic monitoring sites are visited only when there is an anomaly in the data or indication of equipment/communication failure or malfunction. The states that practice this "when issues arise" method, however, have a rigorous traffic data auditing process to pick up errors and unusual patterns in traffic data thus triggering site visit to repair, realign, or otherwise calibrate[1] a device. Some states, e.g,, North Carolina, have an annual schedule of performing electronic testing and validation of the operation of sensors. The State of Indiana reports that all sites are scheduled for two preventive maintenance visits per year – one in the spring and one in the fall – in which all sensors and equipment are inspected, the cabinets are cleaned, filters are changed and any rodent access points are blocked. The State of Nebraska which practices "insourcing" inspects sites in the western part of the State at least once every two months.

The State of Louisiana reports that they have begun cross-training their field technicians to perform routine maintenance while in the area (i.e., change batteries, check voltage, etc.). The State of Arkansas, which also practices "insourcing", reports that "each crew member is assigned a number of sites. Sites are assigned geographically. They visit their sites monthly unless a visit is triggered by unusual or missing data. Site visits may happen more often if it is rainy and grass is growing fast. The area around roadside equipment is trimmed to keep the site visible to any mowing crews."

States were also surveyed on the issue of monitoring sensor's health. In particular, the question asked was "Have you developed advanced computer logic functions that alerts you of anomalies in field data or if the sensors are about to fail?" The State of Indiana reported that they are currently working with a private vendor to develop a plugin to their software which will monitor equipment, communications, and sensors health. However, most states rely on QA/QC checks built into the data processing software to detect anomalies in traffic data. Examples of the QA/QC checks include AADT being out of tolerance with historical AADTs, consecutive zero hours of data, and distribution of vehicles of a particular class being higher than normal. When undercounting, over counting, misclassification, or complete inability to classify is detected through these QA/QC checks, the site is remotely accessed and all sensor activities monitored. In this way, a faulty sensor can be identified.

Also of interest in this survey was finding out states' experience with the longevity of sensor installations. It is clear that there are many factors that might affect how long a sensor lasts including pavement condition at the site, traffic volume particularly truck volume, quality of installation, and routine and quality of regular maintenance. The survey results show that, barring

[1] In the State of Nebraska, calibration of non-WIM sites also consists of adjusting gain and/or registration threshold of piezos as well as frequency and gain of loops. The State of Utah reports that because piezoelectric axle sensors are affected by temperature variation, they adjust data using a front axle weight (Class 9 or Class 13) rolling average.

an unusual condition at a site, loop installation lasts for a long time until they are milled out as a results of scheduled pavement rehabilitation. For example, the State of Ohio reported that loops last indefinitely for them. There are some states that reported a loop installation lasts 5 to 10 years but this is likely because this time frame coincides with pavement rehabilitation schedule in those states. A number of states reported piezos last 3 to 5 years mainly because, unlike loops, they are prone to pavement cracking which is a very common functional failure of pavement on most highways. A number of states reported quartz sensors last longer than BL sensors. For example, the State of Montana reported their quartz sensors last 12 to 15 years while the State of Mississippi reported quartz sensors lasting around 7 years.

2.4. Data Quality Control and Assurance

Data are collected for a purpose and that is, end-use. Thus, traffic data collected have to be of high quality to make them fit for their intended use in transportation planning, design, operations, and maintenance. Consequently, data quality control and assurance is a continuous process that starts when a traffic monitoring site is installed and continues for the lifetime of the site. Of importance in this survey was learning how states control and assure quality of speed, volume, classification, and WIM data; what methodology and equipment are used to countercheck data being reported by the installed systems; and what is the frequency of check/calibration to ensure data quality and to deal with calibration drifts. The responses to these questions are documented and analyzed in the following sections.

2.4.1 Speed Data

Accurate determination of vehicle speed is of paramount importance as this variable is used by roadside classifiers to determine axle spacing used in classification. While not common, the survey results show that some states occasionally use hand-held speed measuring devices – particularly laser guided-radar speed guns and light detection and ranging (LIDAR) speed guns – to check the accuracy of automatic traffic recorders in collecting speed data. The survey results further reveal that some states use portable pneumatic tube counters to countercheck speed data at a traffic monitoring site. The speed data are usually collected for a few days continuously by the tube counters to enable multi-day data comparison.

2.4.2 Volume Data

For states undertaking routine accuracy checks, they report using manual counts, portable tube counters, and video as the means of collecting ground truth data for verifying counts from permanent traffic monitoring stations. The State of Nebraska reported conducting such studies three to four times per year at locations (such as major intersections) near to an ATR site.

2.4.3 Classification Data

Collection of accurate classification data is influenced by many factors including quality of the roadways sensors and the classification table programmed into the classifier. Thus, the survey was first aimed at determining how the classification table is implemented in the field. There is a wide variability of the types of classification tables that are implemented in the field with some states (e.g,, Arkansas) developing and enforcing the use of their table by all vendors regardless of whether the site is permanent or portable. Virginia also has a uniform classification table that all contractors and equipment vendors must use. Similarly, Nevada reported that they only use equipment that allow for the customization of the classification scheme developed by Nevada DOT. On the opposite end, some states (e.g,, Hawaii) allow equipment vendors to use their (vendor's) own scheme.

The survey further reveals that states that have developed their own classification scheme use the same scheme for all sites across the State. It was of interest to know whether the scheme is tweaked based on a site being in a rural or in an urban location, or based on the intensity of traffic volume, or based on some other factors. The State of Kansas reported that one classification scheme is used for all permanent sites but they have additionally developed an urban and a rural scheme for use at temporary sites. It should be noted that most states have a different classification scheme for weigh-in-motion (WIM) sites to take advantage of axle weights as an additional variable for classification. Numerous studies have shown that adding weight as a discriminating variable reduces classification errors, particularly of vehicles pulling trailers being thrown into Class 8 due to the fact that bona fide Class 8 vehicles have heavier axle weights.

The survey results show that the accuracy of classification is checked through visual counts (manually or by video recording) or through the use of portable tube counters. However, manual counting is time consuming and is therefore done for a limited number of hours. While video recording can provide ground truth data for a longer period, it is generally limited to daytime hours. The use of portable tube counters provides capability for multi-day comparative analysis but data collected by tube counters are not truly "ground truth" given that there is a certain amount of reporting error associated with tube counters' data.

The survey was further aimed at determining the type of errors states experience when evaluating the accuracy of their field classification data. The results are summarized below:

- Most states report that the most common error is between Class 2 and Class 3.
- Arkansas has found that concrete mix trucks are generally poorly classified.
- Nebraska is starting to periodically poll per-vehicle records and through this they "noted that at one site, our vehicle classification table was classifying some Class 09s as Class 14s due to the rear tandem being slightly narrower than the limits in our table".
- Tennessee wrote that their table reports "far too many motorcycles".
- Utah says "we fail at designating Class 5 versus large SUVs and long-cab pickups. We have the highest Class 5 percentage in the country. This doesn't affect axle factors and our axle spectra for pavement design is very low so it balances out."
- North Carolina has conducted video-based evaluation and found overlap in axle spacing between classes causes misclassification "particularly between Class 3 and Class 5 as well as between Class 5 and Class 4 (for the 2-axle buses)".

Recent trends in shorter wheelbase vehicles is proving to be a challenge in classification as some motorcycles are longer than these short vehicles. Some states expressed hope that one emerging technology, i.e., loop signature, can help distinguish a motorcycle from a short wheelbase vehicle. For example, the State of Maine reported testing an EMU unit from Jamar Technologies Inc. that utilizes loop signature.

2.4.4 WIM Data

There are many factors influencing the accuracy of weight data collected by weigh-in-motion (WIM) systems installed at permanent traffic monitoring sites. The most important factor is calibration. Of interest in this survey study was to determine what methods are used to calibrate WIM systems and how frequently is calibration done in order to counter "drift" of calibration factors due to seasonal, temperature variations, and other influencing variables.

The results show that most responding states use field calibration procedures that utilize vehicles of a known weight/configuration[2]. The frequency of field calibration varies from State to State. The State of Montana reported calibrating quarterly, i.e., four times per year while the State of Nevada calibrates annually. In the other end is the State of Maine which reported calibrating every three years. It is worth noting that the Long Term Pavement Performance (LTPP) program recommends repeating field calibration procedure at least twice per year for permanent WIM systems.

In addition to calibration using the pre-weighed calibration vehicle method, some states are taking advantage of continuous calibration and auto-calibration methods. The State of Indiana undertakes continuous calibration by allowing a Commercial Vehicle Enforcement officer to access their WIM systems to identify overweight vehicles. When they stop the vehicle and weigh it on static or portable scales, they input the actual weights into the WIM system and the weight differentials (for a number of vehicles) are used to get an adjusted calibration factor. The State of Indiana has found that the more this procedure is done at the sites the more accurate these sites become. However, according to the response from Indiana, "these sites are still included in the calibration schedule but auto calibration keeps them maintained between calibration schedules and helps compensate for the seasonal conditions of snow, ice, temperature, etc."

Auto-calibration is the process of automating the determination of calibration coefficient, *C*, understood to be a number to be multiplied by the measurement data to obtain the estimate of static load exerted by an axle on the road surface. Auto-calibration of WIM systems provides ability to compensate for fluctuations of WIM system parameters due to all kinds of reasons including temperature fluctuations, aging effects, etc. Some WIM equipment vendors now provide auto-calibration feature. The survey did not specifically solicit states' experience with the use of auto-calibration feature in the WIM data recorders that they have in the field.

Data Validation – It was of interest in this survey to determine if states were using automated or manual QA/QC program to validate data. The results of the survey show that the majority of the responding states use specialized QA/QC software for validating data collected from count sites and from WIM sites. Only 7 states reported not using specialized software but use computer routines (some developed in Excel) to process and validate data. The off-the-shelf QA/QC software being used are mostly from three companies well known in the traffic data industry – that is, *Jackalope* by High Desert Traffic LLC; *TCDS* by Midwestern Software Solutions; and *Traffic*

[2] For example, the State of Iowa uses two trucks, Class 6 and Class 9, owned by the Department of Transportation to conduct calibration runs at each WIM site.

Server™ by Transmetric America Inc. The states using these off-the-shelf software report that they were able to customize them to suit their processing and validation needs.

2.5. Recommendations for Florida

The results of the survey show that, comparatively, the Florida DOT traffic monitoring program is performing well and does not experience some types of sealant, sensor, or field equipment failures that some states (particularly northern states) experience due to extreme fluctuations of weather in the spring, summer, fall, and winter seasons. In addition, Florida DOT has over the years instituted processes in the data collection stream – from sensing, to roadside data recording, to data polling and transmission, and to database management – that are robust and somewhat on the cutting edge.

Having said that, there are lessons learned from this survey that can inform Florida DOT and may warrant further consideration in field evaluation. The following recommendations can be made:

- Florida DOT should consider experimenting with *BASF Master Seal SL 180* loop sealant manufactured by BASF Corporation. States using this product report good results.
- The majority of side-fired/overhead-mounted non-intrusive data collection devices that were mentioned in the survey such as *Wavetronix* and video imaging equipment manufactured by Miovision Technologies Inc. have been pitched in Florida over the years but it would be prudent to keep an eye on them as technologies keep improving.
- Most states use the same data recorders found in Florida but the survey revealed the *RAKTEL Universal Traffic Event Logger* manufactured by Mikros Traffic Monitoring Ltd. of South Africa which might be a good candidate for testing at the Site 9900 testbed.
- New methodologies and techniques for dealing with shorter vehicles – shorter than motorcycles – such as “loop signature” are being tested by other states and Florida can learn and be part of the testing regime.
- Florida should consider continuous calibration procedure, particularly for WIM sites located close to Commercial Vehicle Enforcement’s portable or permanent static scales.

TASK 3: EVALUATION OF THE QUALITY OF WIM DATA AT TTMS 9900

3.1 Purpose and Scope

Weigh-in-Motion is defined by ASTM E 1318 as the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces. The systems for collecting WIM data consist of sensors embedded into the pavement surface and a data acquisition system equipped with software capable of processing sensor signals into weight, computing additional traffic data elements, and summarizing them into various database formats. WIM data are collected by the Florida Department of Transportation for a variety of purposes including designing pavements, bridge structural analysis, freight management and operations, facility planning and programming, and standards and policy development.

WIM systems are susceptible to producing inaccurate weight data. Weight data errors may be attributed to (1) dynamic factors (e.g,, vehicle speed, vehicle suspension system, and profile of pavement); (2) equipment (e.g,, WIM sensor used); (3) how a data logger interprets the signal; and (4) improper calibration resulting in discrepancy between static and WIM weights. The purpose of calibration is generally to reduce WIM systematic errors but unfortunately temperature and seasonal variations have an effect in causing drift in calibration. In the recent past, manufacturers of WIM sensors and WIM data loggers have tried to deal with this problem by providing auto-calibration and other features aimed at reducing calibration errors. A number of WIM sensors and WIM data loggers have been installed at Site 9900 for evaluation and they provide a suitable setup for studying the quality and consistency of WIM data collected by modern equipment. Thus, the objective of this task was to analyze the WIM data collected at the test site by various WIM data loggers which have been paired with a variety of WIM sensors.

3.2 Field Equipment Setup

The testbed located at the Capital Circle Highway was utilized in this study. The testbed is designated as TTMS 9900 and was established in September 2014 for the purpose of consolidating field evaluations – that were scattered throughout the state – to one location; conducting short-term and long-term evaluation of piezo, loops, and sealants as well as long term evaluation of WIM sensors. The testbed has also been equipped with the capability to evaluate intrusive and non-intrusive sensors and the accompanying data loggers. Figure 3.1 shows the setup of the test site. As can be seen in Figure 3.1, there are five WIM data loggers that are being evaluated. These data loggers are hooked up with three different types of WIM sensors. The WIM data loggers and sensors are installed as follows: (1) TDC data logger connected to TDC quartz sensors, (2) Kistler data logger connected to Kistler sensors, (3) ADR 3000 WIM data logger connected to Kistler sensors, (4) iSINC WIM data logger connected to Kistler sensors, and (5) TDC data logger connected to Intercomp strip scales. The following sections discuss in sufficient detail the capabilities and limitations of the data loggers and sensors.

3.2.1 WIM Sensors

The WIM data collection procedure starts with sensing of weights. The most common technologies for weighing vehicles are bending-plate systems, load-cell systems, and piezoelectric systems. The bending plate WIM systems use electronic strain gauges bonded to the underside of a steel plate. As a vehicle passes over the bending plate, installed flush with the roadway surface, the strain gauges measure the bending force applied to the scale platform. The static load is estimated using the measured dynamic load and calibration parameters to account for the effects of uncontrollable factors such as vehicle speed and vehicle/roadway interaction. The load cell-based in-motion weighing scale generally uses single platform supported by four 50 kips stainless steel compression load cells. Piezoelectric WIM systems contain one or more piezoelectric sensors that detect a change in voltage caused by pressure exerted on the sensor by an axle and thereby measure the axle's weight. As a vehicle passes over the piezoelectric sensor (made of quartz or other ceramics), the system records the sensor output voltage and calculates the dynamic load. As with bending plate systems, the dynamic load provides an estimate of the static load when the WIM system is properly calibrated.

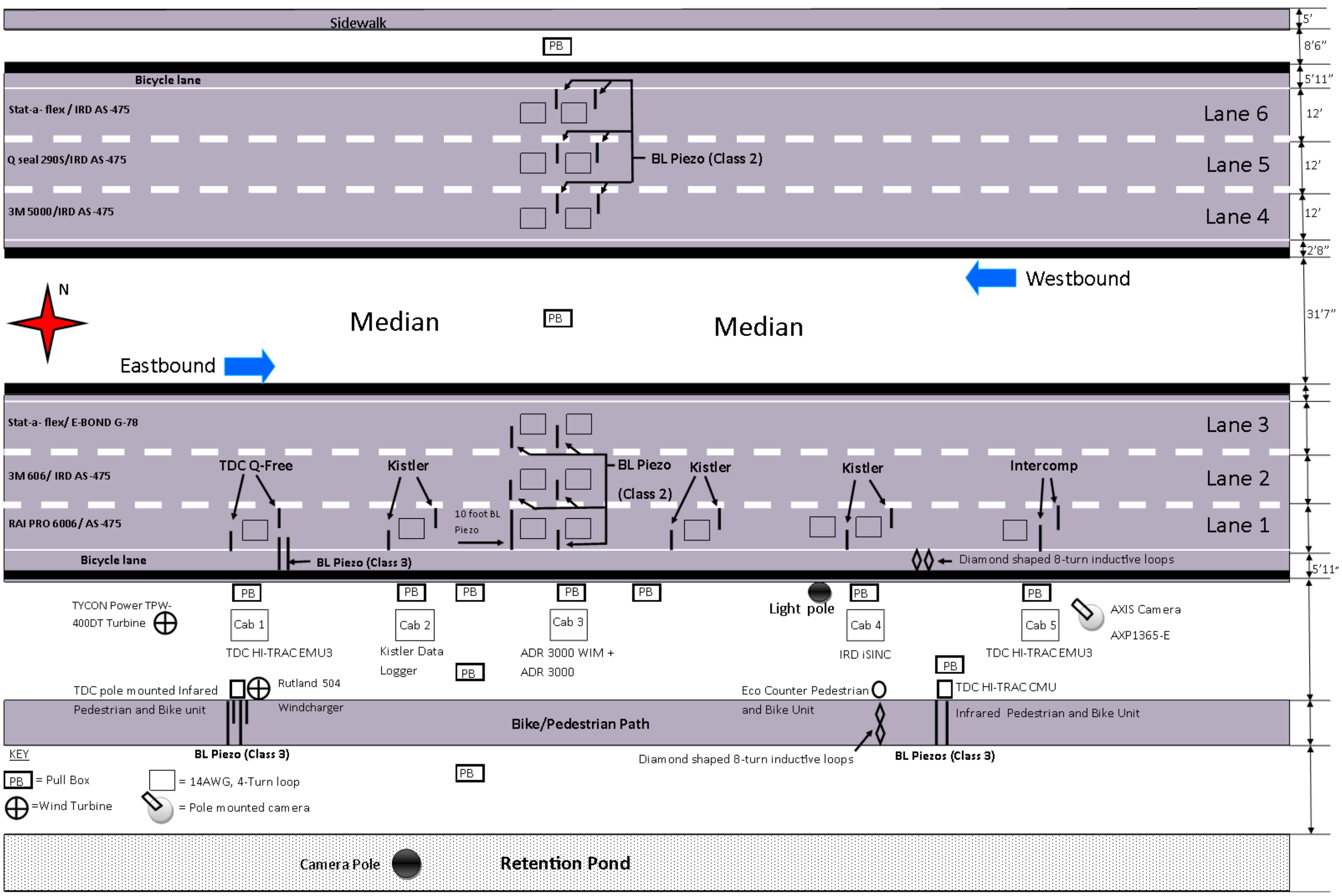


Figure 3.1 Setup of WIM Equipment at Site 9900

3.2.2 Kistler Sensor

Lineas® WIM sensor, manufactured by Kistler, utilizes quartz sensing system whose characteristics were described above. The manufacturer's data sheet indicates that it can be installed in any kind of road pavement like solid asphalt, drain asphalt, and concrete. The data sheet also states that in case of pavement rutting, the sensors topcoat can be re-ground to match the profile of the road surface. The data sheet additionally claims that the performance of the Lineas® WIM sensors is not affected by changing weather conditions such as large variations of temperature or humidity, rain or sunshine.

3.2.3 TDC Q-Free Sensor

The *Q-free* sensor supplied by TDC uses the principle of quartz piezoelectric to detect vehicle weights. The manufacturer's data sheet indicates that this sensor is insensitive to temperature changes, and weighs all vehicle classes.

3.2.4 Intercomp Sensor

Intercomp weigh-in-motion strip sensors also utilize strain gauge technology to measure vehicle loads. The WIM strip sensors can be configured in sets of 1, 2, 3, or 4 pairs depending on the application and required accuracy. The sensors are sold in variable lengths that include 59", 69", and 79". The manufacturer claims that the sensors have "internal temperature compensation mechanism that adjusts for changes in temperature at the sensor. This improves consistency of output from day to day and season to season and reduces calibration frequency as compared to piezo-electric and quartz sensors." The manufacturer's data sheet also indicates that the sensor can be integrated with third-party electronics and software.

3.2.5 RoadTrax BL Sensor

The RoadTrax Brass Linguini (BL) axle sensor, manufactured by TE Connectivity, utilizes piezoelectric principle in which the sensor generates an electric charge in response to applied mechanical stress, i.e., axle load. The Roadtrax BL traffic sensor is designed for permanent or temporary installation into or onto the road surface for the collection of traffic data. The manufacturer's data sheet states that the unique construction of the sensor allows direct installation into the road in a flexible format so that it can conform to the profile of the road.

3.2.6 WIM Data Loggers

All roadside data loggers for collecting WIM data generally have similar principle of operation. They all require power supply, loop card, WIM card, and communication unit installed in a small roadside cabinet. The following sections describe WIM data recorders installed at Site 9900.

3.2.7 iSINC Data Loggerim

The iSINC® data logger form the core of International Road Dynamics Inc. traffic and truck Weigh-In-Motion (WIM) systems. The iSINC® roadside data logger interfaces with in-road sensors and camera but is also capable of connecting with communication systems and AVI readers. The iSINC unit installed at the Site 9900 has a Quartz Sensor Module (KSM) for connecting with quartz WIM sensors. The KSM monitors, measures, and reports wheel or axle weight from multiple quartz sensors. It forwards road temperature data to the W3 (iSINC® WIM Control Unit) for use in temperature compensation. The data logger is capable of monitoring up to four quartz sensors simultaneously, reporting wheel or axle weights in real-time, forwarding road temperature data from an in-road temperature sensor, and producing real-time sensor signal traces on request.

3.2.8 TDC WIM Data Logger

The TDC HI-TRAC® EMU3 data logger installed at the site is a third-generation data logger which includes 32 MB on-board flash memory and standard 8 GB micro SD Memory which is expandable to 32 GB. The manufacturer's data sheet indicates that the unit incorporates interfaces to both piezoelectric sensors, inductive loop sensors, and a road-installed temperature probe. The HI-TRAC ® EMU3 can be powered from either mains supply or solar panel and associated battery and charge regulator. The detection options include weigh-in-motion, axle classification, loop profiling classification, and cycle classification.

3.2.9 ADR WIM Data Logger

The ADR WIM data logger utilizes an ADR-WIM card from Peek Traffic, installed in ADR 3000 to enable the ADR 3000 classifier to emulate the dynamic weighbridge method of weighing commercial vehicles at high speeds while retaining the full functionality and ease of use of the ADR interface. The module enables collection of the vehicle's arrival time, vehicle speed and classification, gross vehicle weight, volumetric flow, individual axle weights and spacings. Also, collected are the gaps and headways – all in either binned or per-vehicle records.

3.2.10 Kistler WIM Data Logger

The manufacturer's data sheet indicates that the Kistler WIM Data Logger is specifically designed to process signals from the Lineas WIM sensors and can be easily integrated into an overall system. The data logger can process a wide range of traffic data like vehicle weight, axle loads, vehicle length, axle distances, vehicle imbalance, and driving behavior.

3.3 Data Collection

The various WIM equipment at Site 9900 were calibrated on April 19, 2016, and again on October 31/November 1, 2016. **Phase 1** of the data collection involved downloading PVR data every Wednesday_for all active WIM systems beginning Wednesday, April 20, 2016, to Wednesday, October 26, 2016. **Phase 2** of the data collection involved downloading PVR data every Wednesday from all active WIM systems beginning Wednesday, November 2, 2016, and continuing to the last Wednesday prior to the next calibration of Site 9900 slated for February 2017. Table 3.1 below shows the days in which the PVR data were collected since the initial calibration. Table 3.1 reveals that the TDC/Intercomp system was not active prior to November 1, 2016. In addition, for various reasons, some days have missing data.

TABLE 3.1 Days of Data Collection

Date	TDC/Quartz	ADR/Kistler	iSINC/Kistler	TDC/Intercomp
	Equipment			
4/19/2016	Site Calibration			
4/27/2016		✖	✖	
5/4/2016		✖	✖	
5/11/2016		✖	✖	
5/18/2016		✖	✖	
5/25/2016		✖	✖	
6/1/2016		✖	✖	
6/8/2016		✖	✖	
6/15/2016		✖	✖	
6/22/2016	✖	✖	✖	
6/29/2016	✖	✖	✖	
7/6/2016	✖	✖	✖	
7/13/2016	✖	✖	✖	
7/20/2016	✖	✖	✖	
7/27/2016	✖	✖	✖	
8/3/2016	✖	✖	✖	
8/10/2016	✖	✖	✖	
8/17/2016	✖	✖	✖	
8/24/2016	✖	✖	✖	
8/31/2016	✖	✖	✖	
9/7/2016	✖	✖	✖	
9/14/2016	✖	✖	✖	
9/21/2016	✖	✖	✖	
9/28/2016	✖	✖	✖	
10/5/2016	✖	✖	✖	
10/12/2016	✖	✖	✖	
10/19/2016	✖	✖	✖	
10/26/2016	✖	✖	✖	
10/31/11-1/2016	Site Calibration			
11/2/2016	✖	✖	✖	✖
11/9/2016	✖	✖	✖	✖
11/16/2016	✖	✖	✖	✖
11/23/2016	✖	✖	✖	✖
11/30/2016	✖	✖	✖	✖
12/7/2016	✖	✖	✖	✖
12/14/2016	✖	✖	✖	✖
12/21/2016	✖	✖	✖	✖
12/28/2016	✖	✖	✖	✖
1/4/2017	✖	✖	✖	✖
1/11/2017	✖	✖	✖	✖
1/18/2017	✖	✖	✖	✖
1/25/2017	✖	✖	✖	✖

3.4 Data Analysis

Following the acquisition of data, the first step was to match Class 9 vehicles passing on all the WIM systems under study. Appendix E shows sample of the results of the matched vehicles. A total of 698 Class 9 vehicles were matched in Phase 1 while a total of 413 Class 9 vehicles were matched in Phase 2 of this study. Some vehicles were not matched for various reasons including ghost axles, vehicles changing lanes, wrong classification, etc.

The statistical analysis was aimed at determining the degree of drift in weights following calibration. Ideally, the use of groundtruth data obtained by running a vehicle of known weight over the WIM systems at the site on the analysis dates would have been the proper method of determining weight drifts as reported by each WIM system being evaluated. Unfortunately, this method was deemed too expensive to undertake. Thus, the statistical analytical methods chosen were geared towards determining weekly inter-equipment and intra-equipment vehicle weights variations as recorded by each equipment.

The determination of inter-equipment differences in recording weights was accomplished through the use of confidence limit analysis and single factor analysis of variance (ANOVA). The intra-equipment variation was assessed using deviation of vehicle weights from daily averages. Following the matching of vehicles, the weight of each vehicle as reported by individual WIM system was averaged across all WIM equipment. The deviation from average (*Weight_Dev*) was then calculated as follows:

$$Weight\_Dev_i = \frac{Weight_i - Avg}{Avg} x100$$

The *Weight_Dev* of all vehicles recorded in a day were then averaged to get a single daily value that were then plotted in a time-series graph.

The weight measures used in the analysis were the Gross Vehicle Weight (GVW) and the Front Axle Weight (FAW) of Class 9 vehicles. The Class 9 vehicle type was chosen because it is the most prevalent heavy vehicle type on this highway. It was hypothesized that the front axle load of Class 9 vehicles is fairly stable given that tractor-trailer truck loads will mainly be distributed among Axles 2 through 5 and recorded gross vehicle weights would vary widely depending on the cargo carried by the truck.

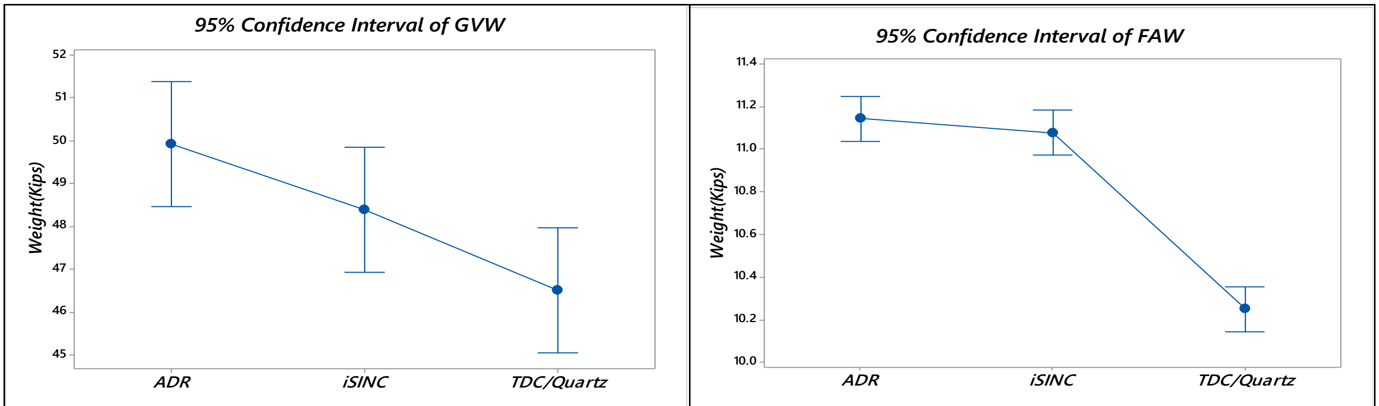
3.4.1 Analysis of Phase 1

As discussed earlier, Phase 1 refers to the data collected after April 19, 2016 calibration and ending prior to October 31, 2016 calibration. As was seen in Table 3.1 above, TDC/Quartz and TDC/Intercomp systems were not active for some time during this analysis period. Therefore, only three equipment are analyzed for a period beginning Wednesday, June 22, 2016 and ending on Wednesday, October 26, 2016. Sample matched raw data is shown in Appendix E.

3.4.1.1 Phase I Confidence Limit Analysis

Figure 3.2 shows the 95 percent confidence interval for the mean of the vehicle weights collected by the three equipment. The mean was calculated for all Class 9 trucks recorded for all Wednesdays during the Phase 1 analysis period. There were 698 Class 9 trucks recorded during the study period. As discussed earlier, the analysis is based on Gross Vehicle Weight (GVW) and Front Axle Weight (FAW). The results in Figure 3.2 show that TDC/Quartz WIM setup reports weight measurements lower than both ADR/Kistler and iSINC/Kistler equipment. The results further show that the trend is similar between gross vehicle weights (GVW) and front axle weights

(FAW). The width of the confidence interval looks to be similar for all equipment across GVW and FAW measurements, i.e., approximately 2,920 pounds for the GVW and about 223 pounds for the FAW. However, the variability in weight measurement can only be assessed by the analysis of variance (ANOVA) as discussed in the next section.



Factor	N	Mean	StDev	95% CI
ADR	698	49.93	20.32	(48.47, 51.39)
iSINC	698	48.38	19.88	(46.92, 49.84)
TDC/Quartz	698	46.52	18.77	(45.06, 47.98)

Factor	N	Mean	StDev	95% CI
ADR	698	11.14	1.38	(11.04, 11.28)
iSINC	698	11.08	1.48	(10.97, 11.18)
TDC/Quartz	698	10.25	1.40	(10.14, 10.36)

Figure 3.2 Phase 1 Confidence Interval Plots

3.4.1.2 Phase I Analysis of Variance

A single factor ANOVA (analysis of variance) method was used to determine if there is a significant difference in the means of the vehicle weights as reported by each equipment under study. Table 3.2 shows the *F*-statistic resulting from ANOVA.

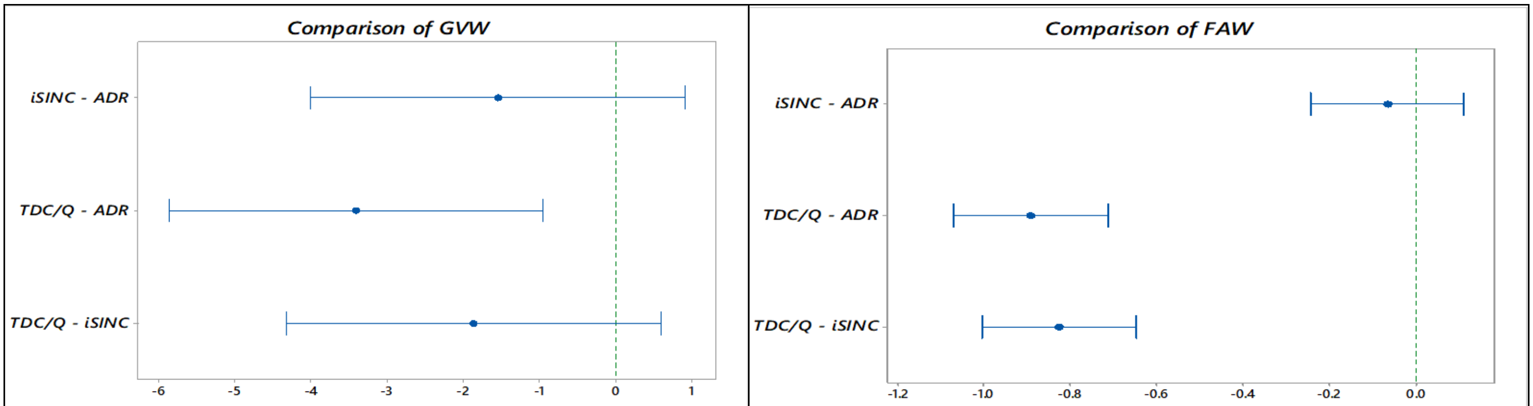
TABLE 3.2 Single Factor Analysis of Variance for Phase 1

Gross Vehicle Weight (GVW)						Front Axle Weight (FAW)					
Source	SS	DF	MS	F	*p*-value	Source	SS	DF	MS	F	*p*-value
Factor	4055	2	2027.6	5.24	0.005	Factor	344.6	2	172.3	85.5	0.000
Error	808472	2091	386.6			Error	4213.9	2091	2.0		
Total	812528	2093				Total	4558.6	2093			

The results show that there are differences in the mean weights as reported by the machines, particularly in the front axle weight. A follow-up pairwise comparison is thus necessary to determine the significance of the difference between all possible pairs of mean weights. The Tukey's range test based on studentized range distribution was used to compare all possible pairs of means as shown in Figure 3.3. It is prudent to conclude from the results displayed in Figure 3.3 that ADR/Kistler and iSINC/Kistler mean weights are not statistically significantly different, particularly for the front axle weight (FAW). However, the results in Figure 3.3 show that the means resulting from TDC/Quartz weight data are very different from those reported by ADR/Kistler and iSINC/Kistler WIM equipment.

3.4.1.3 Analysis of Weekly Variations in Phase 1

The confidence limit analysis and the analysis of variance discussed above were based on the average weight of all Class 9 vehicles recorded during the study period. To capture day-to-day variations in the performance of the three WIM equipment, a time-series analysis was performed.



Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
iSINC - ADR	-1.54	1.05	(-4.01, 0.92)	-1.47	0.306
TDC/Q - ADR	-3.40	1.05	(-5.87, -0.94)	-3.23	0.003
TDC/Q - iSINC	-1.86	1.05	(-4.32, 0.60)	-1.77	0.181

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
iSINC - ADR	-0.0663	0.0760	(-0.2441, 0.1116)	-0.87	0.658
TDC/Q - ADR	-0.8918	0.0760	(-1.0697, -0.7140)	-11.74	0.000
TDC/Q - iSINC	-0.8256	0.0760	(-1.0034, -0.6477)	-10.86	0.000

Figure 3.3 Tukey Pairwise Comparison of Phase 1 Means

Table 3.3 shows the deviation of vehicle weights from the daily averages calculated using the formula:

$$Weight\_Dev_i = \frac{Weight_i - Avg}{Avg} x100$$

where *Weight*$_i$ is the weight of a vehicle as recorded by Equipment *i*, *Avg* is the average weight calculated by averaging the weights reported by all four WIM equipment, and *Weight_Dev*$_i$ is the deviation (in percent) of the weight of Vehicle *i* recorded by Equipment *i*. Table 3.3 shows the results of the analysis while Figure 3.4 shows the graphical depiction of the data displayed in Table 3.3. Note that the percentages in Table 3.3 do not add up to 100%.

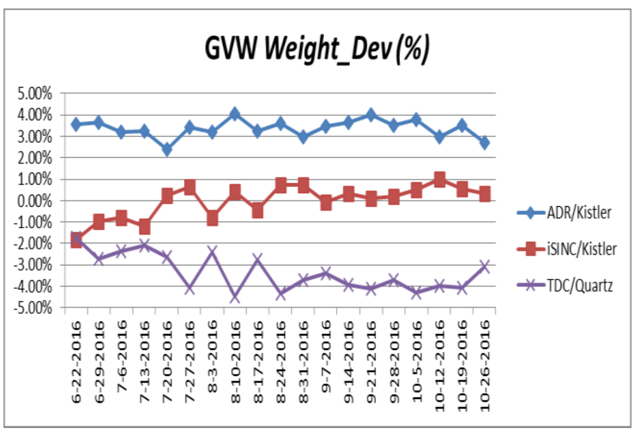
Examination of Table 3.3 and Figure 3.4 shows that the trend lines for Gross Vehicle Weight (GVW) and Front Axle Weight (FAW) are fairly similar. The TDC/Quartz setup consistently gives below average weight measures while ADR/Kistler setup gives above average measures, particularly for GVW. The weights recorded by iSINC/Kistler setup are in between the other two. As for daily weight measurements drifts, weights recorded by iSINC/Kistler setup seems to be drifting upwards while weights recorded by TDC/Quartz set up seem to be drifting downwards. Weights recorded by ADR/Kistler setup do not seem to be drifting upward or downward.

3.4.2 Analysis of Phase 2

As discussed earlier, Phase 2 data were collected after recalibration of the WIM equipment that was undertaken on October 31, 2016 and November 1, 2016. All four WIM equipment were for the first time made active and calibrated thus affording the research team an opportunity to evaluate all four WIM setups simultaneously. The analysis reported herein is truncated on the last Wednesday of January, i.e., January 25, 2017. However, data collection and analysis will was to be continued until the next calibration.

TABLE 3.3 Phase 1 Daily Variation of GVW and FAW

Date	GVW Weight_Dev (%)			FAW Weight_Dev (%)		
	ADR/Kistler	iSINC/Kistler	TDC/Quartz	ADR/Kistler	iSINC/Kistler	TDC/Quartz
6-22-2016	3.55%	-1.81%	-1.74%	3.37%	0.80%	-4.17%
6-29-2016	3.67%	-0.97%	-2.70%	2.79%	1.62%	-4.41%
7-6-2016	3.19%	-0.81%	-2.38%	2.68%	1.72%	-4.40%
7-13-2016	3.27%	-1.19%	-2.08%	2.98%	0.95%	-3.94%
7-20-2016	2.39%	0.25%	-2.64%	1.35%	2.14%	-3.49%
7-27-2016	3.42%	0.66%	-4.07%	3.49%	1.70%	-5.18%
8-3-2016	3.22%	-0.81%	-2.42%	2.95%	1.59%	-4.55%
8-10-2016	4.06%	0.40%	-4.46%	4.36%	2.84%	-7.20%
8-17-2016	3.23%	-0.45%	-2.78%	2.35%	1.75%	-4.10%
8-24-2016	3.62%	0.74%	-4.36%	2.79%	3.03%	-5.82%
8-31-2016	2.99%	0.74%	-3.73%	2.26%	3.88%	-6.14%
9-7-2016	3.49%	-0.09%	-3.39%	2.56%	2.09%	-4.65%
9-14-2016	3.63%	0.32%	-3.95%	3.77%	2.47%	-6.24%
9-21-2016	4.02%	0.08%	-4.11%	4.04%	2.23%	-6.27%
9-28-2016	3.52%	0.20%	-3.72%	3.61%	2.36%	-5.97%
10-5-2016	3.80%	0.52%	-4.31%	3.42%	2.47%	-5.88%
10-12-2016	3.00%	0.98%	-3.98%	2.31%	2.72%	-5.02%
10-19-2016	3.51%	0.58%	-4.09%	2.81%	3.05%	-5.86%
10-26-2016	2.72%	0.35%	-3.07%	3.22%	2.11%	-5.33%



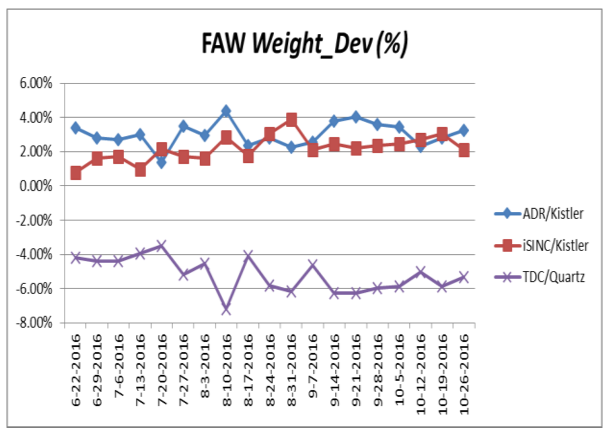
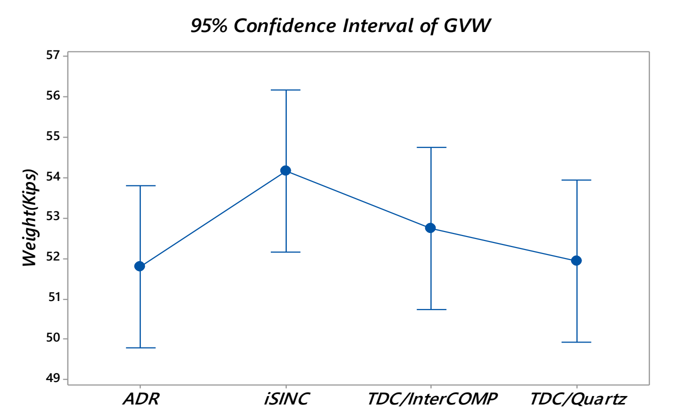


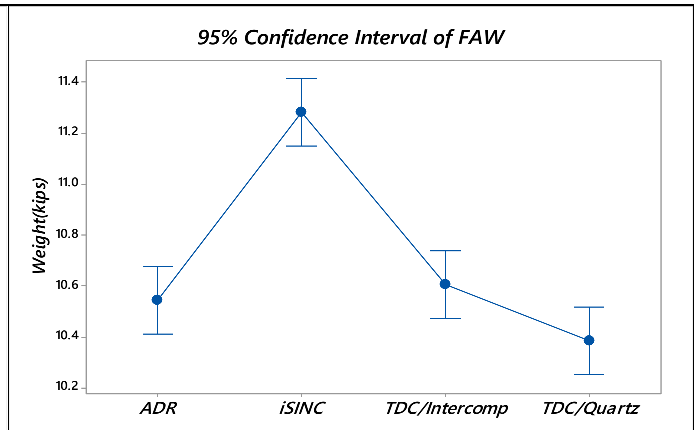
Figure 3.4 Plot of weight deviations of GVW and FAW for Phase 1

3.4.2.1 Phase 2 Confidence Limit Analysis

Figure 3.5 shows the 95 percent confidence interval for the mean of the three equipment. The mean was calculated for the average of all Class 9 trucks recorded on Wednesdays during the Phase 1 analysis period. There were 413 Class 9 trucks recorded during the study period. Similar to Phase 1, the analysis is based on Gross Vehicle Weight (GVW) and Front Axle Weight (FAW).



Factor	N	Mean	StDev	95% CI
ADR	413	51.80	20.42	(49.79, 53.81)
iSINC	413	54.18	21.65	(52.17, 56.19)
TDC/Intercomp	413	52.75	21.26	(50.74, 54.76)
TDC/Quartz	413	51.94	20.01	(49.93, 53.95)



Factor	N	Mean	StDev	95% CI
ADR	413	10.55	1.30	(10.41, 10.68)
iSINC	413	11.29	1.44	(11.15, 11.42)
TDC/Intercomp	413	10.60	1.40	(10.47, 10.74)
TDC/Quartz	413	10.38	1.38	(10.25, 10.52)

Figure 3.5 Phase 2 Confidence Interval Plots

The results in Figure 3.5 shows that iSINC/Kistler WIM set-up recorded the highest average weight compared to the other three WIM equipment. Again, as was revealed in Phase 1 analysis, the trend in GVW and FAW is fairly similar. It is equally important to note that the width of the confidence interval for all four WIM equipment weight data is about the same, i.e., approximately 4,000 pounds for the GVW and about 270 pounds for the FAW. However, the variability in weight measurements can only be assessed by the analysis of variance (ANOVA) as discussed in the next section.

3.4.2.2 Phase 2 Analysis of Variance

As in Phase 1 analysis, a single factor analysis of variance (ANOVA) method was used to determine if there is a significant difference in the means of the vehicle weights as reported by the equipment under study. Table 3.4 shows the F-statistic of the ANOVA.

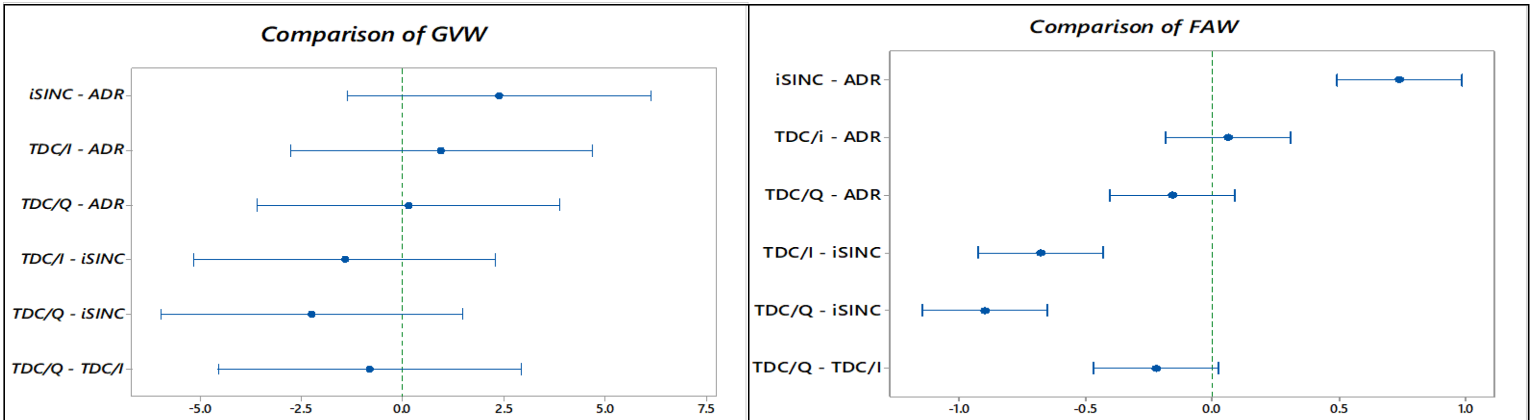
TABLE 3.4 Phase 2 Single Factor Analysis of Variance

Gross Vehicle Weight (GVW)						Front Axle Weight (FAW)					
Source	SS	DF	MS	F	*p*-value	Source	SS	DF	MS	F	*p*-value
Factor	1477	3	492.3	1.13	0.334	Factor	195.6	3	65.2	34.15	0.000
Error	715969	1648	434.4			Error	3145.7	1648	1.9		
Total	717446	1651				Total	3341.3	1651			

The summary of the data shown in Table 3.4 shows split results, in which the GVW means are not significantly different while the means of the front axle weight are statistically significantly different (*p*-value=0.000). Thus, it is important to follow-up the ANOVA analysis with the pairwise comparisons to determine which pairs contribute more to the difference. Figure 3.6 displays the Tukey Pairwise Comparison of the Means.

Closer examination of the results in Figure 3.6 confirms that the differences in gross vehicle weights (GVWs) recorded by the four WIM equipment are statistically insignificant based on pairwise comparisons. As for the front axle weights (FAWs), the differences are mainly attributable to iSINC equipment which recorded weights heavier that the other three equipment.

Take iSINC weights out of the picture and the pairwise comparisons seems to mirror the results of the GVWs analysis.



Difference of Levels	Difference of Means	SE of Difference	95% CI	*t*-value	Adjusted *p*-Value
iSINC - ADR	2.38	1.45	(-1.34, 6.10)	1.64	0.356
TDC/I - ADR	0.95	1.45	(-2.77, 4.68)	0.66	0.913
TDC/Q - ADR	0.14	1.45	(-3.58, 3.86)	0.10	1.000
TDC/I - iSINC	-1.43	1.45	(-5.15, 2.30)	-0.98	0.759
TDC/Q - iSINC	-2.24	1.45	(-5.96, 1.48)	-1.54	0.411
TDC/Q - TDC/I	-0.81	1.45	(-4.54, 2.91)	-0.56	0.944

Difference of Levels	Difference of Means	SE of Difference	95% CI	*t*-value	Adjusted *p*-value
iSINC - ADR	0.7394	0.0961	(0.4926, 0.9862)	7.69	0.000
TDC/I - ADR	0.0625	0.0961	(-0.1843, 0.3093)	0.65	0.916
TDC/Q - ADR	-0.1605	0.0961	(-0.4072, 0.0863)	-1.67	0.340
TDC/I - iSINC	-0.6769	0.0961	(-0.9237, -0.4301)	-7.04	0.000
TDC/Q - iSINC	-0.8999	0.0961	(-1.1466, -0.6531)	-9.36	0.000
TDC/Q - TDC/I	-0.2230	0.0961	(-0.4698, 0.0238)	-2.32	0.094

Figure 3.6 Phase 2 Tukey Pairwise Comparison of Means

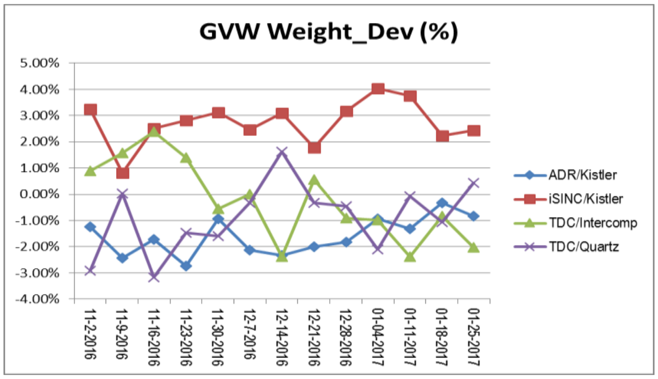
3.4.2.3 Daily Variation Analysis in Phase 2

Similar to Phase 1 analysis, the deviation of individual equipment weight from the average of the weights from the four equipment (*Weight_Dev*) in percent was used to analyze daily variations for the study period. The results are displayed in Table 3.5 and plotted in Figure 3.7.

TABLE 3.5 Phase 2 Daily Variation of GVW and Front Axle Weight (FAW)

Date	GVW *Weight_Dev (%)*				FAW *Weight_Dev (%)*			
	ADR/Kistler	iSINC/Kistler	TDC/Intercomp	TDC/Quartz	ADR/Kistler	iSINC/Kistler	TDC/Intercomp	TDC/Quartz
11-2-2016	-1.24%	3.26%	0.89%	-2.91%	-1.07%	4.90%	0.76%	-4.60%
11-9-2016	-2.44%	0.82%	1.59%	0.03%	-2.16%	4.79%	-0.14%	-2.50%
11-16-2016	-1.73%	2.51%	2.38%	-3.17%	-1.96%	6.46%	-0.26%	-4.24%
11-23-2016	-2.75%	2.82%	1.40%	-1.47%	-2.94%	6.13%	0.05%	-3.24%
11-30-2016	-0.95%	3.11%	-0.55%	-1.61%	-0.19%	5.35%	-1.55%	-3.62%
12-7-2016	-2.13%	2.46%	0.00%	-0.33%	-1.99%	4.42%	-1.68%	-0.75%
12-14-2016	-2.33%	3.10%	-2.39%	1.62%	-1.32%	6.33%	-2.97%	-2.04%
12-21-2016	-2.01%	1.78%	0.56%	-0.33%	-1.87%	4.69%	-0.21%	-2.61%
12-28-2016	-1.82%	3.18%	-0.91%	-0.45%	-1.99%	5.50%	-0.67%	-2.83%
1-4-2017	-0.95%	4.02%	-0.98%	-2.10%	-0.58%	4.11%	0.35%	-3.88%
1-11-2017	-1.31%	3.76%	-2.37%	-0.07%	-1.07%	5.84%	-2.12%	-2.66%
1-18-2017	-0.32%	2.22%	-0.84%	-1.06%	-0.48%	5.61%	-1.61%	-3.52%
1-25-2017	-0.84%	2.44%	-2.04%	0.44%	-0.27%	5.22%	-2.83%	-2.12%

Examination of Table 3.4 and Figure 3.7 shows that the trend lines for Gross Vehicle Weight (GVW) and Front Axle Weight (FAW) are fairly similar. The iSINC/Kistler setup consistently gives above average weight measures compared to the other three WIM equipment. The deviations of the other three equipment – i.e., ADR/Kistler, TDC/Intercomp, and TDC/Quartz – seems to bunch together below the average. Furthermore, iSINC/Kistler and ADR/Kistler seems to operate on a narrow range of 0 to 3 percent from daily averages while TDC/Intercomp and TDC/Quartz have a wider range of 0 to 5 percent. The results in Figure 3.7 also show that the trend line for iSINC/Kistler and ADR/Kistler is somewhat flat while the trend line for TDC/Intercomp seems to drift downward while the trend line for TDC/Quartz seems to drift upward.



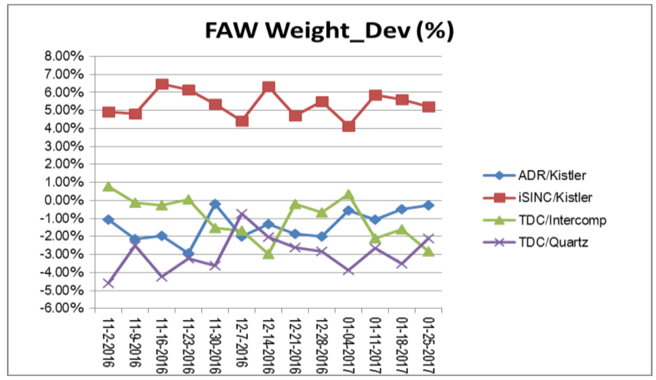


Figure 3.7 Plot of Weight Deviations of GVW and FAW for Phase 2

3.5 Conclusions and Recommendations

This study was aimed at evaluating the performance of WIM data collection equipment installed at the Test Site No. 9900 on Capital Circle Road. There were five WIM data loggers connected to three different types of WIM sensors at the test site. The WIM data loggers and sensors were installed as follows: (1) TDC data logger connected to TDC quartz sensors, (2) Kistler data logger connected to Kistler sensors, (3) ADR 3000 WIM data logger connected to Kistler sensors, (4) iSINC WIM data logger connected to Kistler sensors, and (5) TDC data logger connected to Intercomp strip scales. The WIM equipment at Site 9900 were calibrated on April 19, 2016 and again on October 31/November 1, 2016. **Phase 1** of the data collection involved downloading PVR data every Wednesday from all active WIM systems beginning Wednesday, April 20, 2016 to Wednesday, October 26, 2016. **Phase 2** of the data collection involved downloading PVR data every Wednesday from all active WIM systems beginning Wednesday, November 2, 2016 and continuing to the last Wednesday prior to the next calibration of Site 9900 slated for end of February 2017.

Comparison of the results of Phase 1 analysis to Phase 2 analysis seems to suggest that calibration has a major influence on the longitudinal performance of the WIM equipment at Site 9900. For example, following Phase 1 calibration on April 20, 2016, the 95 percent confidence interval was 2,920 pounds for GVW and 223 pounds for FAW. The 95 percent confidence interval increased to 4,000 pounds for GVW and 270 pounds for FAW following Phase 2 calibration on October 31/November1, 2016. The effect of calibration on equipment performance is further heightened by considering the fact that in Phase 1, ADR and iSINC had fairly similar performance but that changed in Phase 2 with iSINC showing performance fairly different from ADR/Kistler, TDC/Intercomp and TDC/Quartz.

The analysis results further suggest that there is an element of drift in weight measurements over time. In Phase 1, the gross vehicle weight measurements by TDC/Quartz seem to have been drifting downward while in Phase 2, the weight values were drifting upward. Similarly, TDC/Intercomp weight values were drifting downward in Phase 2[3]. The iSINC/Kistler weight values were drifting upward in Phase 1 but barely so in Phase 2. The only WIM equipment set-up not showing perceptible degree of drift was ADR/Kistler.

While this study clearly shows the major effect calibration has on equipment performance as well as possible drift in equipment performance, it is difficult to conclude what are the effects of seasonal and temperature changes on equipment performance. Moreover, the WIM data loggers were hooked up with different WIM sensors (Kistler, Quartz, and Intercomp) thus confounding the effect a sensor has over the weight measurements. Future study can be designed to determine the effect of sensors on daily variation of weights and weight drifts that were observed both in Phase 1 and Phase 2.

[3] TDC/Intercomp was not active during Phase 1 analysis period.

TASK 4: EVALUATION OF SEALANTS FOR TTMS USE

4.1 Purpose and Scope

Consistent with the Transportation Data and Analytics Office desire to improve the quality and cost-effectiveness of traffic data collection, adhesives used to seal loops and piezos at telemetered traffic monitoring sites were tested in a laboratory setting. Two sealants from two different vendors were supplied for testing to determine their efficacy for possible incorporation into the Florida Department of Transportation (FDOT) Approved Product List (APL). Many factors affect the durability of loop and piezo installations. These factors can be divided into three groups: (a) pre-installation factors, (b) installation factors, and (c) post-installation factors. Pre-installation factors include site selection, pavement characteristics, drainage characteristics, site topography, traffic characteristics, material selection and handling, weather conditions, and equipment and skill level of crew. Installation factors that may affect the durability of a TTMS site include site inspection, groove cutting, preparation, and placement of the sensor in the groove, as well as adhesive mixing and pouring. Post-installation factors that should be controlled to ensure durability of the sensors include curing time and the time lapse prior to opening of lanes to traffic.

Of all the factors mentioned above, the material characteristics of the adhesives used for installation of loops/piezos generally have the largest influence on the durability of a TTMS site. Consequently, it is important that adhesive materials approved by the Florida Department of Transportation for use on Florida highways should at all times exhibit the same characteristics that got them approved in the first place. To this end, the two supplied adhesive materials were evaluated through numerous lab tests.

4.2 Characteristics of the Sealants Submitted for Evaluation

As indicated earlier, two sealants were supplied to the FDOT Springhill Office for testing purposes. Originally, one batch was supplied and shipped to the FDOT Gainesville Materials Laboratory where the tests were to be conducted. Subsequently, additional materials were ordered and shipped directly to Gainesville in order to conduct all necessary tests to determine the physical and mechanical characteristics of the supplied materials. The following sections describe the characteristics of the materials submitted for testing.

4.2.1 FastPatch by Willamette Valley Company

FastPatch produced by the Willamette Valley Company headquartered in Eugene, Oregon, is an adhesive supplied in three parts: sand, resin, and hardener. According to the manufacturer's technical data sheet, for cold climates, a fourth part, i.e., FastPatch Kicker, which is sold separately, can be added to the mix in order to speed up the curing process. Based on the information from the manufacturer's Technical Data Sheet, FastPatch is not uniquely designed for use in loops and piezo sealing but rather for a wide range of use, including roadway patching and repair of holes in parking lots, warehouses, and sidewalks. FastPatch is a polymer material that can be categorized as a two-part epoxy. Appendix G displays the manufacturer's Technical Data Sheet.

4.2.2 QFQ 700 Summer by Global Resins Limited

The QFQ 700 Summer sealant is a polyurethane material specifically for use in piezo quartz sensors installation. The material is produced by the Global Resins Ltd headquartered in the United Kingdom. It is supplied in 4kg kits in two parts – resin and hardener – which are mixed in the ratio of 7.22:1 by weight or 7:53:1 by volume. The manufacturer's Technical Data Sheet indicates that the set time of this material is 10-15 minutes but it might take up to 2 days to fully cure. The shelf life on this material is listed as 12 months. Appendix H shows the Technical Data Sheet for this product.

4.3 Laboratory Testing of the Sealants

The services of the testing laboratory operated by the Florida Department of Transportation State Materials Office in Gainesville were utilized in conducting all the necessary tests. The American Society of Testing and Materials (ASTM) tests standards were adapted for testing these sealants used for installation of loops and piezoelectric sensors. The tests that were to be performed were aimed at examining the performance of these materials during working time and the materials resistance under subjection to different forces while the material is in service. The physical and mechanical characteristics of the sealants were to be assessed by performing the following tests: Vicat set time, viscosity, water absorption, hardness, adhesive strength, compressive strength, strain, modulus of elasticity, flexural bond strength, and peak exothermic temperature. However, due to various issues arising at the Gainesville lab only five tests were conducted, i.e., viscosity, water absorption, Shore D hardness, peak exothermic temperature, and adhesion strength. The results discussed below and the conclusions made thereof are based on the test results and experience with similar materials tested in the past.

4.3.1 Viscosity

The workability of an adhesive in an uncured state can be estimated by measuring its viscosity. The ASTM D 4016-14 procedures were used in measuring the viscosity of the test samples. The ASTM D 4016-14 is standard laboratory test method for viscosity of chemical grouts by Brookfield Viscometer. Viscosity is the term used to express the coefficient of internal friction resistance to fluid flow or mobility. A Brookfield digital rheometer shown in Figure 4.1 was used to measure the fluid parameter of shear stress and viscosity at a given shear rate.

A small sample of about 500 mL was mixed and placed in a cylinder. The cylinder was then immediately placed under the viscometer before the sample started curing. A rotating spindle attached to the viscometer was then lowered into the material. Viscosity measurements were then read directly from the screen attached to the viscometer. It should be noted that different spindles were used for different ranges of viscosity. Figure 4.2 shows the test results.

Figure 4.1 Brookfield Digital Rheometer

The results in Figure 4.2 show that FastPatch sealant is the less viscous than *QFQ* sealant mainly because one of its components is sand. The viscosity values were measured 30 seconds after mixing. It was noted by the lab technician that *QFQ 700* showed characteristics of "fast setting up and heating up". Compared to other materials that were tested previously, the viscosity measurements of these two materials are in the mid-range.

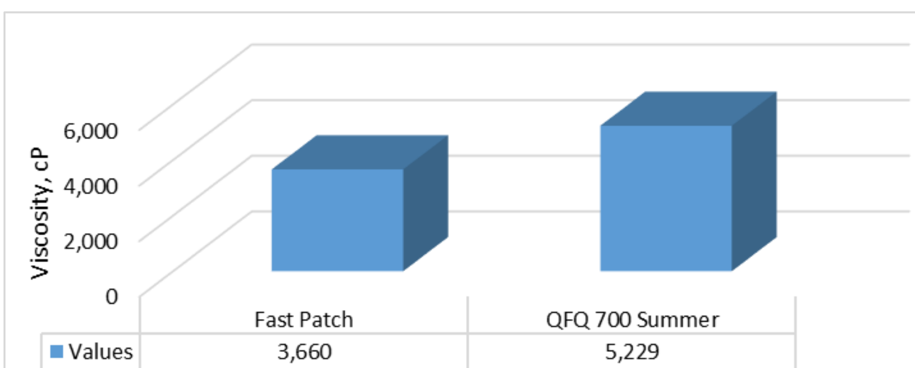


Figure 4.2 Viscosity Test Results

4.3.2 Water Absorption

Water absorption in a sensor installation can degrade the properties of the sealant. The water absorption of the test samples was conducted in accordance with ASTM 570-98. Test specimens 2-inch in diameter and $\frac{1}{8}$-inch thick were made as shown in Figure 4.3 and then conditioned in the oven set at 110°F for 24 hours. They were next cooled, weighed, and immersed in a container of distilled water maintained at 72°F for 24 hours. At the end of 24 hours, the specimens were removed from the water one at a time and then all surfaces were wiped off with a dry cloth and weighed immediately. The water absorption value of each specimen was calculated using the following formula:

$$Water\ Absorption\ (\%) = \frac{wetweight - conditionedweight}{conditioned\ weight} x100$$

Figure 4.3 Water Absorption Test Specimens

Figure 4.4 shows that both sealants had positive water absorption rates meaning that their samples wet weights were higher than their dry weights. Compared to the results of previous studies, the water absorption rate of FastPatch sealant is in mid-range while *QFQ 700* sealant has favorably water absorption characteristics – i.e., less than most of the materials tested in the past

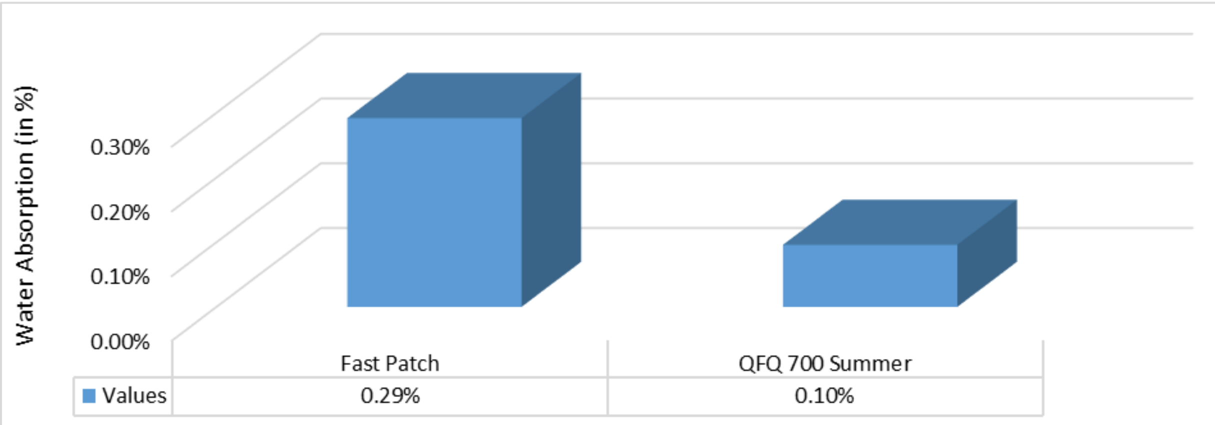


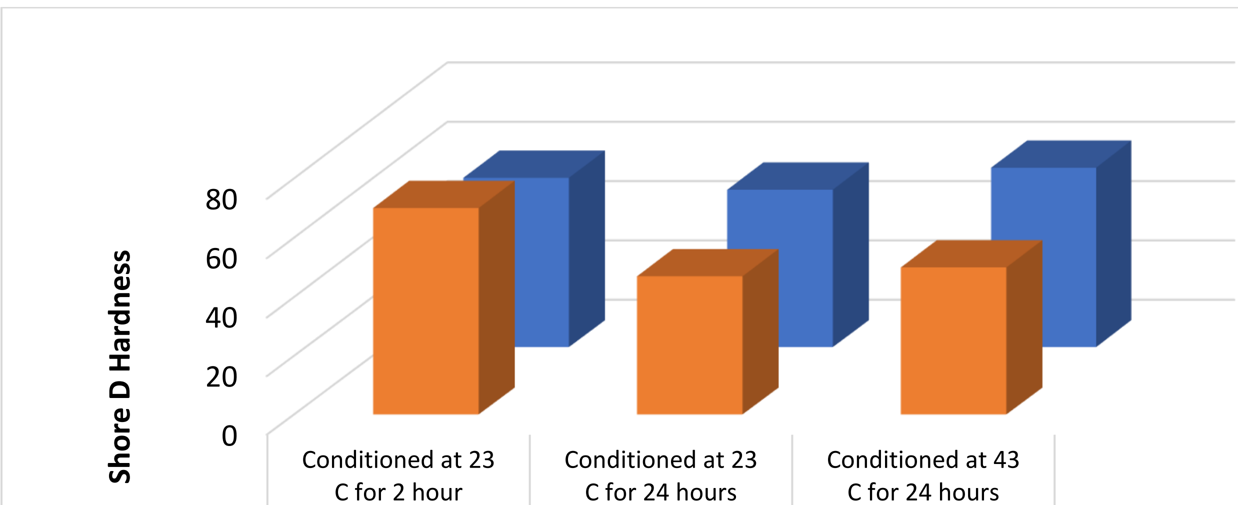
Figure 4.4 Water Absorption Test Results

4.3.3 Hardness

Hardness is defined as the ability of a material to withstand scratching or indentation by another hard body. Measurement of this property can only be relative to other materials and is given in the form of hardness number with no units. The hardness tests were conducted in accordance with ASTM D 2240-05. Six (6) test specimens of 2.6-inch diameter and 0.65-inch thick were molded and were left to cure. The hardness of two specimens were measured at one hour at 72^{o}F, two samples were measured at 24 hours after molding at 72^{0}F. The last two samples conditioned for 24 in oven set at 110^{0}F and then measured after being cooled to 72^{0}F. The measurements were taken using a Rex Gauge Durometer shown in Figure 5.5 which measures Shore D hardness. The results of the hardness tests are shown in Figure 5.6.

Figure 4.5 Shore D Hardness Tester

The results in Figure 5.6 show that the two sealants display relatively similar hardness characteristics. These results are comparable to those obtained in previous studies.



	Conditioned at 23 C for 2 hour	Conditioned at 23 C for 24 hours	Conditioned at 43 C for 24 hours
Fast Patch	70.02	47	50
QFQ 700 Summer	57.2	53.2	60.6

Figure 4.6 Shore D Hardness Test Results

4.3.4 Peak Exothermic Temperature

The peak exothermic temperature reached and the time it took to reach peak temperature were conducted using ASTM D 2471-99. As shown in Figure 5.7, two holes 1-inch in diameter and 1½-inch deep were drilled into an asphalt concrete sample[4]. Thermocouples were then inserted

[4] The asphalt concrete specimen was of Type SP-12.5 according to Superpave Mix Design. More information about Superpave Mix Design can be obtained from http://www.dot.state.fl.us/specificationsoffice/Implemented/SpecBooks/2014/Files/334-114.pdf

½-inch depth into the holes prior to pouring sealant which was generally mixed for 5 minutes. The center surface of the sealant was probed every 15 seconds with an applicator stick which allowed to record the gel time as the elapsed time from the start of mixing. The time and temperature were recorded until the temperature started to drop. The highest temperature reached was recorded as the peak exothermic temperature and the accompanying time was recorded as peak exothermic time, i.e., the elapsed time from the start of mixing when the exothermic temperature was reached.

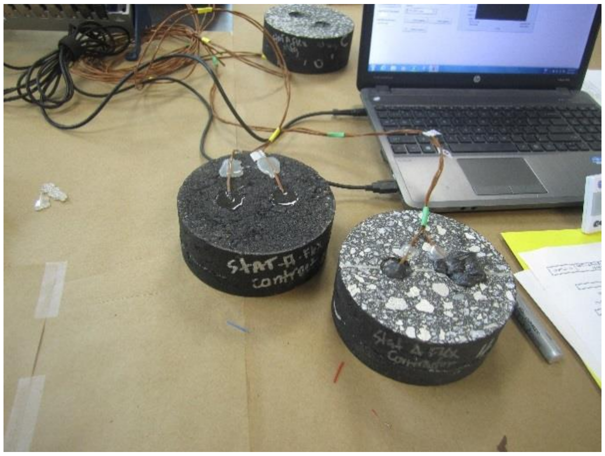


Figure 4.7 Peak Exothermic Test Setup

Compared to previous tests, the results displayed in Figure 8.8 shows that both FastPatch and *QFQ 700* sealants generate a reasonable amount of heat. In previous studies, some sealants generated upwards of 140^0F of heat. Peak exothermic temperature is a concern if the temperature generated is so high as to melt insulation of loops. Based on these test results, the peak exothermic temperatures are within tolerable range. The Oven and Omega 8 voltmeter were used for conducting the heat transfer test. It should be noted that this test did not measure heat transfer from sealant to the sensor. Field observations have shown that sensor outputs at high temperature are different compared to normal temperatures. It is therefore important for a sealant to have less ability to transfer heat to the sensor.

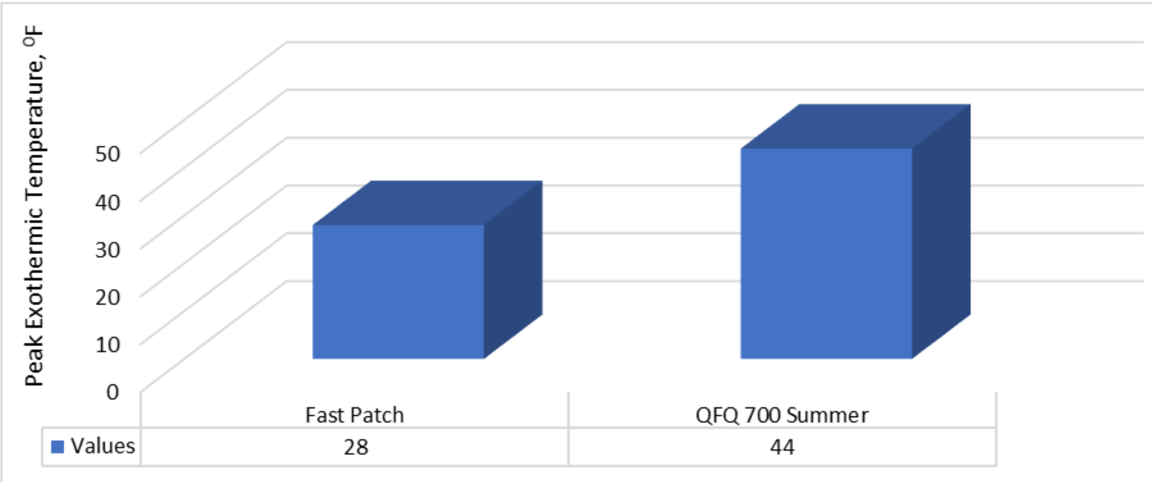


Figure 4.8 Peak Exothermic Test Results

4.3.5 Pull-off Adhesion Strength Test

The adhesion strength test was performed to measure the bonding between the sealant and the pavement. The test was performed according to the American Society of Testing and Materials ASTM D7234-12. A core was cut from asphalt pavement and used as a substrate which was then coated with respective sealant using a standard coating thickness of ¼-inch. Three circular holes were drilled on each core and a 20-mm diameter dolly was attached using commercially available gorilla glue as shown in Figure 4.9.

Figure 4.9 Pull-off adhesion test specimens

The specimens were then allowed to cure for 24 hours at 72^0F. The self-aligning Type V hydraulic portable tester was connected to the dollies and used to exert the greatest tensile force that a surface area can bear before material is detached. The final pulling force and the nature of failure was qualified using guidance shown in Figure 4.10.

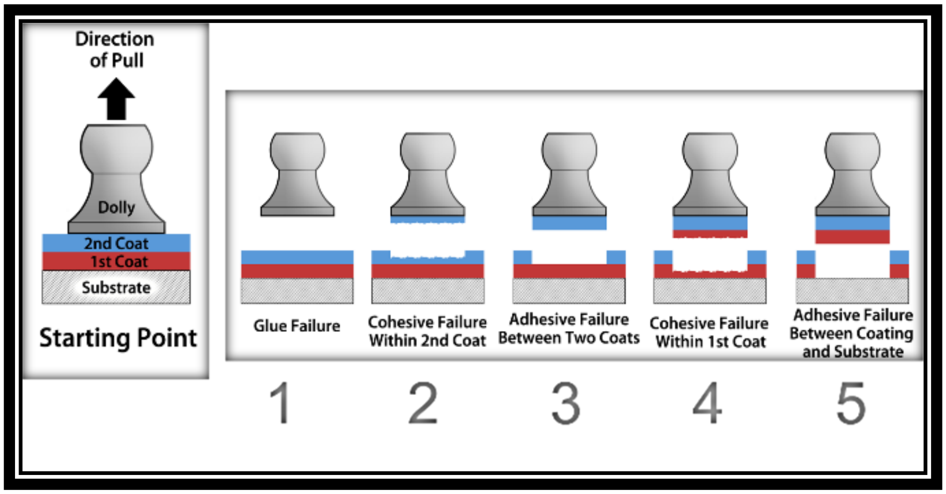


Figure 4.10 Types of Failures

The results of pull-off adhesion test on a concrete substrate indicated that FastPatch experienced glue failure in Position 1 and Position 2 while in Position 3, the reading was 287 psi.

As for the *QFQ 700* sealant, it experienced substrate failure in all Position 1, 2, and 3. The results of tests on an asphalt substrate showed that for FastPatch the dolly pulled off during scoring at Position 1, 2, and 3 while *QFQ 700* experienced substrate failure at Position 1 and 2 while the dolly pulled of immediately without any resistance at Position 3. These results are well below the results found in previous studies.

4.4 Conclusions and Recommendations

The evaluation of the laboratory test results reveals that the FastPatch sealant and the *QFQ 700* sealant have physical properties similar to other sealants in their category that were previously tested. As seen in Appendix C[5], bonding materials for loop and piezo installation generally fall in three main categories – epoxies, polyurethanes, and acrylics. The FastPatch sealant is an epoxy-based material while the *QFQ 700* sealant is a polyurethane-based material. Epoxies are associated with high hardness behavior, high compressive strength, and with high modulus of elasticity. Epoxies were also found to have relatively higher peel strength. Polyurethanes are generally associated with high hardness behavior but with lower compression strength and lower modulus of elasticity. Previous laboratory test results further suggested that polyurethanes have the lowest peel strength among all bonding materials. The *QFQ 700* sealant seems to display these negative properties when subjected to pull-off adhesion strength test with asphalt substrate.

Based on the literature review, previous test results of similar sealants, previous field observations of the performance of sealants, and the current laboratory test results reported herein, it is recommended that the Florida Department of Transportation should hold off on approving the FastPatch and the *QFQ 700* sealants until they have been subjected to field installation and evaluation. The FastPatch sealant is an epoxy-based material supplied in three parts – sand, resin, and hardener – similar to *G78* sealant which has not been performing well in some TTMS field installations. In addition, the *QFQ 700* sealant is a polyurethane-based material similar to *PU200* sealant that was recommended for removal from the FDOT approved product list more than a decade ago[6] because of premature failures in some TTMS field installations. Thus, it is recommended that field performance of FastPatch and *QFQ 700* sealant be longitudinally observed over a number of years prior to making a decision on the suitability of the use of these products in Florida.

[5] Extracted from Moses, R. & T. Sando. "Evaluation of Bonding Materials Used in Piezoelectric Axle Sensor Installation." *Final Report, Contract BD-313,* Florida Department of Transportation, Tallahassee, FL, July 2003.

[6] Ibid.

APPENDIX A – LAYOUT OF THE TEST SITE

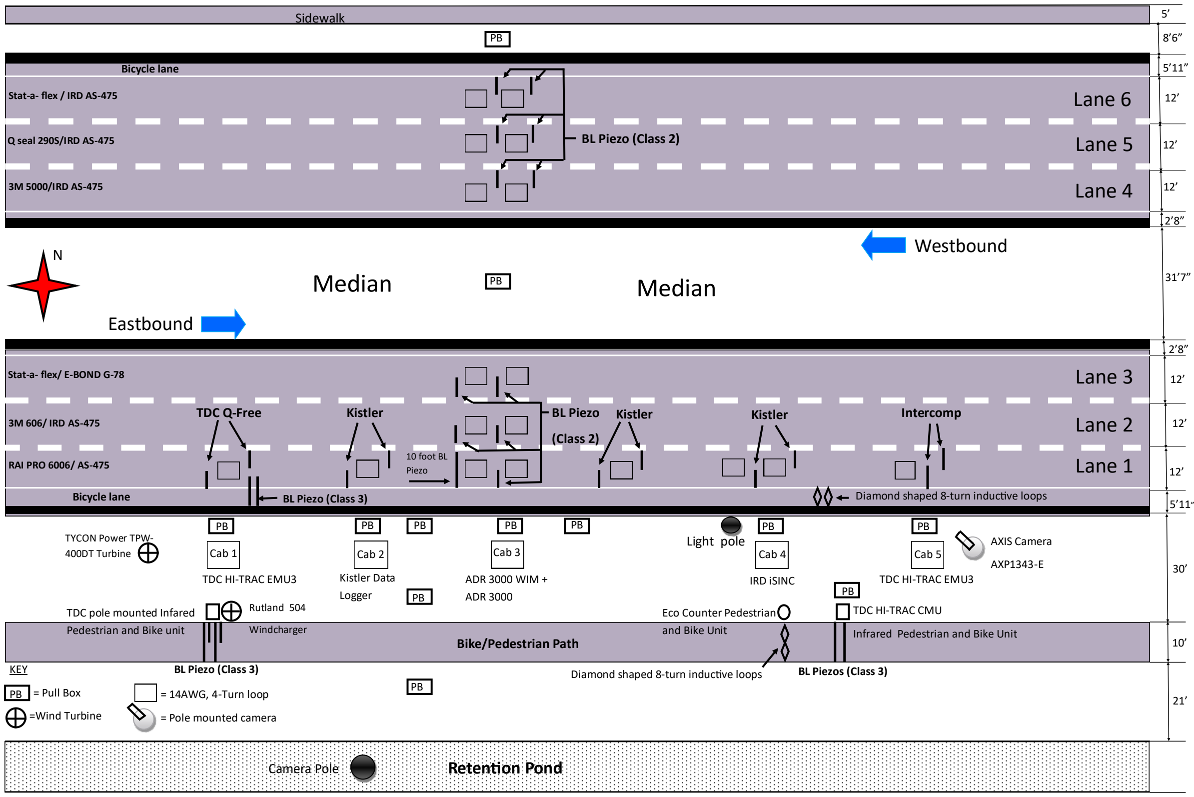


Figure A-1. Layout of the Test Site

APPENDIX B – VEHICLE CLASSIFICATION TABLES

TABLE B-1. MetroCount Classification Scheme- Scheme F2*

Class	Type	Axles	Axle spacing (ft)								
			SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	Aggregate
1	F1	2	1.0-6.0								1 (Light)
2	F2	2	6.0-10.2								
		3	6.0-10.2	6.0-18.0							
		4	6.0-10.2	6.0-18.0	0.0-6.0						
3	F3	2	10.2-13.0								
		3	10.2-13.0	6.0-18.0							
		4	10.2-13.0	6.0-18.0	0.0-6.0						
4	F4	2	20.0-40.0								2 (Medium)
		3	20.0-40.0	0.0-6.0							
5	F5	2	13.0-20.0								
6	F6	3	6.0-23.0	0.0-6.0							
7	F7	4	6.0-23.0	0.0-9.0	0.0-9.0						
		5	6.0-17.0	0.0-6.0	0.0-6.0	0.0-6.0					
		6	6.0-17.0	0.0-6.0	0.0-6.0	0.0-6.0	0.0-6.0				
8	F8	3	6.0-17.0	14.0-40.0							3(Heavy)
		4	6.0-20.0	0.0-6.0	6.0-40.0						
		4	6.1-17.0	14.0-40.0							
9	F9	5	6.0-22.0	0.0-6.0	6.0-40.0	0.0-12.5					
		5	6.0-22.0	0.0-6.0	6.0-23.0	1.1-23.0					
10	F10	6	6.0-22.0	0.0-6.0	0.0-40.0	0.0-11.0	0.0-11.0				
		7	6.0-22.0	0.0-6.0	0.0-40.0	0.0-13.0	0.0-13.0	0.0-13.0			
11	F11	5	6.0-17.0	11.0-25.0	6.0-18.0	11.0-25.0					
12	F12	6	6.0-22.0	0.0-6.0	1.0-25.0	6.0-18.0	11.0-25.0				
13	F13	7-9	0.0-40.0	0.0-40.0	0.0-40.0	0.0-40.0	0.0-40.0	0.0-40.0	0.0-40.0	0.0-40.0	
14	UNCLASSIFIABLE VEHICLE CLASS										

*Scheme F2 is an implementation of the FHWA's visual classification scheme as an axle-based classification scheme
*Car class: 2

TABLE B-2. iSINC Classification Table

	Class	Axles	Min axle spacings (cm)	Max axle spacings (cm)	Axle markings	List of minimum axle weights (kg)	List of maximum axle weights (kg)	Min gvw (kg)	Max gvw (kg)	Min length (cm)	Max length (cm)	Minimum distance front bumper to first axle, and of rear and last axle	Maximum distance front bumper to first axle, and of rear and last axle	Compliance data table
MOTORCYCLE	1	2	4	180	x x	0 0	32767 32767	46	100000	0	32767	0 0	32767 32767	1
CAR	2	2	180	305	x x	0 0	32767 32767	454	100000	0	32767	0 0	32767 32767	1
PICKUP,VAN,RV	3	2	305	406	x x	0 0	32767 32767	454	100000	0	32767	0 0	32767 32767	1
BUS	4	2	702	1222	x x	0 0	32767 32767	2722	100000	0	32767	0 0	32767 32767	1
	5	2	406	702	x x	0 0	32767 32767	454	100000	0	32767	0 0	32767 32767	1
2S1	8	3	305 336	702 1222	x x x	0 0 0	32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
BUS	4	3	702 4	1222 183	x x x	0 0 0	32767 32767 32767	2722	100000	0	32767	0 0	32767 32767	1
3 AXLE	6	3	183 4	702 183	x x x	0 0 0	32767 32767 32767	2722	100000	0	32767	0 0	32767 32767	1
	3	3	305 183	406 762	x x x	0 0 0	32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
	2	3	183 183	305 762	x x x	0 0 0	32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
2D	5	3	406 183	702 762	x x x	0 0 0	32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
3S1	8	4	305 336 61	702 1222 366	x x x x	0 0 0 0	32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
3S2	8	4	183 4 183	702 183 1343	x x x x	0 0 0 0	32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	7	4	183 3 3	702 183 397	x x x x	0 0 0 0	32767 32767 32767 32767	3629	100000	0	32767	0 0	32767 32767	1
	3	4	305 183 3	406 762 183	x x x x	0 0 0 0	32767 32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
	5	4	406 183 4	702 762 183	x x x x	0 0 0 0	32767 32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
	2	4	183 183 3	305 762 183	x x x x	0 0 0 0	32767 32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
3S2	9	5	183 4 183 4	793 183 1403 336	x x x x x	0 0 0 0 0	32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
32	9	5	183 4 183 336	793 183 702 823	x x x x x	0 0 0 0 0	32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
2S12	11	5	183 336 183 336	793 793 610 793	x x x x x	0 0 0 0 0	32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	3	5	305 183 3 3	406 762 183 183	x x x x x	0 0 0 0 0	32767 32767 32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
	5	5	406 183 4 4	702 762 183 183	x x x x x	0 0 0 0 0	32767 32767 32767 32767 32767	454	100000	0	32767	0 0	32767 32767	1
3S3	10	6	183 4 4 4 4	793 183 1403 336 336	x x x x x x	0 0 0 0 0 0	32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
3S12	12	6	183 4 336 183 336	793 183 793 732 793	x x x x x x	0 0 0 0 0 0	32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	10	7	183 4 406 4 4 4	510 183 1220 406 406 406	x x x x x x x	0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	13	7	31 31 31 31 31 31	1372 1372 1372 1372 1372 1372	x x x x x x x	0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	13	8	31 31 31 31 31 31 31	1372 1372 1372 1372 1372 1372 1372	x x x x x x x x	0 0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	13	9	31 31 31 31 31 31 31 31	1372 1372 1372 1372 1372 1372 1372 1372	x x x x x x x x x	0 0 0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	13	10	31 31 31 31 31 31 31 31 31	1372 1372 1372 1372 1372 1372 1372 1372 1372	x x x x x x x x x x	0 0 0 0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1
	13	11	31 31 31 31 31 31 31 31 31 31	1372 1372 1372 1372 1372 1372 1372 1372 1372 1372	x x x x x x x x x x x	0 0 0 0 0 0 0 0 0 0 0	32767 32767 32767 32767 32767 32767 32767 32767 32767 32767 32767	5444	100000	0	32767	0 0	32767 32767	1

TABLE B-3. ADR-FDOT Class Scheme

Class	Axles	Axle spacing (ft)							
		SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8
1	2	0.1-6.0							
2	2	6.0-10.0							
	3	6.0-10.0	6.0-25.0						
	4	6.0-10.0	6.0-25.0	0.1-6.0					
3	2	10.0-13.3							
	3	10.0-13.3	6.0-25.0						
	4	10.0-13.3	6.0-25.0	0.1-6.0					
	5	10.0-13.3	6.0-25.0	0.1-6.0	0.1-6.0				
4	2	23.0-40.0							
	3	23.0-40.0	0.1-6.0						
5	2	13.3-23.0							
	3	13.3-23.0	6.0-25.0						
	4	13.3-23.0	6.0-25.0	0.1-6.0					
	5	13.3-23.0	6.0-25.0	0.1-6.0	0.1-6.0				
6	3	6.0-23.0	0.1-6.0						
7	4	6.0-23.0	0.1-6.0	0.1-6.0					
8	3	10.0-23.0	11.0-40.0						
	4	10.0-23.0	11.0-40.0	2.0-12.0					
	4	6.0-23.0	0.1-6.0	6.0-44.0					
9	5	6.0-26.0	0.1-6.0	6.0-46.0	0.1-11				
	5	6.0-26.0	0.1-6.0	6.0-23.0	11-27.0				
10	6	6.0-26.0	0.1-6.0	0.1-46.0	0.1-11.0	0.1-11.0			
	7	6.0-16.7	0.1-6.0	13.3-40.0	0.1-13.3	0.1-13.3	0.1-13.3		
11	5	6.0-26.0	11.0-26.0	6.0-20.0	11.0-26.0				
12	6	6.0-26.0	0.1-6.0	11.0-26.0	6.0-24.0	11.0-26.0			
13	8	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	
	9	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0	1.0-45.0
15	DEFAULT - ALL VEHICLES THAT DO NOT FIT THE ABOVE CATEGORIES								

APPENDIX C – SURVEY QUESTIONNAIRE

A Survey of State DOT's Experience with Operation of Traffic Monitoring Sites, and Traffic Data Quality Control and Assurance

This survey is being conducted on behalf of the Florida Department of Transportation, Transportation Statistics Office, and is aimed at soliciting input from your organization on the subject topics. The survey is divided into three parts – installation issues, maintenance issues, and data quality control and assurance issues. Please fill in the information to the best of your knowledge. Your cooperation is fully appreciated.

A. Installation of Traffic Monitoring Sites

1. What data are you reporting to FHWA?
2. What technologies are you using to collect this data?
3. What non-intrusive devices are you using and what data are you collecting and reporting from these devices.
4. What factors do you consider in selecting the type and location of a traffic monitoring site?
5. Which sealants do you use for loop installation? For piezo installation?
6. What processes do you have in place to ensure that the sealants ordered for installation meet your specifications?
7. Do you generally use your in-house installation crew or pushbutton contractors?
8. Do you have DOT personnel present during installation? If not, how is the quality of the installation verified?
9. Do you record and keep installation notes such as sealant used, date of installation, etc.? If so, what information do you record, how do you recorded? How is this information stored, i.e. database, spreadsheet, etc.? Could you provide an example of the data and/or reports used?
10. What are your wire splicing standards when installing loops and/or piezos?
11. Do your require training/certifications for installation crews? If so, what training/certifications do you require?

B. Maintenance of Traffic Monitoring Sites

12. What is your maintenance schedule for realignment and recalibration of non-intrusive devices?
13. Do you inspect your traffic monitoring sites on a regular schedule or only when something goes wrong? What generally triggers inspection of the site? If there is a regular cycle, does it vary based on factors such as more frequent for high volume facilities or more frequent based on equipment type?
14. What is your schedule for calibration and/or validation of sites? What factors trigger a recalibration? What is the typical frequency of recalibration?
15. Have you developed advanced computer logic functions that alerts you of anomalies in field data or if the sensors are about to fail? Can you provide an example of them? How do you determine a sensor failure?
16. What is the typical life cycle of your inductive loops? Piezos?

17. Please enumerate types and modes of failures you frequently observe at a failed or failing site.
18. Do you have a WIM calibration procedure? Please provide us with a copy.

C. Data Quality Control and Assurance

19. To determine the accuracy of data collected, do you conduct ground truth studies? If yes, what method do you use to collect ground truth data of volume, speed, classification, and weight?
20. How frequently do you conduct ground truth studies at a functioning site?
21. Do you have a uniform vehicle classification table for all classifiers or do you allow each vendor to tweak your classification table?
22. Do you implement a uniform classification table at all of your classification sites or do you employ different classification tables depending on the site? If so, what factors do you consider in implementing different classification tables for different sites?
23. Have you conducted detailed evaluation of the performance of your classification table (s)? If so, what are the type of classification errors you have observed? If possible, can you provide an example?
24. Recent changes in vehicle population (shorter vehicles, electric vehicles) are raising concerns regarding operation of traffic monitoring sites and data collected therefrom. Has your agency addressed this issue and how?
25. Have you conducted a study on accuracy, consistency, and reliability of data collected from your traffic monitoring sites over the years? If so, can you share the major findings of such a study with Florida DOT?
26. Do you use an automated or manual QC program to validate your data? If automated, what program are you using? Are you using this same program to validate WIM data? If not, what program/process are you using? If possible, please provide copies of these reports.
27. What kind of QA/QC software are you using to analyze and validate WIM and class count data? Is the software off the shelf or was developed in-house?

APPENDIX D – LIST OF RESPONDENTS

TABLE D-1. List of Respondents

First Name	Last Name	Job Title	Agency	State	Work Phone	Email Address
Howard	Helkenn	Highway Data Manager	Alaska Department of Transportation and Public Facilities	AK	907-269-0876	howard_helkenn@dot.state.ak.us
J.R	Lowry	GIS Tech – INT	Tennessee Department of Transportation	TN	615-253-2415	j.r.lowry@tn.gov
Marc	Antich	Manager	Indiana Department of Transportation	IN	2199382016	mantich@indot.in.gov
Susannah	Seal	Traffic Analysis Manager	Mississippi Department of Transportation	MS	601-359-7066	sseal@mdot.ms.gov
Bill	Hughes	Staff Engineer	Kansas Department of Transportation	KS	785-296-3841	bhughes@ksdot.org
Todd	Hadden	Traffic Statistician	Utah Department of Transportation	UT	801 243-7319	thadden@utah.gov
Mark	Catchpole	Program Manager	Arizona Department of Transportation	AZ	602-712-8596	mcatchpole@azdot.gov
Goro	Sulijoadiku sumo	Highways Planning Survey Engineer	Hawaii Department of Transportation	HI	8085872839	goro.sulijoadikusumo@hawaii.gov
Don	Butler	Transportation Planner III	Nebraska Department of Roads	NE	402-479-4520	don.butler@nebraska.gov
Tom	Schinkel	Traffic Monitoring System Program Manager	Virginia Department of Transportation	VA	804-225-3123	Tom.Schinkel@VDOT.Virginia.Gov
Becky	Duke	Traffic Data Collection and Analysis Supervisor	Montana Department of Transportation	MT	406-444-6122	bduke@mt.gov
Kent	Taylor	State Traffic Survey Engineer	North Carolina Department of Transportation	NC	919-771-2520	kltaylor@ncdot.gov
Mike	Merrill	Research Analyst Specialist	Minnesota Department of Transportation	MN	6513663863	michael.merrill@state.mn.us
Randy	Travis	Planning Data and Research Chief	Nevada Department of Transportation	NV	775-888-7158	rtravis@dot.state.nv.us
Deborah	Morgan	Supervisor, Traffic Monitoring	Maine Department of Transportation	ME	(207) 624-3606	deborah.morgan@maine.gov
Steven	Abeyta	Traffic Analysis Unit Manager	Colorado Department of Transportation	CO	3037579495	steven.abeyta@state.co.us
Steven	Jessberger	Senior Transportation Specialist	Federal Highway Administration	-	202-366-5052	steven.jessberger@dot.gov
Joshua	Joshua	Engineering Tech. 7	Louisiana Department of Transportation and Development	LA	225-242-4560	joshua.albritton@la.gov
Ben	Timerson	Program Manager, Trans. Data & Analysis	Minnesota Department of Transportation	MN	651-366-3855	benjamin.timerson@state.mn.us
Harimander	Khalsa	Planner IV	Arizona Department of Transportation	AZ	602-531-6436	hkhalsa@azdot.gov
Steven	Littlejohn	FTS Manager	South Carolina Department of Transportation	SC	803-737-0256	littlejosl@scdot.org
Lindsey	Pflum	Engineer 3	Ohio Department of Transportation	OH	6147524057	lindsey.pflum@dot.ohio.gov
Barry	Balzanna	Transportation Engineer IV ATR Manager	Maryland Department of Transportation	MD	410-545-5509	bbalzanna@sha.state.md.us
Lawrence	Whiteside	Supervisor	Michigan Department of Transportation	MI	517-373-2272	whitesidel@michigan.gov

TABLE D-1. (Cont'd)

First Name	Last Name	Job Title	Agency	State	Work Phone	Email Address
Ken	Lakey	Field Operations Manager	Washington State Department of Transportation	WA	360-570-2374	lakeyk@wsdot.wa.gov
Brian	Thompson	-	Ohio Department of Transportation	OH	405-990-0302	bthompson@odot.org
Dwight	Peters	Program Planner	Iowa Department of Transportation	IA	515-239-1197	dwight.peters@dot. iowa.gov
Elizabeth	Mayfield-Hart	Staff Traffic Information Systems Engineer	Arizona Department of Transportation	AR	501-569-2111	elizabeth.mayfieldhart@ahtd.ar.gov

APPENDIX E – SAMPLE OF MATCHED CLASS 9 VEHICLES

TABLE E-1. Sample of Matched Class 9 Vehicles

Date	Gross Weight (kips)					Percent Deviation From Average				
Date	Vehicle #	ADR	ISINC	TDC/ Intercomp	TDC/ Quartz	AVG	ADR	ISINC	TDC/ Intercomp	TDC/ Quartz
Wed. 01-25-17	1	41.80	42.60	39.84	45.86	42.52	-1.70%	0.18%	-6.32%	7.84%
	2	31.40	31.50	30.64	35.27	32.20	-2.50%	-2.19%	-4.84%	9.53%
	3	30.26	33.70	31.00	31.75	31.68	-4.47%	6.39%	-2.14%	0.22%
	4	73.43	76.80	75.60	74.52	75.09	-2.20%	2.28%	0.68%	-0.76%
	5	30.64	28.80	27.27	32.85	29.89	2.50%	-3.64%	-8.76%	9.90%
	6	67.17	70.70	64.24	66.36	67.12	0.07%	5.34%	-4.28%	-1.13%
	7	31.95	31.10	29.87	34.17	31.77	0.56%	-2.12%	-5.99%	7.54%
	8	31.55	30.80	30.29	32.63	31.32	0.75%	-1.66%	-3.28%	4.18%
	9	44.44	47.60	44.07	45.19	45.33	-1.95%	5.01%	-2.77%	-0.29%
	10	48.85	50.70	46.45	52.03	49.51	-1.32%	2.41%	-6.17%	5.09%
	11	73.99	77.50	71.30	74.52	74.33	-0.45%	4.27%	-4.07%	0.26%
	12	54.53	58.00	56.31	56.88	56.43	-3.36%	2.78%	-0.22%	0.80%
	13	64.81	68.20	63.32	65.48	65.45	-0.98%	4.20%	-3.26%	0.04%
	14	48.17	50.80	48.35	45.19	48.13	0.08%	5.55%	0.46%	-6.09%
	15	70.39	79.10	68.98	69.23	71.93	-2.13%	9.98%	-4.09%	-3.75%
	16	32.34	32.90	32.01	33.95	32.80	-1.42%	0.31%	-2.40%	3.51%
	17	79.83	83.10	82.10	74.96	80.00	-0.21%	3.88%	2.63%	-6.30%
	18	29.24	30.40	27.03	29.98	29.16	0.26%	4.25%	-7.32%	2.81%
	19	85.37	92.50	90.06	83.11	87.76	-2.72%	5.40%	2.62%	-5.30%
	20	62.51	64.90	61.97	64.15	63.38	-1.38%	2.39%	-2.23%	1.21%
	21	74.72	79.80	76.30	74.96	76.44	-2.26%	4.39%	-0.19%	-1.94%
	22	80.34	81.80	81.15	78.93	80.55	-0.27%	1.55%	0.74%	-2.02%
	23	29.24	28.20	27.78	29.10	28.58	2.30%	-1.33%	-2.80%	1.83%
	24	32.82	34.50	33.38	33.73	33.61	-2.35%	2.66%	-0.68%	0.37%
	25	33.14	33.60	32.45	31.53	32.68	1.42%	2.81%	-0.70%	-3.53%
	26	33.22	36.80	34.33	36.16	35.12	-5.43%	4.77%	-2.27%	2.94%
	27	85.03	86.70	87.02	82.67	85.35	-0.38%	1.58%	1.95%	-3.14%
	28	33.88	34.80	32.96	34.17	33.95	-0.22%	2.50%	-2.92%	0.65%
	29	32.04	33.50	32.61	28.66	31.70	1.07%	5.67%	2.85%	-9.60%
	30	72.74	74.90	71.76	71.43	72.71	0.05%	3.01%	-1.30%	-1.76%
	31	69.35	70.90	70.92	68.34	69.88	-0.76%	1.46%	1.49%	-2.20%

TABLE E-1. (Cont'd)

Date	Gross Weight (*kips*)						Percent Deviation From Average			
	Vehicle #	ADR	ISINC	TDC/ Intercomp	TDC/ Quartz	AVG	ADR	ISINC	TDC/ Intercomp	TDC/ Quartz
	32	36.28	34.70	32.76	37.26	35.25	2.92%	-1.56%	-7.06%	5.70%
	33	77.61	78.70	79.83	77.60	78.44	-1.05%	0.34%	1.78%	-1.06%
	34	45.55	45.70	44.22	44.75	45.06	1.09%	1.43%	-1.85%	-0.67%
	35	33.68	35.80	34.19	35.05	34.68	-2.89%	3.22%	-1.41%	1.07%
	36	81.05	81.90	82.32	81.57	81.71	-0.81%	0.23%	0.75%	-0.17%
					Daily Avg.		-0.84%	2.44%	-2.04%	0.44%

APPENDIX F – BOX PLOTS

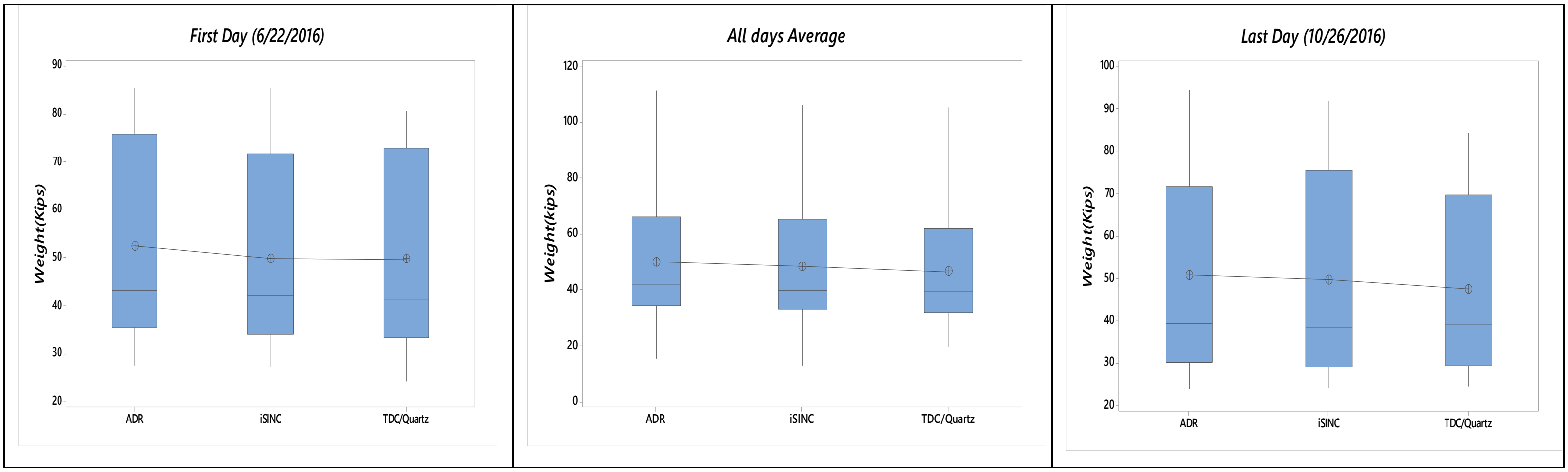


Figure F-1. Boxplots of Phase 1 Gross Vehicle Weight (GVW)

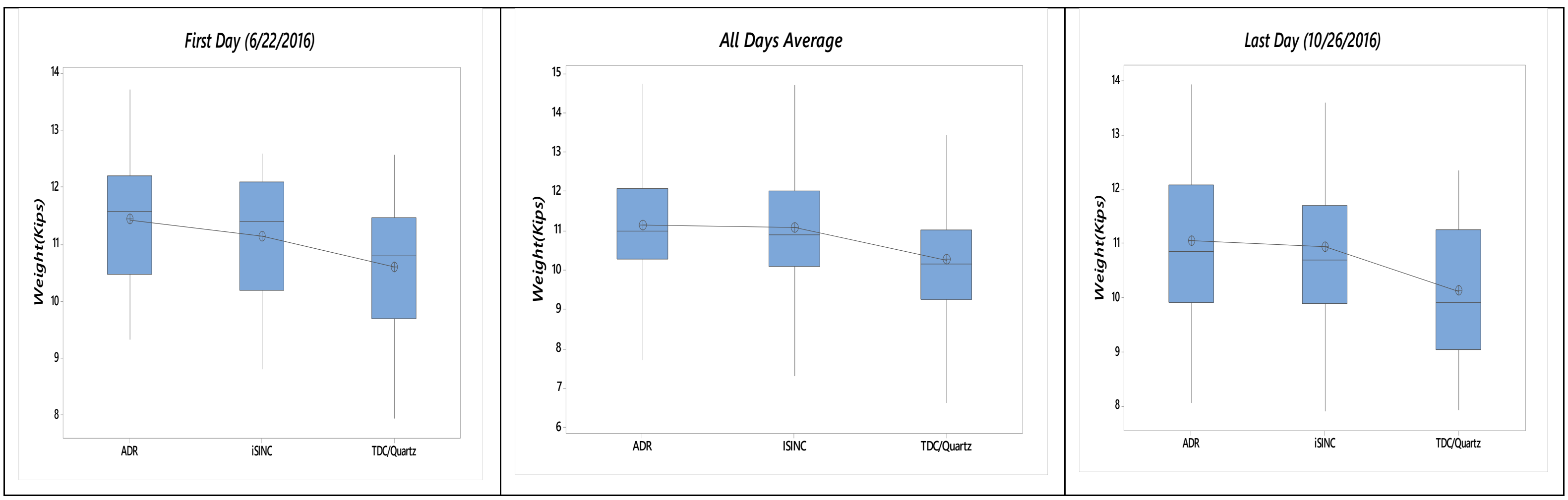


Figure F-2. Boxplots of Phase 1 Front Axle Weight (FAW)

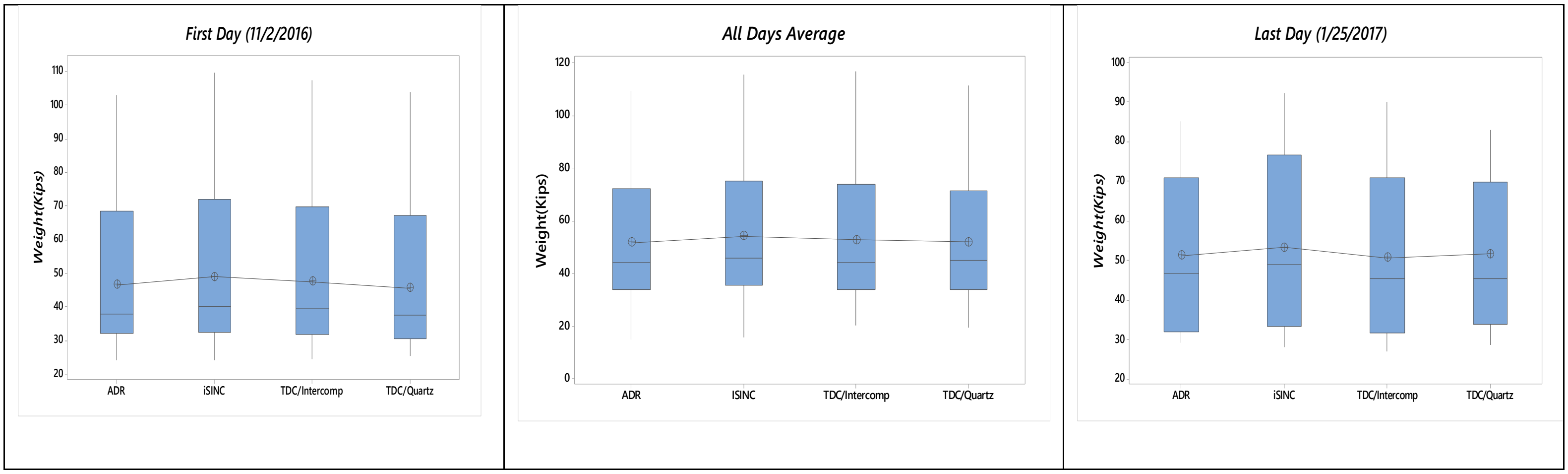


Figure F-3. Boxplots of Phase 2 Gross Vehicle Weight (GVW)

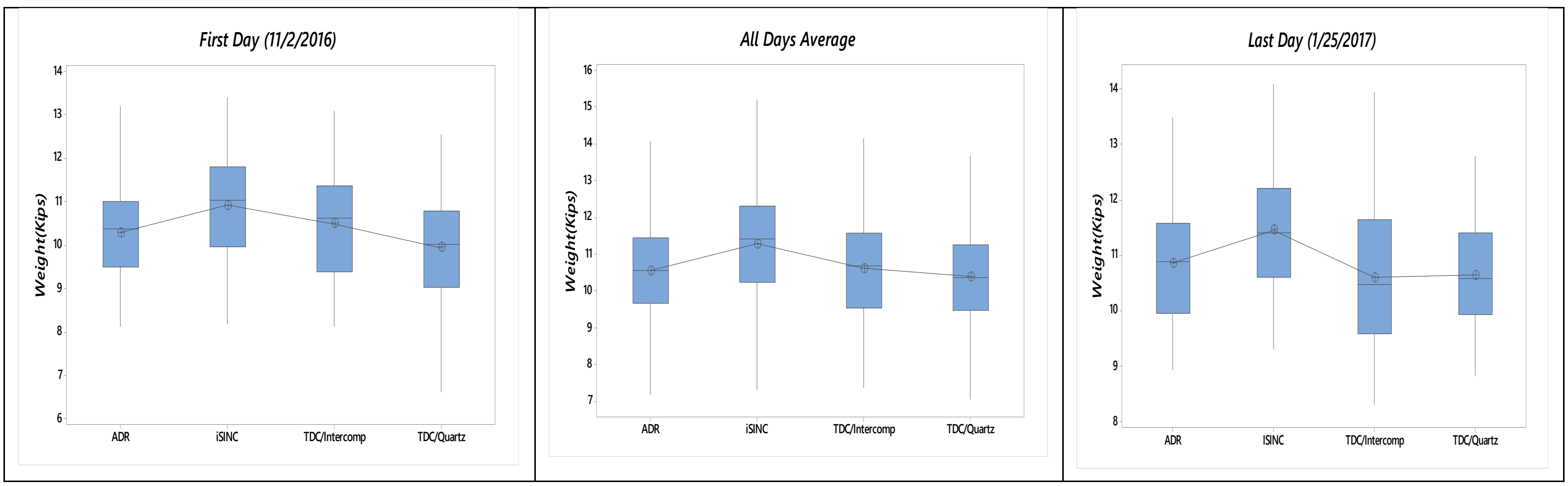


Figure F-4. Boxplots of Phase 2 Front Axle Weight (FAW)

APPENDIX G – *FASTPATCH* TECHNICAL DATA SHEET

Technical Data Sheet

W V C O

Willamette Valley Company

www.wilvaco.com

800.333.9826

Partnering through service, innovation, and integrity

FastPatch DPR Kit

Distressed Pavement Repair

DESCRIPTION

FastPatch DPR is an easy-to-apply, long-lasting repair material for distressed pavement. It is supplied in complete, ready-to-use kits with a polymer blend of recycled and renewable materials. Each kit comes with two color options of Gray or Black, and topping sand to blend repair areas with the surrounding pavement. It can be applied in warm conditions, or in cooler conditions with the aid of FastPatch Kicker accelerator, to form a permanent repair that is quickly ready for traffic.

WHERE TO USE

- **Roadways**–spalls, wheel path areas, approaches and departures
- **Parking Lots**–holes, walkways, broken areas
- **Warehouses**–floors, spalls, loading areas
- **Sidewalks**–trip hazards, walkways, "repair instead of replace"

FEATURES AND BENEFITS

- **Easy-to-Apply**—Mix with cordless drill, pour, & finish in minutes
- **Lasting Repair**—Excellent adhesion & absorbs impact
- **Open to Traffic Quickly**—Reduce traffic interruptions
- **Recycled & Renewable Materials**—Sustainable sources
- **Odorless**—100% solids & suitable for indoor applications
- **Freeze-Thaw Resistant**—Long term repair for colder climates

PACKAGING

5-gallon kit

COLORS

Gray or Black

YIELD

5-gallon kit = 3.0 US gal (11 Liters)

SHELF LIFE

1 year when properly stored.

STORAGE

Store and ship this product in a clean, dry, low-humidity, shaded or covered environment at 60-90° F (15-32° C).

TECHNICAL INFORMATION

Typical Properties:

VOC, lbs/gal (g/L), ASTM D 2369	0
Viscosity, cps, ASTM D 4878, mixed	500
Service Temperature, ° F (° C)	-30 to 170 (-34 to 77)
Potlife, min., 70° F (21° C)	9 minutes
Set Time In Mass, 70° F (21° C)	12 minutes
Tack Free Time In Mass, 70° F (21° C)	30 minutes
Tensile Strength, ASTM D 412	1100 psi
Elongation, ASTM D 412	60%
Hardness, Shore A, ASTM D 2240	90 A
Adhesion, ASTM D 7234	800 psi, 100% substrate failure

Process Parameters:

Ratio by Volume	1 to 1 (resin to ISO)
Application Temp ° F (° C)	40 to 105 (4 to 40)
Application Method	Mechanical mix & pour
Recommended Thickness	> 1/4 in. (0.635 cm)
Recommended Repair Area	< 16 ft2 (1.49m2).

Set Time:

Temp. °F (°C)	Set Time (min.)	With Optional FastPatch Kicker (1 oz.)
110 (40)	7	3
75 (21)	30	18
40 (10)	80	40

APPLICATION

PAVEMENT PREPARATION

1. Pavement must be structurally sound (200psi or greater according to ASTM D7234), clean (ASTM D4258), and dry (less than 5%, ASTM E1907).
2. Moisture or oil in repair areas will result in poor adhesion. Apply product only if surface is dry and ambient temperature is 5° F (3° C) above dew point.
3. Remove all contaminants (e.g., oil, dust, sand, moisture) from surface for proper adhesion.
4. For maximum adhesion, profile surface according to ICRI Guide 03732, to a minimum of CSP 3, by abrasive blasting.
5. Shape spall perimeter into a square by saw cut, 1-3 inches (2.54-7.6 cm) deep. Hammer (15 lb) repair area and remove debris. Remove all loose rebar. Exposed non-moving rebar can remain. Maximum recommended repair size is less than 16 ft^2 (1.49m^2).
6. Use a minimum 120 PSI continuously dry compressed air to blow out loose debris, dirt and dust prior to applying product. Moist pavement can be torched dry. If moisture returns immediately after torching, stop and do not install FastPatch in this area.
7. Use a steel bristle brush to remove dirt on vertical and horizontal pavement surfaces. Use a minimum 120 PSI continuously dry compressed air to blow out repair area, prior to applying product.
8. As necessary, plug all gaps or joints surrounding the repair area with foam.
9. Protect surrounding surfaces to the repair area with tape to prevent contamination.
10. Priming all surfaces with POLYPrime is recommended to strengthen bonding surface and maximize adhesion. Refer to primer TDS sheets for detailed instructions.
11. Honor all moving joints or moving cracks in the repair area by saw-cutting after FastPatch has cured or installing form board during application. Joints or cracks without movement do not require honoring. Contact manufacture for more details.

OTHER MATERIALS

1. Previously installed polymer materials must be tested to determine best method of preparation for acceptable adhesion. Typically, methods will include solvent cleaning, abrading, and vacuuming surfaces.
2. Avoid installing FastPatch on bare ground, dirt, grass or other non-structural surfaces. Applications surfaces must be dry.

PROCESSING

1. Precondition Kits to 70°F (21°C) for 24 hours before use.
2. For colder temperture conditions, use FastPatch Kicker to shorten cure time. Kits can be heated up to 100°F (38°C) to speed cure at colder temperatures.
3. Store all components at 70°F (21°C) while preparing repair area and during application. Cold kits will not flow or level properly, and cure time will be slow.
4. Check that primed surfaces are ready for application before mixing and applying FastPatch.
5. Protect surfaces around the repair area with tape to prevent contamination of surrounding surface.
6. Place mixing station a short distance from the application area.
7. Wear gloves and safety glasses while mixng and applying material.
8. Attach a clean, "eggbeater–style" mixing paddle to a mechanical drill with a minimum of 500RPM.
9. Use entire kit and do not divide.

APPLICATION

1. Remove contents of FastPatch kit and leave aggregate in the bucket.
2. Open Part A package and pour over aggregate. Mix 3 minutes.
3. OPTION 1: For gray, mix Part B with aggregate mixture.
   OPTION 2: For black, add BLACK pigment to aggregate mixture then add Part B.
   OPTION 3: For speeding system, add FastPatch Kicker to aggregate mixture then add Part B. FastPatch Kicker is sold separately, and recommended in cold weather.
4. Mix for 2 minutes. Scrape sides and bottom while mixing. MATERIAL WILL NOT SET IF POORLY MIXED. Signs of poor mixing include dark swirls and tacky material that does not solidify.
5. Immediately pour in area. Level to surrounding surface.
6. After 10 minutes, sprinkle NATURAL or BLACK topping sand to match surrounding surfaces.
7. Material is typically ready for traffic in 1-hour at 70°F (21°C). Colder temperatures will slow cure. Warmer temperatures will speed cure.

SKID RESISTANCE: It is the responsibility of the Applicator to ensure product meets minimum skid resistance requirements. Refer to the agency or end-user friction management policy or specifications to determine minimum skid resistance and test method requirements. Aggregate (Sand, pumice, flint) can be added topically at the gel stage or Fastpatch can be ground, sanded or abraded to achieve any necessary skid resistant texture.

CLEANING & MAINTENANCE

Clean equipment with POLYQuik® Cleaner or acetone immediately after use. Cured material must be removed mechanically.

HEALTH AND SAFETY

Before handling, you should become familiar with the Material Safety Data Sheet (MSDS) regarding the risks and safe use of this product. To obtain an MSDS please call 800 333 9826 or send an email to: msds@wilvaco.com.

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Revision Date: March 2014

APPENDIX H – *QFQ SUMMER* TECHNICAL DATA SHEET

globalresins ltd
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Tel: 01249 715566 Fax: 01249 715533 E-Mail: office@globalresins.co.uk
www.globalresins.co.uk www.safetycope.co.uk

DATA SHEET

QFQ 700 SUMMER
Polyurethane Resin for Piezo Quartz Sensors

QFQ 700 has been developed as a cold pour system to encapsulate piezo quartz sensors and to stick surface mounted sensors.

The material is available in 4kg kits.

METHOD OF USE

The resin is a filled system and therefore some degree of sedimentation may occur, particularly if the resin has been left standing over long periods of time or stored at elevated temperatures (in excess of 25°C). This can be readily dispersed by mixing with an electric drill and suitable attachment or a broad bladed spatula.

The resin and hardener are mixed in the ratio:

7.22 : 1 By weight
7.53 : 1 By volume

Colour of mixed system	Black
Density of resin	1.86
Density of hardener	1.23
Density of mixed system	1.74
Viscosity of resin	15,000 cp at 20 - 25°C
Viscosity of hardener	4 Poise at 20 - 25°C
Viscosity of mixed system	13,000 cp at 20 - 25°C
Pot life	8 - 15 minutes at 15 - 25°C (150g mass)
Set time	10 - 15 minutes at 15 - 25°C (150g mass)
Full Cure time	2 days
Peak Exotherm	60°C (150g mass)
Shore D Hardness after 24hrs at room temp.	A: 75 B: 70 after 5 seconds

Gel time is very much dependent upon ambient temperature, mixing time and road temperature

It should be noted that road slots are natural heat sinks and cure times may be extended by the prevention of exothermic heat developing.

Company Registration No: 2960700

WATER ABSORBTION: After 5 Days at 40°C = 2.5% (Test Piece 50mm diameter x 6mm thick)

TENSILE STRENGTH RESULTS (REF: ISO R527)

QFQ 700:

Surface Area of Test Piece:	10mm x 4.5mm = 45mm^2
Result MPa:	8.4
Elongation:	12%

COMPRESSIVE STRENGTH AT YIELD POINT (REF: ISO 844 - 1978)

QFQ 700:

Surface Area:	3.14×10^3 = 314mm^2
Result MPa:	35.7
Test Piece Lengths:	50mm
Compression at Yield Point	14mm

Cleaning Equipment
All equipment should be cleaned before the compound has hardened.

Storage
The resin and hardener should be stored separately in tightly sealed containers until required for use. The shelf life on this material is 12 months unless otherwise stated on the label.
Preferred storage temperature is around 20°C but must not be allowed to reach freezing or exceed temperatures of 30°C.

CAUTION
Polyurethane systems are generally quite harmless to handle, provided that certain precautions normally taken when handling chemicals are observed. The uncured materials must not, for instance, be allowed to come into contact with foodstuffs or food utensils, and measures should be taken to prevent the uncured materials from coming into contact with the skin. The use of barrier creams or impervious gloves is advised. The skin should be thoroughly cleansed at the end of each working period, either by washing with soap and warm water or by using a resin removing cream - use of solvents is to be avoided. Disposable paper towels - not cloth towels should be used to dry the skin. Adequate ventilation of the working area is recommended.

Polyurethane hardeners are moisture sensitive. Containers of both resin and hardener should be kept tightly closed when not in use to prevent ingress of atmospheric moisture.

The information given is derived from test and/or extrapolations believed to be reliable. However, the product is offered for evaluation on the understanding that the customer will satisfy himself that the product is suitable for his intended use.

APPENDIX I – RESULTS FROM PREVIOUS TESTS OF SIMILAR MATERIALS

EXECUTIVE SUMMARY[7i]

Introduction

The main goal of this research project was to develop test procedures that can be used to test adhesives for installation of piezoelectric axle sensors in the State of Florida. In addition, this research undertaking was also aimed at developing material specifications that will be used to select adhesives to achieve long-term field performance of piezoelectric axle sensors. The study was prompted by the fact that there are no standard procedures locally and nationally for testing adhesives and no state has so far developed material specifications for adhesives specifically for use in piezoelectric sensor installation.

Long-term observation of sensor performance in Florida suggested that the use of adhesives with characteristics unsuitable for Florida traffic, pavement, and environmental conditions might be contributing to premature failures of piezoelectric sensors. The excessive failures of piezos at telemetered traffic monitoring sites (TTMS) is of major concern to the Florida Department of Transportation (FDOT) because of the high cost of replacements and the attendant disruption of traffic flow. This executive summary gives an overview of adhesives approved for use in Florida, the methodology used in the study, findings, and recommendations.

Characteristics of adhesives approved by FDOT Planning Office

Information supplied by the Project Manager, Mulder Brown, indicated that there are five adhesives that have been 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 invariably 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, in 11½, 26, and 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 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

[7] Extracted from Moses, R.& T. Sando. "Evaluation of Bonding Materials Used in Piezoelectric Axle Sensor Installation." *Final Report, Contract BD-313*, Florida Department of Transportation, Tallahassee, FL, July 2003.

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 pail 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 pre-measured so that there is no need of calculating the mix ratio. The manufacture indicates that the material should be left to cure for approximately one hour before opening the site to traffic.

Table 1 compares pertinent material characteristics for the five adhesive types. The information in Table 1 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, they indicated that the material composition has not changed much since Euber *et al.* study was conducted.

Methodology

A research protocol was designed to evaluate the performance of piezos so as to recommend which adhesives would be suitable for Florida conditions. The protocol included (a) comprehensive literature search on the characteristics of epoxies, acrylics, and polyurethanes, (b) survey of the experience of State Departments of Transportation in the U.S. on the use of these adhesives for piezo installations, (c) laboratory testing of the approved adhesives, and (d) long-term field monitoring of ANOVA-designed experiments.

TABLE 1. 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^{o}C	30 to 40 min	20 min
Gel Time	17-25 min. @ 77^{o}F	17 to 25 min.	13 min. @ 25^{o}C	17 min. @ 25^{o}C	10 min. @ 20^{o}C

Findings

The materials studied can be categorized in three main groups—epoxies, polyurethanes, and acrylics. Different sources that were used to examine each type of bonding materials i.e., literature review, state experience survey and laboratory testing suggest that there are distinctive properties associated with each material. The following discussion is a synthesis of information found from various sources and would build a basis for the recommendations about to be made.

Epoxies

The laboratory results shows that epoxies are associated with hardness behavior, high compressive strength, with high modulus of elasticity. No significant difference was observed between epoxies and other types of materials. The epoxies were also found to have relatively higher peel strength with an exception of Bondo 7084. The epoxies also resulted with higher peel strength. However laboratory results suggested little flexibility of epoxy materials with exception on E-Bond 1261.

The state survey respondents commented on some epoxies. The respondent from the State of Connecticut reported that G100 performed well in concrete pavement installations while it developed cracks when sensors were installed in asphalt pavements. The State of Utah reported that it had used G100 in the past but it failed in the first summer after installation. The State of West Virginia also reported that at numerous sites installed with G100 cracks were observed. The State of Nebraska reported that 7084 adhesive was very stiff during installation but had minimum cupping and weather effects. The State of Kentucky reported that 7084 adhesive did not have good long term bonding characteristics. E-Bond 1261 was not in use around the country at the time of this study, therefore there was no information about the product from states' survey.

Polyurethanes

As with epoxies, the laboratory results showed that polyurethanes are associated with hardness behavior but with lower compression strength and modulus of elasticity. The results further suggest that polyurethanes have the lowest peel strength among the rest of the materials. PU200 is the only polyurethane material that was reported to be used by some states. The respondent from the State of Virginia said that PU200 has not performed well in the state and he suspected that the material could be suffering from long-term creep and stress relaxation problems. In addition, according to one FDOT contractor, eighteen sites in Ohio installed with PU 200 have failed. The contractor suspects that part of the problem with PU200 is excessive shrinkage, which affects bonding between the sensor and the adhesive.

Acrylics

Contrary to epoxies and polyurethanes, laboratory test results suggested that acrylics are softer than epoxies and polyurethanes. The laboratory results also indicated that acrylics have lower compressive strength, lower modulus of elasticity and moderate strain hence reasonably more flexible than epoxies and polyurethanes, with an exception of E-Bond 1261. While P5G and P6G resulted in relatively lower peel strength, AS475 resulted in higher peel strength than some polyurethanes and epoxies.

Several states reported on performance of acrylics (P5G and AS475). The State of Kentucky reported that P5G had good long term bonding characteristics while Colorado surmised that since switching to P5G from other adhesives, the failure rate of piezo installations has been greatly reduced. The State of Montana reported that they have been pleased with the performance of P5G since most of the failures have been in cabling, sensor itself, and pavement, but generally not the adhesive. However, Montana also reported that they noticed that when P5G is installed in pavements with thin overlays it generally tends to fail prematurely. The State of Washington reported that using AS475 has greatly reduced their piezo installations failure rate. Likewise, the State of Utah reported that the field crew prefers AS475 over PU200 since it mixes and pours well, as well as it cures quicker than PU200. The study by Euber et al. (1994)[8] also found that acrylic-based adhesives performed better than epoxies in most cases during the field trials.

Recommendations

The preliminary recommendations on the type of adhesives to be used in Florida are based on the review of literature, contact with various state personnel and technicians, survey of different states' practices, review of manufacturer's own technical data sheets, and the laboratory test results. The recommendations are termed preliminary since long-term performance monitoring of the recommended grouts in the field is needed to ascertain their suitability for Florida environmental and traffic conditions. A prolonged field monitoring will also lead to recommendation of test

[8] Ueber, E.J., Fowler, D.W., and Carrasquillo, R.L. *Investigation of Bonding Materials for Piezoelectric Traffic Monitoring Equipment.* Research Report No. 2039-1, University of Texas at Austin, Austin, TX, November 1994.

procedures and material specifications to be used in approving future adhesives submitted by manufacturers for review by FDOT. These recommendations are related to adhesives used only in installation of sensors in asphalt concrete pavements.

The research results summarized above indicate that acrylic-based adhesives generally have better performance characteristics compared to epoxy and polyurethane-based adhesives. Acrylics tend to have characteristics similar to flexible pavements, i.e., good impact resistance and flexibility. In addition, the research results indicated that acrylics also have reasonable peel and shear strength. These characteristics were also confirmed by a study conducted in Texas by Euber *et al*. (1994). This study found that acrylic-based adhesives performed better than epoxies in most cases during the field trials. Likewise, numerous states that have used adhesives extensively report a reasonable degree of satisfaction with the performance of acrylic-based adhesives in flexible pavements.

The difference in performance of acrylics compared to epoxies and polyurethanes can also be explained by considering the glass transition temperature of these materials. Increased stiffness at low temperature may result in cohesive failure of the adhesive. At very low temperatures, the adhesives become very rigid (glassy region) as shown in Figure 1. The rigidity is represented by a high modulus of elasticity. After reaching the glass transition temperature, T_g, the increase in temperature results into a rapid decrease in modulus of elasticity. Eventually, a point is reached beyond which the modulus of elasticity remains relatively constant as the temperature increases (rubbery region).

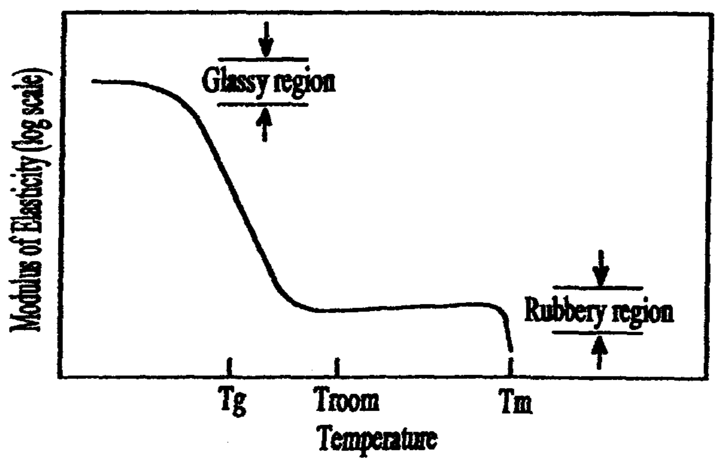

FIGURE 1. Variation of Modulus of Elasticity with Temperature (Rogers et al., 1999)[9]

Figure 1 suggests that a good adhesive material for application with flexible pavements should have a low glass transition temperature, T_g. The brittleness and rigidity of epoxy and polyurethane-based adhesives suggest that they do have a high glass transition temperature and

[9] Rogers, A.D., Lee-Sullivan P., and Bremmer, T.W. “Selecting Concrete Pavement Joint Sealants. I: Proposed Test Protocol.” *Journal of Materials in Civil Engineering*, Volume 11, Issue 4, 1999.

thus they become more brittle than acrylics at temperatures between T_g and T_{room}. This phenomenon might partially explain lack of good bonding characteristics of epoxies and polyurethane adhesives used in colder regions of the United States.

Based on the literature review, state survey and laboratory test results it is recommended that the Florida Department of Transportation should use acrylic-based adhesives with increasing frequency in the installation of piezoelectric axle sensors in asphalt concrete pavements. Though there are only two acrylic-based adhesives currently approved by FDOT, i.e., IRD AS475 and ECM P5G, it is recommended that P6G—which is the modified product of P5G—be included in the Florida Department of Transportation approved list of adhesives. It is also recommended that a monitored field test be conducted on E-Bond 1261, the only epoxy-based material that had a number of properties that may be suitable for installation of piezoelectric axle sensors in asphalt concrete pavements.