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

National Road Research Alliance

MnDOT Contract 1034192 Task 5: Load Restriction Toolkit Development

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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 5. Using information from MnROAD (and other agency data if made available to researchers) on pavement sub-surface moisture states and pavement surface deflections (from FWD testing), researchers will calibrate and validate the toolkit in Task 6. 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 5 (Load Restriction Toolkit Development) of the study.

1.3 ORGANIZATION OF THE REPORT

This report is organized in 3 chapters. Chapter 2 describes the technical background and assumptions for development of the load restriction toolkit. Chapter 3 presents the toolkit components and provides an instruction for users. Chapter 4 briefly presents a summary of the toolkit and the next step in improving the application.

CHAPTER 2: Technical background and assumption

2.1 INTRODUCTION

A coupled hydro-mechanical model was programmed in MATLAB to evaluate the performance of flexible pavements prone to moisture variations. The model was developed to simulate the real time behavior of pavement systems due to moisture variations. Similar to the system dynamics model presented in Task 3 deliverable report, the model included three coupled structures: (1) a hydrological structure to capture moisture movement in saturated and unsaturated pavement layers; (2) a geotechnical structure to capture moisture-dependent mechanical properties of geomaterial; and (3) a pavement response structure to estimate pavement performance in terms of surface deflection. This chapter describes formulations and assumptions made for development of each structure.

2.2 HYDROLOGICAL STRUCTURE

2.2.1 Technical background and formulations

The first step in the mechanistic analysis of pavement response to moisture variations is the simulation of moisture movement in pavement layers. This is performed through the hydrological structure. The hydrological structure consists of two main components; (1) climate information and (2) unsaturated soil hydraulics. The climate information provides material and information data that controls water flux into and out of the soil surface (i.e., flows associated with water infiltration and discharge). This includes precipitation rate and duration, evaporation rate, surface water runoff, and the height of water ponded on top of the subgrade surface. The current toolkit version obtains the precipitation data for up to 5 precipitation events with given duration and rates. The evaporation rate can be obtained based on the local weather information. Surface water runoff pertains to the portion of precipitated water (in percent) that is excluded from the pavement structure (i.e., aggregate base and subbase layers) and it depends on the topography of the natural ground and performance of pavement drainage systems. A surface water runoff of 100% is expected for pavements with significant grades or proper drainage system and a surface water runoff of 0% is expected for pavements located in flat areas with no drainage systems.

The second component in hydrological structure of the toolkit is the unsaturated soil hydraulics. This component includes the variables and governing equations related to estimation of initial pavement layers' moisture content, moisture movement in unsaturated pavement layers, and their time dependent moisture content. The initial moisture content of the subgrade is 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 implemented in the toolkit due to its accuracy in predicting SWRC and its common use. The model has the following form:

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

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/foot. The initial moisture content (i.e., before precipitation initiation) of aggregate base and subbase layers were assumed to be equal to their residual water content. It is noteworthy that the infiltration process in this study was assumed to occur through pavement shoulders. Since the permeability of aggregate base and subbase layers are typically much higher than natural subgrade soil, the infiltration of water through these layers may result in ponding of water above subgrade layer. Therefore, the degree of saturation in these layers is governed by both water infiltration in these layers and ponded water height above the subgrade. Accordingly, the aggregate base and subbase layers' degree of saturation are calculated based on the weighted average of the inundated portion and the unsaturated portion of each layer. The moisture movement in subgrade soil is governed by its hydraulic properties including saturated and unsaturated hydraulic conductivity and moisture content. Richards' equation for the one-dimensional transient unsaturated flow through subgrade layers to the ground water table in an isotropic soil deposit can be expressed as follows:

$$\frac{\boldsymbol{\delta\theta}}{\boldsymbol{\delta t}} = \frac{\boldsymbol{\delta}}{\boldsymbol{\delta z}}[\boldsymbol{K}_{(\boldsymbol{\theta})}(\frac{\boldsymbol{\delta h}}{\boldsymbol{\delta z}} + \mathbf{1})]$$

Equation 2-2

where, θ is the volumetric water content, z is the depth from the subgrade surface, h is the soil pressure head, t is time, and $K_{(\theta)}$ is the moisture dependent hydraulic conductivity of soil. The moisture-dependent hydraulic conductivity at each soil layer soil can, then, be calculated according to Mualem (1976):

$$\boldsymbol{K(\theta) = K_{sat}(\frac{\theta - \theta_r}{\theta_s - \theta_r})^{0.5}[1 - \left(1 - (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{\frac{1}{m_{vG}}}\right)^{m_{vG}}]^2}$$

Equation 2-3

where K_{sat} is the hydraulic conductivity of soil at fully saturated state. The hydraulic conductivity of fully saturated soil layer can be obtained from field tests or be estimated by semi-empirical equations. Table 2-1 summarizes empirical equations for estimating the hydraulic conductivity of soils in fully saturated state used in the toolkit.

Table 2-1: Empirical relations for estimation of hydraulic conductivity of fully saturated soils.

Reference	Equation number	Hydraulic conductivity (cm/s)	Notation	Remarks
Chapuis (2004)	Equation 2-4	$k_s = 2.46[D_{10}^2 \frac{e^3}{(1+e)}]^{0.78}$	e= void ratio of soil	Applicable for uniform gravel and sand and non-plastic silty sands
Mbonimpa et al. (2002)	Equation 2-5	$k_s = C_p \frac{\gamma_w}{\mu_w} \frac{e^{3+x}}{(1+e)} \frac{1}{\rho_s^2 w_L^{2x}}$	γ_ω=unit weight of water (kN/m3) μ_ω= Water dynamic viscosity (Pa·s) ρ_s= Density (kg/m^3) of solids W_L= Liquid limit (%) x= $7.7w_L^{-0.15}$-3	Applicable for plastic soils, $\gamma_\omega \approx 9.8$, $\mu_\omega \approx 10^{-3}$, χ=1.5

While Richards' equation is one of the most accurate methods to model the moisture infiltration into unsaturated soils, it requires a numerical solution due to the challenges in setting the initial and boundary conditions. Yang et al. (2009) suggested a simple numerical solution of Equation 2-2 for water movement in unsaturated soils and demonstrated that the solution works satisfactorily. The solution uses the integration of Equation 2-2, vertically, over the soil layer to simulate moisture movement in unsaturated soil layers (Yang et al. 2009):

$$\Delta\theta = (\frac{v_{wi} - v_{wi+1}}{\Delta z})\Delta t$$

Equation 2-6

where i is the number of layer, Δt is time step, Δz is the soil layer thickness, v_{wi} and v_{wi+1} are the water flow rate from layer i to $i+1$. The flow rate at each layer is calculated based on the volumetric water content, moisture dependent hydraulic conductivity, and soil pressure head at a given time step:

$$v_{wi} = K_{(\theta_i)}(\frac{\Delta h_{i,i-1}}{\Delta z} + 1)$$

Equation 2-7

$$v_{wi+1} = K_{(\theta_{i+1})}(\frac{\Delta h_{i,i+1}}{\Delta z} + 1)$$

Equation 2-8

where $\Delta h_{i,i-1}$ and $\Delta h_{i,i+1}$ represent the differences in soil total head between the given layer and its adjacent top and bottom layers. To simulate water movement in subgrade layers, the simplified numerical solution of Equation 2-2 was formulated into MATLAB. The toolkit incorporates the climate variables and variables related to the flow in unsaturated soil layers to simulate the moisture movement in real time.

2.2.2 Assumptions and limitations

The assumptions and limitations of the hydrological structure formulated in the toolkit are as follows:

1. The hydrological structure considers one dimensional vertical flow into the pavement layers. Although the impact of ground topography can be incorporated by adjusting surface water runoff, it is not directly modeled in the toolkit. A two- or three-dimensional model is to be developed to consider the impact of topography and complex hydrology of the area.
2. The toolkit assumes constant ground water level throughout the analysis. In other words, it is assumed that the water entering the ground water flows out from the system with the same rate. A complex model considering the hydrology of the specific location is to be developed to consider ground water level fluctuations during and after extreme weather.
3. The hydrological structure assumes a homogenous subgrade layer. The results of analyses may not be applicable to subgrade soils with highly variable soil layers.
4. The base and subbase layers are assumed to be clean granular (i.e., fines content less than 10%) material with relatively high permeability and low water retainability.

2.3 GEOTECHNICAL STRUCTURE

2.3.1 Technical background and formulations

The second structure in the toolkit is the geotechnical structure. The geotechnical structure incorporates the time dependent moisture content of pavement layers estimated from the hydrological structure to estimate their resilient modulus. This is performed by using Equation 2-9 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 2-9

where S_{OPT}= degree of saturation at optimal water content (in decimals); 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 k_m, as summarized in Table 2-2.

Table 2-2: Suggested values for fitting parameters in geotechnical structure of the toolkit (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

2.3.2 Assumptions and limitations

The assumptions and limitations of the geotechnical structure formulated in the toolkit are as follows:

1. The geotechnical structure does not consider the stress dependency of resilient modulus. In other words, the optimum resilient modulus of each layer is to be input based on estimated stress level in the layer and does not change with a change in stress levels during the analysis.
2. The model assumes homogenous aggregate base, subbase, and subgrade layers. An equivalent resilient modulus may be used for nonhomogeneous layers.

2.4 PAVEMENT RESPONSE STRUCTURE

2.4.1 Technical background and formulations

The pavement surface deflection is considered as an indicator of the pavement performance indicator in the current pavement response structure. Therefore, the pavement structure incorporates the real time moisture movement and pavement layers' mechanical variables from hydrological and geotechnical structures to estimate surface deflection based on traffic and current pavement condition information. In this regard, Odemark's Equivalent Thickness Method (ETM) is employed to reduce the multilayer elastic pavement system to an equivalent single half-space layer (Ullidtz 1987). ETM is also used in MnPAVE (Minnesota Department of Transportation 2012) to reduce multiple asphalt concrete (AC) layers into single layer. ETM uses each layer's elastic modulus (E) and Poisson ratio (ν) to convert the layered pavement system to a single homogenous half-space layer according to Equation 2-10:

$$\mathrm{H_{Eq}} = H_n + \sum_{i}^{n} C_i H_i \left[\frac{\mathrm{E}_i(1-\nu_n{}^2)}{\mathrm{E}_n(1-\nu_i{}^2)}\right]^{1/3}$$

Equation 2-10

Where H_{Eq}, is the equivalent thickness of pavement layers, H_n is the thickness of layer n with young's modulus= E_n and Poisson ratio= ν_n, and H_i is the thickness of layer i with young's modulus= E_i and Poisson ratio= ν_i, and C_i is a fitting parameter and depends on the ratio of modulus of the equivalent pavement (E_n) and the pavement layer thickness (H_i). Analyses using Equation 2-10 and layered elastic analysis software, General Analysis of Multi-layered Elastic Systems (GAMES) (Maina and Matsui 2004) indicated less than 20% error in stress distribution estimations when $E_n = E_{Subgrade}$, $\nu_n = \nu_{Subgrade}$, and C_{AC}= 0.5, C_{Base}= 0.7, $C_{Subbase}$= 0.85, and $C_{subgrade}$= 1. Equation 2-10 converts each pavement layer to a new layer with equivalent thickness and mechanical properties to ones in layer *n*. The stress distribution and deflection in each layer can then be calculated using (Boussinesq 1885) theory for a homogenous and isotropic linear elastic half-space system in axisymmetric condition (Equation 2-11, Equation 2-12, and Equation 2-13):

$$\sigma_z = q(1 - \frac{z^3}{(R^2 + z^2)^{1.5}})$$

Equation 2-11

$$\sigma_r = \frac{q}{2}[1 + 2\nu_z - \frac{2(1 + \nu_z)z}{(R^2 + z^2)^{0.5}} - \frac{z^3}{(R^2 + z^2)^{1.5}}]$$

Equation 2-12

$$\epsilon_z = \frac{1}{E_z}[\sigma_z - \nu_z(2\sigma_r)]$$

Equation 2-13

where *R* is the equivalent tire radius and is calculated based on wheel load (L) and tire pressure (*q*):

$$R = \sqrt{\frac{L}{q \times \pi}}$$

Equation 2-14

ε_z is the vertical strain at depth z, σ_r is the horizontal stress, and E_z and ν_z are the young modulus and Poisson ratio of layer *i* located at depth *z*. The wheel load and tire pressure are assigned based on vehicle tire and axle configuration and loading. In this regard, the 13-category FHWA vehicle classification shown in Figure 2-1 is adopted (FHWA, 2014).

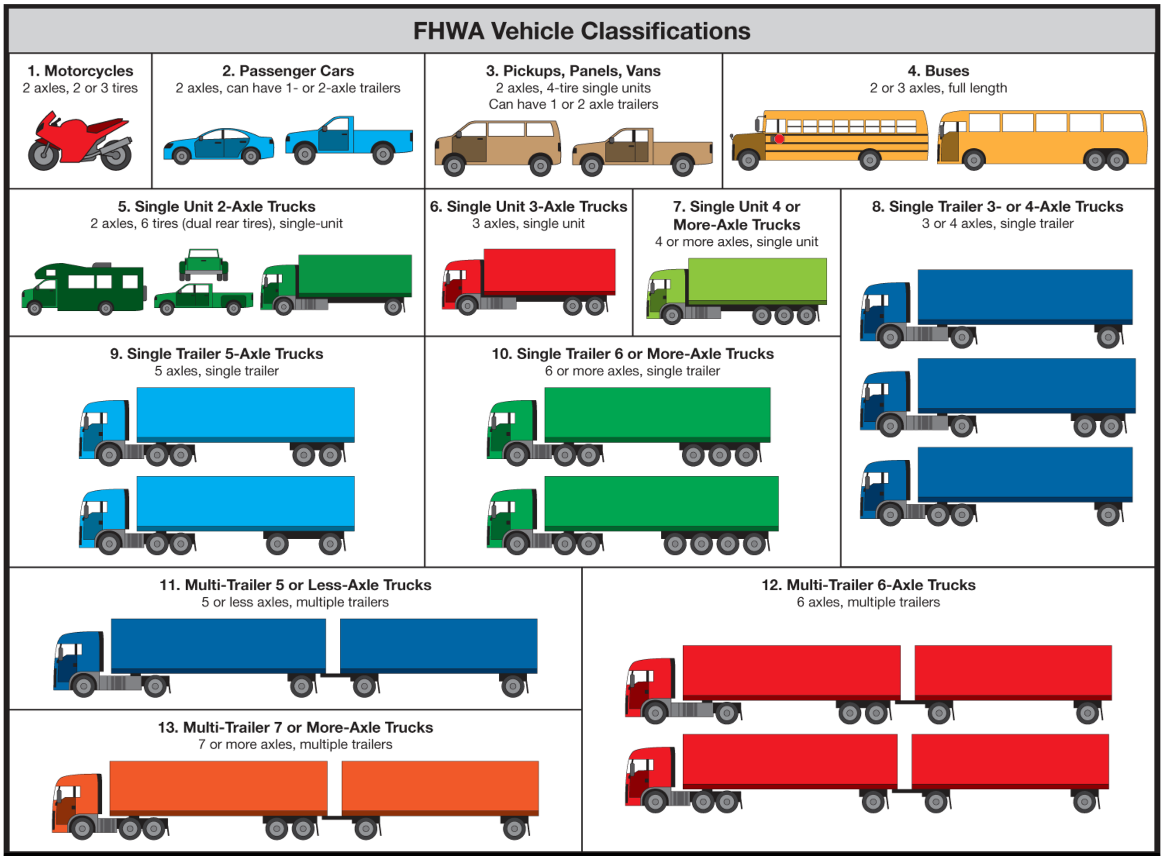


Figure 2-1. 13-category FHWA vehicle classification (FHWA, 2014).

The induced stress on AC surface by each vehicle class is calculated by an equivalent footprint method. In this method, the axle loads are assumed to be distributed uniformly in a rectangular footprint enclosing the tandem/tridem and dual tires on one side of the axle. For example, Figure 2-2 presents a conceptual schematic of the equivalent footprint method to calculate induced pressure and its radius for vehicle class 6. According to this figure, it is assumed that the loads applied on the tandem dual tires of the rear axle is distributed uniformly over a rectangular area with $2R+S_H \times 2R+S_V$ dimensions; where R is the equivalent radius of the tire footprint calculated based on tire load and pressure (See Equation 2-14), S_H is the spacing between tandem tires, and S_v is the spacing between dual tires. The equivalent footprint radius and the equivalent pressure is calculated by having the rectangular area and the load on the four tires.

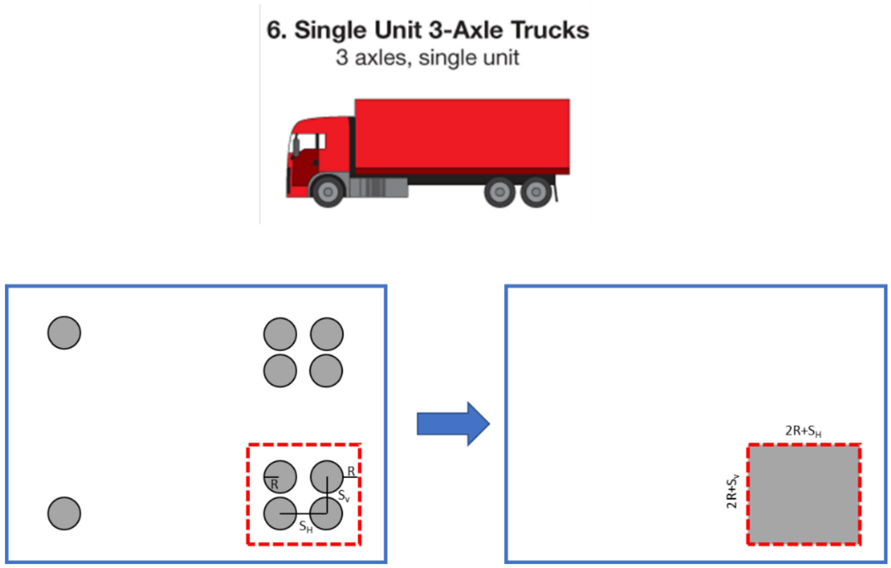
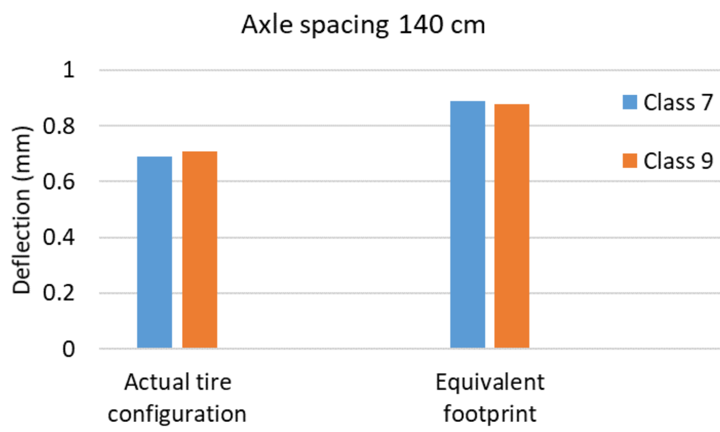
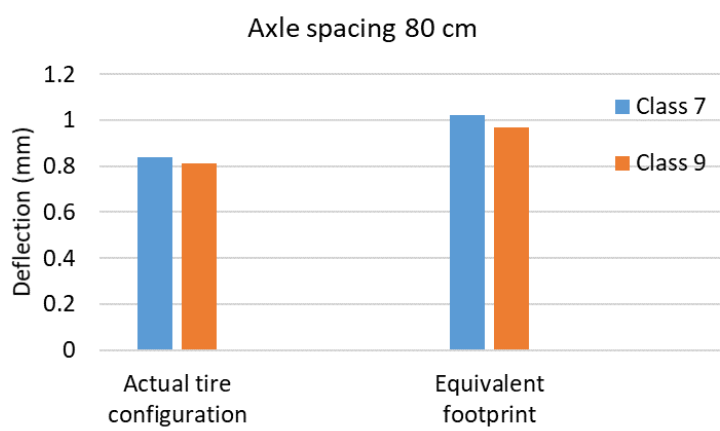


Figure 2-2. Conceptual example of the equivalent footprint method for calculation of induced pressure and radius on AC surface.

The layered elastic analysis software, GAMES, was used to evaluate the accuracy of the equivalent footprint method in estimating the induced deflection on AC surface. In this regard, the deflections on AC surface of a given flexible pavement system were analyzed by (1) considering the actual tire configuration (this does not refer to the actual tire footprint. It just means the actual arrangement of the wheels as opposed to an equivalent block footprint) and (2) equivalent footprint method. Results of analyses indicate that the equivalent footprint method leads to a conservative estimation of AC surface deflection as shown in Figure 2-3. In general, the surface deflections estimated considering the equivalent footprint method were approximately 20-25% higher than the ones estimated considering the actual tire configuration.



(a)

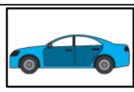
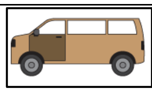
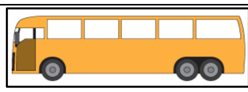
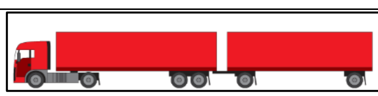


(b)

Figure 2-3. Comparisons of AC deflection estimations assuming actual tire configuration and the equivalent footprint method for vehicle class 7 and class 9. (a) Axle spacing 140cm (b) Axle spacing 80cm.

The maximum allowable axle loads from comprehensive truck size and weight study (based on a Report prepared for FHWA, 1995), shown in Figure 2-4, were considered to estimate the load on equivalent footprint for each vehicle class. The axle and tire spacing, and tire pressures considered for each vehicle class are summarized in Table 2-3.

Table 2-3: The axle and tire spacing, and tire pressures considered for each vehicle class.

Vehicle class	Representative configuration	Tire Spacing meter (inch)	Axle spacing meter (inch)	Tire pressure kPa (psi)
2		-	-	275.8 (40)
3		-	-	551.6 (80)
4		0.35 (13.5)	1.37 (54)	689.476 (100)
5		0.35 (13.5)	1.37 (54)	689.476 (100)
6		0.35 (13.5)	1.37 (54)	689.476 (100)
7		0.35 (13.5)	1.37 (54)	689.476 (100)
8		0.35 (13.5)	1.37 (54)	689.476 (100)
9		0.35 (13.5)	1.37 (54)	689.476 (100)
10		0.35 (13.5)	1.37 (54)	689.476 (100)
11		0.35 (13.5)	1.37 (54)	689.476 (100)
12		0.35 (13.5)	1.37 (54)	689.476 (100)
13		0.35 (13.5)	1.37 (54)	689.476 (100)

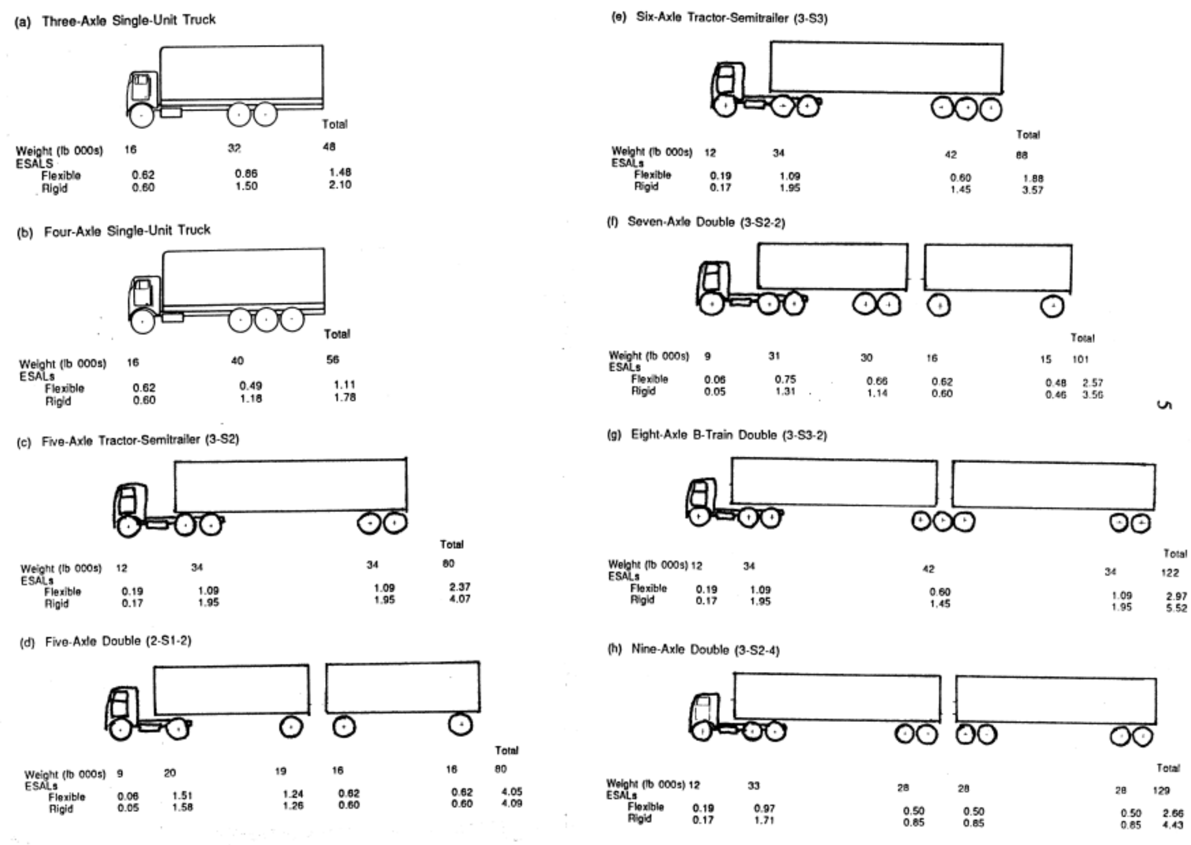


Figure 2-4. Axle weights for different truck sizes from comprehensive truck size and weight study.

2.4.2 Assumptions and limitations

The assumptions and limitations in the pavement structure formulated in the toolkit are as follows:

1. The model assumes homogenous aggregate base, subbase, and subgrade layers. The variations in layers strength with depth is not considered in this study.
2. Although the ETM method with equivalent footprint used in the toolkit provides an approximate estimation of stress distribution in pavement layers, layered elastic formulations can provide more accurate estimations.
3. For the axle loads, and axle and tire configurations and vehicle classes considered in this study, the equivalent footprint method may provide a conservative estimation of stresses and deformations induced in pavement layers. Consideration of other configurations and loads are beyond the scope of this study.
4. The model assumes homogenous aggregate base, subbase, and subgrade layers. An equivalent resilient modulus may be used for nonhomogeneous layers.

5. The toolkit is developed for estimation of surface deflection in flexible pavement systems prone to moisture variations. The estimation of surface deflection in other pavement systems such as rigid pavement is beyond the scope of this study.
6. The pavement response structure does not consider the mechanical behavior of problematic soils such as expansive clay and collapsible soils.
7. The impact of frost and thaw on geomaterial mechanical hydro-mechanical behavior is not considered in this study.

CHAPTER 3: TOOLKIT USER MANUAL: PAVESAFE V1.0.2

3.1. REQUIREMENTS AND INSTALLATION PROCEDURE

The toolkit "PaveSafe" is currently at version v1.0.2. The toolkit requires MATLAB Compiler Runtime (MCR) to be installed on the host system.

MCR inherits identical system requirements as of the MATLAB version used to build the toolkit. MATLAB 2019b Update 3 has been used for toolkit development.

General MCR requirements are listed below:

1. For Macintosh systems: https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/support/sysreq/files/system-requirements-release-2019b-macintosh.pdf
2. For Windows systems: https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/support/sysreq/files/system-requirements-release-2019b-windows.pdf
3. For Linux systems: https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/support/sysreq/files/system-requirements-release-2019b-linux.pdf

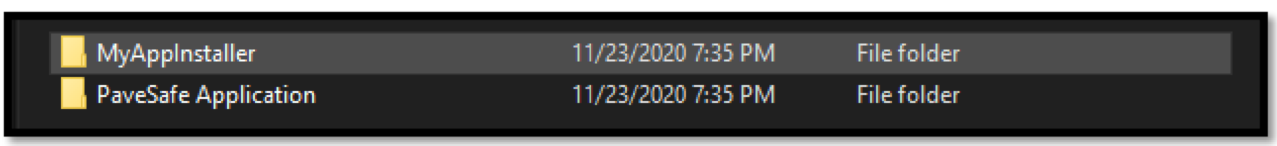
Installation Procedure:

Step 1: The toolkit package is provided in two folders:

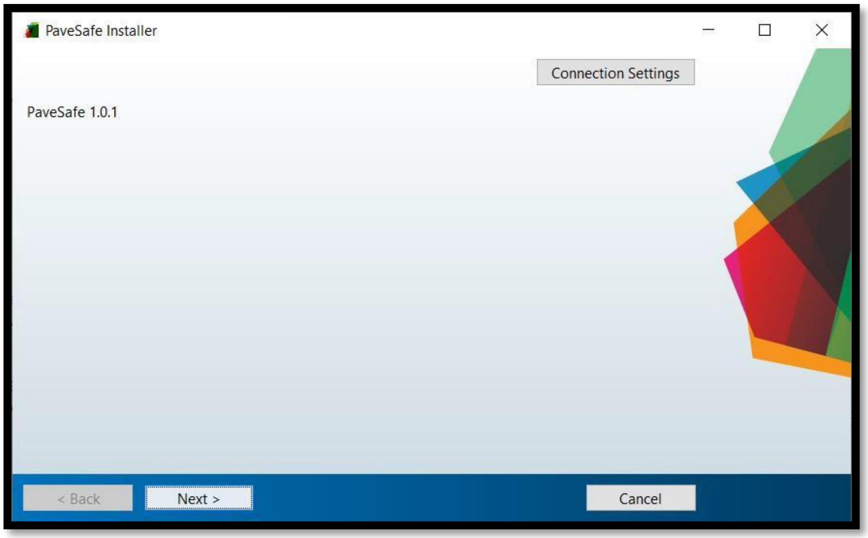
- PaveSafe Application
- MyAppInstaller

Users can choose to use the PaveSafe Application folder which contains the toolkit to run the application, given, MCR already configured in the host system.

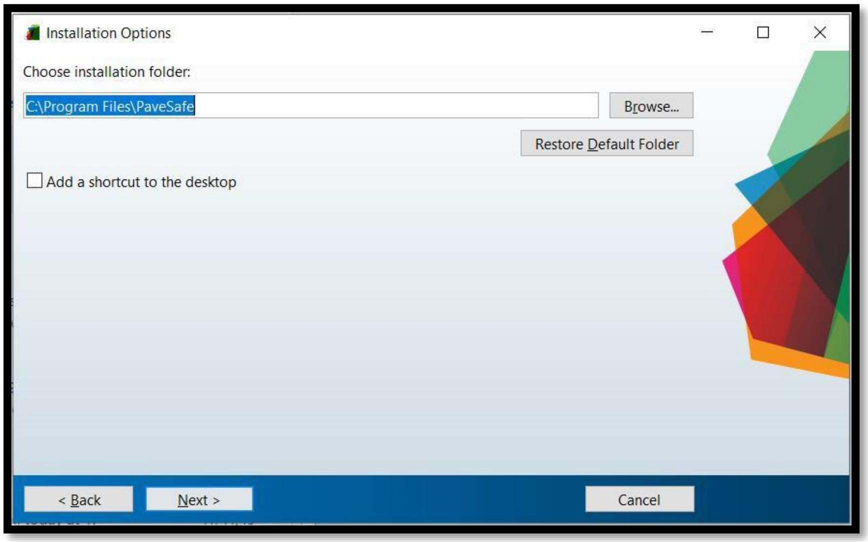
If MCR is not configured on the host system, users may need to use the MyAppInstaller folder and launch the contained installer file "MyAppInstaller_web". Detailed installation procedure using the installer is mentioned in the following steps



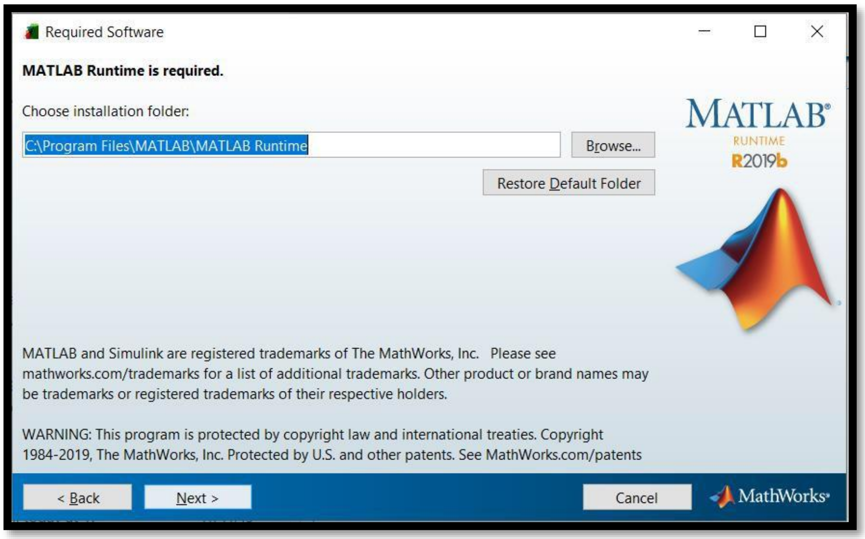
Step 2: Open the MyAppInstaller_web installer.



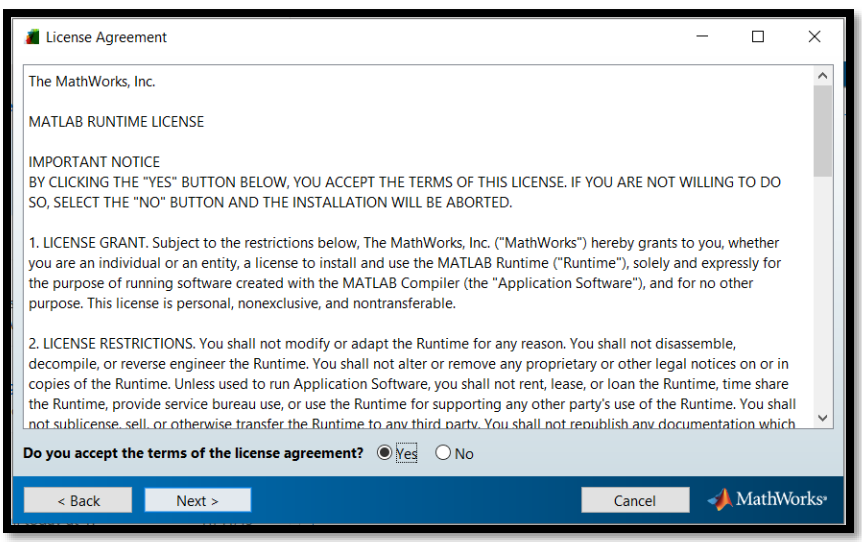
Step 3: Select the application installation folder.

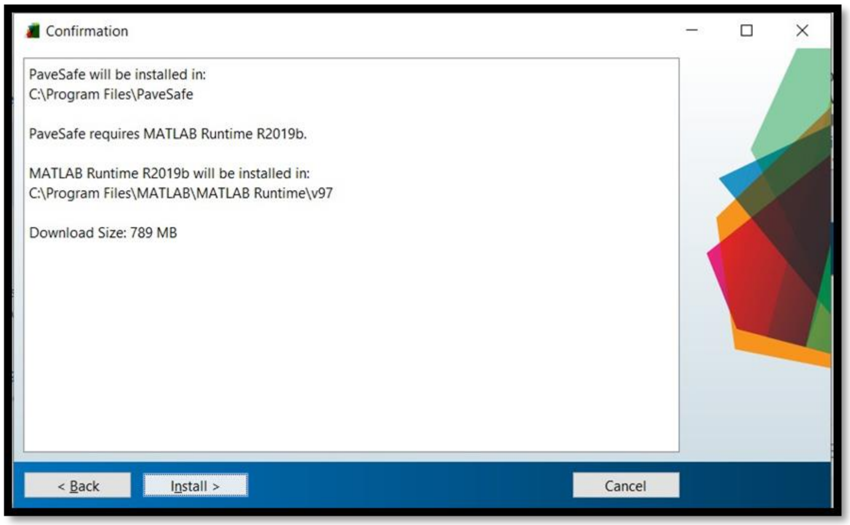


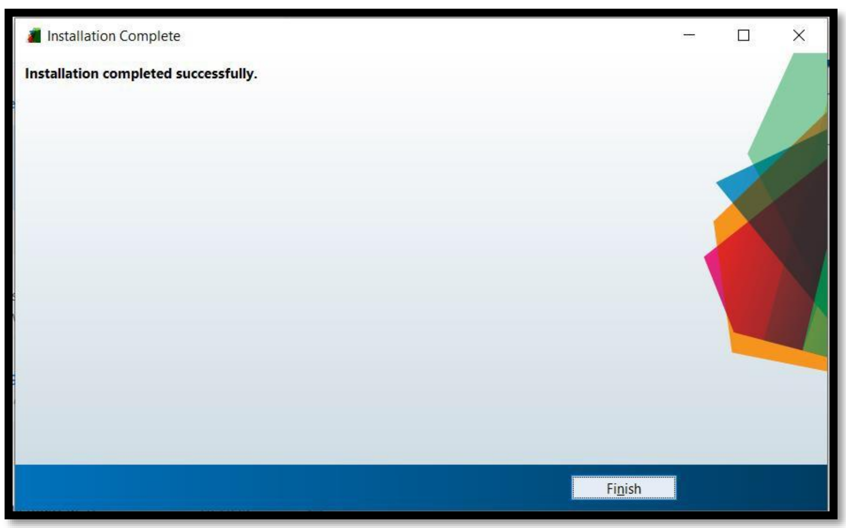
Step 4: Installer will detect if the MRC is installed on the host computer. If it is not already configured, a prompt for choosing the installation folder appears.



Step 5: Accept the license agreement, confirm and wait until installation is completed.




Confirmation
PaveSafe will be installed in:
C:\Program Files\PaveSafe
PaveSafe requires MATLAB Runtime R2019b.
MATLAB Runtime R2019b will be installed in:
C:\Program Files\MATLAB\MATLAB Runtime\v97
Download Size: 789 MB
< Back
Install >
Cancel


Installation Complete
Installation completed successfully.
Finish

3.2. INTRODUCTION

The toolkit PaveSafe v1.0.2 is password protected via password protected window and requires the user to provide inputs across 5 panels after correct password has been provided. In addition to these sections, the toolkit offers the Menu Tab on top of the PaveSafe application window. In the version PaveSafe v1.0.2 we have added the flexibility for user to select SI Units or use US Customary instead.

The application collectively contains the following sections:

- Password Protection Window
- SI Units vs US Customary Selection Stage
- Project Information Panel
- Pavement Structure Panel
- Subgrade Properties Panel
- Hydrological Information Panel
- Results Panel
- Menu Tab

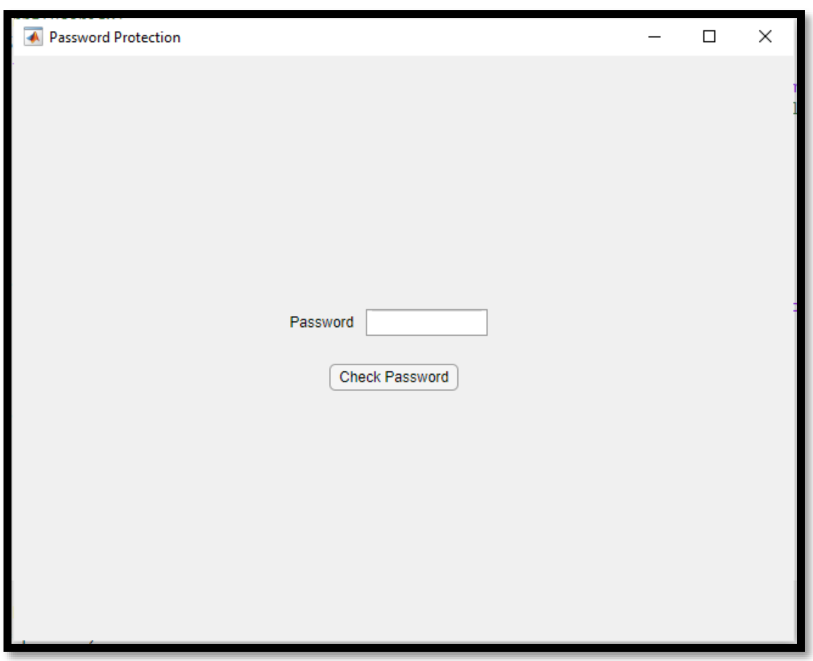
These panels and windows are described in more detail in the upcoming sections.

3.3. PASSWORD PROTECTION MENU

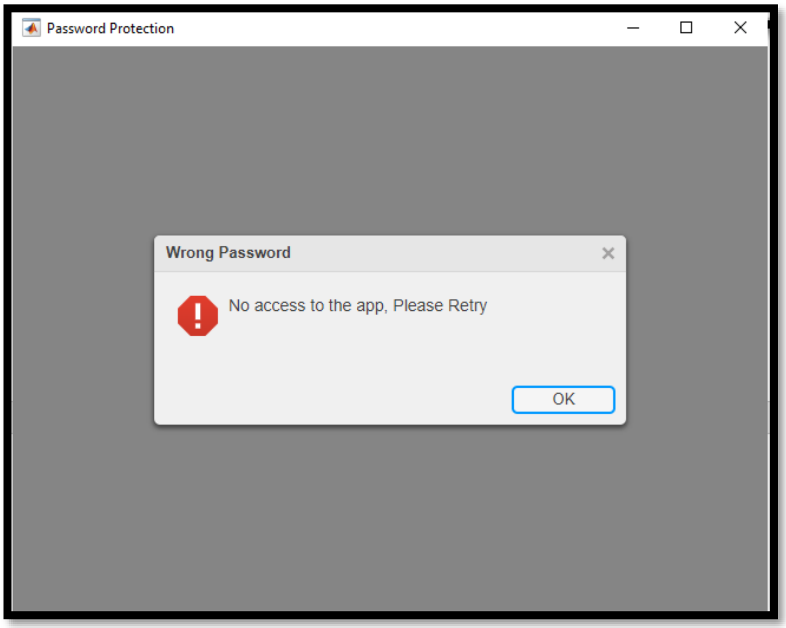
Inherently, MATLAB does not provide a password protection for the generated applications. A password protection window that secures the app from unauthorized access is prepared as first line of defense.

Disclaimer: Please note that there is no underlying encryption mechanism which protects the application from people who have intentions to misuse the application. Simple methods such as brute force (example – John the Ripper password cracking software) can still break the password. It is advised to share the application with the intended users only. In workspaces, users should be trained to be aware of attacks such as Shoulder Surfing, Tailgating, Phishing and other forms of Social Engineering attacks. The host systems can be secured by using anti-virus and setting up appropriate firewall settings. These preventive measures along with provided password protection can reduce the risk of misuse. We do not guarantee complete protection against hackers or take accountability for any misuse of the application. It is the responsibility of the intended users to keep the application secure.

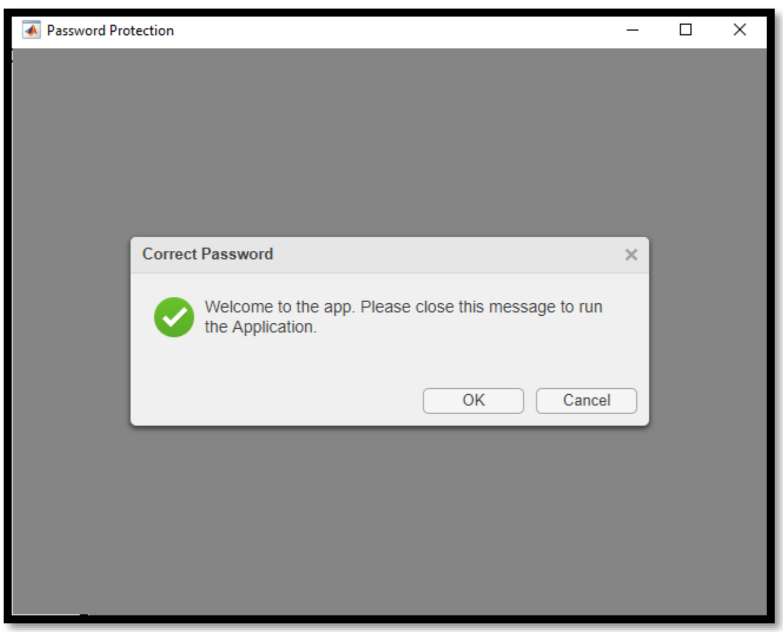
On launch, a password protection screen pops out and requires the users to enter the password. After providing the password it is requires to press the "Check Password" button in order to proceed.



In the event of providing an incorrect password, a wrong password alert box appears on the screen. You may choose to close the alert box or press "OK" to proceed.



In the event of providing a correct password, a correct password alert box appears on the screen. You must choose to close the alert box by pressing "OK", "Cancel" or closing the alert box by clicking the "X" on top right side of the alert box to proceed working with the PaveSafe application.



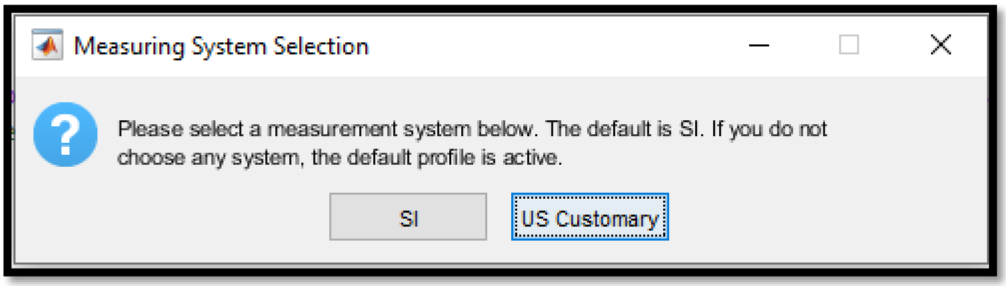
SI UNITS VS US CUSTOMARY UNITS SELECTION STAGE

In this stage, user is required to select the units of measurement.

We have the following units of measurements in place:

- SI Units
- US Customary

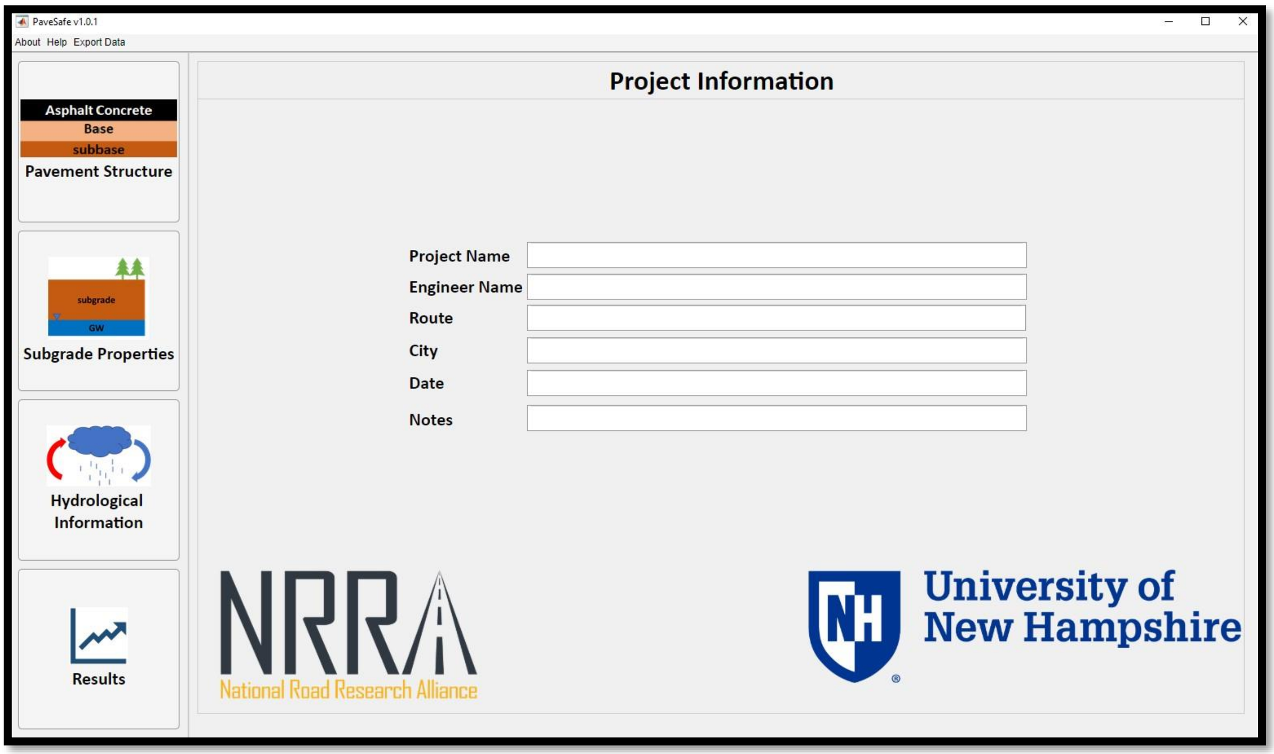
A dialogue box will appear requiring the user to select the desired units of measurement. If user chooses to close the dialogue box without selection, SI Units will be default.



3.5. PROJECT INFORMATION PANEL

On launch of the application post selecting the desired units of measurement, Project Information panel appears in the application which has the following optional inputs to be provided by the user:

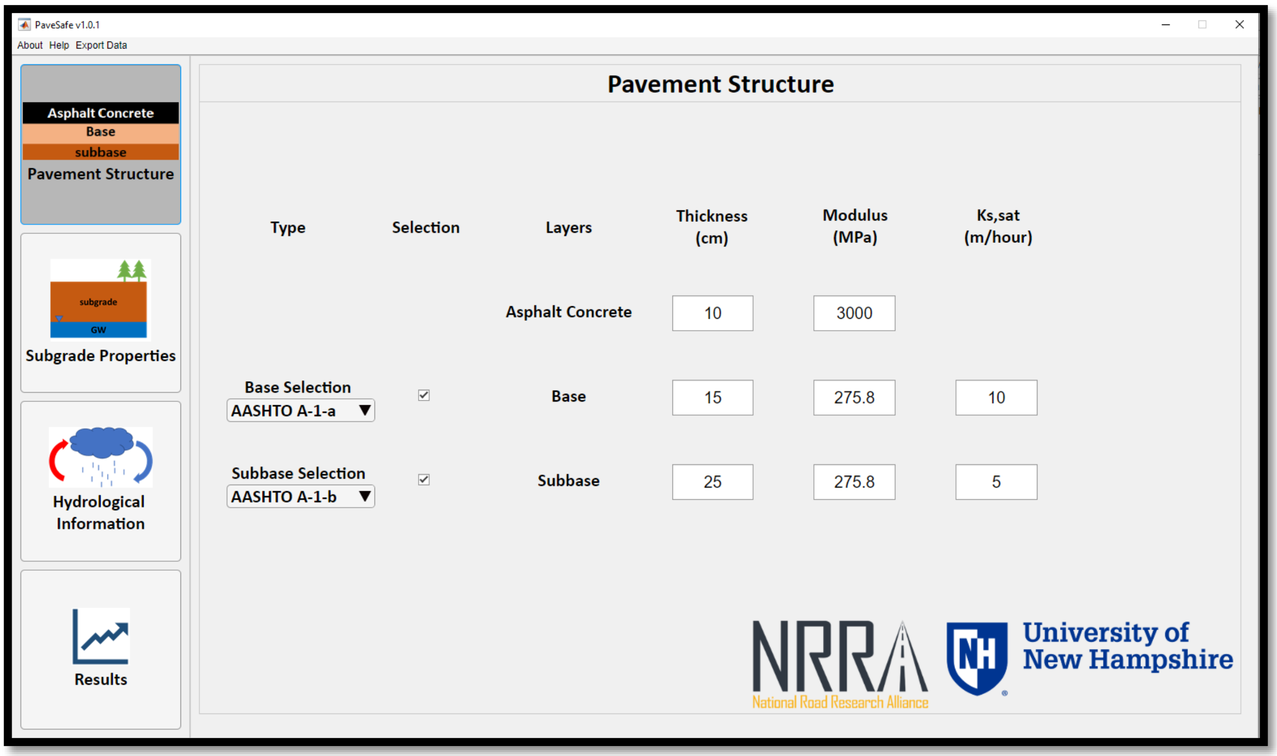
- Project Name:
- Engineer Name:
- Route:
- City:
- Date:
- Notes: Any additional notes to be saved for future reference.



The Pavement Structure, Subgrade Properties, Hydrological Information and Results Panels can be accessed by pressing the individual buttons on the left-hand side of the application screen. If these buttons are pressed again then the button is de-selected, and it brings the users back to the Project Information Panel.

3.6. PAVEMENT STRUCTURE PANEL

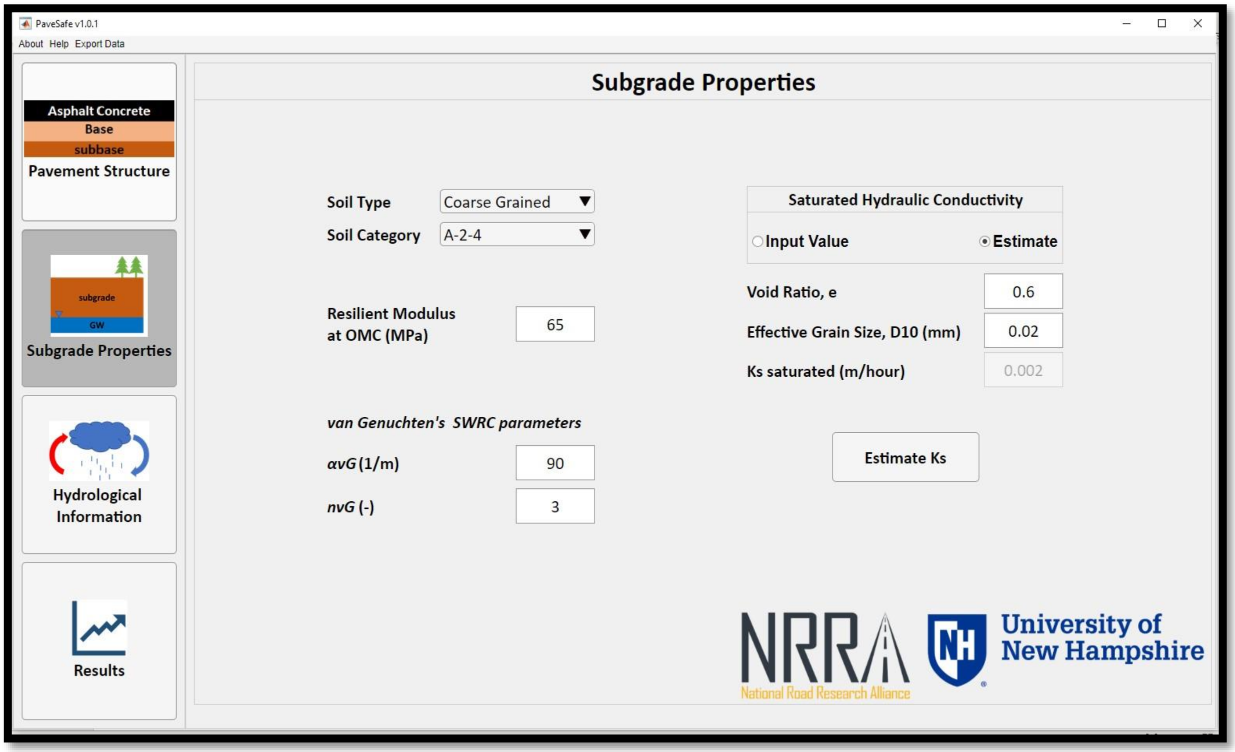
The Pavement Structure panel requires the user to input thickness (in units of cm or inch), resilient modulus (in units of MPa or ksi) and saturated hydraulic conductivity (in units of m/hour or ft/s) for Asphalt Concrete, Base and Subbase layers. Please note that it is not required to provide saturated hydraulic conductivity for the Asphalt Concrete layer. The users may choose to use the default values provided. The field "Type" was added in PaveSafe v1.0.2 and it provides the user 2 dropdowns to choose default values for AASHTO or MnDOT Class with respect to Base and Subbase selection (if other agencies provide us with their default materials and corresponding properties, those will be added to the selection drop-box). Note that, the units will change when US Customary is selected.

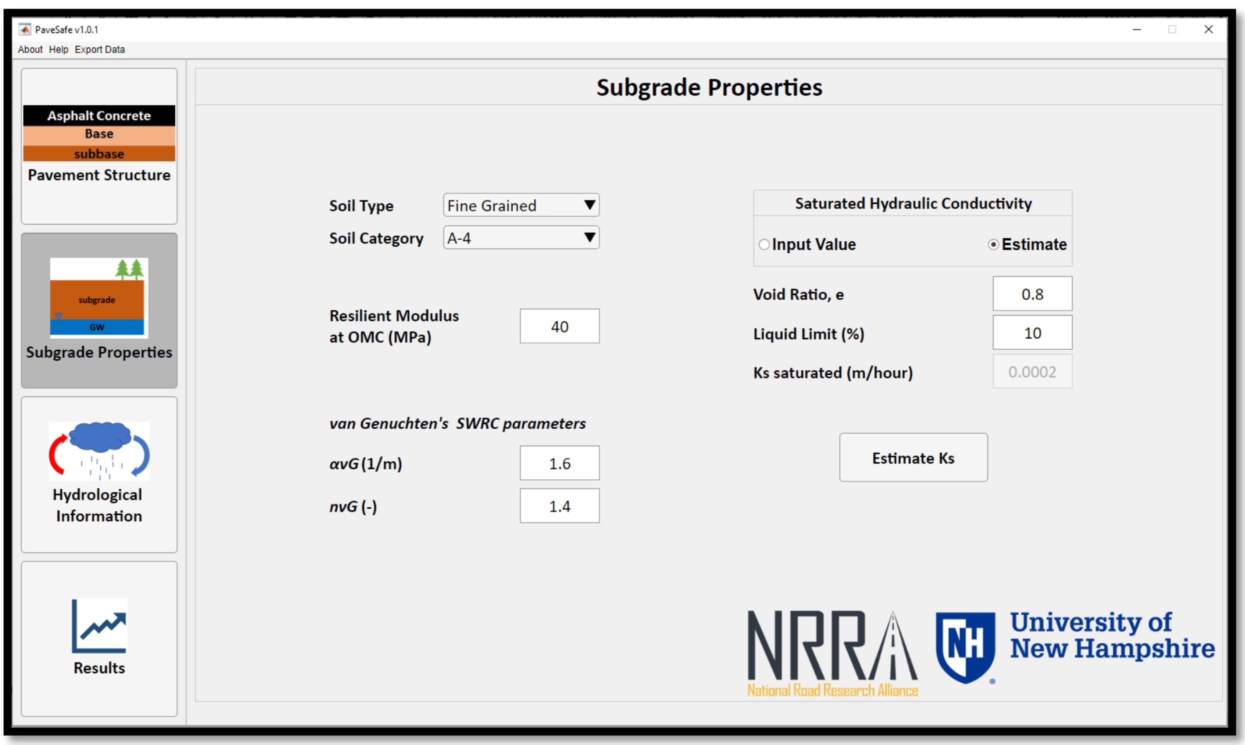


In order to remove Base and Subbase layers from calculations in case those layers do not exist, users may opt to uncheck the respective selection check boxes. By default, these layers are selected for calculations.

3.7. SUBGRADE PROPERTIES PANEL

The default screen for the Subgrade Properties Panel has the following appearance:



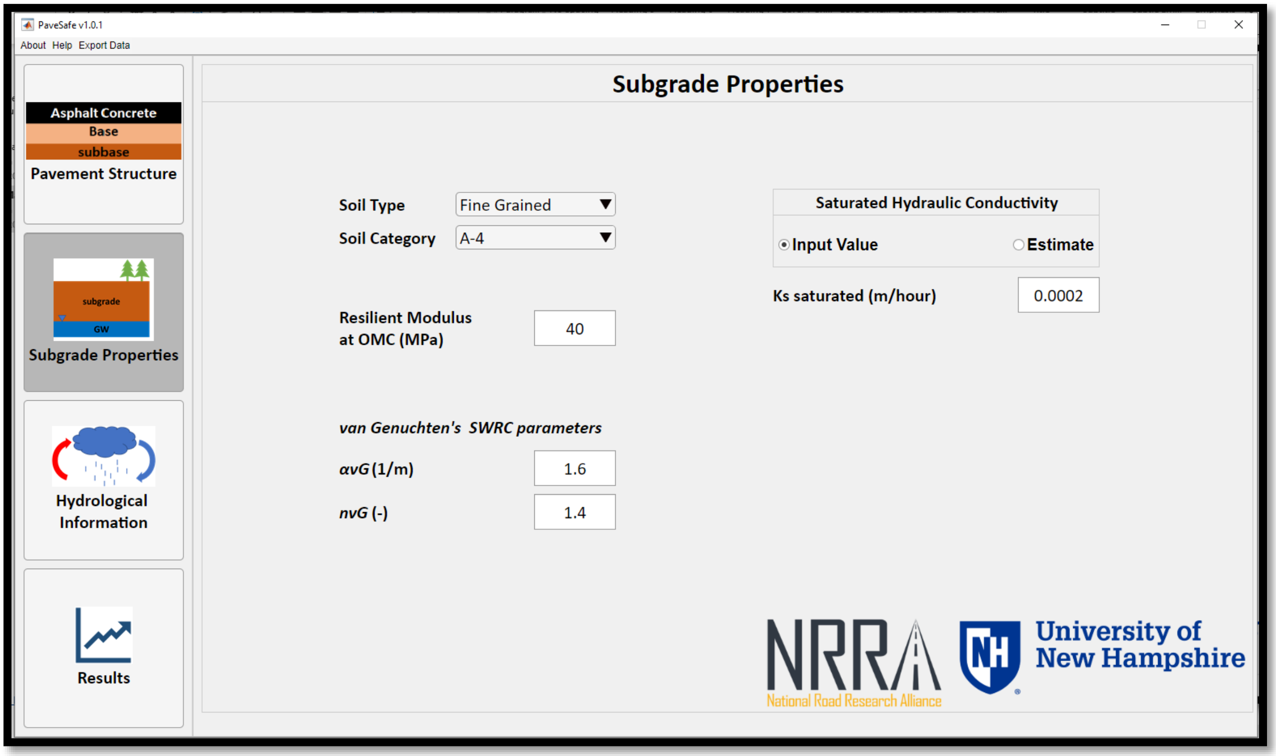


The Soil Type dropdown menu controls the Soil Category dropdown and default values of other inputs appearing on the screen. The default value of Soil Type dropdown menu is “Coarse Grained” and can be changed to “Fine Grained”.

After the selection of the Soil Type, Soil Category based on AASHTO soil classification system must be selected. Based on the Soil Category default values of other inputs on the screen are populated. Users always have an option to change these values including resilient modus at optimum moisture content (in units of MPa or ksi), van Genuchten’s SWRC fitting parameters, void ratio, effective grain size (D10) (in units of mm or inch).

The saturated hydraulic conductivity will be estimated based on either the default soil parameters or the input values, by pressing “Estimate Ks” button. If this button is not pressed, then a default value will be assigned, which may not exactly reflect the Soil Category.

Also, there is an option provided for the user to directly input saturated hydraulic conductivity via selecting the “Input value” radio button under the Saturated Hydraulic Conductivity box, if such value is available (in units of m/hour or ft/s).

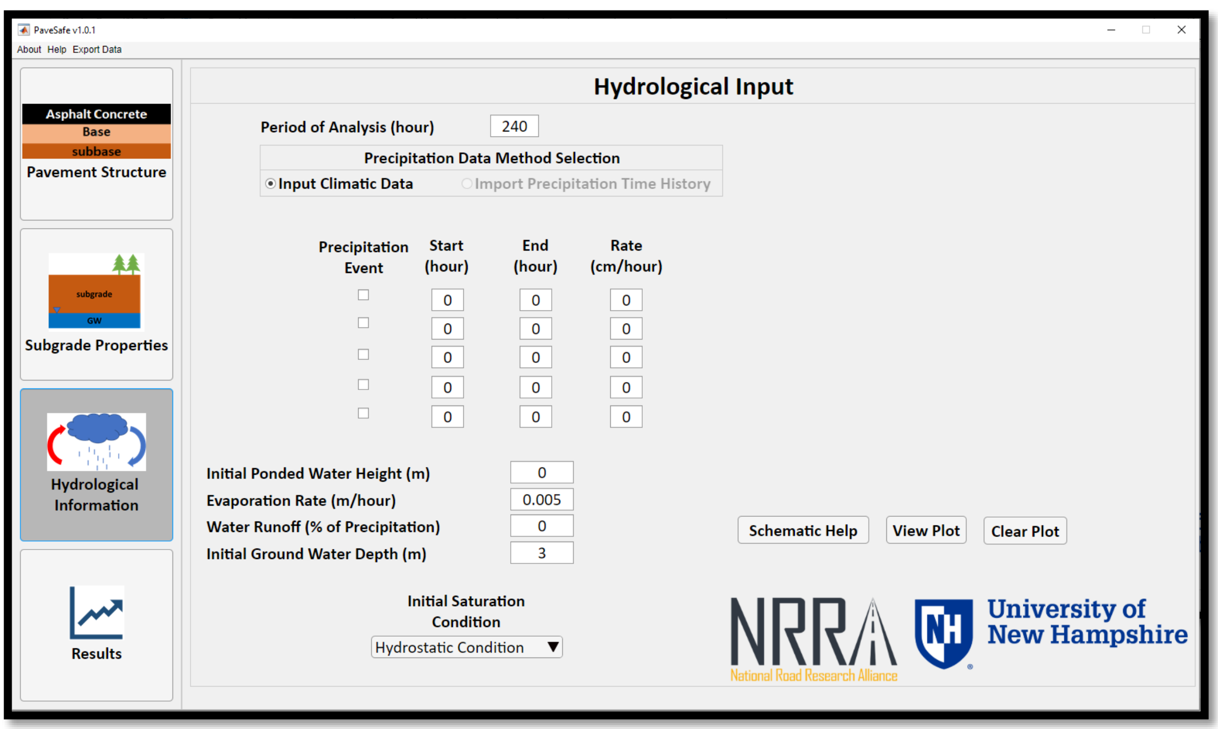


3.8. HYDROLOGICAL INFORMATION PANEL

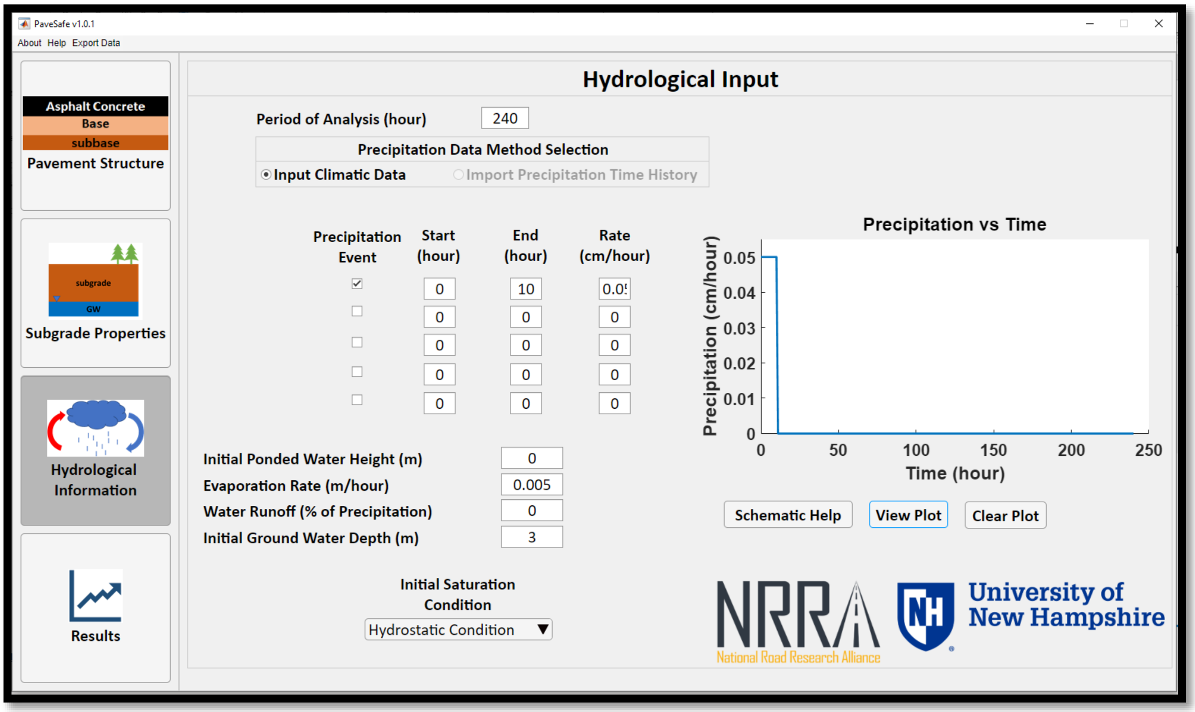
Hydrological Information Panel has the following required inputs:

- Period of Analysis (in hour): By default, this value is set to be for 10 days of analysis i.e. 240 hours.
- Input Climatic Data: The precipitation events can be provided as input to the application by first selecting the "Precipitation Event" checkbox and then providing the starting and ending hour values with the rate of precipitation (in units of cm/hour or inch/hour). However, if the box assigned for each precipitation event is not checked, that event would not be considered in the analysis.
- Initial Ponded Water Height (in units of m or ft): By default, we assume there is no ponded water above the ground hence default value is 0.
- Evaporation Rate (in units of m/hour or ft/hour): The default value set inside the application is 0.005 m/hour; however, if there is no ponded water above the ground, there will be no evaporation in the calculations.
- Water Runoff (as % of precipitation): This input is the percentage of precipitation water that runs off from the ground.
- Initial Ground Water Depth (in units of m or ft): This is the depth at which ground water table exists. By default, 3 meters is taken as input value.
- Initial Saturation Condition: The users can select the initial saturation condition of the ground above the water table to be hydrostatic or fully saturated. The default value set is hydrostatic condition above the water table, meaning linear suction profile with depth.

The default screen appears as below:

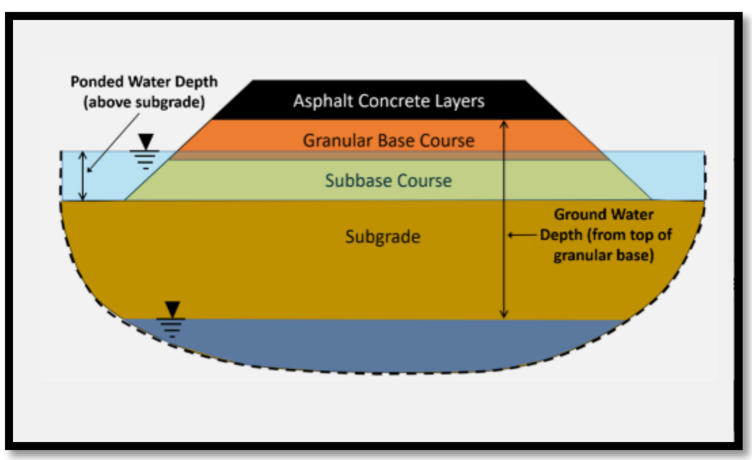


After providing the precipitation event data, the user can view the plot of precipitation data by clicking "View Plot" button and "Clear Plot" to clear the plot from the screen. A view plot example is as shown below:



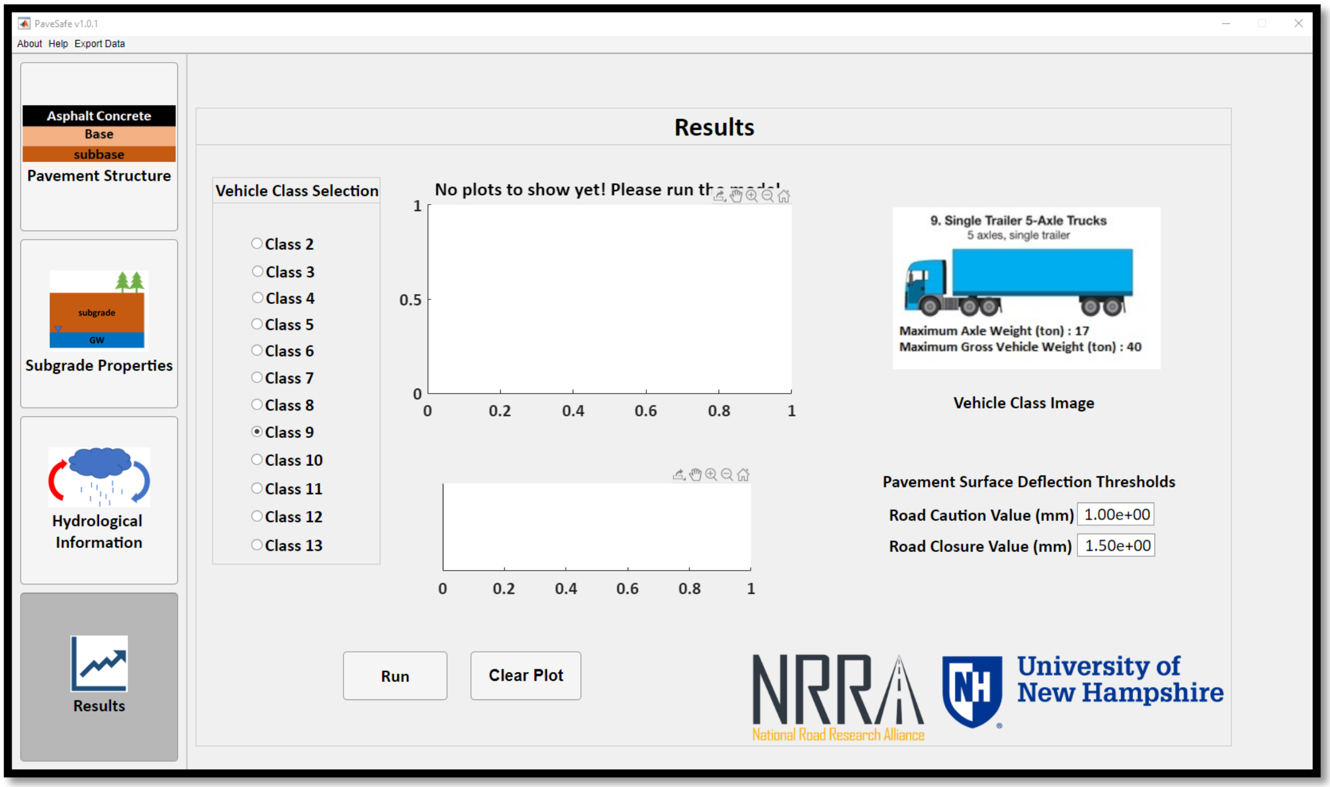
Note that currently the option to import precipitation time histories are disabled as this feature is projected to be accommodated in future release.

In PaveSafe v1.0.2, a "Schematic Help" button was introduced explaining the underlying model. The schematic help is mentioned below for reference.



3.9. RESULTS PANEL

By default, the results panel has the following appearance:

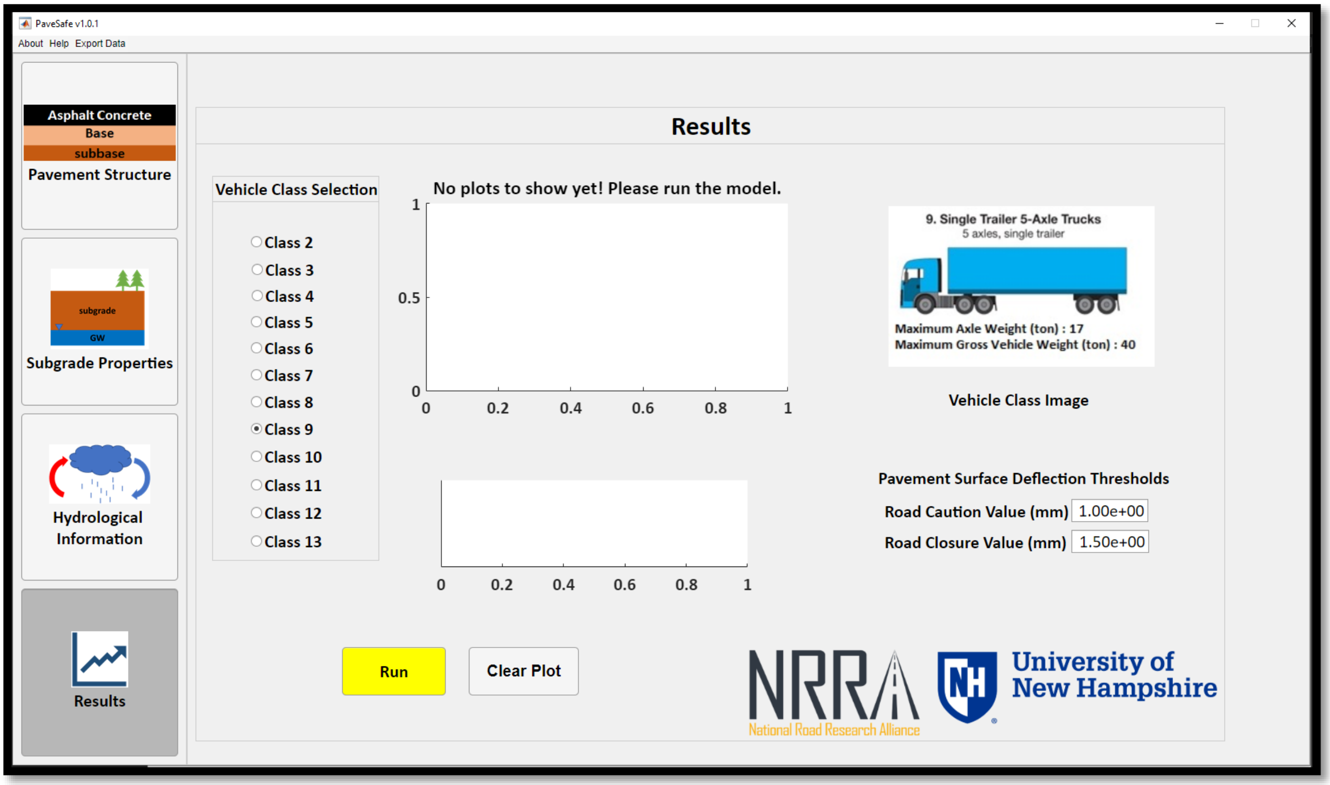


The users can opt to select the desired vehicle class and a representative image of that vehicle class will appear on the screen.

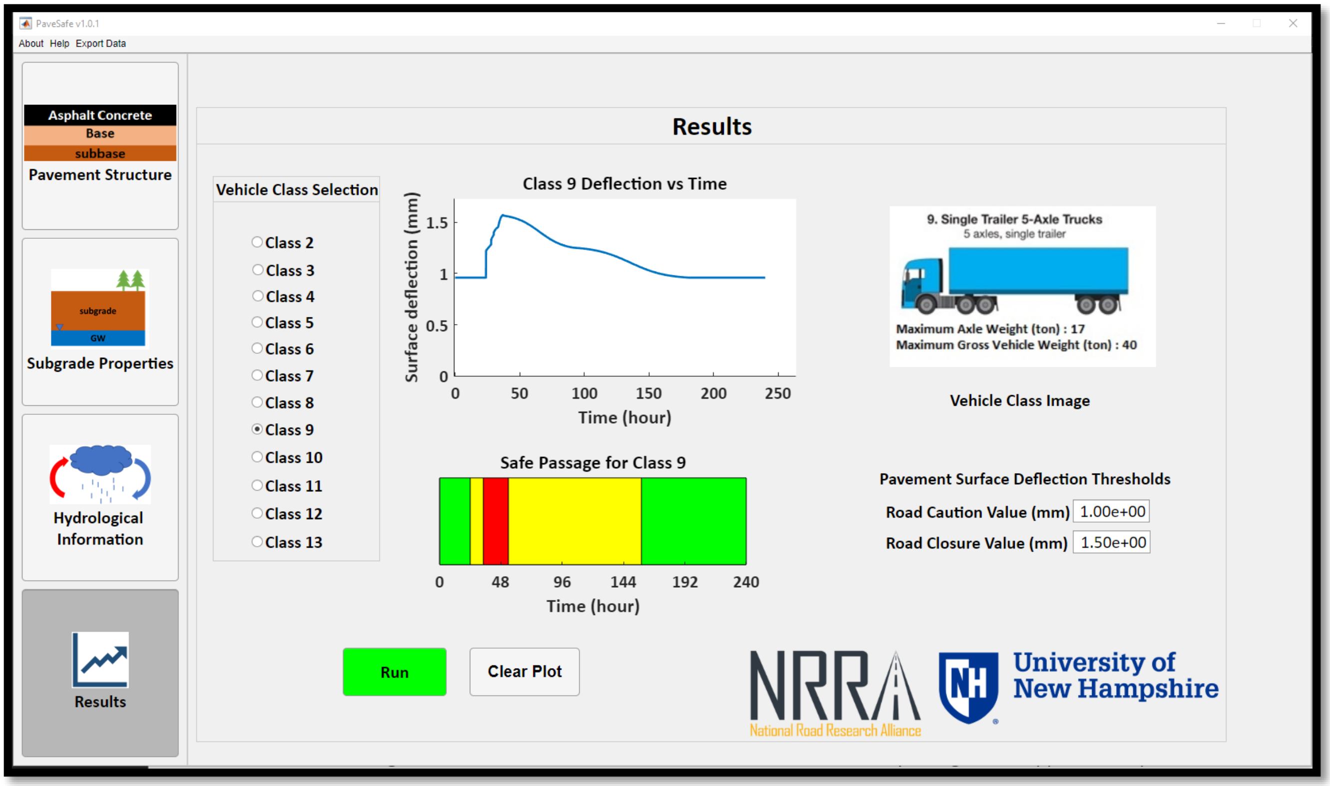
As input to the application, users can set the Pavement Surface Deflection Threshold for Road Caution and Road Closure (in mm or inch). By default, these values are set to 1 mm (0.04 inch) and 1.5 mm (0.06 inch) for Road Caution and Road Closure, respectively.

After the inputs are provided or retained, the application is ready to run. To run the application please press the “Run” button appearing on the screen.

While the model is running the “Run” button turns Yellow in color and users must wait until the model has completed the run cycle. The running state appears as below:



Once the model has finished its run cycle, the "Run" button turns Green and the deflection results are displayed on the figure at the top as a graph. A bell sound alerts the user of completed run. Also, safe passage information is visible at the bottom of the graph giving information about the condition of the road with respect to the selected vehicle class. Green Passage means the vehicle is safe to pass, Yellow means it is a caution zone and Red means completely unsafe. After the run cycle the Results Panel appears as below:



The users are provided the freedom to change the Road Caution and Road Closure values to view the effect on safe passage with the new values. Users must keep in mind that it is required to change the vehicle class to reflect changes with new Road Caution and Road Closure values. Also, any change in the application inputs (excluding changes to Project Information Panel) turns the "Run" button to Gray, which means a new analysis and run are needed.

Note that, users are also provided with a feature to export the analysis data. This feature is available in the Menu Tab and will be explained in detail in the following section.

3.10. MENU TAB

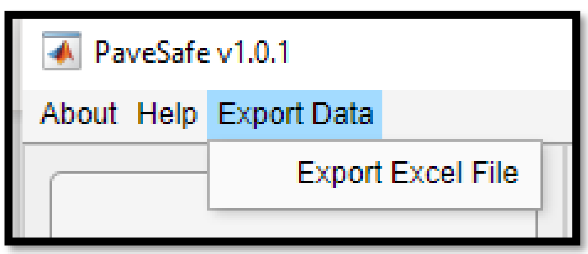
The Menu Tab appears at the top of the application and contains the following options:

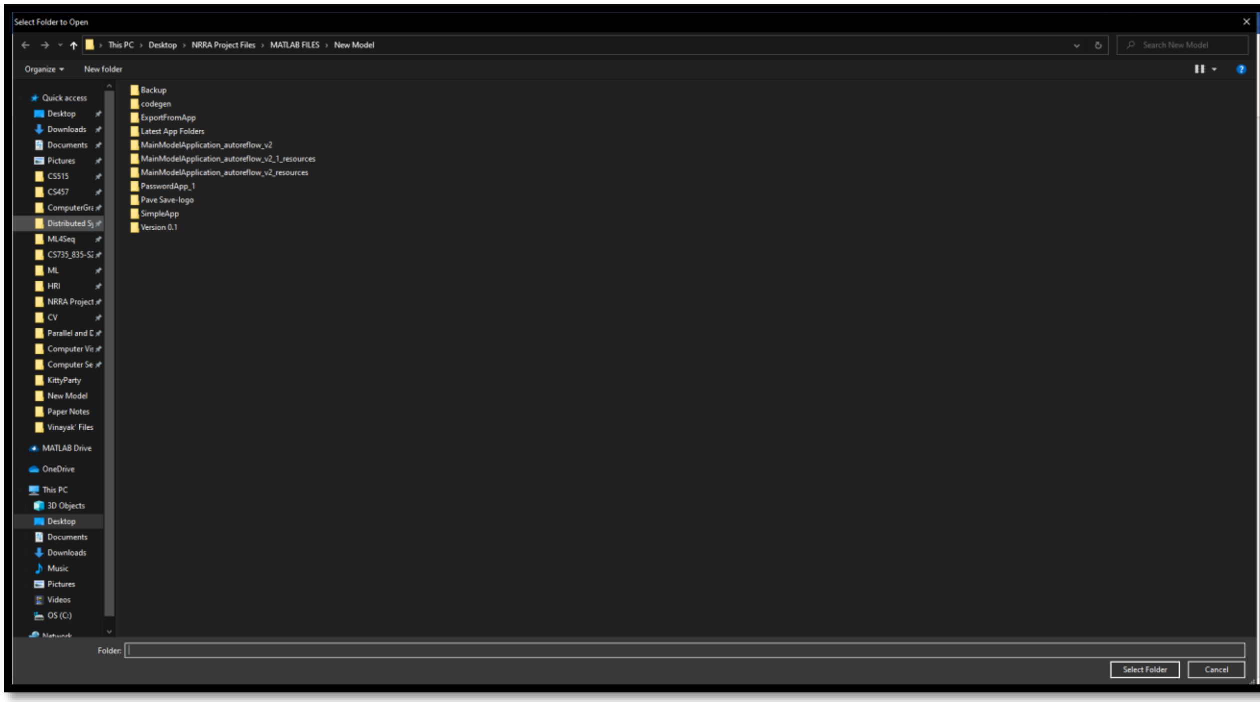
- About
- Help
- Export Data

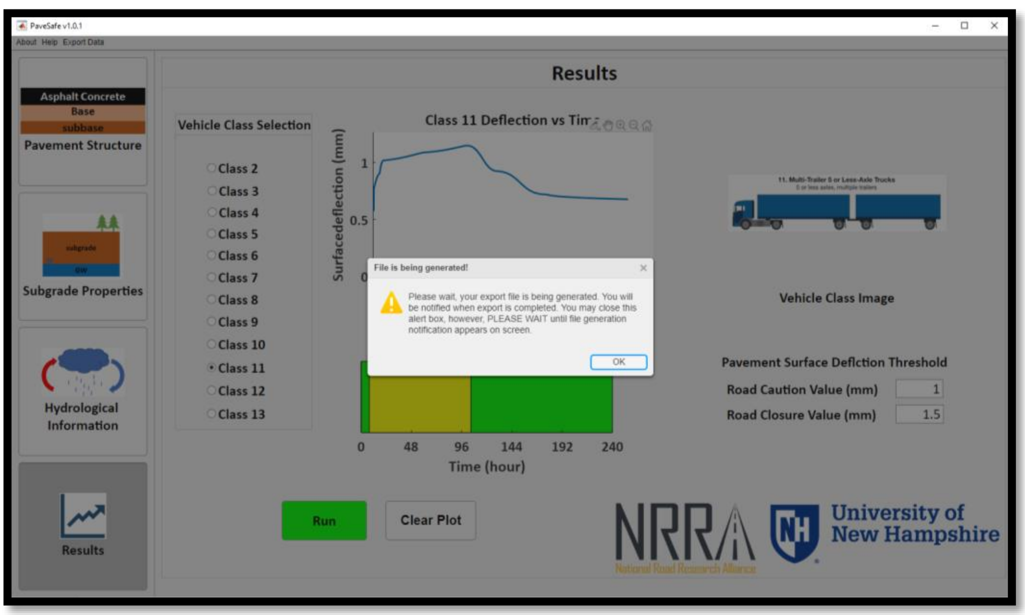
The About menu brings up details about the application in the default browser. It is a pdf file and it has a possibility to be opened within the default pdf viewer on the system.

The Help menu brings up the User Manual for detailed information about the application.

The Export Data menu brings down “Export Excel File” dropdown. When this dropdown is clicked, it asks the users to provide the location where the generated file would be saved. Also, an alert box appears on the screen informing the user about the file generation process. Users may close this alert box, but they must wait until “File Generated” alert appears on the screen before they continue to interact with the application. The output file generated is a Microsoft Excel Worksheet with name “PaveSafe_ExportData”.




Select Folder to Open
This PC › Desktop › NRRA Project Files › MATLAB FILES › New Model
Organize
New folder
Backup
codegen
ExportFromApp
Latest App Folders
MainModelApplication_autoreflow_v2
MainModelApplication_autoreflow_v2_1_resources
MainModelApplication_autoreflow_v2_resources
PasswordApp_1
Pave Save-logo
SimpleApp
Version 0.1
Folder:
Select Folder
Cancel


PaveSafe v1.0.1
About Help Export Data
Asphalt Concrete
Base
subbase
Pavement Structure
Subgrade Properties
Hydrological Information
Results
Results
Vehicle Class Selection
Class 2
Class 3
Class 4
Class 5
Class 6
Class 7
Class 8
Class 9
Class 10
Class 11
Class 12
Class 13
Class 11 Deflection vs Tim
Surfacedeflection (mm)
Time (hour)
File is being generated!
Please wait, your export file is being generated. You will be notified when export is completed. You may close this alert box, however, PLEASE WAIT until file generation notification appears on screen.
OK
Vehicle Class Image
Pavement Surface Deflction Threshold
Road Caution Value (mm)
Road Closure Value (mm)
Run
Clear Plot
University of New Hampshire


PaveSafe v1.0.1
About Help Export Data
Results
Asphalt Concrete
Base
subbase
Pavement Structure
Subgrade Properties
Hydrological Information
Results
Vehicle Class Selection
Class 2
Class 3
Class 4
Class 5
Class 6
Class 7
Class 8
Class 9
Class 10
Class 11
Class 12
Class 13
Class 11 Deflection vs Time
Surfacedeflection (mm)
Time (hour)
File has been generated!
Your file has been generated! You may proceed to close the alert now.
OK
Vehicle Class Image
Pavement Surface Deflction Threshold
Road Caution Value (mm) 1
Road Closure Value (mm) 1.5
Run
Clear Plot
University of New Hampshire


PaveSafe_ExportData
11/23/2020 11:34 PM
Microsoft Excel Worksheet
494 KB

CHAPTER 4: SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The toolkit v1.0.2 is an early version of this initiative. It is provided as part of Task 5 of the project and is subject to future improvements and modifications. The toolkit is able to assess the pavement performance during and after high moisture events (such as storms or flooding) given the initial pavement structure, subgrade, and hydrological information.

4.2 FUTURE WORK

This version of the toolkit needs to be validated and enhanced using conventional pavement analysis methods and software and also both field and scaled laboratory experiments. In addition, several other options such as input precipitation time history and interactive analysis with linear elastic pavement models and software among others.

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