Mechanistic Load Restriction Decision Platform for Pavement Systems Prone to Moisture Variations

National Road Research Alliance

MnDOT Contract 1034192 Task 6: Calibration and Preliminary Validation of the Toolkit

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CHAPTER 1: INTRODUCTION

1.1 RESEARCH PROJECT ABSTRACT AND OBJECTIVES

Excess moisture in aggregate base and subgrade soil layers has detrimental impacts on longevity and serviceability of pavements. Seasonal ground water level fluctuations, inundations due to storms and post-storm recess, frost penetrations and freeze-thaw effects lead to continuous moisture hysteresis and change of stress states in pavement foundation. Current analysis and design procedures rely on approximate empirical approaches, which renders their ability to incorporate moisture-dependency and to conduct real-time and forecasted pavement capacity and load restriction analyses. A load restriction decision platform is proposed to provide a reliable and mechanistically-informed tool for pavement engineers to assess pavement performance and make traffic allowance decision during and after periods of excessive moisture. This platform encompasses three core attributes: (1) A mechanics-based model that correctly captures soil and base response to saturated and unsaturated soil states. It will be validated using actual field pavement tests such as MnROAD and can be further enhanced through the use of physically modelled scaled pavement sections; (2) a system-based approach to integrate impacts of various stressors (soil moisture state, vehicular loads and volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly system for pavement load restriction decision making; and (3) a policy-informed decision-platform that incorporates inputs from transportation agencies and users to facilitate its implementation and to realize the cost-effectiveness of such mechanistic approach.

1.2 SUMMARY OF RESEARCH METHODOLOGY (SCOPE)

This project is developing a mechanistic pavement load restriction decision framework using system dynamics approach. The main outcome of this project will be a toolkit for pavement engineers to make decisions regarding load restrictions due to seasonal soil moisture variations as well as during post-flooding instances. The use of system-based approach is necessary to integrate impacts of various stressors (soil moisture state, vehicular loads and traffic volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to a very large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly tool for pavement load restriction (both in current time and for future forecasting) decision making. This research is divided into 10 tasks. The study initiated with development of an initial memo to quantify research benefits and potential implementation steps (Task 1) and literature review (Task 2). This was followed with development of the system dynamics framework to mechanistically evaluate pavement load restrictions (Task 3). The next task pertained to conducting sensitivity analysis of the system dynamics model (Task 4). The next step was to develop a user-friendly toolkit that can be readily implemented for a pavement load restriction decision process (Task 5). This report details the research activities of Task 6. In Task 6, the results in terms of deflection on the pavement surface from PaveSafe were compared to Layered Elastic Analysis (LEA) performed through the use of the commercial software for pavement evaluation GAMES. In addition, PaveSafe was validated using data from Falling Weight Deflectometer (FWD) testing data on pavement sections before and after flooding events. Task 8 will finalize the quantification of research benefits and provide guidance on implementation of the research products. Task 7 is out of state travel for researchers to present findings of this project at the annual meeting of the Transportation Research Board and Tasks 9 and 10 will develop and revise the final report for the study.

This report serves as the primary deliverable for Task 6 (Verification and field-based validation of PaveSafe) of the study.

1.3 ORGANIZATION OF THE REPORT

This report is organized in 3 chapters. Chapter 2 describes the approach that was followed for the verification of the toolkit with comparison to a layered elastic analysis software (GAMES) and the results obtained for different scenarios and vehicle classes. Chapter 3 presents all the results for the verification portion, where FWD testing results are compared to the ones from simulations using GAMES software and PaveSafe.

CHAPTER 2: VERIFICATION PROCEDURE AND RESULTS

2.1 INTRODUCTION

A pavement analysis software GAMES (developed by Maina and Matsui, 2004), which is based on layered elastic solution, was used for the verification of PaveSafe. The procedure that was followed and the assumptions that were made to build the pavement structure model in GAMES is presented herein. In addition, all the results obtained using GAMES software and PaveSafe for different scenarios and vehicle classes are presented and compared in this chapter.

2.2 ADOPTED PROCEDURE FOR THE VERIFICATION OF PAVESAFE

2.2.1 Simulated Scenarios

Three scenarios were taken into consideration for the verification of PaveSafe including one scenario representing a regular condition with no flooding, and two fully saturated scenarios (flooded condition) with different ponded water heights. The scenario details in terms of hydrological information for the three scenarios are shown in Table 2-1: Hydrological information for the three scenarios taken into consideration.

Table 2-1: Hydrological information for the three scenarios taken into consideration.

Case scenario #	Condition	GWT depth (m) (from top of granular base)	Ponded water height (m) (above subgrade layer)	Fully Saturated Layers
1	Hydrostatic	3.8	0	Subgrade below GWT
2	Fully Saturated	3.8	0.05	Subgrade + 5 cm of Subbase
3	Fully Saturated	3.8	0.8	Subgrade + Subbase + Base

The reference pavement cross-section that was utilized is shown in Table 2-2. As can be seen from the table, all of the aforementioned scenarios were simulated considering both a fine sand subgrade (AASHTO A-3) and a high-plasticity clay subgrade (AASHTO A-7-6). This was done in order to verify the models for pavement systems with both coarse and fine grained soil types.

Table 2-2: Cross-section with either A-3 or A-7-6 subgrade type.

Layer	Material type	Thickness [cm]	MR [MPa] (at OMC for subsurface layers)
HMA	Dense-graded	10	3000
BASE	AASHTO A-1-a	30	275.8
SUBBASE	AASHTO A-1-b	50	275.8
SUBGRADE	AASHTO A-3	Semi-infinite	65
	AASHTO A-7-6	Semi-infinite	37

The GWT depth is calculated from the top of granular base layer while the ponded water height was estimated above the top of subgrade layer as can be seen in Figure 2-1. As shown in Table 2-2, the combined thickness of base and subbase layers is 0.8 m. Therefore, Scenario 3 in Table 2-1, represents a condition were all the subsurface layers are fully saturated. Scenario 2 instead represents a fully saturated subgrade with 5 cm of fully saturated subbase layer while the rest of the 45 cm of subbase layer and the whole base layer are unsaturated.

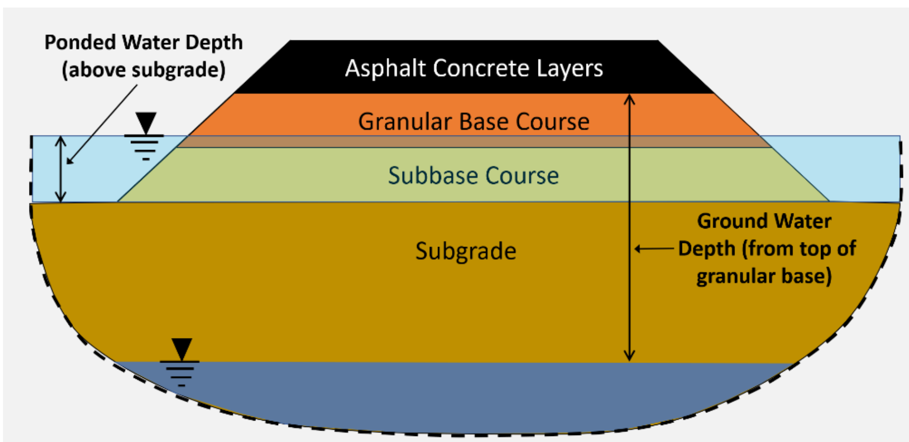

Figure 2-1. Schematic of the pavement cross section.

2.2.2 Saturation Profile and Resilient Modulus Calculation

For Scenario 1, the initial moisture content of the subgrade was estimated based on the soil water retention curve (SWRC) data and initial ground water level (GWL) (i.e., depth of ground water to the subgrade natural surface). In this regard, van Genuchten's formula (van Genuchten 1980) was utilized , shown below, to correlate the height above the ground water level and the moisture content:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha h)^{n_{vG}}}\right]^{m_{vG}}$$

Equation 2-1

where θ_r is residual volumetric water content, θ_s is saturated volumetric water content, α, m_{vG} and n_{vG} are VG model fitting parameters ($m_{vG} = 1 - 1/n_{vG}$), and h is the matric suction head in meter (or ft.). The saturation profile was calculated based on the soil water retention curve (SWRC). In Figure 2-2, an example of saturation profile for the AASHTO A-3 subgrade type is shown.

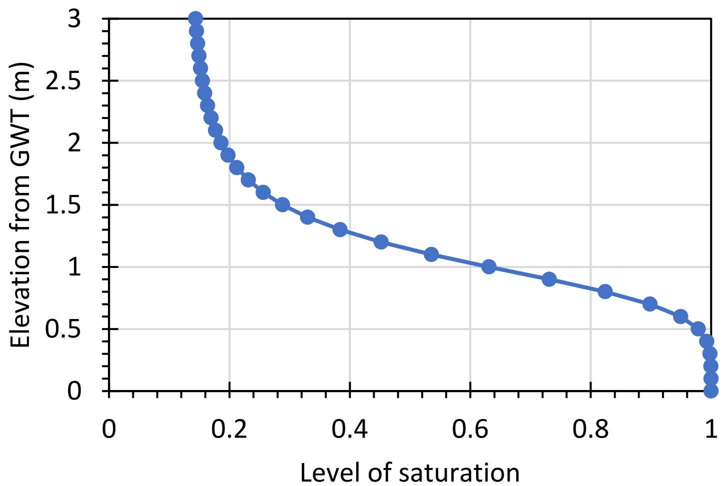

Figure 2-2. Saturation profile for the hydrostatic scenario with AASHTO A-3 soil type.

The Resilient Modulus at different depth was estimated based on the foreshown degree of saturation profile. This was performed by using Equation 2-2, which estimates unbound pavement layers' resilient modulus (M_R) based on their resilient modulus at the optimum degree of saturation ($M_{R\text{-}OPT}$) (Zapata et al. 2007).

$$log\left(\frac{M_R}{M_{R-OPT}}\right) = a + \frac{b-a}{1 + exp\left[ln\left(-\frac{b}{a}\right) + k_m(S - S_{OPT})\right]}$$

Equation 2-2

where S_{OPT} = degree of saturation at optimal water content (in fraction); a= minimum of log ($M_R/M_{R\text{-}OPT}$); b= maximum of log-log ($M_R/M_{R\text{-}OPT}$); and k_m = regression parameter. Based on soil type, Zapata et al. (2007) suggested some typical values for fitting parameters a, b, and km, as summarized in Table 2-3.

Table 2-3: Suggested values for fitting parameters (Zapata et al. 2007).

Parameters	Value/note
a	=-0.3123 for coarse grained soils =-0.5934 for fine grained soils
b	=0.3 for coarse grained soils =0.4 for fine grained soils
k_m	=6.8157 for coarse grained soils = 6.1324 for fine grained soils

In Figure 2-3, an example of the Resilient Modulus at different elevations above the GWT is shown for the scenario with AASHTO A-3 subgrade type.

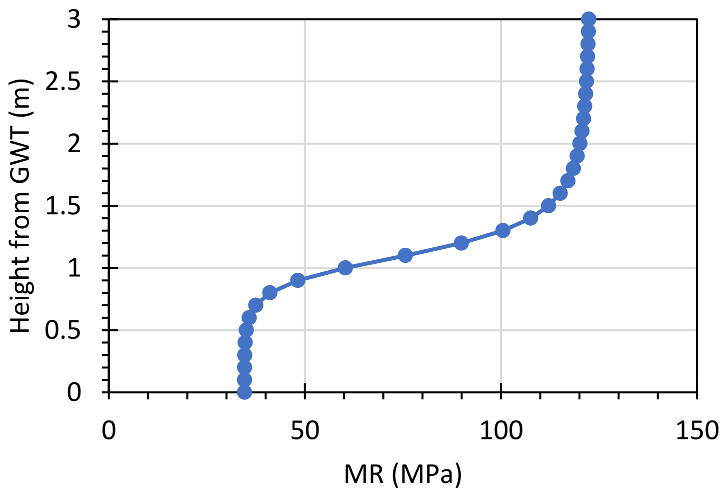

Figure 2-3: Resilient Modulus profile for the hydrostatic scenario with AASHTO A-3 soil type.

To model the Resilient Modulus variation with depth in GAMES, the subgrade was divided into sublayers of 0.5 m thickness. Each sublayer was assigned a constant Resilient Modulus calculated as the average of the distribution in each selected gap. The bottom subgrade layer (below GWT), was considered fully saturated and modeled as semi-infinite layer.

For Scenarios 2 and 3, the subgrade was considered fully saturated (constant saturation level of 1), and consequently modeled as a single semi-infinite layer with constant Resilient Modulus value. The aggregate base and subbase layers' degree of saturation were calculated based on the weighted average of the inundated portion and the unsaturated portion of each layer. In Scenario 2, 0.05 m of the subbase layer was considered fully saturated while in scenario 3, both base and subbase layers were considered fully saturated (based on ponded water height).

The variation of Resilient Modulus for base and subbase layers between the fully saturated and unsaturated condition was calculated using Equation 2-2.

2.2.3 Vehicle Classes and Load Configurations

Two FHWA vehicle classes were selected for the verification of all the aforementioned scenarios. The two vehicle classes that were selected are the number 5 (Single Unit 2-Axle Trucks) and number 9 (Single Trailer 5-Axle Trucks). These two vehicle types were selected due to their most prevalent usage on highways as well as their ability to capture most significant range of commercial vehicles from perspective of highway loadings. In addition, for Scenario 1 with AASHTO A-3 subgrade type, all the FHWA vehicle classes were simulated. More information on the vehicle classes can be found in Figure 2-4.

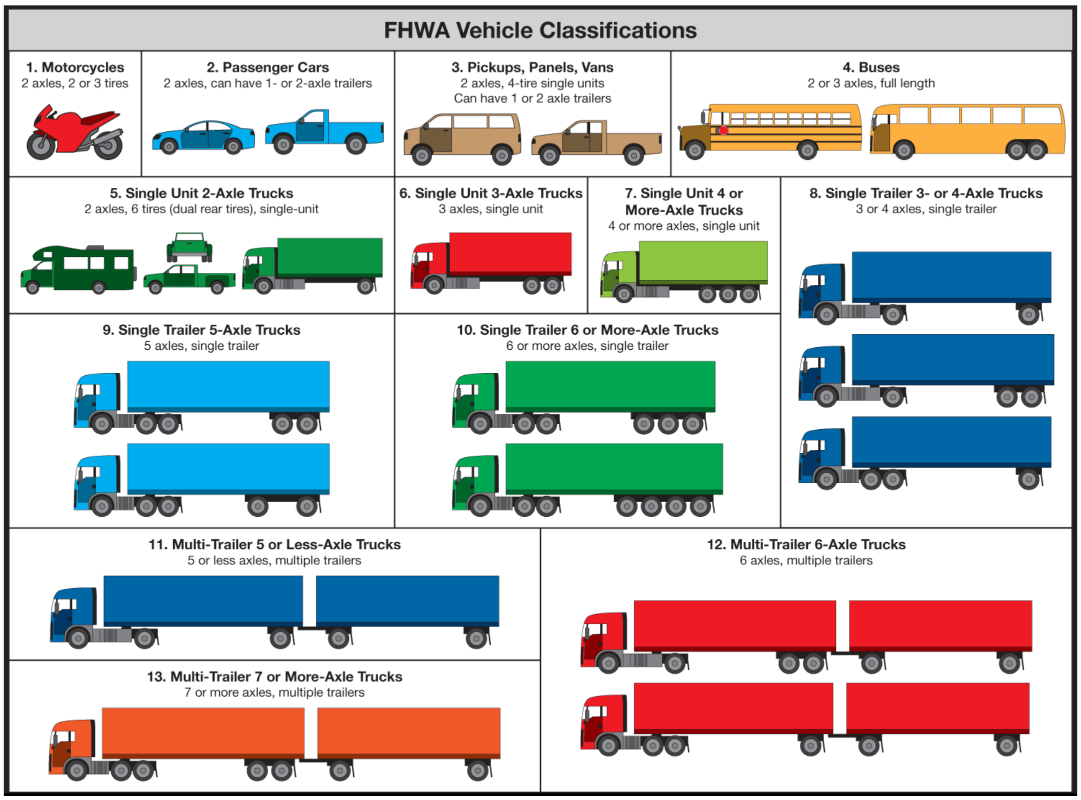

Figure 2-4. 13-category FHWA vehicle classification (FHWA, 2014).

The simulation of the vehicle load in GAMES was performed by modeling the actual tire configuration for the different vehicle classes. Nonetheless, PaveSafe is based on the assumption of equivalent tire footprint for the modeling of the vehicle load on the asphalt concrete (AC) surface. The difference between the two methods is shown in Figure 2-5 and was extensively discussed in Task 5 report.

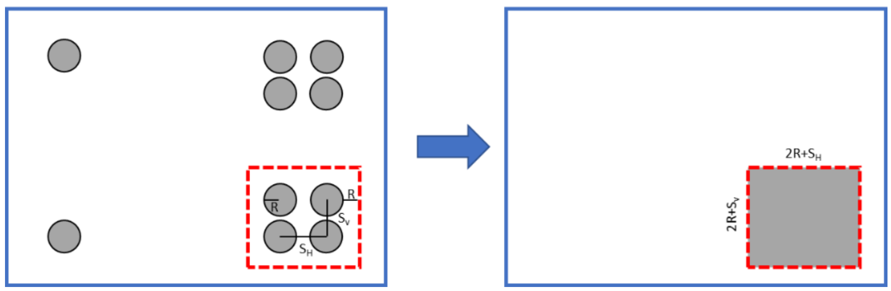

Figure 2-5. Conceptual example of the equivalent footprint method for calculation of induced pressure and radius on AC surface.

In the bottom left of Figure 2-5, the actual tire load configuration is shown, which indicates the approach that was utilized to model the load on the pavement surface in GAMES software. In the right bottom end, the equivalent tire footprint method is shown, which replicates the approach adopted within PaveSafe for modeling the load distribution on the pavement surface.

2.3 RESULTS FOR THE VERIFICATION OF PAVESAFE

2.3.1 Verification of Different Case Scenarios

In this section, all the results obtained from GAMES software and PaveSafe are presented for three different case scenarios (flooded with high ponded water, hydrostatic condition and flooded with lower amount of ponded water), two different soil types (AASHTO A-3 and AASHTO A-7-6) and for two vehicle classes (5 and 9).

In Figure 2-6 and Figure 2-7, the results in terms of deflection on the AC surface from GAMES and PaveSafe are presented and compared.

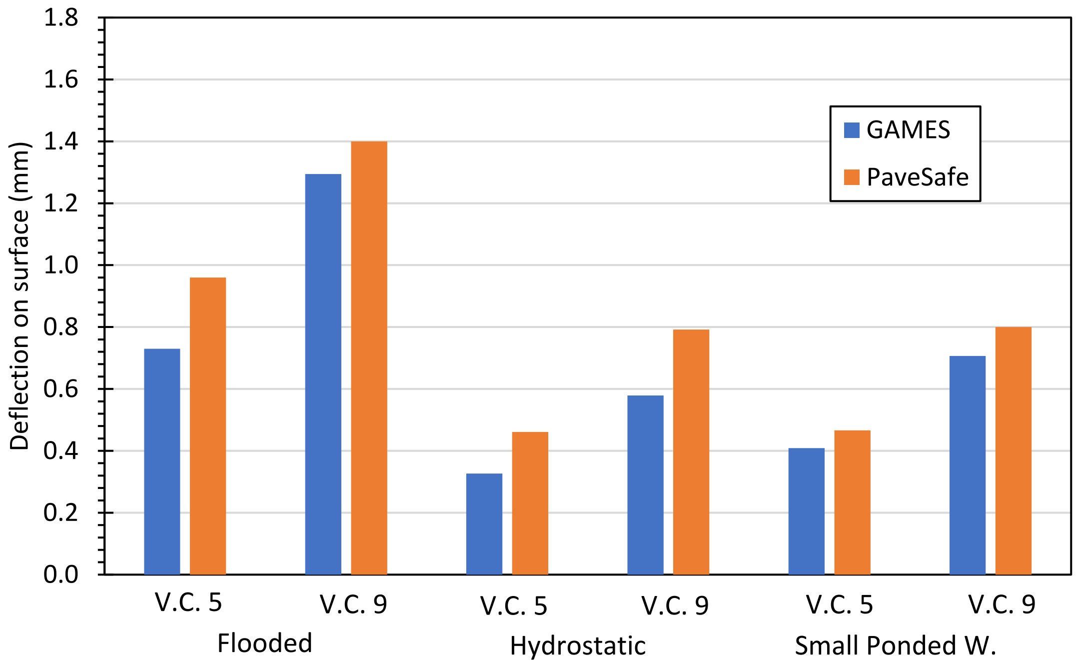

Figure 2-6. Comparison results from GAMES and PaveSafe for the three scenarios with A-3 subgrade type for vehicle class (V.C.) 5 and 9.

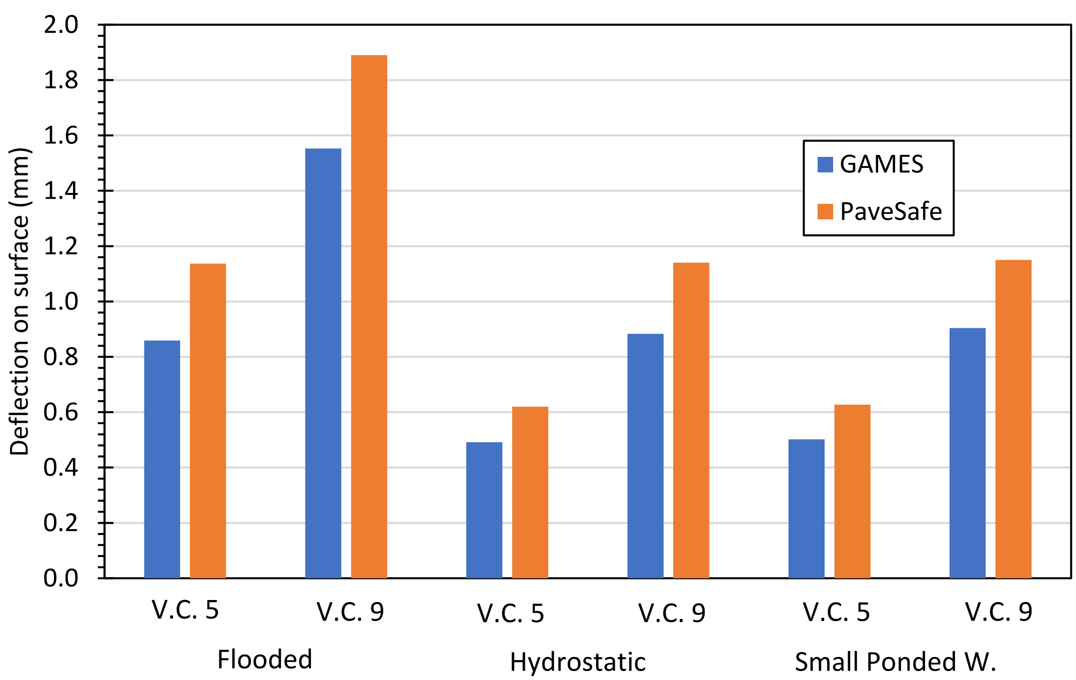

Figure 2-7. Comparison results from GAMES and PaveSafe for the three scenarios with A-7-6 subgrade type for vehicle class (V.C.) 5 and 9.

Results of analyses indicate that the equivalent footprint method implemented in PaveSafe leads to a conservative estimation of AC surface deflection. In general, the surface deflections estimated considering the equivalent footprint method were approximately 30% higher than the ones estimated considering the actual tire configuration. At present, the predictions are left as is (they can be easily calibrated since difference is constant), however research team believes that this approximately 30% increase in predicted deflection provides for a factor of safety in decision process and also serves to account for some in-situ variabilities (due to construction, natural soils variabilities etc.).

2.3.2 Verification Using All Vehicle Classes

For the case scenario 1 (hydrostatic condition) with AASHTO A-3 subgrade type, all the vehicle classes were simulated in order to verify the consistency between the two software for all the possible loading scenarios. In Figure 2-8, the normalized surface deflection values for vehicle classes 2 to 13 are shown. The results were normalized for both the utilized methods by dividing all the surface deflections by the highest deflection calculated (in both cases the one from vehicle class 13) and this was done in order to verify the trend of correlation between the two simulation methods for all the FHWA vehicle classes implemented in PaveSafe.

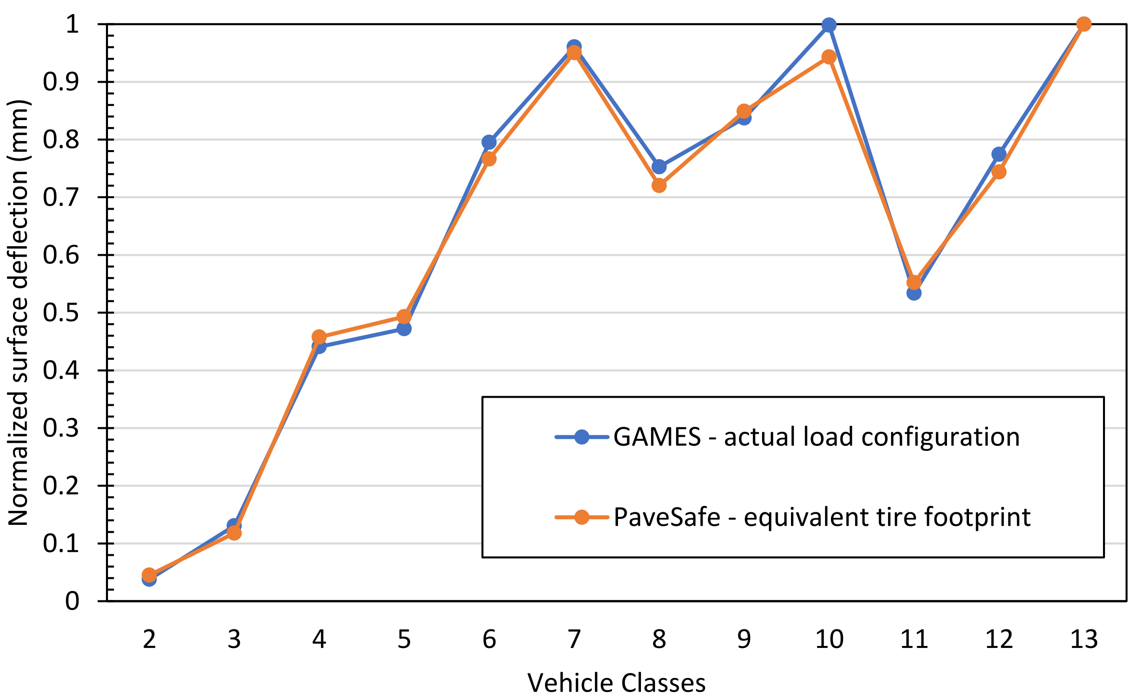

Figure 2-8. Normalized surface deflection for all vehicle classes in hydrostatic scenario with A-3 subgrade type from GAMES and PaveSafe.

In Figure 2-9, the same results are shown but ordered using actual load on the tire block (i.e. tires composing of half of the heaviest axle for each vehicle were considered as actual tire configuration for GAMES and as equivalent tire footprint in PaveSafe) instead of vehicle classes.

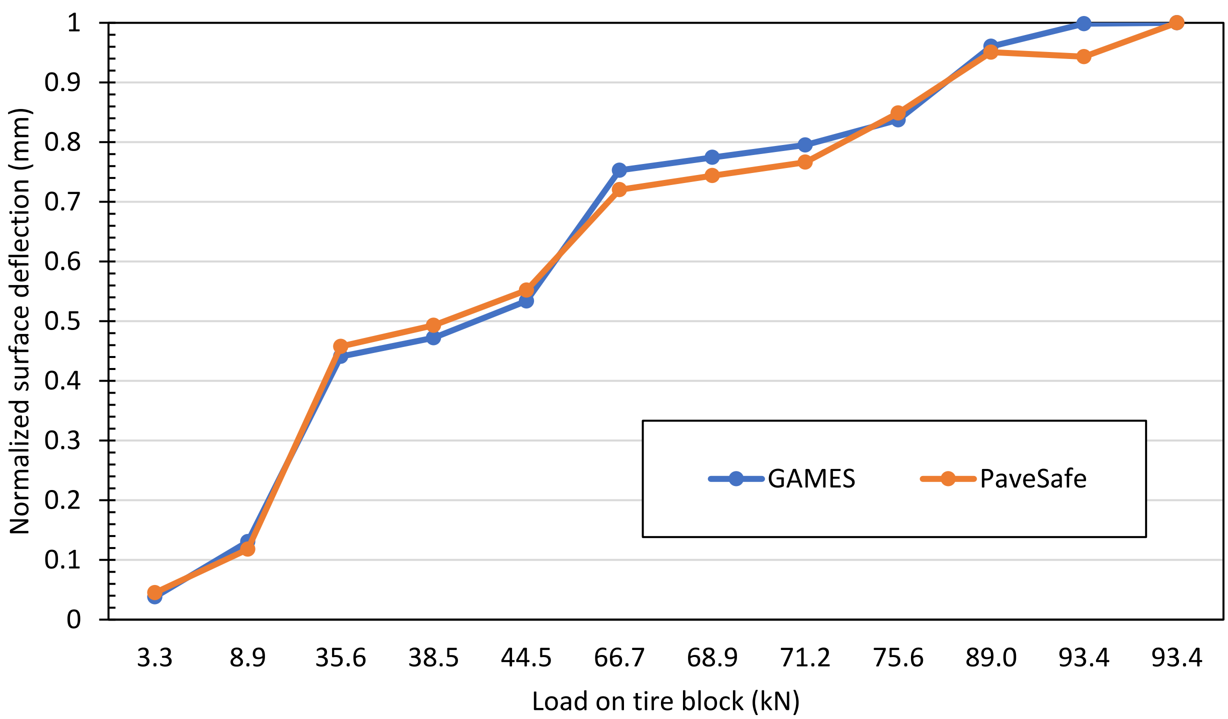

Figure 2-9. Normalized surface deflection for all axle loads in hydrostatic scenario with A-3 subgrade type from GAMES and PaveSafe.

It is clear how the two different methods utilized for the simulations are consistent for all the vehicle classes. These results confirm that the increased deflection in PaveSafe (shown in previous section) is tied both to the use of equivalent tire footprint method and to the different type of analysis performed in PaveSafe (i.e. Equivalent Thickness Method) with respect to actual tire configuration and layered elastic solution adopted in GAMES.

The only vehicle class that resulted in bigger discrepancy between GAMES and PaveSafe is vehicle class 10. Vehicle class 10 represents Single Trailer 6-Axle Trucks, which is the heaviest vehicle type in terms of maximum axle weight together with vehicle class 13. In addition, vehicle 10 is modeled in the software as three dual tires mounted on three parallel axles. The combination of very high load together with a higher discrepancy between the actual load configuration and equivalent tire footprint method, might be the factor causing the higher discrepancy between the two calculated surface deflections. However, it should be re-emphasized that PaveSafe yielded higher value than GAMES.

In Figure 2-10, a correlation between results obtained with PaveSafe and GAMES is shown.

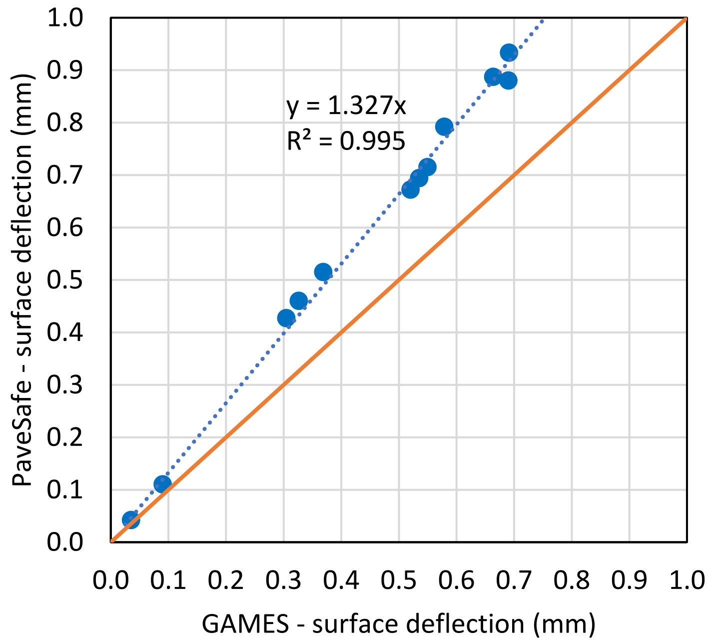

Figure 2-10. Correlation of results from GAMES and PaveSafe simulations.

The values that were utilized to build the plot are the actual values of surface deflection calculated using the two software. It is clear how the trend of correlation between the two simulations is very close to linear, proving again the consistency of the two different analysis methods.

CHAPTER 3: FIELD-BASED VALIDATION PROCEDURE AND RESULTS

3.1 INTRODUCTION

The results obtained with FWD testing in Minnesota and North Dakota, respectively on MN 93 and ND 200, are compared with the simulations performed with GAMES software and PaveSafe. Multiple realistic scenarios were simulated, and all the results are presented using box plots (whiskers, quartiles and median values) in this chapter.

3.2 FIELD-BASED VALIDATION OF PAVESAFE

3.2.1 FWD Data Provided

Falling Weight Deflectometer (FWD) testing results were provided for two testing locations, one in Minnesota and the other one in North Dakota. These two tested sections were used for preliminary validation of PaveSafe application.

The FWD testing in Minnesota was carried out on MN 93 between Le Sueur and Henderson from RP 1.8 to RP 5.4 in Control Section 7212. This section of roadway often experiences spring flooding from the nearby Minnesota River and in the spring of 2011, water over the road closed it from March 21 until April 15. This roadway is classified as Rural Minor Arterial. Minnesota DOT HPMA shows that it is an HMA road paved 24’ wide with 4.3’ wide gravel shoulders. The current roadway was initially constructed in 1946 and the last rehab was a thin overlay in 1998, a chip seal was placed in 2003. HPMA shows that this road has 2350 ADT with 8.9% trucks. Soil maps show that the soils in this area are predominately A-6 with some areas of A-4 in the vicinity of the Rush River crossing. The cross section for MN 93 is shown in Table 3-1.

Table 3-1: Cross section for MN 93.

Layer	Thickness (inches)	Thickness (cm)
HMA	5	12.7
Base (CL 5)	6	15.24
Subbase (Granular material)	19	48.26
Subgrade (AASHTO A-4 and A-6)	Semi-infinite	Semi-infinite

The roadway section was first tested on 24th of April 2010 prior to flooding event. On March 21st, 2011 the section was closed since the water level reached 733.7 ft. and it crested at 737.66 ft. on March 27$^{th.}$ The roadway section was reopened on April 15th, 2011 and it was tested on April 18th, 2011 with a water level at 732.4 ft. It was subsequently tested again on April 25th of the same year with water level at 731.0 ft. and on May 9th with water level at 728.8 ft.

The FWD testing in North Dakota was carried out on ND 200 from RP 1 to RP 3.1 in 2019. The cross section for ND 200 is shown in Table 3-2.

Table 3-2: Cross section for ND 200.

Layer	Thickness (inches)	Thickness (cm)
HMA	8	20.32
Base (Granular material)	10	25.4
Subgrade	Semi-infinite	Semi-infinite

In this case, information on the subgrade type was not available but Resilient Modulus calculation for the subgrade (tested on April 3rd, 2019 in unflooded condition) was provided and it can be seen in Figure 3-1.

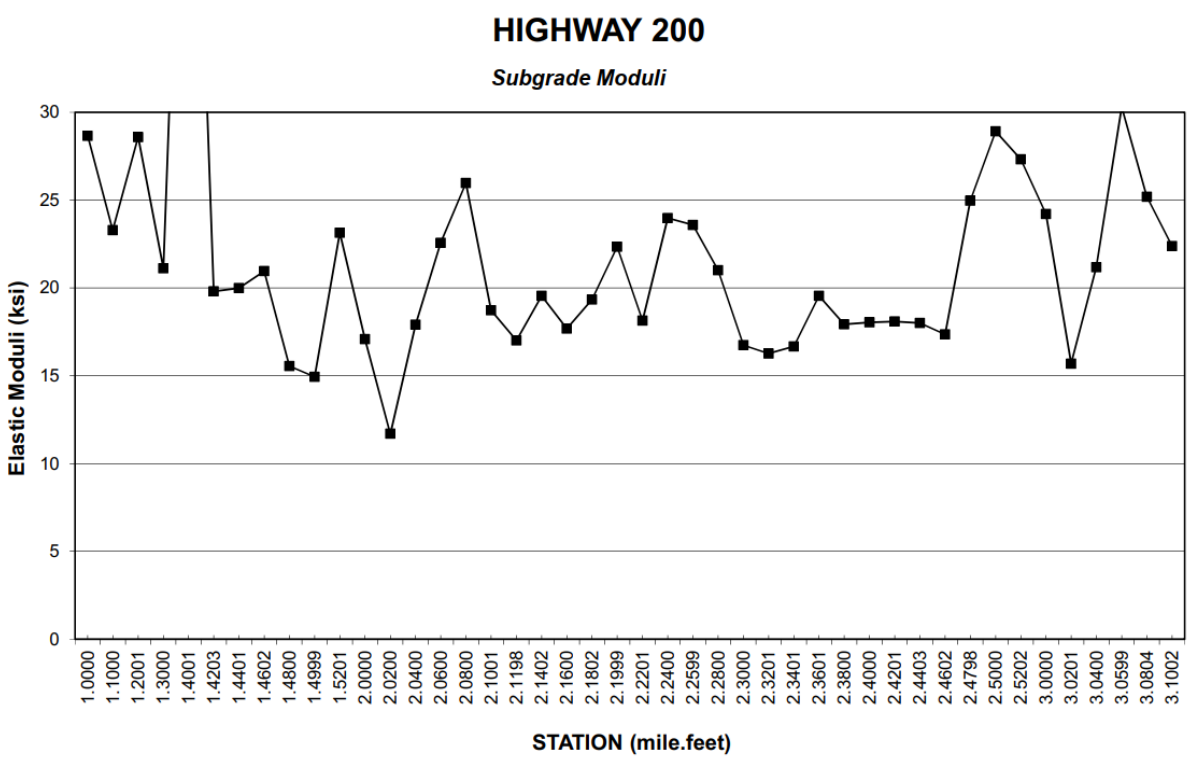

Figure 3-1. Resilient Modulus of subgrade on ND 200.

Data in terms of resilient modulus and pavement surface deflection determined using FWD testing results were provided for both unflooded and flooded conditions.

3.2.2 Adopted Approach for Simulation

FWD testing on the aforementioned cross sections was simulated using GAMES software. GAMES software allows to model the exact shape of the FWD plate (300 mm diameter), assign the same force as recorded in the field and eventually calculate the deformation on the pavement surface.

The same procedure as mentioned in the previous Chapter was adopted to build the pavement structure model for the different locations and scenarios. Information were collected both on thicknesses of different layers in the pavement cross sections and materials used along with soil type. For each day of simulation, depending on the measured water level on site, the depth of the GWT was calculated. Based on that, the saturation profile in the pavement structure was determined and the Resilient Modulus accordingly calculated (Equation 2-1 and Equation 2-2). GAMES software allows to divide each layer in multiple sub-layers and assign different properties for the same material in different locations with depth. This feature allowed to accurately describe the variation of Resilient Modulus with depth in the pavement structure and within each pavement layer.

It could be argued that GAMES software does not allow to solve the water flow problem, but in this validation procedure, only a “single day” was simulated at a time while the water level was provided for that specific day. Therefore, including the water flow was not required. Nevertheless, the assumption to have the same saturation profile in the pavement structure during the testing hours was made, but this is a realistic assumption.

Based on the deformation obtained from GAMES, a surface deflection that would have been predicted by PaveSafe was estimated considering that PaveSafe (based on equivalent tire footprint method) was shown to provide more conservative results. Specifically, the earlier verification chapter showed an approximately 30% overestimation of surface deflection in PaveSafe. In addition, in order to have a direct surface deflection estimated from PaveSafe simulation, deflection caused by vehicle classes 3 and 4 were compared with the previously mentioned simulations. Vehicle classes 3 and 4 were selected since they are comparable in terms of applied pressure on the AC surface to FWD testing pressures.

For both MN 93 and ND 200, the GWT position for the unflooded scenario was considered at a depth of 1 m from the subgrade surface. For MN 93, since water level data were available for all the testing days, the level of saturation of subgrade and subsurface layers for the different models were calculated. For ND 200, the flooded scenario was simply modeled as a pavement structure with fully saturated subsurface layers.

3.3 RESULTS FOR THE FIELD-BASED VALIDATION OF PAVESAFE

All of the results are presented for the different testing days and locations using box and whisker plots. These plots were used because the available FWD data were measured at multiple points/locations along the pavement sections. Therefore, this was considered the best approach to present and consider the data in order to keep the variability of the results at the site in perspective while making comparison with GAMES and PaveSafe results.

In these plots, FWD represents the data coming from field testing on the pavement sections, G represents results coming from GAMES software based on layered elastic solution, and PS represents results from PaveSafe calculated as 20-25% increment with respect to GAMES software on the basis of the 30% difference evaluated in the verification chapter. Lastly, PS – 3 & 4 represents the actual surface deflection results obtained using PaveSafe and specifically for vehicle classes 3 and 4. As mentioned earlier, vehicle classes 3 and 4 were selected since the applied pressure on the surface calculated based on the load on tire block and area of application are comparable with the pressure applied by FWD.

3.3.1 Results from MN 93 Roadway Section

The simulations in GAMES and PaveSafe were implemented with variability associated to the soil type present in the area (AASHTO A-3 and AASHTO A-6). A range for the Resilient Modulus between 39.5 and 62 MPa was utilized based on Ji et al. (2014). In addition, SWRC parameters for each soil type, such as n and α, were variated between ranges identified based on literature studies: Ghanbarian-Alavijeh et al. (2010), Puckett et al. (1985), Huang et al. (2005), and Nemes al. (2001).

Results associated with the FWD data for June 24th, 2010 are shown in Figure 3-2.

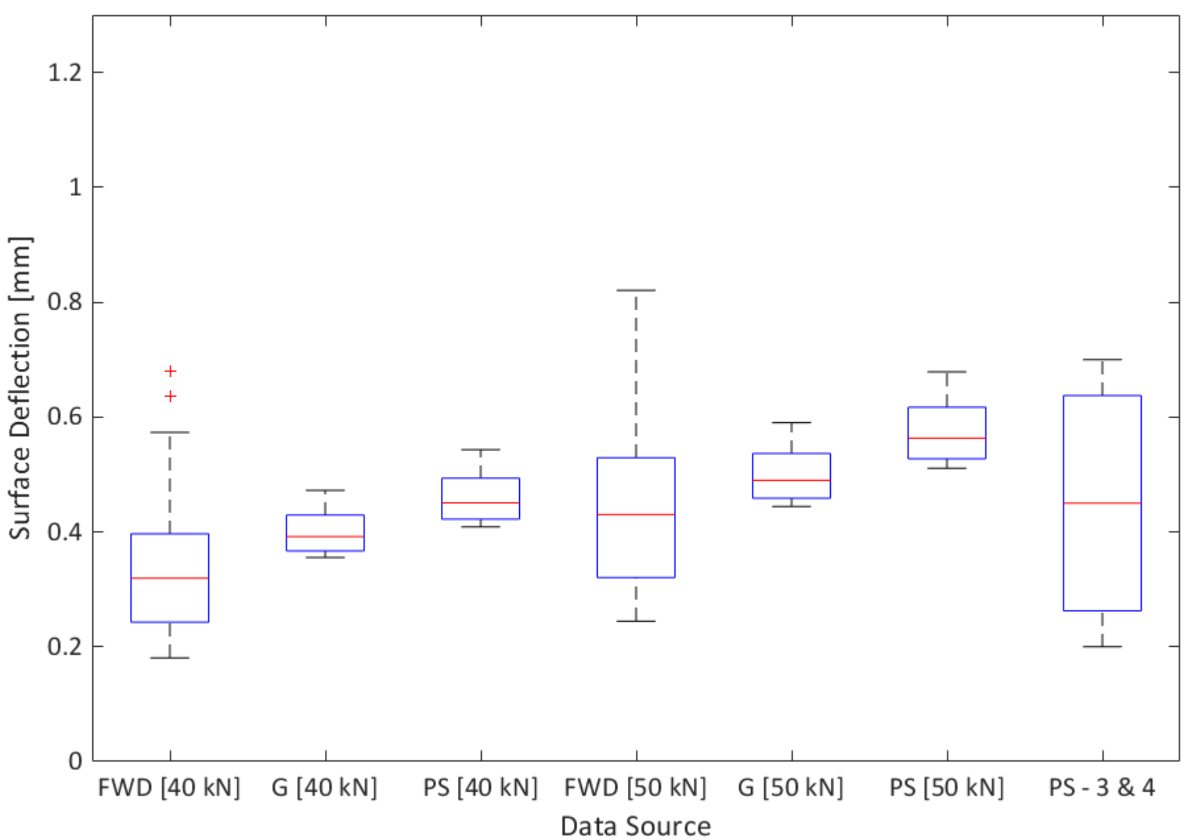

Figure 3-2. Results MN 93 (6/24/2010).

From Figure 3-2, it can be seen how results from both GAMES and PaveSafe under both loading conditions (40 and 50 kN) are inside the range of the results obtained from the field with FWD testing. The pressure applied on the surface by vehicle classes 3 and 4 is between the pressure generated with FWD performed at 40 kN and FWD performed at 50 kN, and this is reflected in the results obtained from direct PaveSafe simulation (PS – 3 & 4).

In addition, PaveSafe results are not only within FWD measurement range but also always within or slightly above the upper quantile. This result is preferable to be considered in order to ensure that instead of the average response, the actual weaker part of pavement section is taken into consideration, since that is what will control the ability to reopen the roadway section to traffic.

In Figure 3-3, the results obtained in April 18th, 2011 on MN 93 are shown. On this day, the water level was measured to be at 732.4 ft. or 223.3 m, which means approximately 1.5 m higher with respect to the hydrostatic condition scenario shown in Figure 3-2 for June 24th, 2010.

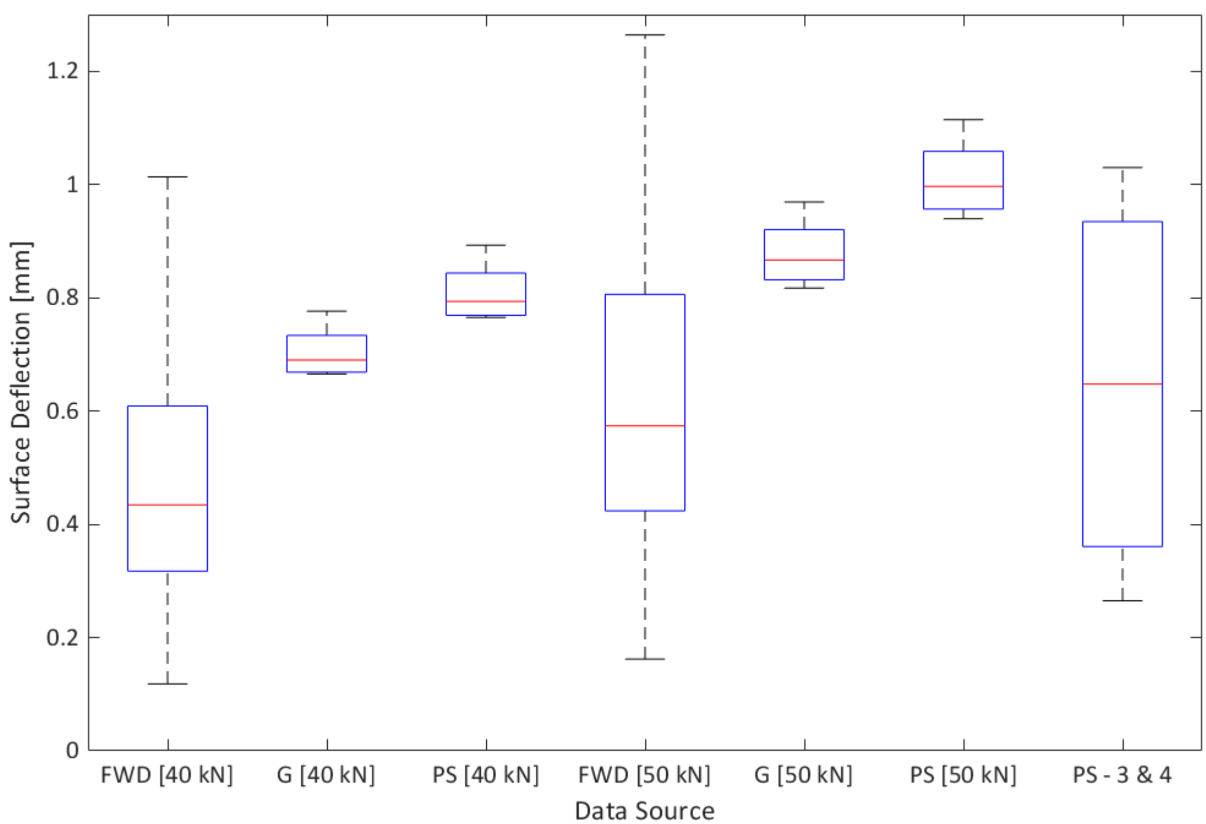

Figure 3-3. Results MN 93 (4/18/2011).

The first thing that can be noticed from Figure 3-3 is that the results in terms of surface deflection under the loading application are higher when compared with Figure 3-2. This is the effect of the level of saturation in different pavement layers, which in this case, based on the cross section information and measured water level, they are fully saturated. Nonetheless, even in this case, GAMES and PaveSafe are able to capture the increment in surface deflection caused by flooding and all the simulations results are inside the range of variability of FWD data at both load levels.

Also in this case, PaveSafe results are not only within FWD measurement range but also always within or slightly above the upper quantile. In Figure 3-4, Figure 3-5 and Figure 3-6, results from FWD testing at 40 and 50 kN and from simulations performed with GAMES and PaveSafe are shown.

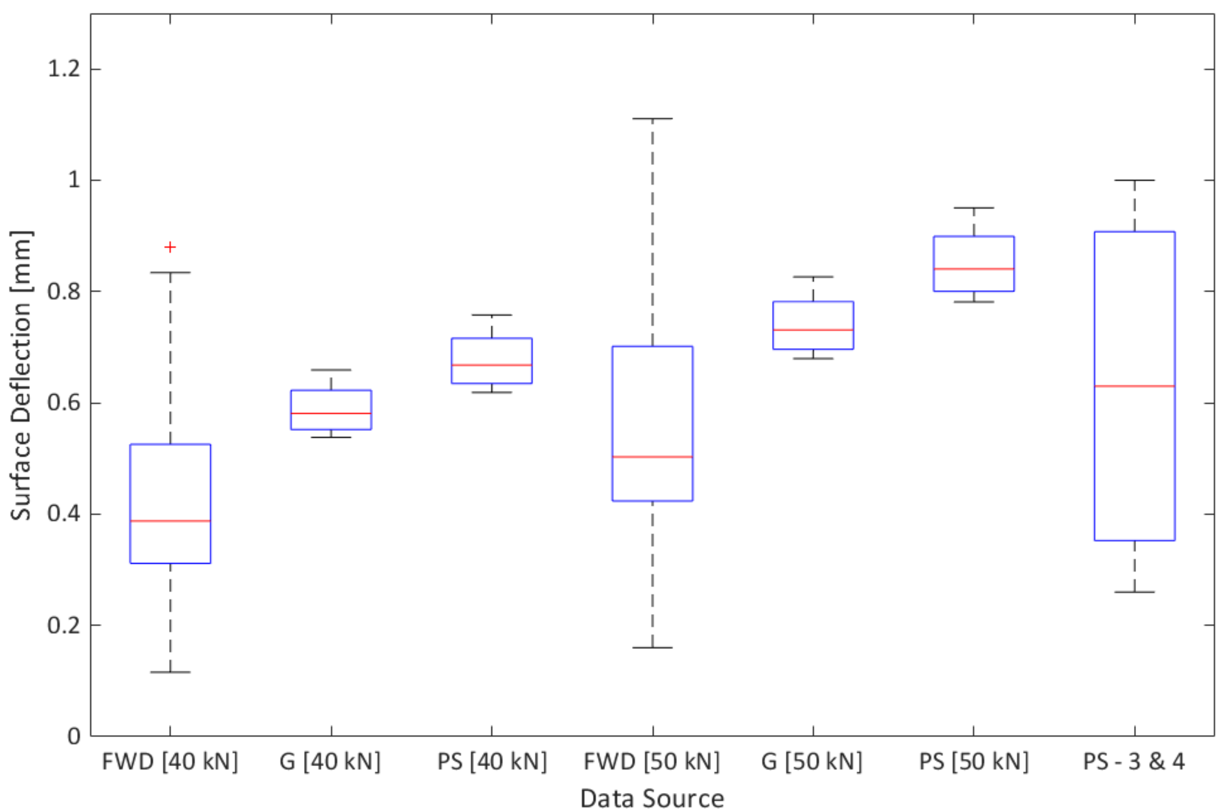

Figure 3-4. Results MN 93 (4/21/2011).

The FWD data shown in Figure 3-4 were collected on April 21st, 2011. In this case, the saturation profile was considered partially flooded. The water level measured in that day was of 731.7 ft. or 223 m, which, based on cross section information, means fully saturated subgrade and fully saturated subbase with a completely unsaturated base layer.

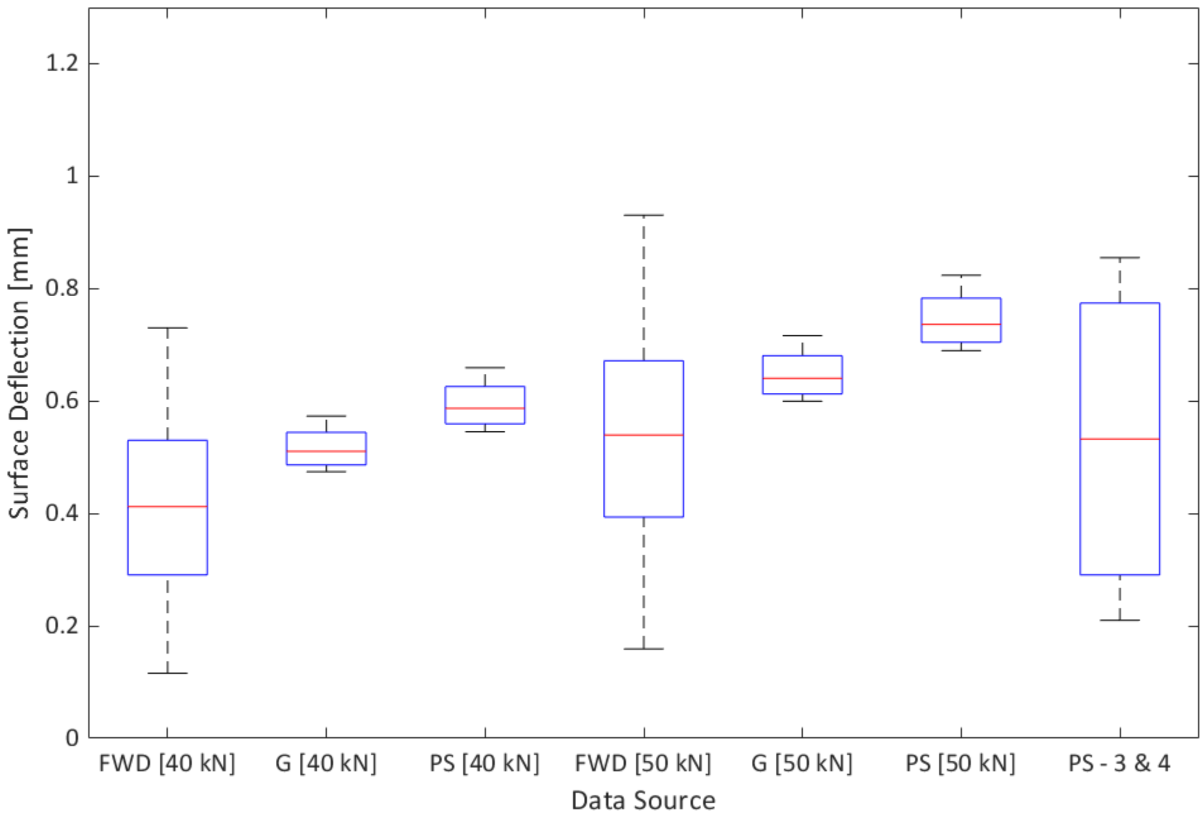

Figure 3-5. Results MN 93 (4/25/2011).

This case scenario can be also considered as partially flooded. The water level measured in April 25th, 2011 was of 731 ft. or 222.8 m, which, based on pavement cross section information, means fully saturated subgrade, partially saturated subbase and completely unsaturated base layer.

The results in Figure 3-5 reflect the lower level of saturation of the pavement layers with respect to Figure 3-4. In addition, the simulation results were consistent with the field data.

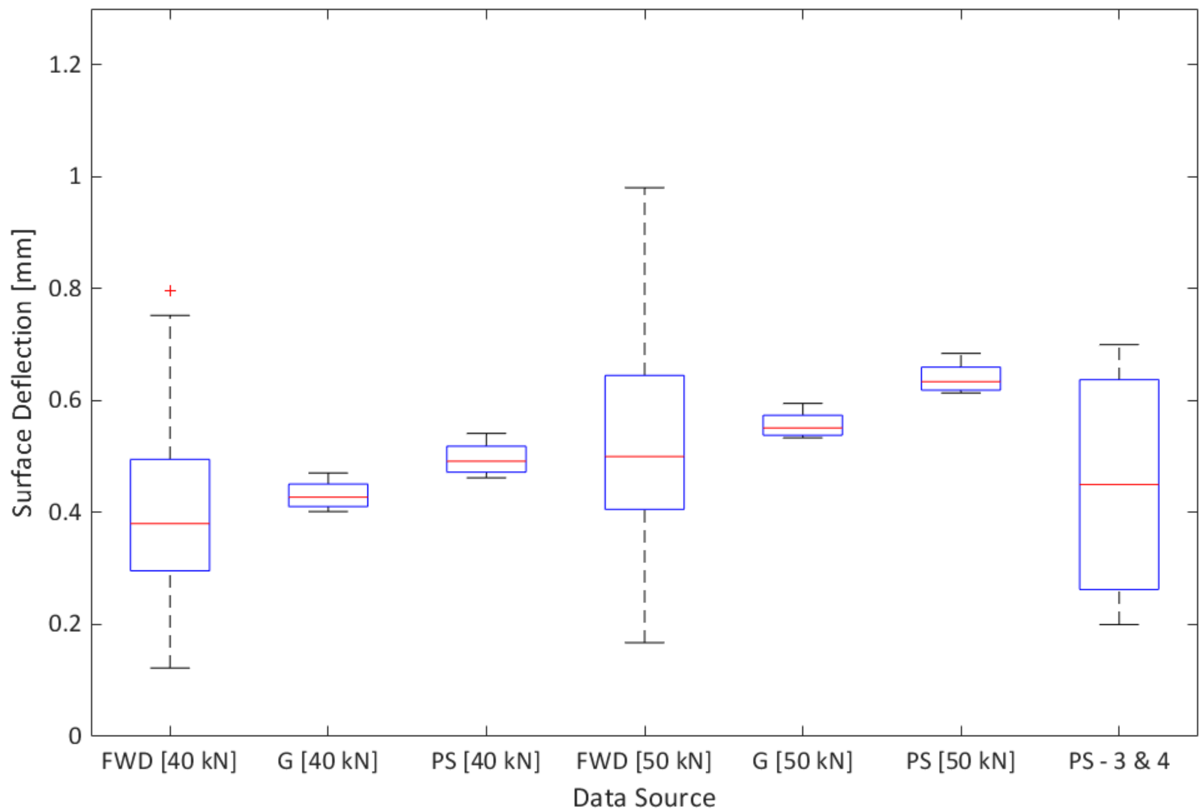

Figure 3-6. Results MN 93 (5/9/2011).

Data on May 9th, 2011 were collected in a scenario where the measured water level was of 728.8 m or 222.1 m. This means that base and subbase were completely unsaturated and subgrade was still in fully saturated condition. The results obtained in this day are comparable to the ones that were obtained on the previous testing day (shown in Figure 3-5). Once again, the results from simulation were inside the range of variability of FWD testing data for both loading conditions.

For all those last three scenarios, PaveSafe results are not only within FWD measurement range but also always within or slightly above the upper quantile. As mentioned earlier, this result is preferable to be considered in order to ensure that instead of the average response, the actual weaker part of pavement section is taken into consideration, which will control the ability to reopen the roadway section to traffic.

3.3.2 Results from ND 200 Roadway Section

The same approach followed for MN 93 was adopted for ND 200. Variability of subgrade Resilient Modulus and SWRC parameters were implemented in the simulations based on literature information: Ji et al.

(2014), Ghanbarian-Alavijeh et al. (2010), Puckett et al. (1985), Huang et al. (2005), and Nemes et al. (2001).

For ND 200, water level data were not available for the different testing days and consequently it would have been difficult to estimate the GWT position in the different case scenarios. For this reason it was decided to simulated only two case scenarios: one in hydrostatic condition with GTW level at -2 m from subgrade surface (based on USGS data in Carrington, ND) and a fully saturated scenario with all the pavement layers in fully saturated condition.

Figure 3-7 shows results for ND 200 in the hydrostatic condition.

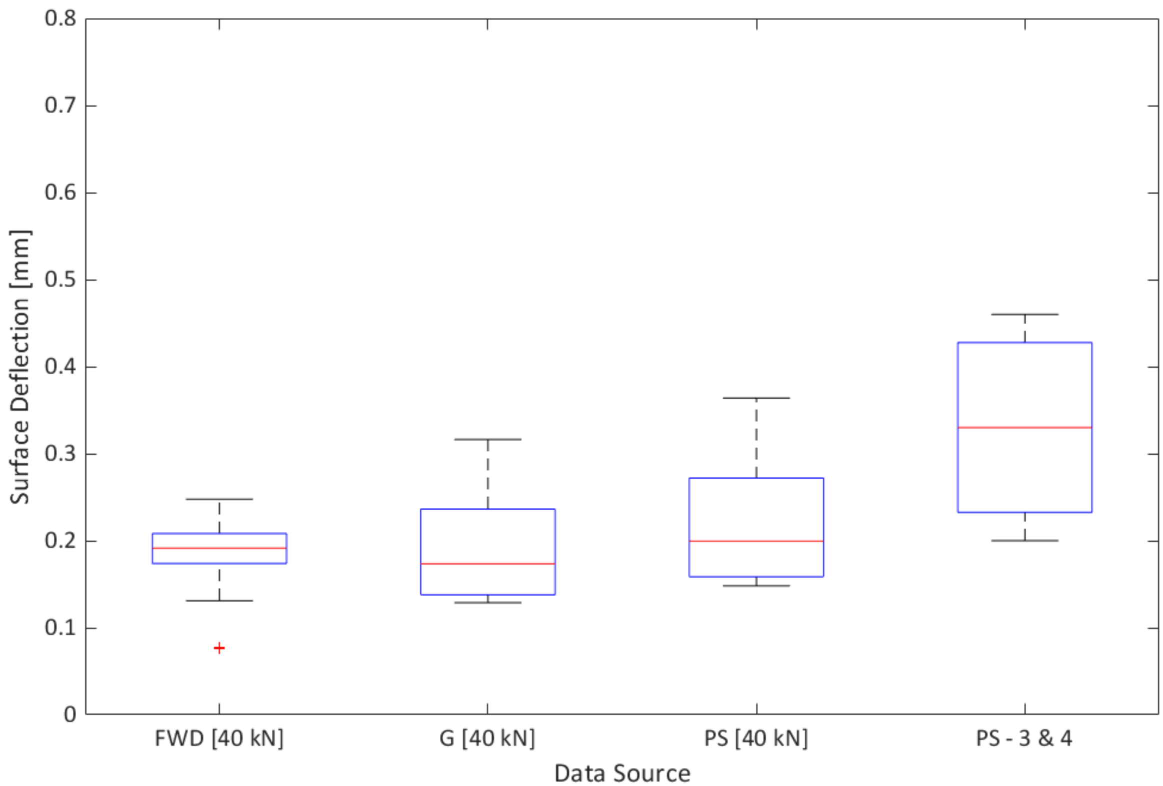

Figure 3-7. Results ND 200 before flood.

In Figure 3-7, it can be noticed that only 40 kN was used as testing load for FWD in ND 200. For this reason, the higher values obtained from PaveSafe using vehicle classes 3 and 4 make sense since they are obtained with pressure values that, as mentioned earlier, are between the pressure applied using FWD at 40 and 50 kN.

In Figure 3-8, results for ND 200 in flooded condition are shown. Here, it can be noticed again that results were available just at 40 kN load application which justifies the higher surface deflection obtained with vehicle classes 3 and 4 using PaveSafe, since the pressure applied on the surface by those vehicles is higher than the pressure generated with FWD performed at 40 kN. In addition, it can be noticed that the surface deflection data recorded on this day reflect the higher level of saturation of the pavement layers with respect to Figure 3-7.

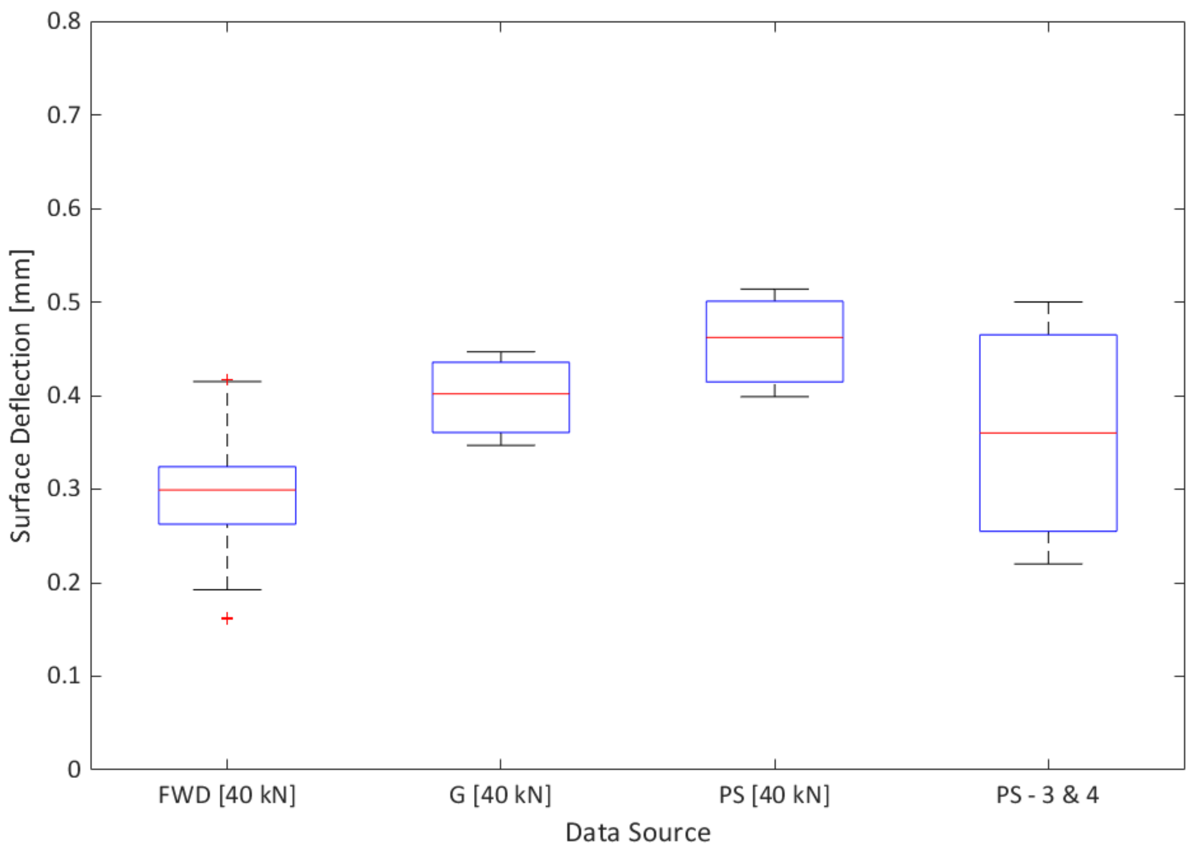

Figure 3-8. Results ND 200 flooded.

In this case scenario, the simulations were able to predict the increment of surface deflection with respect to the previous scenario. In addition, results obtained from both PaveSafe and GAMES, are very close to the field recorded ones for both scenarios.

CHAPTER 4: SUMMARY, CONCLUSIONS AND FUTURE WORK

4.1 SUMMARY

The accuracy of PaveSafe application was verified by comparing the results in terms of surface deflection with layered elastic analysis (LEA) using the commercial software for pavement evaluation GAMES. The correlation between the two methods was proven consistent even though PaveSafe (utilizing equivalent tire footprint) resulted in deflections that were conservative for every scenario and vehicle type (approximately 30% higher surface deflection than GAMES). Those results were consistent with the preliminary verification procedure described in previous Task 5 report.

Subsequently, PaveSafe performance was validated by comparing the results with field data from FWD testing performed on roadway sections in Minnesota (MN 93) and North Dakota (ND 200). PaveSafe surface deflection was estimated by increasing the results from GAMES by 30%, since the ability of simulating FWD plate dimension and load magnitude has not been integrated in the toolkit yet. Nonetheless, results directly obtained from PaveSafe simulation for vehicle classes 3 and 4 were included in the comparison for all the scenarios since they apply a pressure on the pavement surface which is between the ones generated by FWD testing at 40 kN and 50 kN.

4.2 CONCLUSIONS

PaveSafe provided consistent results with GAMES software. The results from PaveSafe are constantly higher of approximately 30%, and this is in part due to the equivalent tire footprint method adopted in the toolkit for modeling the loaded area on the surface, while GAMES is based on actual tire configuration. In addition to that, the two results are different since two different types of analysis are performed in PaveSafe and GAMES, in which, PaveSafe analysis is based on Equivalent Thickness Method while GAMES adopts the Layered Elastic Solution.

In general, PaveSafe provides more conservative results but when looking at normalized results, it is consistent with LEA under different case scenarios (hydrostatic and flooded conditions with different ponded water heights) and for the different load magnitudes and configurations (vehicle classes 2 to 13 of the FHWA classification).

In addition, PaveSafe is able to predict the results from FWD testing. This was proven for two different testing locations (in Minnesota on MN 93 and in North Dakota on ND 200), and for different saturation levels in the pavement layers. For all times of testing, PaveSafe predicted deflections which were consistently within upper quantile of FWD measurements. This is important since flooded pavement opening decisions should be based on the weaker part of pavement section not necessarily average structural capacity of pavement.

4.3 FUTURE WORK

The possible future implementation for the research study are listed below:

- Additional sites and roadway sections can be tested in the future using FWD under different flooded or hydrostatic conditions and the toolkit can be furtherly validated;
- The toolkit could be implemented with the ability of using LEA for the simulations and the FWD plate and loading conditions can be added to the traffic spectrum portion in order to facilitate future verifications;
- The graphical interface can be enhanced and some marginal bugs are going to be fixed;
- Physical modeling of the saturation profiles and hydraulic conductivity can be performed using available commercial software to further verify the reliability of the hydrological structure of the toolkit;
- Pavement analysis and design could be implemented in the future with considerations on the capacity of the pavement structure based on the approach adopted for this research study;
- The toolkit could be implemented with the ability of running a probabilistic analysis and include the variability associated with SWRC parameters for the different subgrade materials (as it was done for the verification portion in this Task report). Once probabilistic distribution functions are implemented in the hydraulic portion, Monte Carlo simulation could be implemented in the toolkit in order to enhance its reliability.

In addition, memo on research benefits (Task 8) and final report (Task 9) are going to be prepared in the upcoming weeks. Task 8 report will include all the steps followed in this research study and also brief discussions on research benefits as well as implementation steps.

REFERENCES

FHWA. (1995). *Comprehensive Truck and Weight (TS&W) Study, Phase 1-Synthesis, Pavement and Truck Size Regulations. https://www.fhwa.dot.gov/reports/tswstudy/TSWwp3.pdf*

Zapata, C. E., Witczak, M. W., Houston, W. N., and Andrei, D. (2007). "Incorporation of Environmental Effects in Pavement Design." *Road Materials and Pavement Design*, Taylor & Francis Group , 8(4), 667–693.

Ji, R., Siddiki, N., Nantung, T., & Kim, D. (2014). Evaluation of resilient modulus of subgrade and base materials in Indiana and its implementation in MEPDG. The Scientific World Journal, 2014.

Ghanbarian-Alavijeh, B., Liaghat, A., Huang, G. H., & Van Genuchten, M. T. (2010). Estimation of the van Genuchten soil water retention properties from soil textural data. Pedosphere, 20(4), 456-465.

Huang, G., & Zhang, R. (2005). Evaluation of soil water retention curve with the pore–solid fractal model. Geoderma, 127(1-2), 52-61.

Nemes, A. D., Schaap, M. G., Leij, F. J., & Wösten, J. H. M. (2001). Description of the unsaturated soil hydraulic database UNSODA version 2.0. Journal of Hydrology, 251(3-4), 151-162.

Puckett, W. E., Dane, J. H., & Hajek, B. F. (1985). Physical and mineralogical data to determine soil hydraulic properties. Soil Science Society of America Journal, 49(4), 831-836.

Maina, James & Matsui, Kunihito. (2004). Developing Software for Elastic Analysis of Pavement Structure Responses to Vertical and Horizontal Surface Loadings. Transportation Research Record. 1896. 107-118. 10.3141/1896-11.