Portable Weigh-in-Motion System Evaluation

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January 2015

Research Project
Final Report 2015-03

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Technical Report Documentation Page

1. Report No. MN/RC 2015-03	2.	3. Recipients Accession No.
4. Title and Subtitle Portable Weigh-in-Motion System Evaluation		5. Report Date January 2015 6.
7. Author(s) Scott Petersen, Zach Hanson, Michael Janson, Erik Minge		8. Performing Organization Report No.
9. Performing Organization Name and Address SRF Consulting Group, Inc. One Carlson Parkway North, Suite 150 Minneapolis, MN 55447-4443		10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. 03683
12. Sponsoring Organization Name and Address Minnesota Local Road Research Board Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/pdf/201503.pdf		

16. Abstract (Limit: 250 words)

The Minnesota Local Road Research Board, MnDOT, and SRF performed an evaluation of a portable weigh-in-motion (WIM) system at several locations throughout Minnesota. The system was developed at the University of Minnesota-Duluth and offers roadway designers a low-cost method for obtaining vehicle load distribution data across the state's road network. To deploy the system, the weigh pads of the system were temporarily affixed sensors across the roadway lanes. As vehicles passed over the weigh pads, pressure sensors within the pads detected the weight of vehicles and the system recorded the data for later analysis.

Traditional methods for travel monitoring generate traffic volume and classification data, but weigh-in-motion systems give designers a more accurate idea of current and projected traffic loading demands. SRF's testing provided implementation refinements that were incorporated into the system. During the two-year deployment process, the portable WIM system was installed under a wide array of environmental conditions to demonstrate the system's capabilities. Data generated by the system was analyzed. The Final Report details system deployment, calibration, and system accuracy.

17. Document Analysis/Descriptors weigh in motion, traffic surveillance, traffic data, data collection, traffic data collection sensors, traffic counts, road tubes		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 43	22. Price

Portable Weigh-in-Motion System Evaluation

Final Report

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January 2015

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

Acknowledgements

We wish to thank the Minnesota Local Road Research Board (LRRB) and its Research Implementation Committee (RIC) for the financial support to make this important report a reality. The Technical Advisory Panel (TAP) that steered this project was extremely helpful in identifying key issues and concerns related to traffic data collection. In addition, the TAP was very generous with its time in attending meetings, reviewing, and providing oversight for this final document.

The authors would like to thank TAP members and their organizations for their contributions to this document.

Technical Advisory Panel

The following members comprise the project's Technical Advisory Panel (TAP) that contributed to the development of the testing process:

- Ben Timerson, MnDOT
- Rick Kjonaas, MnDOT
- Nelson Cruz, MnDOT
- Alan Rindels, MnDOT
- Gene Hicks, MnDOT
- Josh Kuhn, MnDOT
- Susan Anderson, MnDOT
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The following county representatives provided resources to assist with data collection.

- Jeff Adolphson, Wadena County
- Tim Becker, Sibley County
- John Brunkhorst, McLeod County
- Jim Kollar, Rice County
- Peter Lemke, Hennepin County
- Ryan Sutherland, Itasca County
- Joe Triplett, Chisago County
- Tracey Von Bargen, Grant County

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Executive Summary

During 2013 and 2014, SRF Consulting Group deployed a portable weigh-in-motion (WIM) system that was developed at the University of Minnesota-Duluth on rural Minnesota county two-lane highways. This system collects similar data to permanent WIM systems but at a much lower cost and in a portable form that can be deployed similarly to traditional portable data collection methods such as road tubes.

The system consists of two weigh pads that are attached to the pavement with hardware and utility tape. The system was deployed for durations of 7 days and 48 hours. It was found that 7 days was generally too long for the tape to hold and left the system susceptible to vandalism. However, the system stayed in place during all 48-hour deployments and this duration is recommended for future use. Also, this shorter duration allows operators to plan around weather such that the system is not deployed before forecasts calling for inclement weather which also affects the system's attachment to the pavement.

This project also developed a calibration method that allows operators to efficiently set up the system using vehicles that most counties have available for general road maintenance needs. Those vehicles would need to be weighed at a static scale to determine a baseline weight, but no other special equipment is needed.

While the majority of the effort for this project was to test the system hardware and software in a deployment environment, some accuracy findings were determined. In general, the system matched automatic traffic recorder (ATR) volumes within 6 percent and road tube volumes within about 15 percent. On average, speed accuracy was within 5 percent. Speed accuracy at many sites was within 2 percent. Classification accuracy generally matched baseline data although some classes, such as two-axle classes, matched better when an axle-spacing-based classification was used compared to a weight based system. Considering that both ATR and road tube baselines use axle-spacing based classification schemes, this is to be expected.

Additional analysis was conducted to determine the weight accuracy of collected measurements. These runs were performed during the calibration process when vehicles of known weights were driven over the system. Accuracy findings were compared to WIM gross vehicle weight accuracy standards published by American Society for Testing Materials (ASTM). The following table summarizes what percentage of the data met the accuracy standards.

Percentage of Data Meeting Weight Accuracy Standards

	Accuracy Standard	Half-Ton Pickup	Class 6 Dump Truck	Class 9 (MnROAD) Truck
ASTM Type II	15%	56%	90%	93%
ASTM Type III	6%	24%	49%	58%

This report also includes several lessons learned related to deployment of the system. Hardware and software modifications were made throughout the first half of the project to improve the data quality and system duration.

Minimal wear to the weigh pads was noted when the system was correctly installed and left for no longer than 48 hours. In two cases where the system was deployed for 7 days, weigh pads were detached from the road. In one case, weather and the extended duration appear to have weakened the bond between the pads and the pavement. In the other case, vandalism was suspected.

Overall, it was found that the portable WIM system is capable of collecting traffic data that includes individual axle weights and gross vehicle weights. The system can be deployed by two operators with some minimal training.

Chapter 1. Introduction

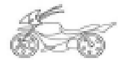
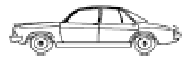
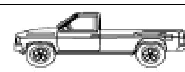
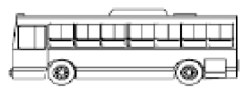
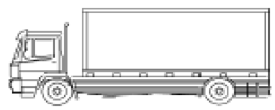
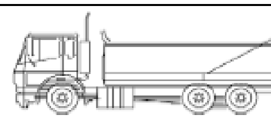
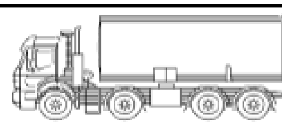
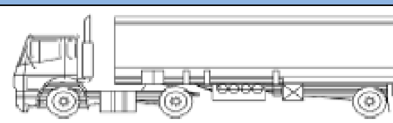
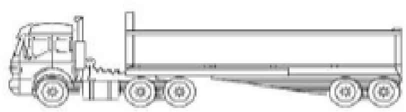
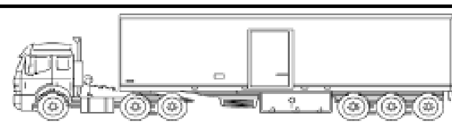
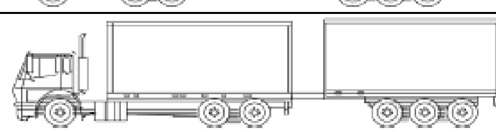
The Minnesota Local Road Research Board (LRRB), Minnesota Department of Transportation (MnDOT), and SRF Consulting Group performed a field evaluation study of a portable weigh-in-motion (WIM) system prototype. The portable WIM system prototype was designed and developed by Taek Kwon, PhD., an electrical engineering professor at the University of Minnesota-Duluth.

Traditional WIM technologies are generally permanent and costly to install. Permanent WIM systems generally require intrusive pavement cuts or expensive boring techniques for proper placement of sensors. Additionally, the inability to gather data from a variety of locations has limited the deployment of existing WIM technologies. A portable WIM alternative would provide greater flexibility for agencies looking to gather vehicle weight data at multiple locations at a greatly reduced cost. The results presented in this report demonstrate the portable WIM system's ability to supplement or replace existing data collection methods currently in use.

The portable WIM system provides gross vehicle weight (GVW), individual axle weights, axle counts, axle spacing, vehicle speeds, and vehicle classification. Currently, the most prevalent portable data collection methods determine a vehicle's classification based solely on axle spacing. By adding weight data to this classification process, the portable WIM uses extra information to classify a vehicle. Figure 1-1 presents the vehicle classifications as designated by the FHWA that MnDOT uses.

This report summarizes the findings of the portable WIM field evaluation and outlines lessons learned and opportunities for advancement in moving this technology forward.

MnDOT VEHICLE CLASSIFICATION SCHEME

TYPE	PASSENGER VEHICLES	
1	Motorcycle	
2	Car	
3	Truck Van	
	SINGLE UNITS	
4	Bus Truck with trailer	
5	2 Axle Single Unit	
6	3 Axle Single Unit	
7	4+ Axle Single Unit	
	COMBO UNITS	
8	3 & 4 Axle Semi	
9	5 Axle Semi	
10	6+ Axle Semi	
11, 12, 13	Twin Trailer Semi	

(http://www.dot.state.mn.us/traffic/data/reports/forecast/Forecast_Manual_2012.pdf)

Figure 1-1: MnDOT Vehicle Classification Diagram

Chapter 2. Methodology

The goals and objectives of the field evaluation as developed by project stakeholders are identified below:

Goal 1. Evaluate Installation/Removal Process and Procedures

- Objective 1-1. Implement and evaluate the suggested procedure for installation/removal.
- Objective 1-2. Evaluate resources required and efficiency opportunities for installation/removal process under varying environmental conditions.
- Objective 1-3. Evaluate safety considerations related to installation personnel, the traveling public, and traffic control needs.
- Objective 1-4. Identify a maximum duration the system can be deployed in a temporary application.
- Objective 1-5. Recommend improvements to the installation/removal process.

Goal 2. Determine System Performance During Field Evaluation.

- Objective 2-1. Determine required calibration measures and identify proper data sets for baseline calibration.
- Objective 2-2. Determine procedure for a high-level accuracy check.
- Objective 2-3. Test/troubleshoot system to resolve unanticipated prototype issues.

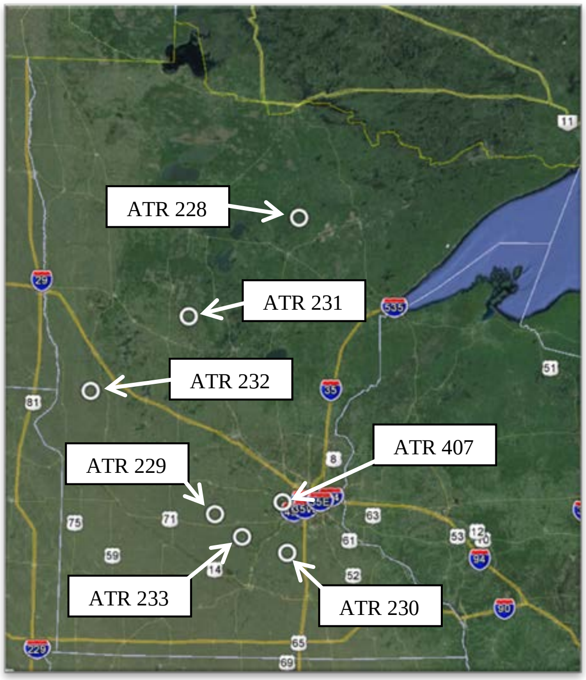
Goal 3. Analyze Data to Evaluate System Accuracy.

- Objective 3-1. Document ease of collecting and processing data.
- Objective 3-2. Review data and compare to baseline data.
- Objective 3-3. Evaluate count/speed/classification accuracy.
- Objective 3-4. Evaluate gross vehicle weight (GVW) accuracy.
- Objective 3-5. Evaluate system potential as a new means of data collection.

Testing occurred in two phases over the two-year evaluation period. The first phase deployed the system at 7 MnDOT-selected ATR sites for an evaluation period of 7 consecutive days at each site. The second phase deployed the system at 10 predetermined locations within Chisago County for an evaluation period of 48 hours at each location.

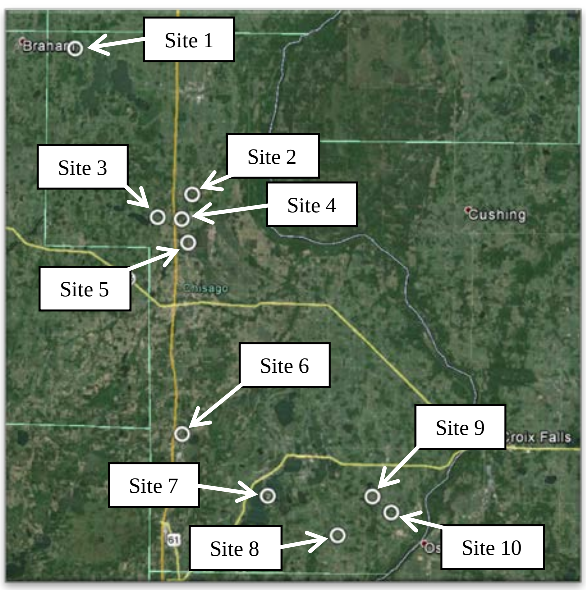
Locations identified by MnDOT and Chisago County are shown in Figure 2-1.

Statewide Test Locations (at ATR Stations)



ATR Station	County	Closest City	Location
233	Sibley	Arlington	CSAH 9, 0.7 MI N OF 226TH ST, N OF ARLINGTON
229	McLeod	Hutchinson	CSAH 18, 4.3 MI W OF CSAH7, SW OF HUTCHINSON
230	Rice	Lonsdale	CSAH 2, 3.4 MI W OF TH19, W OF LONSDALE
407	Hennepin	Orono	CSAH 15, NE OF SPATES AVE IN ORONO
232	Grant	Norcross	CSAH 11, 0.6 MI S OF CSAH12, NE OF NORCROSS
231	Wadena	Nimrod	CSAH 12, 1.6 MI E OF CSAH18, E OF NIMROD
228	Itasca	Hibbing	CSAH 7, N OF CR339, W OF HIBBING

Chisago County Test Locations



Site Number	Closest City	Location
1	Nessel Twp	CSAH 2 between County Line & CSAH 4
2	Harris	CSAH 30 south of CR 59
3	Harris	CSAH 10 between CR 65 & CR 64
4	Harris	CSAH 10 between I-35 & CSAH 30
5	Harris	CSAH 30 between 415th St. & CSAH 10
6	Stacy	CSAH 30 between CSAH 19 & CSAH 30
7	Chisago City	CSAH 24 between Stinson Ave & CSAH 23
8	Fraconia Twp	CSAH 25 between CSAH 23 & CR 86
9	Fraconia Twp	CSAH 26 between TH 8 & CSAH 21
10	Fraconia Twp	CSAH 26 between CSAH 21 & TH 95

Figure 2-1: Portable WIM Evaluation Locations

2.1 Baseline

Baseline data was collected to compare the portable WIM data and determine its accuracy. During the first phase of the evaluation, the system was set up near ATR facilities. ATR stations utilize a series of loops and piezoelectric sensors to determine vehicle counts, speeds, and classifications. The second phase of the evaluation utilized road tubes and video cameras for baseline data comparison. These devices represent the traditional data collection methods. It should be noted that all methods of baseline data collection used in this evaluation have measurable error.

2.2 Data Collection Process

The portable WIM system was installed following the procedure developed by Professor Kwon and MnDOT that was presented at the project kickoff meeting. As the field evaluation proceeded, minor revisions were made to this process to ensure pads remained secure to the pavement and to efficiently install the system.

2.2.1 Required Materials

A typical installation requires the materials listed in Table 2-1. The expendable materials required for each setup cost approximately $140.

Table 2-1: Portable WIM Installation Materials/Equipment List

Materials	Quantity		Equipment
Duct Tape Rolls (Gorilla Brand)	4		Hammer
Sleeve Anchor Screws	30		Drill
Industrial Strength Drill Bit	1		Generator/Source of Power
Washers	30		Broom

Eight rolls of tape are required to keep a continuous strip of tape across the entire width of the roadway for both strips on either side of both pads (four tape strips per pad), but each installation only requires four full rolls of tape. Figure 2-2 shows pad midway through installation with four continuous tape strips used per pad.

Figure 2-2: Photos of Pad Installation

2.2.2 System Installation Procedure

System installation takes approximately 25-40 minutes. County staff provided traffic control at each setup. A complete step-by-step installation procedure can be found in Professor Kwon's portable WIM instruction manual. An abbreviated version of this process is provided below.

1. Begin flagging operation and close lane closest to where system will be placed. Sweep pavement area where pads will unroll.
2. On a smooth road surface, space pads 15 feet apart in the shoulder.
3. Unroll pads to centerline of roadway then secure pads such that they do not unroll into the opposing traffic lane.
4. Drill holes into pavement at the locations marked on each of the pads. Hammer in an anchor screw with washer into each drilled hole. Tighten screw with screwdriver to ensure the pad is secured into the pavement.
5. Sweep excess dirt off of the pads then use two strips of tape on both sides of each pad to secure the edges to the pavement surface.
6. Apply pressure to tape to ensure it is secured to the pavement. Leave tape rolls at centerline for one continuous tape strip across the entire roadway.
7. Gather materials and switch traffic control to opposite lane. Repeat procedure on opposite lane.
8. After pads are firmly attached to the pavement, insert wires into the proper connections on the portable WIM computer system and perform calibration/testing procedure.

Important points to remember for system installation are outlined below:

1. Schedule appropriate traffic control prior to the installation – typical installations require two flaggers for approximately 30 minutes.
2. Ensure a dry, clean pavement surface for portable WIM installation. Wet pavement and/or loose debris/gravel on the road surface can greatly diminish the durability of the sensor pads.

3. Upon completion of pad installation, check both pads to ensure they are firmly attached to the pavement surface.
4. Hide and lock portable WIM equipment out of sight from the traveling public. Vandalism and theft are concerns in populated and unpopulated areas.

2.2.3 System Removal Procedure:

Pad removal takes 15-30 minutes. Removal entails closing the lane furthest from the system, pulling up the tape, using a screwdriver and hammer to remove the anchor screws, and rolling up the pads to the centerline. After traffic control has been switched to the opposite lane, the same procedure is followed to completely remove the pads from the pavement. Holes drilled in the pavement are filled with epoxy or pavement filler.

2.3 Calibration

After each installation, the system was calibrated. The capability to calibrate the system was added midway through the project along with several other enhancements after a year of analysis. System configuration and setting procedures were documented and can be found attached in Appendix A. Many of the settings in the system can remain at default values, but some need to be modified to match location conditions.

For example, the "signal threshold levels" should be configured and verified for each setup. The weigh pads are primarily made of rubber and even while securely fastened to the pavement, give a signal "kickback" after each axle detection. The signal threshold is also set to filter out additional noise from roadway vibration.

Using the live-plotting feature in the weigh-pad software, the system threshold levels are set above the noise level, but below the peak created by the sensed vehicle. Figure 2-3 demonstrates the vibration that needs to be excluded by the signal threshold filtering.

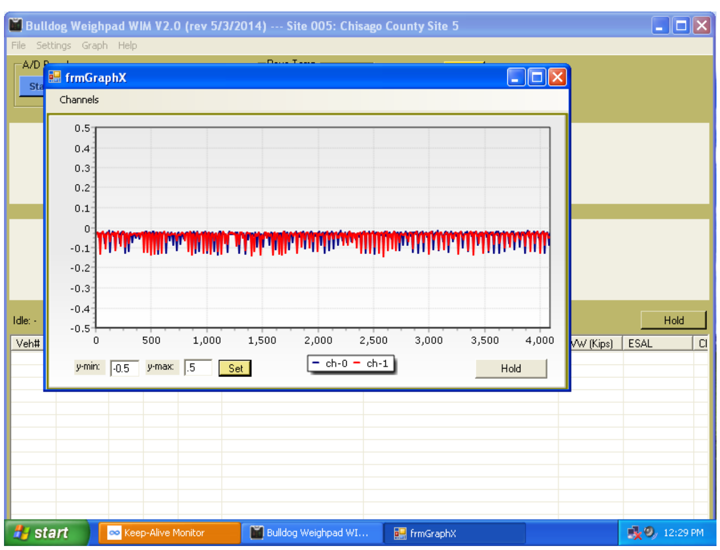


Figure 2-3: Live Plotting Function Showing Roadway Noise

2.3.1 *Weight Calibration*

The weight calibration is configured by adjusting the System Calibration Factor. This parameter normalizes the axle weight measurements. Calibration factors are broken out per lane with a theoretical value of approximately 0.6. The calibration procedure outlined below was used to calibrate with several different types of vehicles. A more detailed calibration procedure worksheet can be found in Appendix B.

Calibration Procedure:

1. Determine the axle spacing, gross vehicle weight, and test speed of calibration vehicle.
2. Perform at least ten calibration runs in each direction of travel. Maintain a constant speed near the roadway's speed limit and be positioned in the center of the subject lane.
3. Upon completion of 10 calibration runs in each direction of travel, determine the average and standard deviation for each lane.
4. For each lane, extract all runs that fall within one standard deviation of the mean and calculate the adjusted mean for each lane. Calculate the calibration factors per lane by taking the actual vehicle weight and dividing it by each of the new adjusted means.
5. Record all data or calculations performed for future reference. Perform several validation runs to ensure system is recording weights close to the actual weight.

The number of needed runs could be modified depending on what vehicle is used and what accuracy level is desired. Using the calibration procedure, an analysis was conducted to determine the number of runs required to ensure a statistically significant sample size for each type of calibration vehicle utilized during the evaluation. These findings are presented in the Results section. For the field evaluation, a 95 percent confidence interval with 5 percent error of estimation was used. Equation 1 can be used to determine sample size required assuming a 95 percent confidence interval.

$$N \geq \left(\frac{1.96}{\delta}\right)^2 \sigma^2 \quad \text{(Equation 1)}$$

N: sample Size Required
δ : error of estimation
σ : standard deviation

The calibration vehicles were a half-ton pickup truck and county-provided trucks. MnDOT's MnROAD facility provided a tractor/trailer combination at one Chisago County test location. This is the same truck that MnDOT uses to calibrate permanent WIM sites. Figure 2-4 shows the truck performing calibration runs.

Figure 2-4: Calibration Runs by MNROAD Truck

Table 2-2 presents the calculated calibration factors for each of the sites where this procedure was used starting with the 2014 data collection. The system calibration was not able to be field calibrated in 2013.

Table 2-2: Calibration Factors

	Chisago 3	Chisago 4	Chisago 5	Chisago 6	Chisago 7	Chisago 8	Chisago 9	Chisago 10	Sibley County	McLeod County	Rice County
Lane 1	1.05*	0.51	0.60	0.50	0.52	0.60	0.55	0.49	0.72	0.55	0.54
Lane 2	1.04*	0.53	0.51	0.62	0.46	0.65	0.45	0.50	0.76	0.51	0.55

**This site setup had excessive noise and the portable WIM software was revised after this setup.*

As shown in the table above, calibration factors were generally very close to the theoretical value of 0.6 provided by Professor Kwon. Additional runs at each location would have further refined calibration factors and narrowed the margin of error.

Chapter 3. Results

This section outlines the volume, speed, and classification results of the portable WIM system when compared to a baseline system. The baseline system is represented by either an Automatic Traffic Recorder (ATR) or pneumatic road tubes (when ATR was not available).

Each result table below summarizes the data from each of the portable WIM testing sites. The sites are listed chronologically and divided based on the baseline system used (ATR or road tubes). The ATR sites are further divided into Phase 1 and Phase 2. The Phase 1 sites took place in 2013. The Phase 2 sites took place during 2014. Between Phases 1 and 2, the portable WIM received several upgrades including important software changes. All of the road tube sites took place in 2014 as part of Phase 2.

3.1 Volume

Table 3-1 shows the recorded volume at each site by the portable WIM, the baseline and the calculated percent difference between these numbers.

Table 3-1: Volume Comparison

Site	Portable WIM Volume	ATR Volume	Tube Volume	Absolute Percent Difference
Itasca CSAH 7*	1858	2257		17.7%
Grant CSAH 11*	1611	2289		29.6%
Wadena CSAH 12*	1666	2031		18.0%
Chisago CSAH 10 (1)	5571		4839	15.1%
Chisago CSAH 10 (2)	5596		5175	8.1%
Chisago CSAH 30	8731		8175	6.8%
Chisago CSAH 24	8541		7729	10.5%
Chisago CSAH 25	4995		4718	5.9%
Chisago CSAH 26 (1)	2617		2261	15.7%
Chisago CSAH 26 (2)	2802		2105	33.1%
Sibley CSAH 9	2680	2718		1.4%
McLeod CSAH 18	2264	2403		5.8%
Rice CSAH 2	4893	5024		2.6%

** 2013 data taken before winter 2013-2014 software upgrades.*

The average volume percent difference for the Phase 1 ATR sites was 22.0 percent. The percent difference dropped to 3.3 percent at the Phase 2 ATR sites. The average percent difference in volume at the road tube sites was 13.6 percent. Note that these findings include error associated with the baseline measurements. Expected error for ATRs and road tubes is generally within 2 percent and 7 percent, respectively.

3.2 Speed

Table 3-2 below compares the average speed measurements between the portable WIM and the ATR or road tubes.

Table 3-2: Speed Comparison

Site	Portable WIM Avg Speed (mph)	ATR Avg Speed (mph)	Tube Avg Speed (mph)	Percent Difference
Itasca CSAH 7*	56.0	56.5		0.8%
Grant CSAH 11*	57.6	59.2		2.8%
Wadena CSAH 12*	57.1	57.4		0.4%
Chisago CSAH 10 (1)	52.8		51.9	1.6%
Chisago CSAH 10 (2)	45.0		46.6	3.4%
Chisago CSAH 30	53.3		49.9	6.8%
Chisago CSAH 24	41.2		39.0	5.5%
Chisago CSAH 25	55.3		57.4	3.7%
Chisago CSAH 26 (1)	55.1		55.4	0.5%
Chisago CSAH 26 (2)	55.0		57.0	3.4%
Sibley CSAH 9	59.7	59.8		0.1%
McLeod CSAH 18	60.8	59.5		2.0%
Rice CSAH 2	60.1	59.7		0.7%

** 2013 data taken before winter 2013-2014 software upgrades.*

The mean percent difference in average speed at the Phase 1 ATR sites was 1.3 percent, while the percent difference at Phase 2 ATR sites was 0.9 percent. The average percent difference in speed at the road tube sites was 3.6 percent. ATRs and road tubes are generally expected to have speed accuracies within 4 percent and 1 percent, respectively.

3.3 Classification

Table 3-3 and Table 3-4 compare the classification results of the portable WIM to the baseline. The tables display the percentage of baseline vehicles which were classified by the portable WIM in each class. In cases where no baseline data existed, the cell was left blank.

By default, the portable WIM classifies vehicles using a weight-based classification scheme. However, the ATR and road tubes rely solely on axle spacing for vehicle classification. There are notable differences in the number of matches per class because the classes can have widely varying counts. For example, Classes 2 and 3 are a large proportion of the traffic stream. Vehicles that are erroneously weighed too heavy by the portable WIM system would be classified in a higher class such as Class 5.

Thus, to perform the analysis, the portable WIM data was also classified using an axle spacing-based scheme like the ATR and road tubes. The results show that the classification results from the portable WIM matched closer to the ATR and road tubes when the axle-only scheme was applied, such as in Figure 3-4.

Table 3-3: Percent of Baseline Vehicles Classified by Portable WIM (Weight-Based Classification)

Site	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10
Itasca CSAH 7*	10%	63%	83%	46%	119%	45%	13%	33%	44%	
Grant CSAH 11*	9%	44%	128%	21%	6%	14%		52%	25%	25%
Wadena CSAH 12*	0%	60%	104%	52%	50%	50%	5%	71%	65%	60%
Chisago CSAH 10 (1)	18%	106%	115%	61%	199%			39%	3900%	1200%
Chisago CSAH 10 (2)	17%	113%	99%	69%	105%	110%	400%	67%	88%	133%
Chisago CSAH 30	14%	92%	131%	158%	335%	107%	113%	150%	164%	175%
Chisago CSAH 24	50%	88%	163%	229%	333%	1080%	600%	80%	1600%	
Chisago CSAH 25	7%	101%	98%	132%	266%	167%	1200%	52%	200%	0%
Chisago CSAH 26 (1)	50%	118%	105%	18%	86%			11%		
Chisago CSAH 26 (2)	600%	129%	75%	57%	94%			41%		1500%
Sibley CSAH 9	0%	82%	118%	82%	247%	115%	64%	92%	108%	19%
McLeod CSAH 18	0%	79%	120%	32%	71%	2400%		17%	307%	1500%
Rice CSAH 2	5%	88%	115%	50%	137%	104%	75%	63%	120%	39%

** 2013 data taken before winter 2013-2014 software upgrades.*

Table 3-4: Percent of Baseline Vehicles Classified by Portable WIM (Axle Spacing-based Classification)

Site	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10
Itasca CSAH 7*	190%	72%	74%	162%	219%	85%	13%	48%	72%	
Grant CSAH 11*	65%	49%	112%	119%	42%	86%		93%	12%	0%
Wadena CSAH 12*	50%	60%	98%	104%	122%	81%	84%	81%	91%	67%
Chisago CSAH 10 (1)	186%	116%	101%	96%	93%			19%	4200%	600%
Chisago CSAH 10 (2)	117%	121%	86%	117%	69%	110%	50%	25%	90%	67%
Chisago CSAH 30	103%	99%	118%	204%	162%	105%	113%	46%	164%	175%
Chisago CSAH 24	371%	97%	140%	200%	175%	1220%	700%	13%	1600%	
Chisago CSAH 25	79%	115%	83%	136%	94%	175%	150%	24%	1400%	200%
Chisago CSAH 26 (1)	206%	124%	91%	25%	81%			9%		
Chisago CSAH 26 (2)	2550%	138%	69%	123%	76%			21%		1300%
Sibley CSAH 9	100%	94%	100%	68%	100%	100%	73%	72%	100%	19%
McLeod CSAH 18	220%	85%	106%	52%	62%	2300%		2%	314%	1300%
Rice CSAH 2	98%	95%	99%	66%	112%	98%	100%	53%	123%	22%

** 2013 data taken before winter 2013-2014 software upgrades.*

Because the ATR and road tubes reported very few vehicles over class 10, they were excluded from Table 3-3 and Table 3-4. Vehicles classified as 14 or 15 by the portable WIM are caused by an error or misread. These vehicles appear in the total volume; however, they are not put into a valid vehicle class.

The figures below display the aggregate results from the Phase 2 testing. Again, the weight-based and axle spacing-based WIM classification schemes can be compared to the baseline system (ATR or road tubes). Figure 3-2 and Figure 3-4 filter the results to show only classes 4-13, because the magnitude of classes 2 and 3 is much higher.

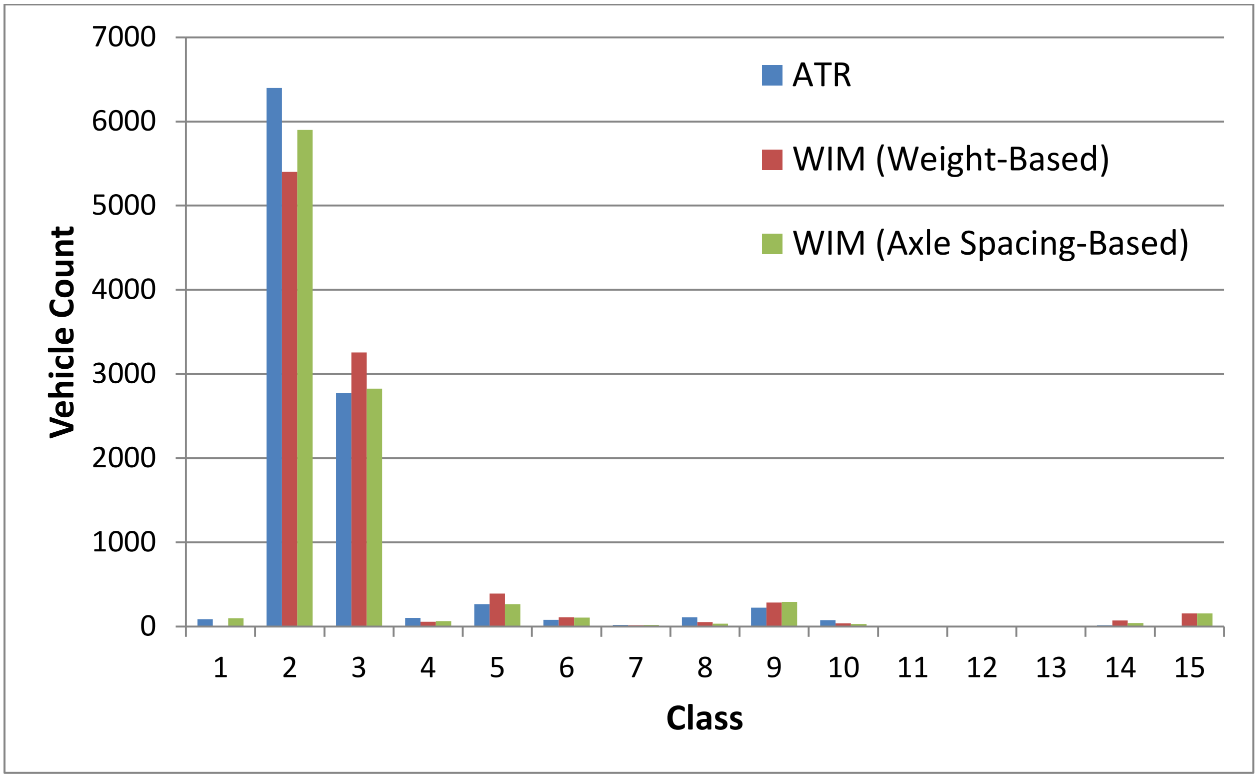


Figure 3-1: Phase 2 Total ATR/WIM Class Comparison (All ATR Sites Combined)

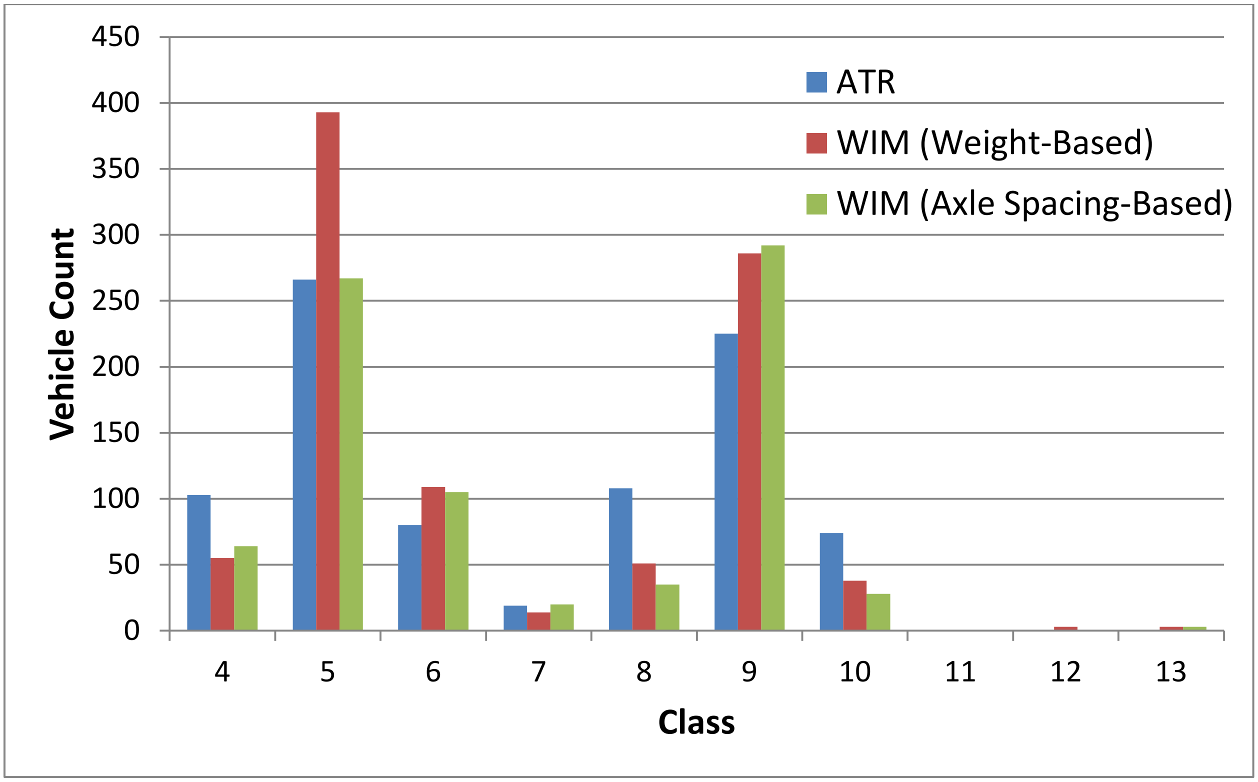


Figure 3-2: Phase 2 Total ATR/WIM Class Comparison (All ATR Sites Combined)

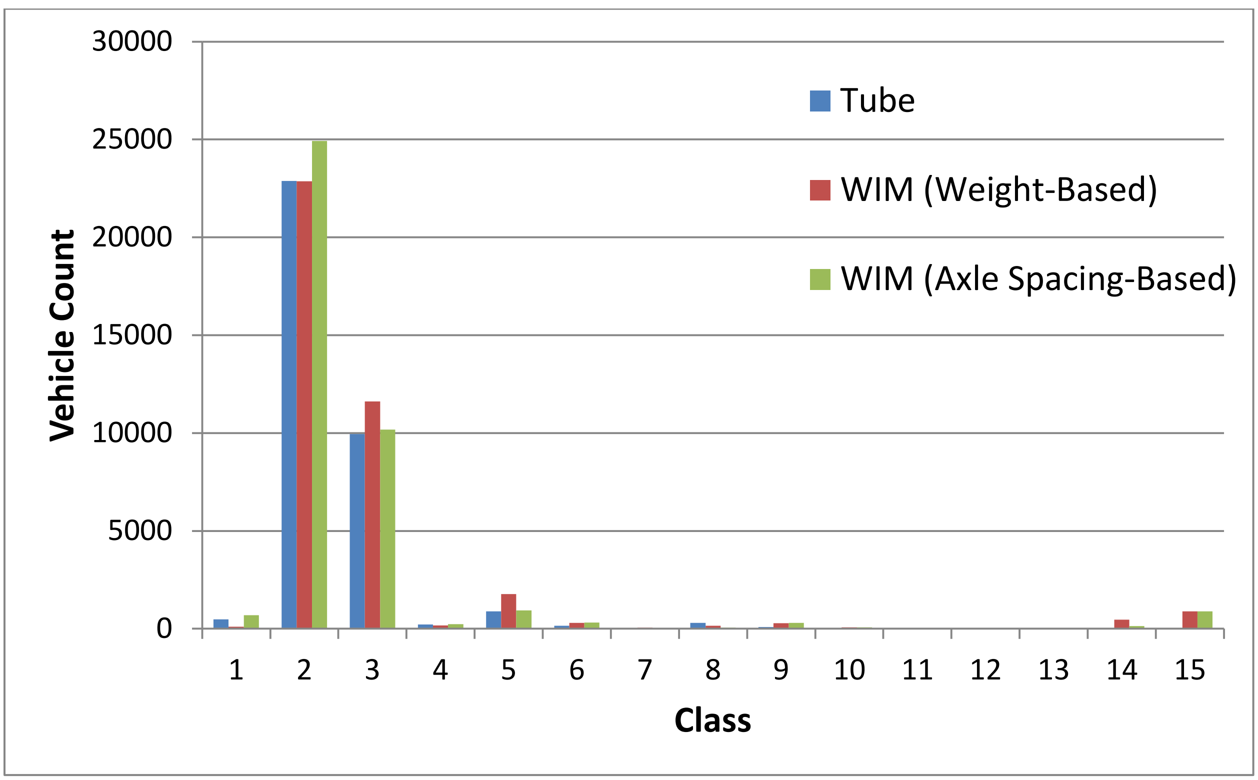


Figure 3-3: Phase 2 Total Tube/WIM Class Comparison (All Tube Sites Combined)

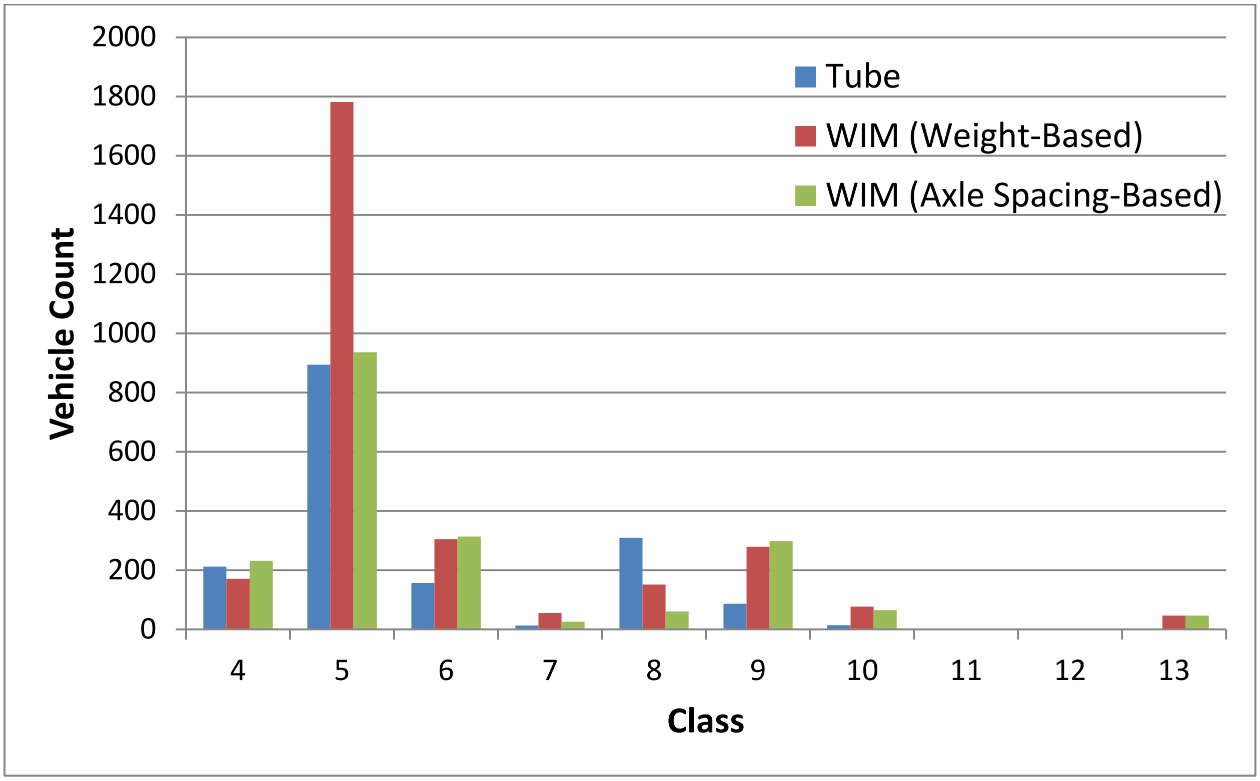


Figure 3-4: Phase 2 Total Tube/WIM Class Comparison (All Tube Sites Combined)

3.4 Weight Accuracy

Calibration run data was used as a baseline to evaluate portable WIM weight measurement accuracy. Pre and post calibration data was normalized and aggregated. Calibrations were performed for all data recorded in 2014 (Chisago County sites 3-10 and three ATR sites).

All trucks used for calibration were weighed at certified static scales. Some small factors could not be controlled such as the variability in the amount of gas in the vehicle and are not expected to have a significant impact on the results relative to the trucks' GVW. Effort was taken to maintain the same conditions between the various test sites.

Figure 3-5 through Figure 3-7 present the calibration data compared to the static weight. These graphs show a bell curve distribution of GVW measurements. The trendline presented is a two-period rolling average. The data average, standard deviation, and percent difference between the calculated average and actual vehicle weight are also shown.

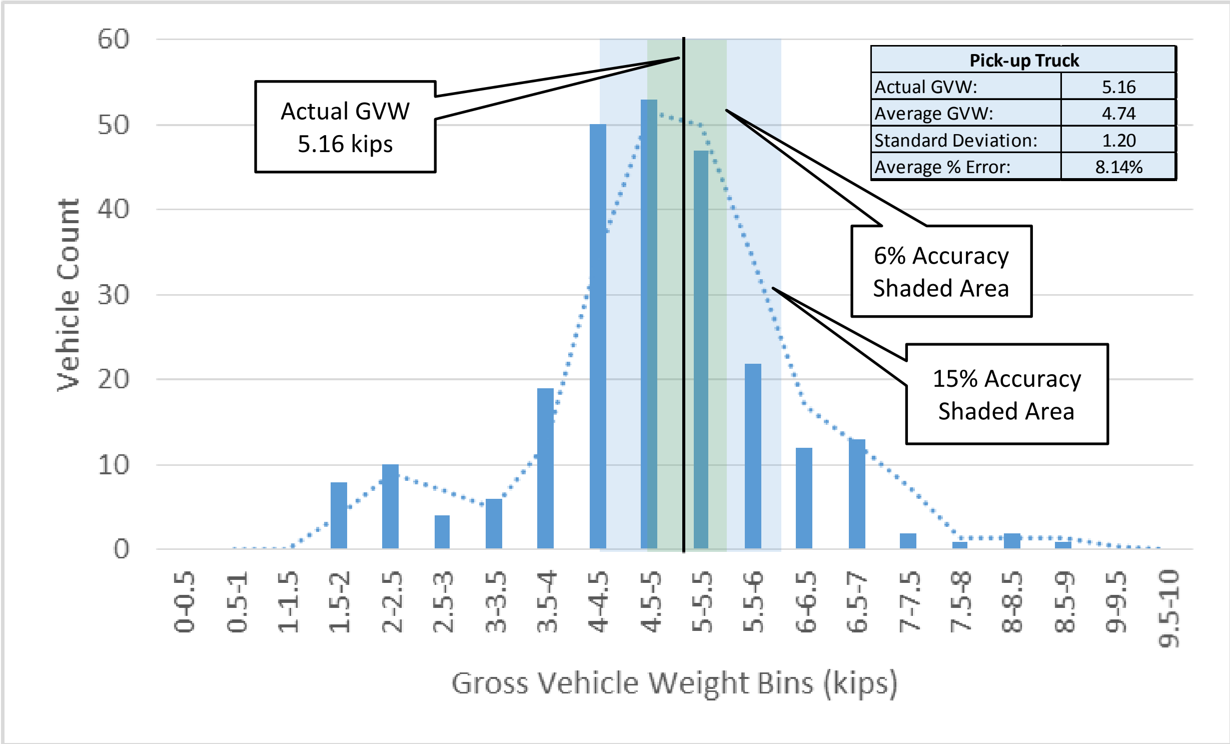


Figure 3-5: Gross Vehicle Weight Binned Data for Half-Ton Pick-up Calibration

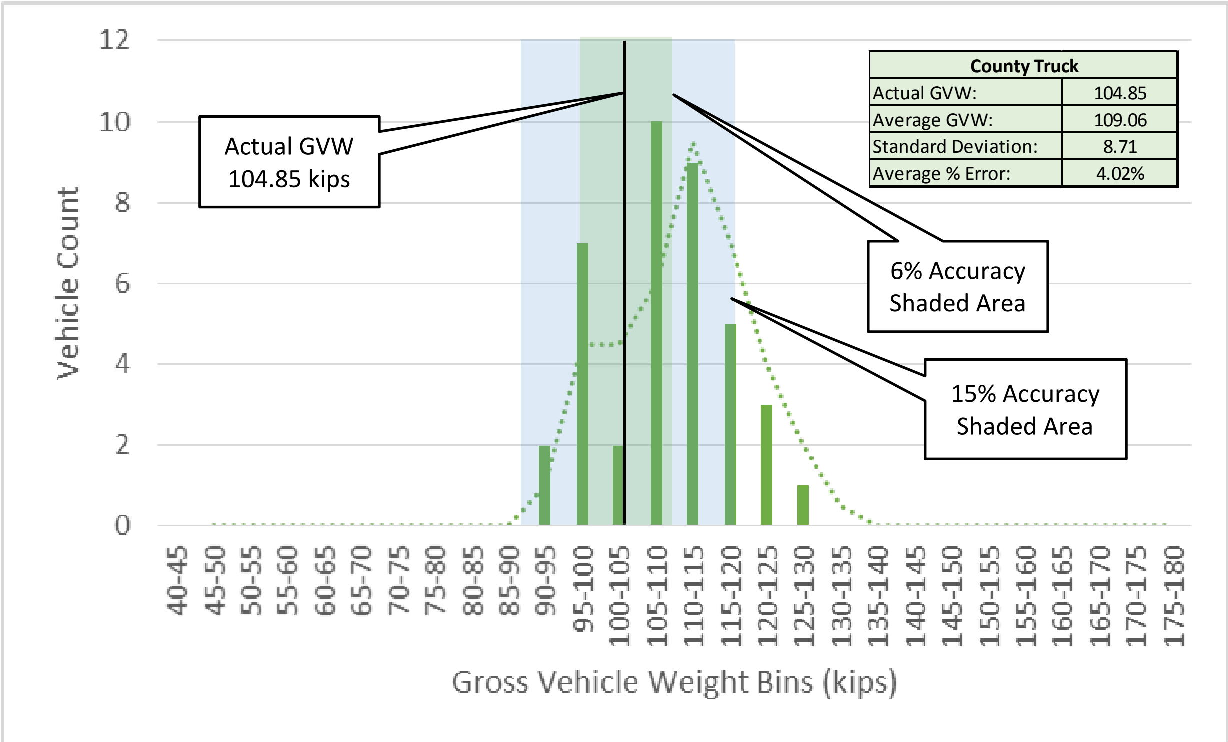


Figure 3-6: Gross Vehicle Weight Binned Data for Chisago County Truck Calibration

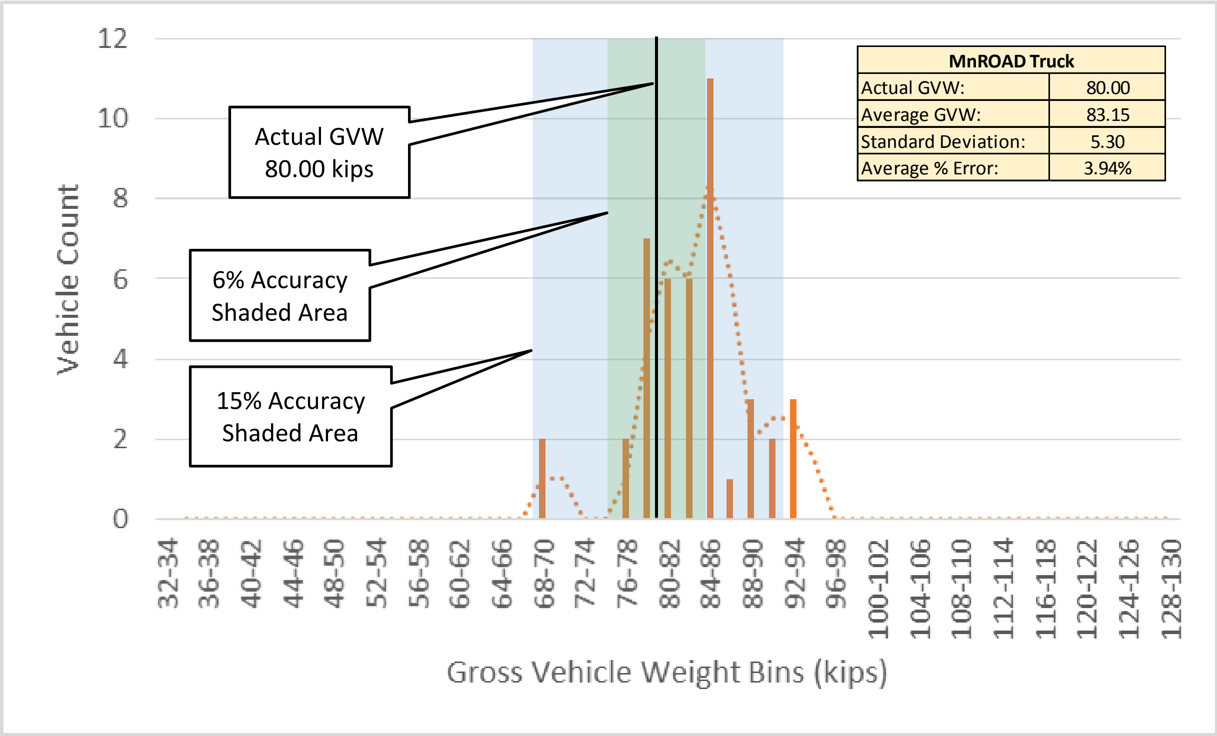


Figure 3-7: Gross Vehicle Weight Binned Data for MnROAD Truck Calibration

The shaded areas on each graph represent data that falls within the ASTM E-1318-09 Standard Specifications for Highway WIM Systems with User Requirements and Test Methods accuracy standards. Type II WIM applications require a maximum 15 percent error in measurements and Type III WIM applications expect 6 percent error in measurements. The portable WIM system developer expected the system to operate within a 10 to 25 percent range of error when measuring gross vehicle weight. Table 3-5 demonstrates the amount of data that fell within each ASTM standard for each calibration vehicle.

Table 3-5: Percent of calibration runs that fell within the ASTM WIM standards

	Accuracy Standard	Half-Ton Pickup	Class 6 Dump Truck	Class 9 (MnROAD) Truck
ASTM Type II	15%	56%	90%	93%
ASTM Type III	6%	24%	49%	58%

While this system is not recommended for commercial vehicle enforcement, it may allow enforcement officers to target enforcement screening times. Further focused research should be conducted to determine the accuracy of the portable WIM system.

3.5 Calibration Process Findings

Throughout 2014, calibration runs were performed using various calibration vehicles that were made available by the participating counties, MnDOT, and the half-ton pickup truck used to transport the portable WIM equipment. Comparison of calibration runs to the statically weighed values was used to generate calibration values. It was found that various types of vehicles provided a range of repeatable measurement, but some vehicles produced more consistent results than others.

In order to calibrate the system, operators need to know how many calibration runs per lane are needed to produce statistically significant results. An assumption was made to consider data that is within a 95 percent confidence interval with a five percent error of estimation. Table 3-6 shows the number of runs, *N*, that would need to be conducted to accept the data and use its mean to determine a GVW calibration factor.

For each vehicle type, results from two analyses are shown. The gray shaded rows show results when all runs were considered to calculate the mean. The other rows show how many runs would be needed if outlier calibration runs (runs outside of one standard deviation) were excluded before calculating the mean. Both methods produce similar mean values, but the method that excludes outlier data has a smaller standard deviation and therefore a smaller number of runs to achieve a 95 percent confidence interval. This data shows that the Class 6 dump truck produced the most repeatable results (lowest standard deviation relative to the GVW) and therefore is expected to require the fewest runs to produce an acceptable calibration. For both the loaded and unloaded Class 6 trucks, only three total runs would have been needed per lane to determine the calibration factor.

Table 3-6: Number of Runs, N, Required to Calibrate Site to 95 Percent Confidence Interval with Five Percent Error of Estimation

Vehicle Type	Number Of Runs Conducted	Standard Deviation (kips)	Mean (kips)	Error of Estimation (kips)	N
Half-Ton Pickup	250	1.20	4.74	0.24	**100**
Half-Ton Pickup (include only data points within one standard deviation)	187	0.54	4.75	0.24	**20**
Unloaded Class 6 Dump Truck	34	1.24	33.48	1.67	**3**
Unloaded Class 6 Dump Truck (include only data points within one standard deviation)	25	0.69	33.50	1.67	**1**
Loaded Class 6 Dump Truck	16	2.01	54.53	2.73	**3**
Loaded Class 6 Dump Truck (include only data points within one standard deviation)	11	1.21	54.98	2.75	**1**
Class 9 Semi (MnROAD) Truck	43	5.30	83.15	4.16	**7**
Class 9 Semi (MnROAD) Truck (include only data points within one standard deviation)	33	2.94	82.85	4.14	**2**
Class 10 (Single Unit Truck with Loaded Trailer)	39	8.71	109.06	5.45	**10**
Class 10 (Single Unit Truck with Loaded Trailer) (include only data points within one standard deviation)	24	3.90	110.19	5.51	**2**

Chapter 4. Lessons Learned

The field deployments throughout this project demonstrated the importance of installing the system under optimal conditions. In addition to the many lessons learned during implementation, this field evaluation led to many hardware and software improvements to the portable WIM prototype system.

The first phase of testing included seven day (168 hour) deployments at various locations around the state. At four of the seven locations the portable WIM pads were pulled up from the roadway due to weather events or vandalism. In the case of weather events, heavy rains, wind, and traffic loosened tape and anchor screws from the pavement. As vehicles traveled over the loose pads, additional screws were loosened causing the pads to become fully removed from the pavement.

Figure 4-1: Weather Pulled Pads at Sibley County Test Location

To avoid this issue, an additional layer of tape was used in later installations and the system was not deployed beyond a 48-hour data collection period. The current design of the weigh pads should only be deployed under calm and dry weather conditions.

The original portable WIM computer case had a flaw in which the lip around the case permitted water to enter it and caused water to pool around the battery. This issue was resolved in the second prototype that has an inverted lip to prevent water intrusion.

Initial system enclosure – Top of case fits inside case and allows entry of water from top	Revised system enclosure – Top of case fits over bottom section

Figure 4-2: Lip Inversion on New System

In two instances it is suspected that vandals damaged the pads and system by cutting cables or the pads. The move to 48-hour data collection periods mitigated this issue. Figure 4-3 shows some of the vandalism experienced in Itasca and Hennepin Counties, respectively.

Figure 4-3: System after Vandalism

It is recommended that the portable WIM system be used in rural areas away from major trucking destinations. If deploying the system beyond 48 hours, it is recommended that the deployment location is a low-volume roadway with AADT less than 5,000 vehicles to limit chances of vibration loosening screws from the pavement.

For this field evaluation, testing only occurred on asphalt surfaces, and it is anticipated that the system will perform similarly over concrete. The rigid nature of concrete would likely require a more rugged drill. Settings within the portable WIM system also need to be modified such that the system accounts for the rigid pavement.

The method for taping the pads to the pavement was refined throughout the project. The recommended method includes using two strips of tape on both sides of each pad and ensuring that the tape has been firmly pressed to the pavement. Installation should attempt to use a single strip of tape across the entire pavement to prevent water from getting between the tape and the pavement.

The system has internal batteries that are designed to operate for 48-hours, but after setup and calibration, they may deplete before 48 hours of data collection so the external battery pack would be needed. Additionally, no attempt to cover the system with a tarp or other water prevention cover should be utilized. Initial attempts to cover the system resulted in the portable WIM system overheating and shutting down, limiting the amount of data collected.

Based on observations of wear and tear during the two-year evaluation period, engineers estimate that pads have a useful life of approximately 50-100 installations. By utilizing existing holes through the pads, as often as possible, and creating additional holes only as older holes wear down, pads are likely to last for several years of data collection. Pad edges wear quickly from placing and removing tape at each location but will not cause damage to the pads as long as they are continually taped down to the road surface.

Chapter 5. Conclusions/Next Steps

During this project, the portable WIM system was deployed 20 times. Throughout the project, the deployment method was revised to avoid issues seen earlier. The lessons learned that are documented in this report will allow future deployments to be done more smoothly.

This project also developed a calibration method that allows operators to efficiently set up the system using vehicles that most counties have on hand for general road maintenance needs. Those vehicles would need to be weighed at a static scale to determine a baseline weight, but no other special equipment is needed.

In general, the system matched automatic traffic recorder (ATR) volumes within 6 percent and road tube volumes within about 15 percent. On average, speed accuracy was within 5 percent. Speed accuracy at many sites was within 2 percent. Classification accuracy generally matched baseline data, although some classes, such as two-axle classes, matched better when an axle-spacing-based classification was used compared to a weight-based system.

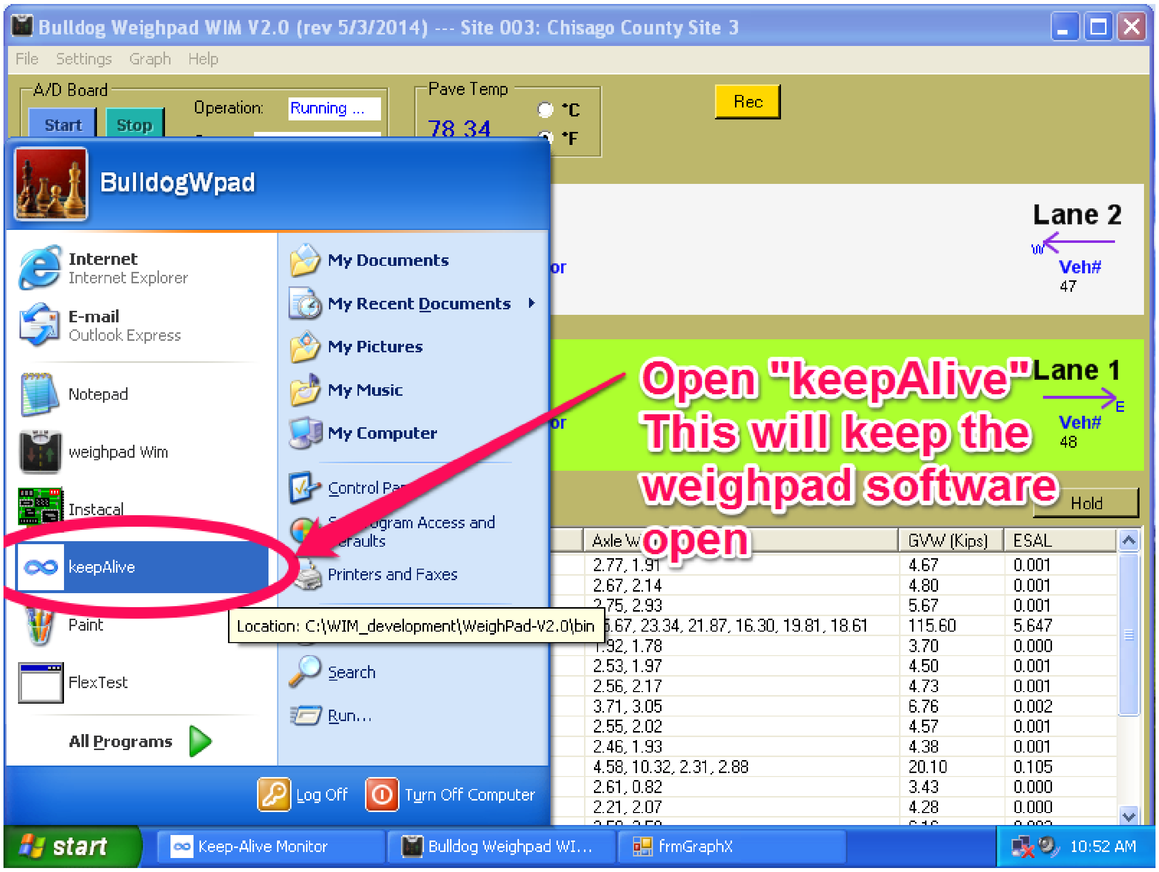
Because the system was able to collect traffic data that includes individual axle weights and gross vehicle weights in a generally cost effective way, it presents new opportunities for data collection. The system is generally limited to low-volume roads and would provide data to allow county engineers to design pavement with more information about the trucks driving on their roads. MnDOT has two complete systems and should make them available to counties with interest in knowing what types of loads travel on Minnesota roads. Outreach to the counties should be conducted so that they understand what data the system can provide and how that can help them improve their pavement design.

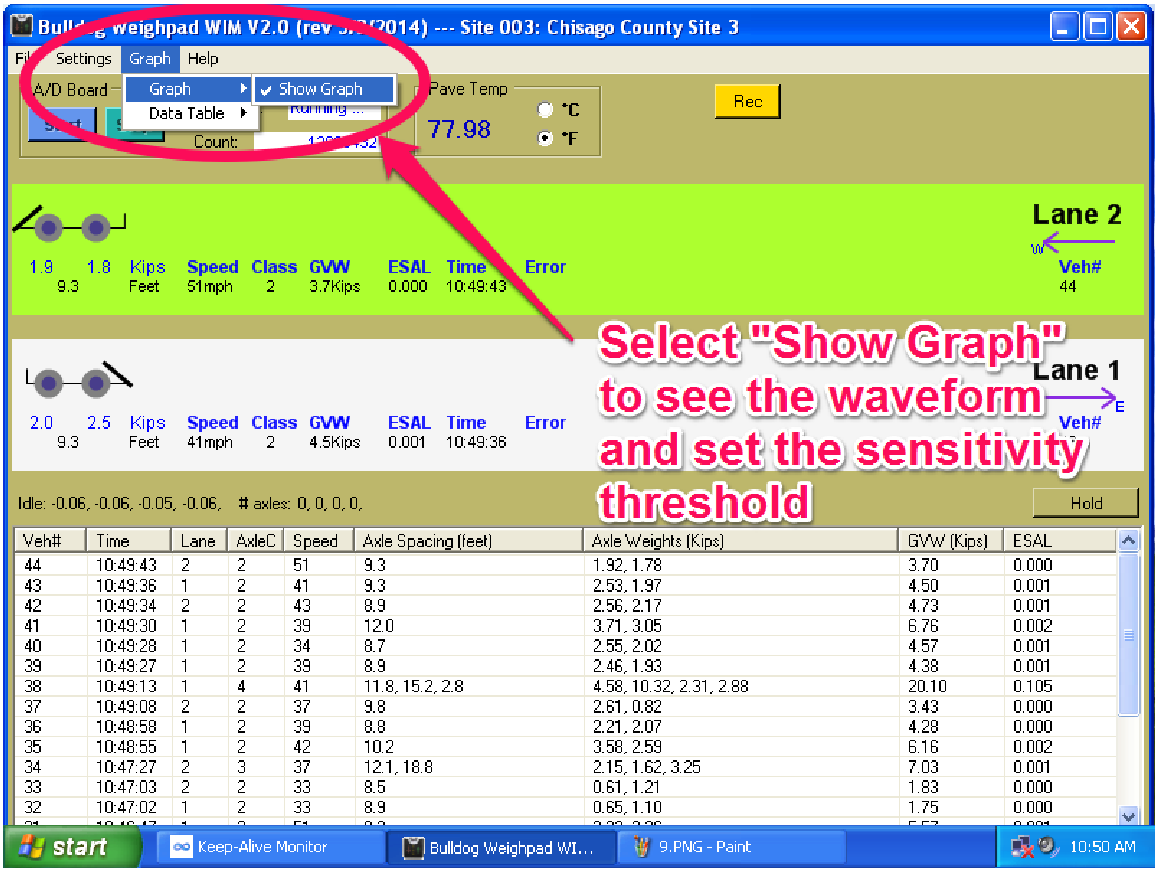
Appendix A. Portable Weigh-in-Motion Calibration Manual

Portable Weigh-in-Motion

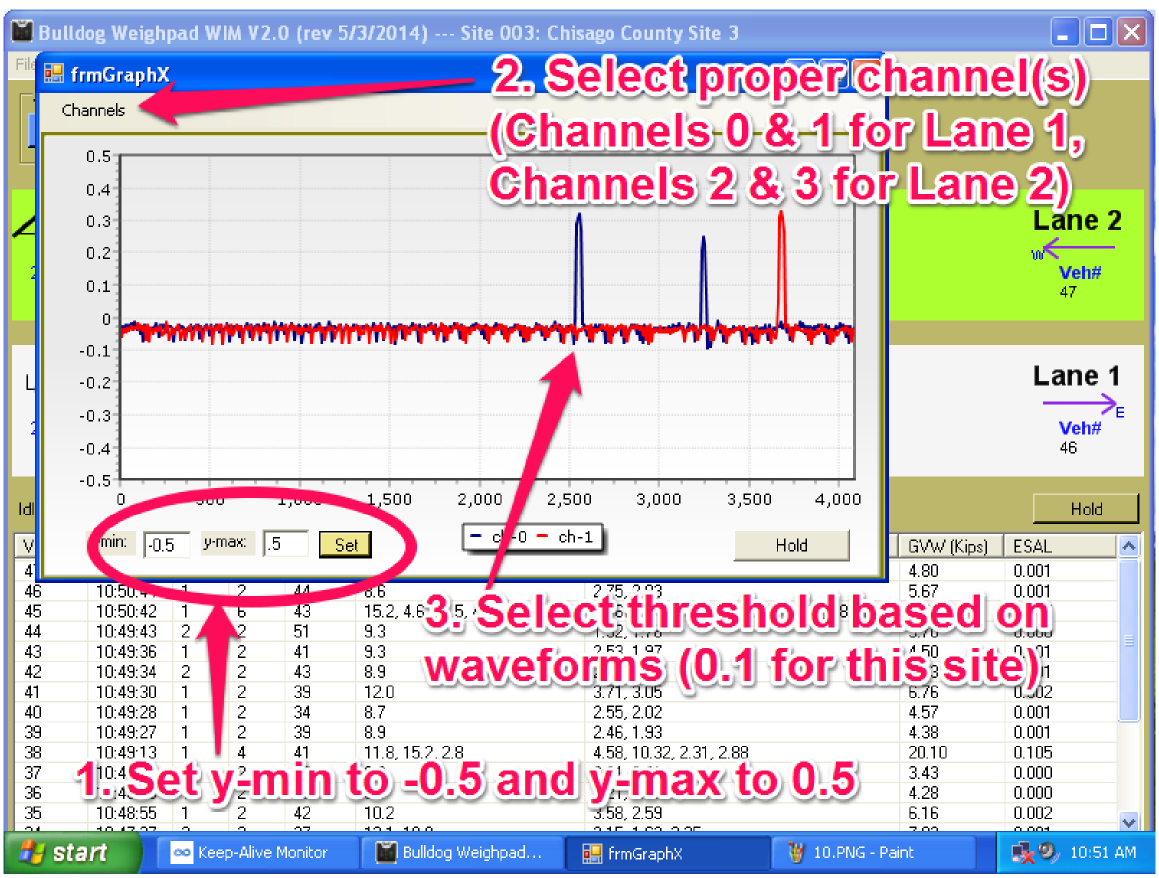
Calibration Manual

June 6, 2014

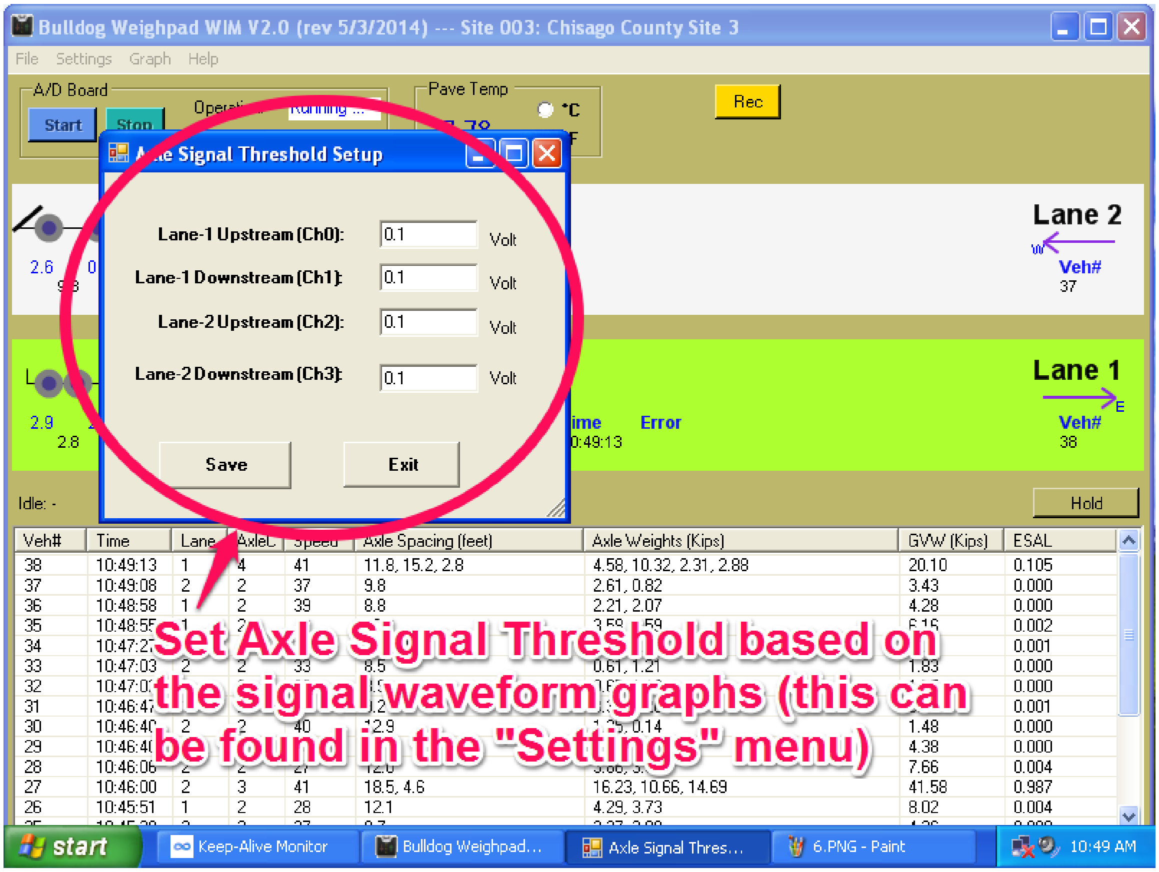

Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
File Settings Graph Help
A/D Board
Start
Stop
Operation:
Running ...
Pave Temp
78.34
°C
°F
Rec
BulldogWpad
Internet
Internet Explorer
E-mail
Outlook Express
Notepad
weighpad Wim
Instacal
keepAlive
Paint
FlexTest
All Programs
My Documents
My Recent Documents
My Pictures
My Music
My Computer
Control Panel
Printers and Faxes
Location: C:\WIM_development\WeighPad-V2.0\bin
Search
Run...
Log Off
Turn Off Computer
Lane 2
Veh#
47
Lane 1
Veh#
48
Open "keepAlive"
This will keep the
weighpad software
open
Hold
GVW (Kips)
ESAL
start
Keep-Alive Monitor
Bulldog Weighpad WI...
frmGraphX
10:52 AM



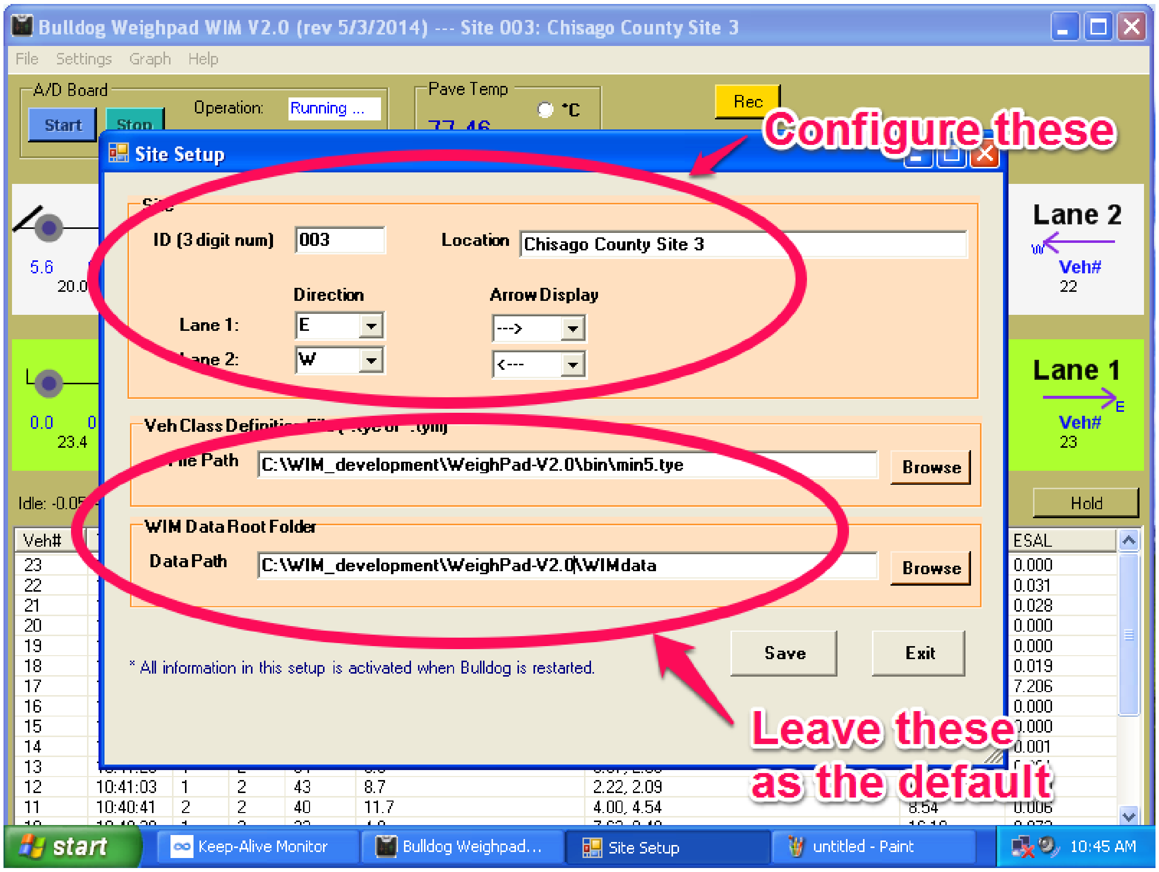
Select "Show Graph" to see the waveform and set the sensitivity threshold

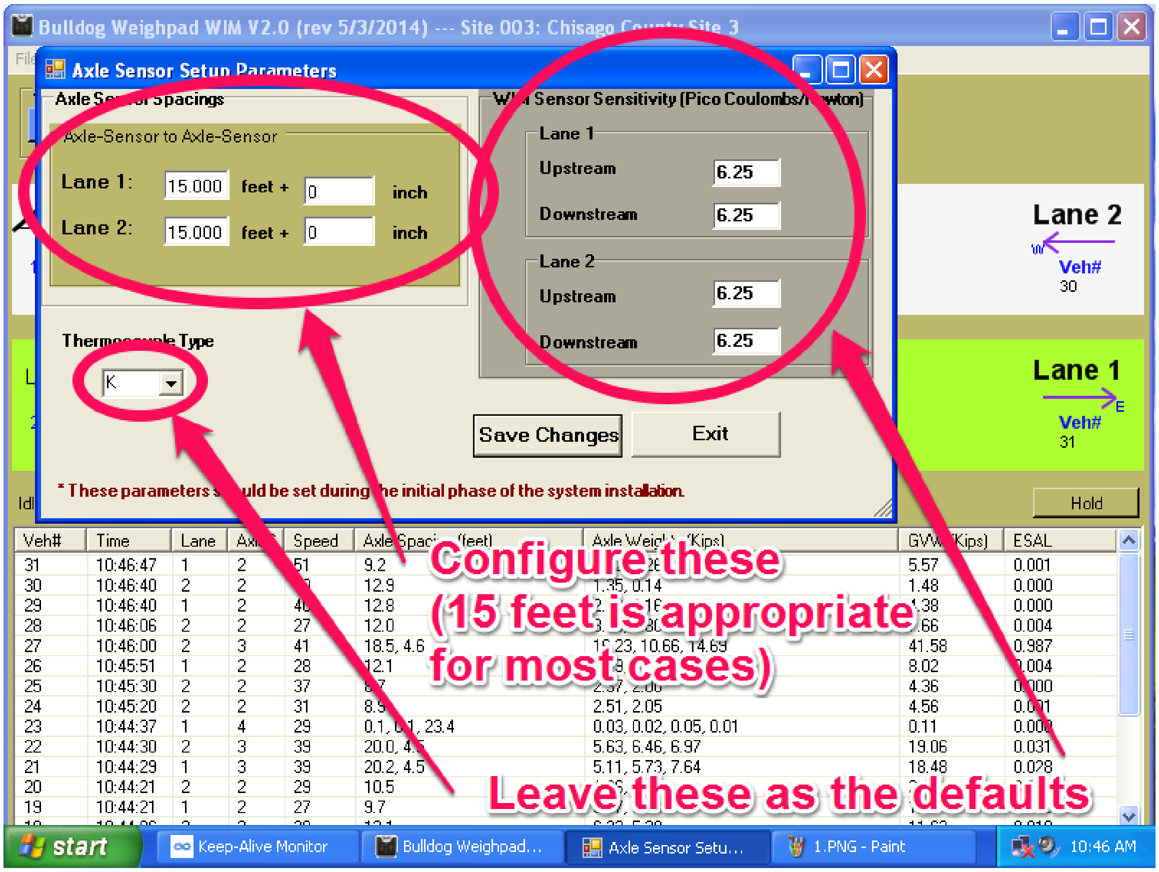


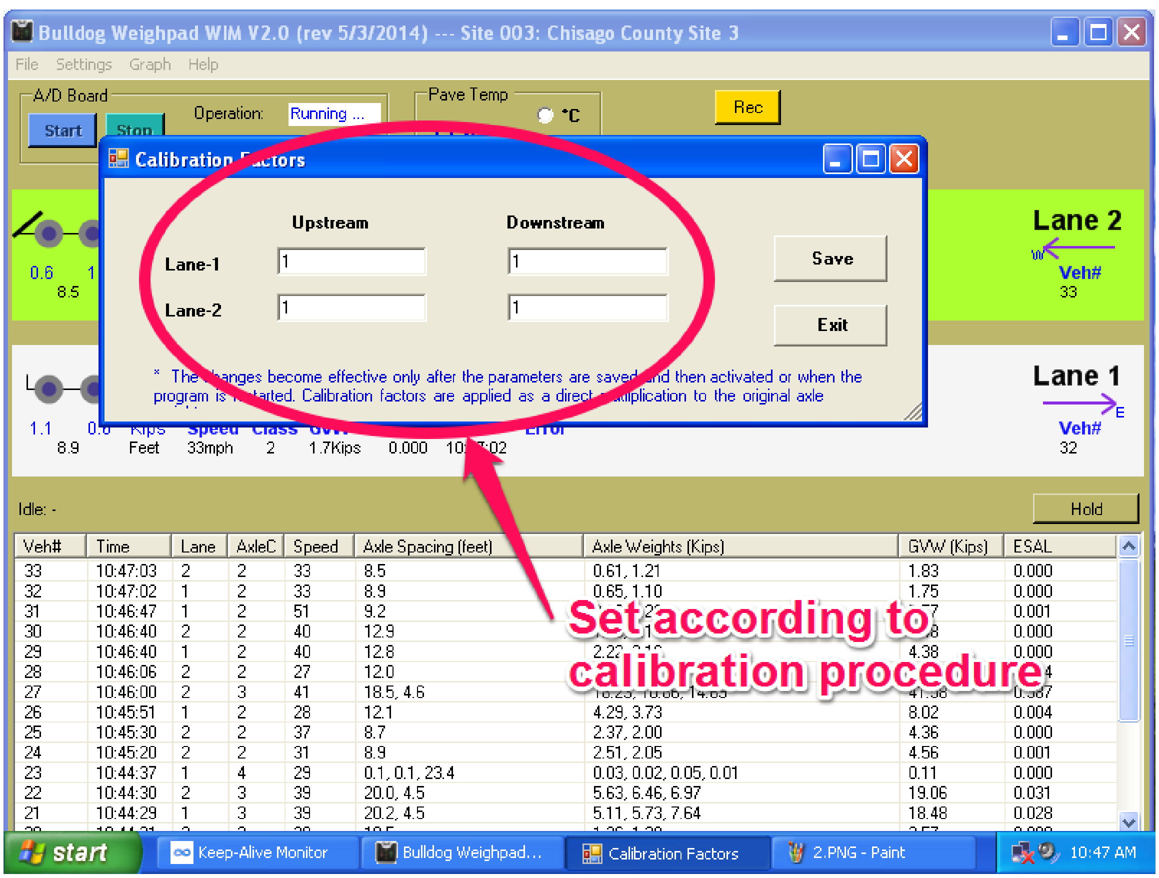
2. Select proper channel(s) (Channels 0 & 1 for Lane 1, Channels 2 & 3 for Lane 2)
3. Select threshold based on waveforms (0.1 for this site)
1. Set y-min to -0.5 and y-max to 0.5

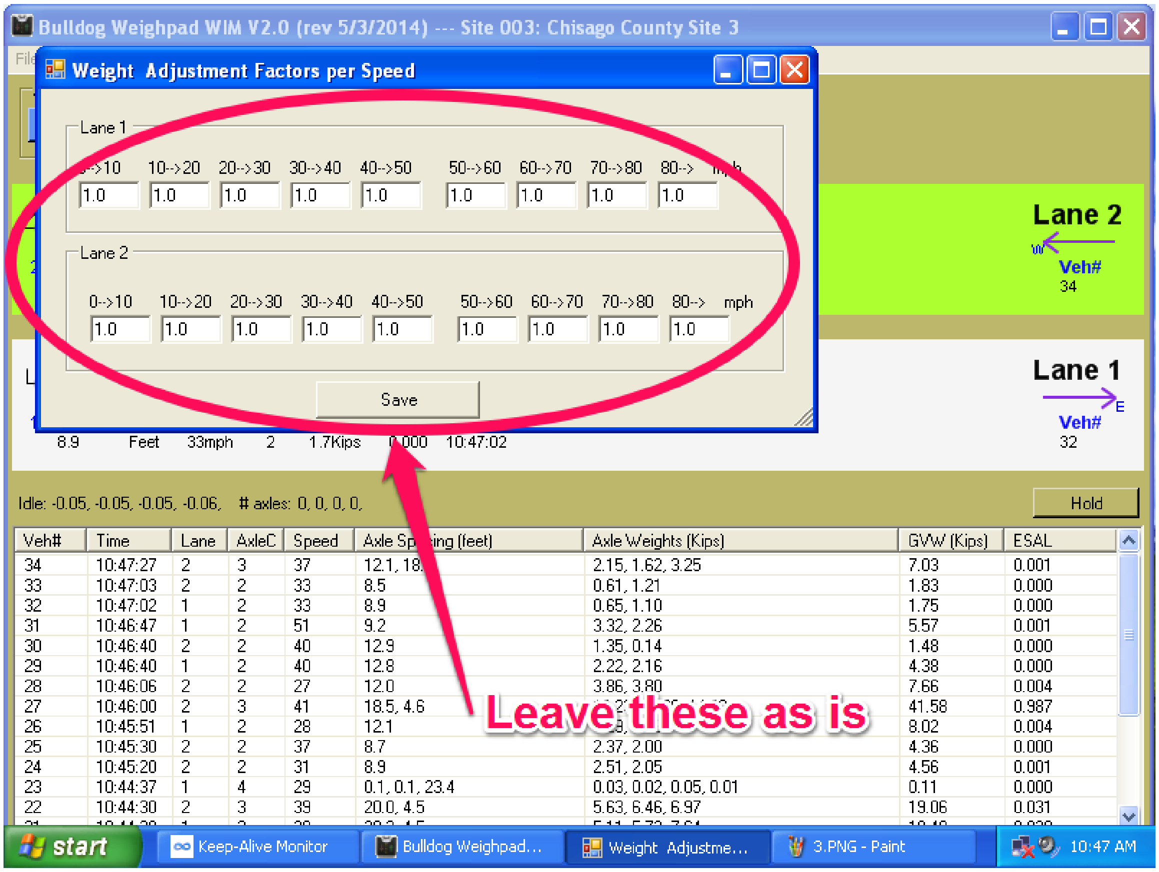

Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
Axle Signal Threshold Setup
Lane-1 Upstream (Ch0): 0.1 Volt
Lane-1 Downstream (Ch1): 0.1 Volt
Lane-2 Upstream (Ch2): 0.1 Volt
Lane-2 Downstream (Ch3): 0.1 Volt
Save
Exit
Set Axle Signal Threshold based on the signal waveform graphs (this can be found in the "Settings" menu)

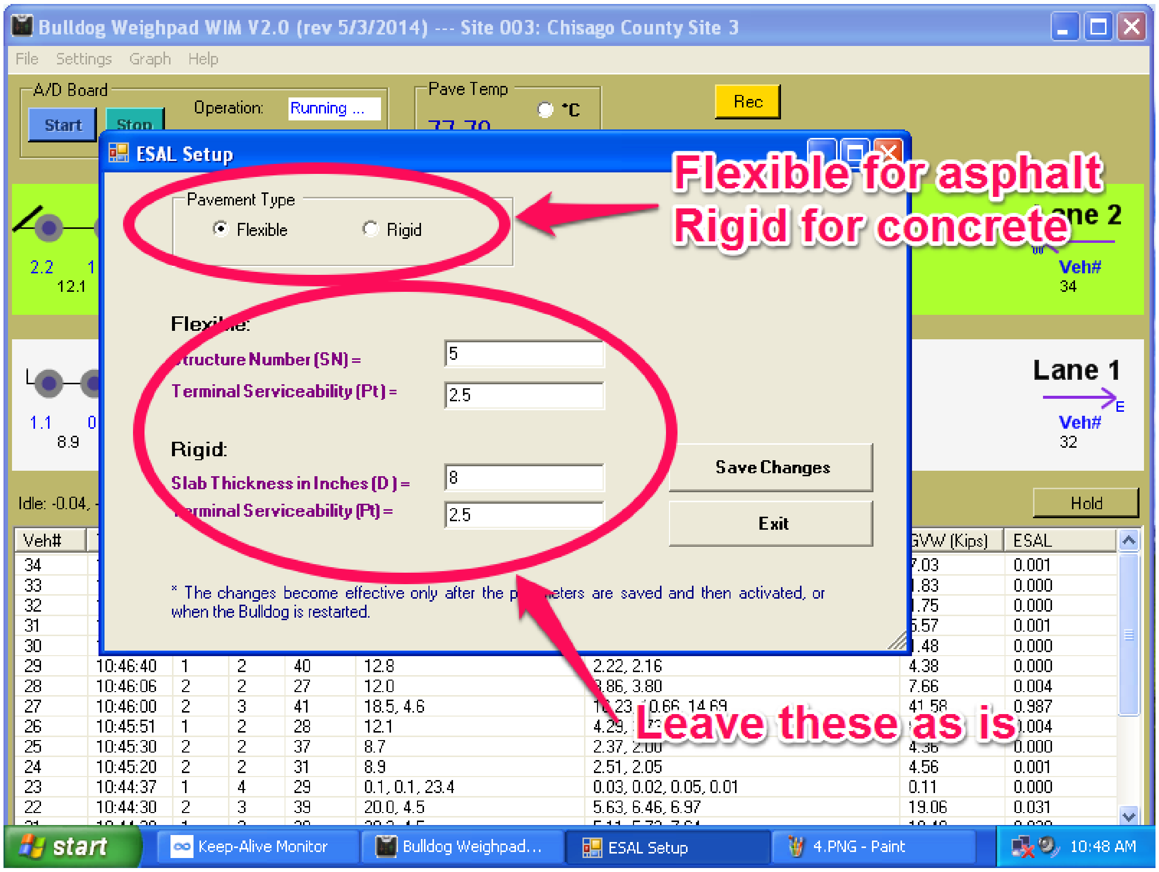
After this initial calibration, configure all other settings in the "Settings" menu with site-specific information



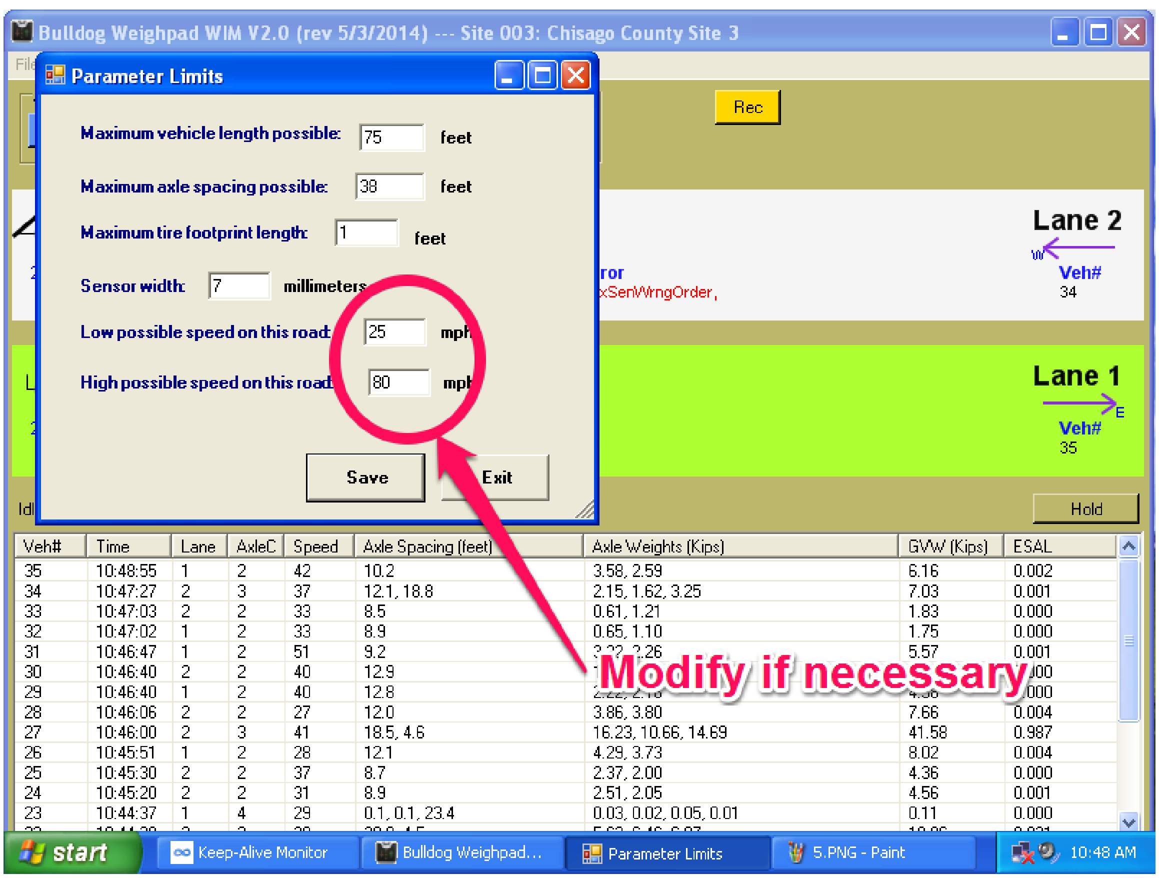

Configure these
(15 feet is appropriate
for most cases)
Leave these as the defaults
Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
Axle Sensor Setup Parameters
Axle-Sensor to Axle-Sensor
Lane 1: 15.000 feet + 0 inch
Lane 2: 15.000 feet + 0 inch
Lane 1
Upstream 6.25
Downstream 6.25
Lane 2
Upstream 6.25
Downstream 6.25
K
Save Changes
Exit
Hold
Lane 2
Lane 1


Set according to
calibration procedure
Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
File Settings Graph Help
A/D Board
Start
Operation: Running ...
Pave Temp
°C
Rec
Upstream
Downstream
Lane-1 1 1
Lane-2 1 1
Save
Exit
Hold
Lane 2
Lane 1
Veh# Time Lane AxleC Speed Axle Spacing (feet) Axle Weights (Kips) GVW (Kips) ESAL

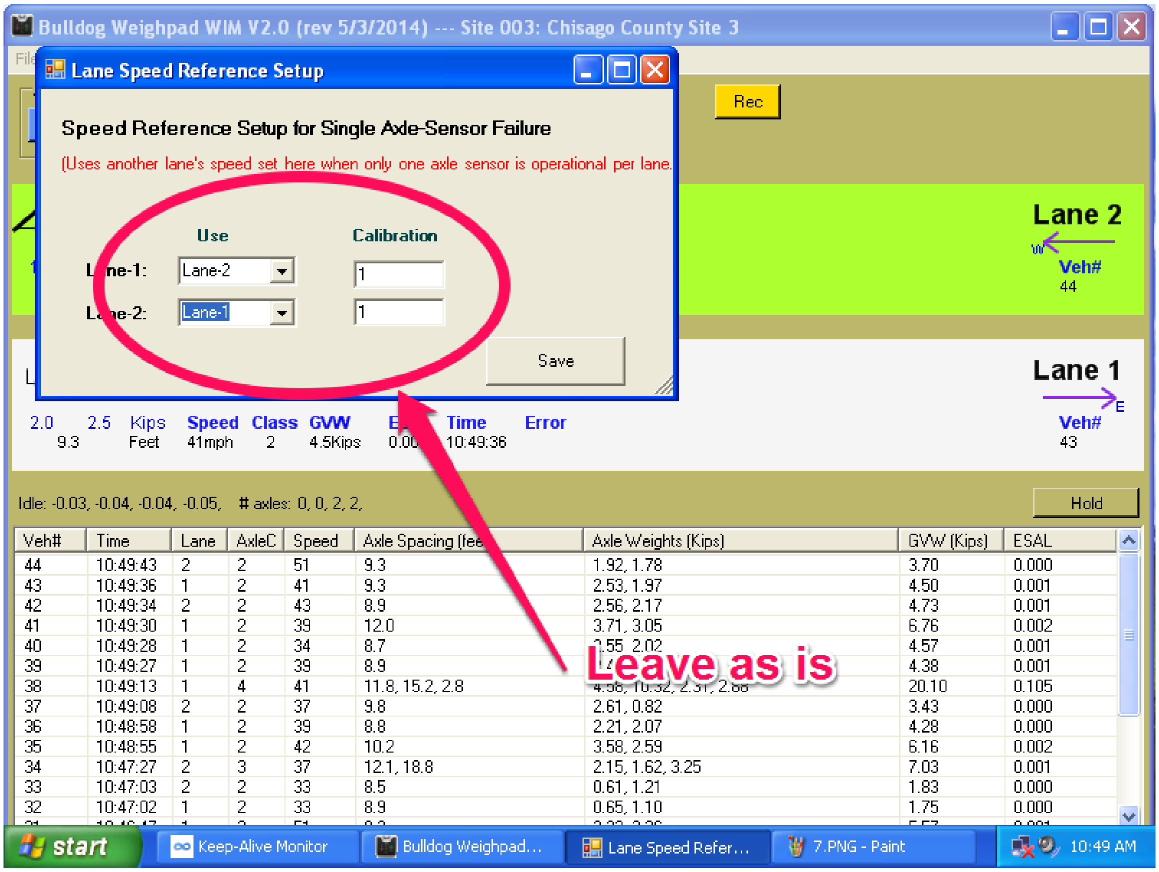

Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
Weight Adjustment Factors per Speed
Lane 1
Lane 2
0-->10 10-->20 20-->30 30-->40 40-->50 50-->60 60-->70 70-->80 80--> mph
Save
Leave these as is
Lane 2
Veh# 34
Lane 1
Veh# 32
Idle: -0.05, -0.05, -0.05, -0.06, # axles: 0, 0, 0, 0,
Hold
Veh# Time Lane AxleC Speed Axle Spacing (feet) Axle Weights (Kips) GVW (Kips) ESAL
start
Keep-Alive Monitor
Bulldog Weighpad...
Weight Adjustme...
3.PNG - Paint
10:47 AM

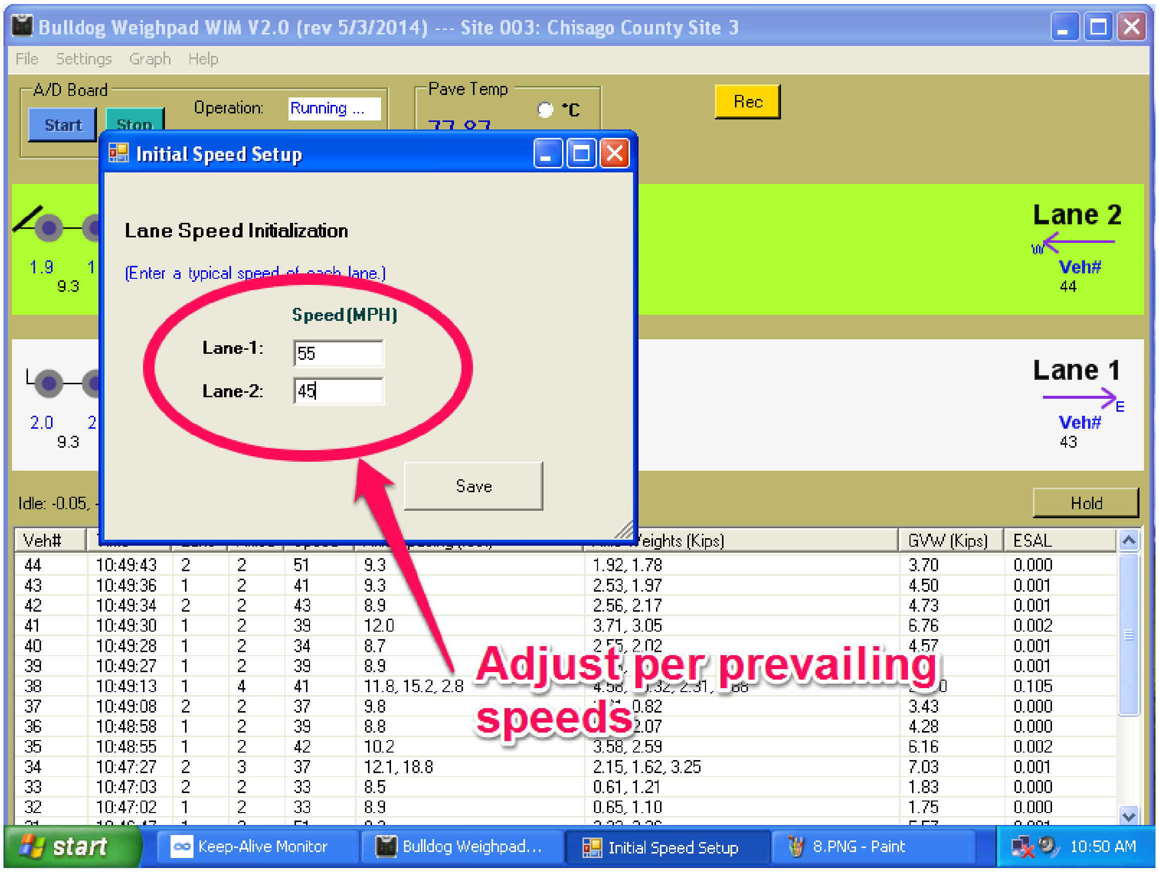


Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
ESAL Setup
Pavement Type
Flexible
Rigid
Flexible:
Structure Number (SN) =
5
Terminal Serviceability (Pt) =
2.5
Rigid:
Slab Thickness in Inches (D) =
8
Terminal Serviceability (Pt) =
2.5
Save Changes
Exit
* The changes become effective only after the parameters are saved and then activated, or when the Bulldog is restarted.
Flexible for asphalt
Rigid for concrete
Leave these as is



Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
Parameter Limits
Maximum vehicle length possible: 75 feet
Maximum axle spacing possible: 38 feet
Maximum tire footprint length: 1 feet
Sensor width: 7 millimeters
Low possible speed on this road: 25 mph
High possible speed on this road: 80 mph
Save
Exit
Modify if necessary


Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
Lane Speed Reference Setup
Speed Reference Setup for Single Axle-Sensor Failure
(Uses another lane's speed set here when only one axle sensor is operational per lane.
Use
Calibration
Lane-1:
Lane-2
1
Lane-2:
Lane-1
1
Save
Rec
Lane 2
Veh#
44
Lane 1
Veh#
43
Leave as is
Speed
Class
GVW
Time
Error
41mph
2
4.5Kips
10:49:36
Hold
Veh#
Time
Lane
AxleC
Speed
Axle Weights (Kips)
GVW (Kips)
ESAL
start
Keep-Alive Monitor
Bulldog Weighpad...
Lane Speed Refer...
7.PNG - Paint
10:49 AM


Bulldog Weighpad WIM V2.0 (rev 5/3/2014) --- Site 003: Chisago County Site 3
File Settings Graph Help
A/D Board
Start
Stop
Operation:
Running ...
Pave Temp
°C
Rec
Initial Speed Setup
Lane Speed Initialization
(Enter a typical speed of each lane.)
Speed (MPH)
Lane-1:
55
Lane-2:
45
Save
Lane 2
Veh#
44
Lane 1
Veh#
43
Hold
Adjust per prevailing speeds
start
Keep-Alive Monitor
Bulldog Weighpad...
Initial Speed Setup
8.PNG - Paint
10:50 AM

Appendix B. Portable WIM Calibration Worksheet

Portable WIM Calibration Worksheet

Test Calibration Vehicle:

Axle Spacing:	Gross Vehicle Weight:	Cruise Control Available?
		YES NO

Pad Spacing:

____

Lane 1 is traveling ______________________ ***Lane 2 is traveling*** ________________________

Calibration Runs:

Lane	Vehicle Count #	Gross Vehicle Weight	Lane	Vehicle Count #	Gross Vehicle Weight
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		

Calculations:

Calculated Average:	
Calculated Standard Deviation:	
All Data Points within 1 Standard Deviation of the Average?	***YES*** ***NO***

If no, complete 5 additional runs in each direction. If yes, skip to scale factor…

Additional Calibration Runs:

Lane	Vehicle Count #	Gross Vehicle Weight	Lane	Vehicle Count #	Gross Vehicle Weight
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		
1			2		

Calculations:

Calculated Average:	
Calculated Standard Deviation:	
All Data Points within 1 Standard Deviation of the Average?	***YES*** ***NO***

Scale Factor:

Calculated Scale Factor for Data Processing:	