State of Florida

Enhanced Hydroplaning Prediction Tool

FINAL REPORT

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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

Hydroplaning is defined as the condition that exists when a film of water or other contaminant is present at the tire-pavement interface and completely separates the tire from the pavement surface, and it has a detrimental effect in roadway safety, especially under wet weather conditions. In 2012, the Florida Department of Transportation (FDOT) developed a tool for predicting the travelling speed at which a vehicle would start hydroplaning.

The primary objective of this research project was to enhance FDOT's existing Hydroplaning Prediction (HP) program because it was found that the existing hydroplaning tool included a number of minor bugs (e.g., incorrect unit conversions) as well as major deficiencies (e.g. incorrectly built-in inputs).

FDOT's new HP tool was implemented in a macro-enabled Excel spreadsheet environment. The new program allows for three different water film thickness models and four different hydroplaning speed models. The new HP tool facilitates the basic hydroplaning analysis option that was implemented in FDOT's old HP tool, as well as some of the new features (e.g., sensitivity analysis and probabilistic analysis options) that were not available in the old HP tool. The results from the new HP tool were validated against the examples provided in previously published literature. In addition, materials for a computer-based training (CBT) course, along with a Hydroplaning Guidance document, were developed to support FDOT's future implementation efforts.

17. Key Word	18. Distribution Statement
Hydroplaning, Safety, Longitudinal Grade, Cross Slope, Texture, Permeability, Water Film Thickness, Rainfall Intensity, Water Flow, Drainage Path.	No restrictions

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EXECUTIVE SUMMARY

The primary outcome of a wet pavement surface is reduction in pavement friction due to water acting as a lubricant between the pavement surface and the vehicle tires. Normally, the vehicle tires are designed to push away the undesired substances (such as standing water, rain, snow, and mud), but under severe circumstances, a tire may encounter more water than it can push aside. When a tire can no longer move the water aside, the water pressure in front of the wheel causes the tire to lift from the road surface. This phenomenon, known as aquaplaning or hydroplaning, may occur when a layer of water builds between the wheels of the vehicle and the pavement surface.

In 2012, the Florida Department of Transportation (FDOT) developed a tool for predicting the travelling speed at which a vehicle would start hydroplaning. The tool was used during the roadway design phase to evaluate the hydroplaning potential of Florida's roadways. Although the existing hydroplaning tool was working properly for roadway design purposes, it was found that the existing tool exhibited numerous limitations (e.g., was not able to evaluate multiple planes with varying slopes) and was not user friendly.

The primary objective of this research project was to enhance FDOT's existing Hydroplaning Prediction (HP) program. The enhancements include the following.

- Assessing the hydroplaning potential in a continuous manner. The user should be able to input roadway geometric design parameters as well as continuous data (e.g., pavement cross-slope, grade, and rut depth) collected using a multi-purpose survey vehicle (MPSV) and pavement texture data for the analysis.

- Analyzing multiple scenarios effectively and efficiently. The program should be capable of making batch runs for different lane widths (or number of lanes, currently referred to as planes in the current HP software) and rainfall intensities.

- Integrating the software with geographic information system (GIS) applications for displaying the computed hydroplaning potential on a map.

During the course of this study, extensive literature was gathered and reviewed for the empirical Water Film Thickness (WFT) and Hydroplaning Speed (HPS) models implemented into the FDOT's existing hydroplaning tool. The existing tool was also reviewed extensively to identify any bugs or shortcomings that were built into the program. It is emphasized that the existing tool was working properly for the WFT and HPS models (i.e., Gallaway WFT and PAVDRN HPS models to be more specific) used for FDOT's roadway design purposes. However, it was found that the existing hydroplaning tool included many minor bugs (e.g., incorrect unit conversions) as well as major deficiencies (e.g. incorrectly built-in inputs) for the other models that are not being used by FDOT.

In addition, a gap analysis conducted on the current tool indicated that the program is lacking many features that may be useful to the users. The next generation hydroplaning tool should take care of all these deficiencies.

The texture and permeability data collected by FDOT has been reviewed in an attempt to develop the necessary relationship between mean texture depth (MTD) and mean profile depth (MPD) and to characterize the permeability of in-service pavement surfaces. Recommendations were provided based on the results and findings.

Building on the lessons learned from the previous HP program, FDOT's new Hydroplaning Program was implemented in a macro-enabled Excel spreadsheet environment. The new program allows for three different WFT models and four different HPS models (i.e., total of twelve combinations of WFT and HPS models).

In addition to the basic hydroplaning analysis that was implemented in FDOT's old HP tool, the new tool also allows for studying the effect of certain variables on WFT and HPS (i.e., sensitivity analysis) or for studying the uncertainties associated with the input variables (i.e., probabilistic analysis). The new tool was validated against the examples provided in previously published literature. The validation results showed that the WFT and HPS equations are correctly implemented in the new HP tool.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Weather-related crashes are defined as those that occur during adverse weather conditions (e.g., rain, sleet, snow, fog, severe crosswinds, blowing snow, sand, or debris, etc.) or during conditions when the pavement surface is slippery (e.g., wet pavement, snowy or slushy pavement, or icy pavement). According to the National Highway Traffic Safety Administration (NHTSA) 10-year average data from 2007 to 2016, over 5.7 million vehicle crashes occur in the U.S. each year (FHWA, 2017). Among these crashes, approximately 22 percent, or 1.2 million, are weather-related. Each year, over 5,000 people are killed and over 410,000 people are injured due to these weather-related crashes.

The 10-year averages of NHTSA data also revealed that 70 percent of weather-related crashes occur on wet pavement surfaces and 46 percent during rainfall (FHWA, 2017). A much smaller percentage of weather-related crashes occur during winter conditions: 17 percent during snow or sleet and 13 percent on icy pavements. These numbers clearly indicate that the vast majority of weather-related crashes happen on wet pavement and during rainfall.

The primary outcome of a wet pavement surface is reduction in pavement friction due to water acting as a lubricant between the pavement surface and the vehicle tires. Normally, the vehicle tires are designed to push away the undesired substances (such as standing water, rain, snow, and mud), but under severe circumstances, a tire may encounter more water than it can push aside. When a tire can no longer move the water aside, the water pressure in front of the wheel causes the tire to lift from the road surface. This phenomenon, known as aquaplaning or hydroplaning, may occur when a layer of water builds between the wheels of the vehicle and the pavement surface.

In order for a vehicle to respond to a driver's controlling or maneuvering inputs, the vehicle tires must be in contact with the pavement surface. In other words, the vehicle tires enable a driver to start, stop, change speed, and make turning maneuvers only if the tires are in contact with the pavement and if sufficient friction is provided at the tire-pavement interface. However, when hydroplaning occurs, the vehicle tires become separated from the pavement surface and skate on a sheet of water with little to no traction, compromising the driver's ability to steer, brake, or accelerate. Furthermore, when all tires of a vehicle undergo hydroplaning, the driver may lose control of the vehicle and slide until it either collides with an obstacle or slows down enough such that one or more tires contact the pavement and friction is regained.

1.1. OVERVIEW OF HYDROPLANING

1.1.1. <u>Definition of Hydroplaning</u>

According to Horne (1968), hydroplaning is defined as the condition that exists when a film of water or other contaminant is present at the tire-pavement interface and completely separates the tire from the pavement surface, as shown in Figure 1.

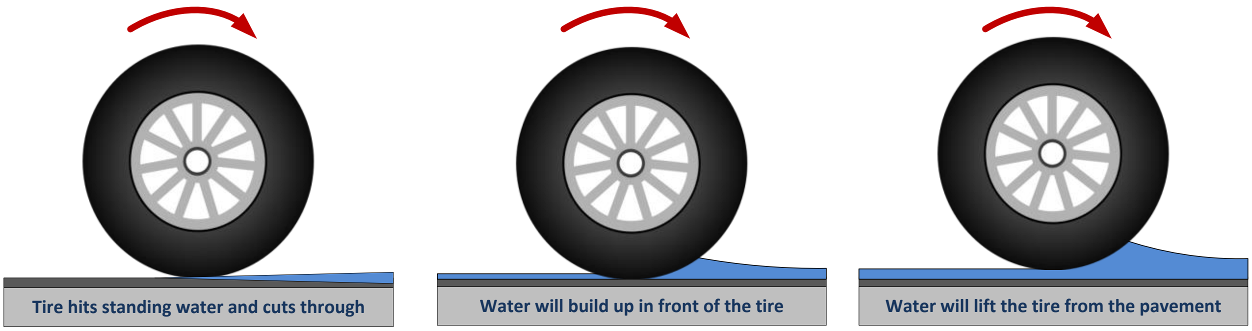


Figure 1. Simplified illustration of hydroplaning.

Along with the above definition, Horne (1968) also categorized the hydroplaning phenomenon into three categories as shown in Figure 2. These categories are dynamic, viscous, and reverted-rubber hydroplaning.

- Dynamic Hydroplaning is the most frequent type of hydroplaning encountered in roadways. It occurs when a moving tire runs over a wet pavement with more water than it can push away and becomes completely separated from the pavement. Dynamic hydroplaning usually occurs at high speeds (typically above 45 mph).

- Viscous Hydroplaning only occurs on pavements with little or no micro-texture. The typical example is a pavement with significant amount of bleeding where the asphalt completely covers the pavement surface. Viscous hydroplaning can also occur on pavements that have been polished smooth by traffic. Under these conditions, even a very thin film of water may separate the moving tire from pavement because of insufficient micro-texture to break down the water film. Viscous hydroplaning can occur at any speed.

- Reverted-rubber hydroplaning occurs when the friction between the tire and the pavement generates excessive heat to the point where the tire rubber has melted and reverted to its uncured state (therefore closing all the treads). This type of hydroplaning typically does not occur on roadways but occurs rarely on runways with high speed aircrafts.

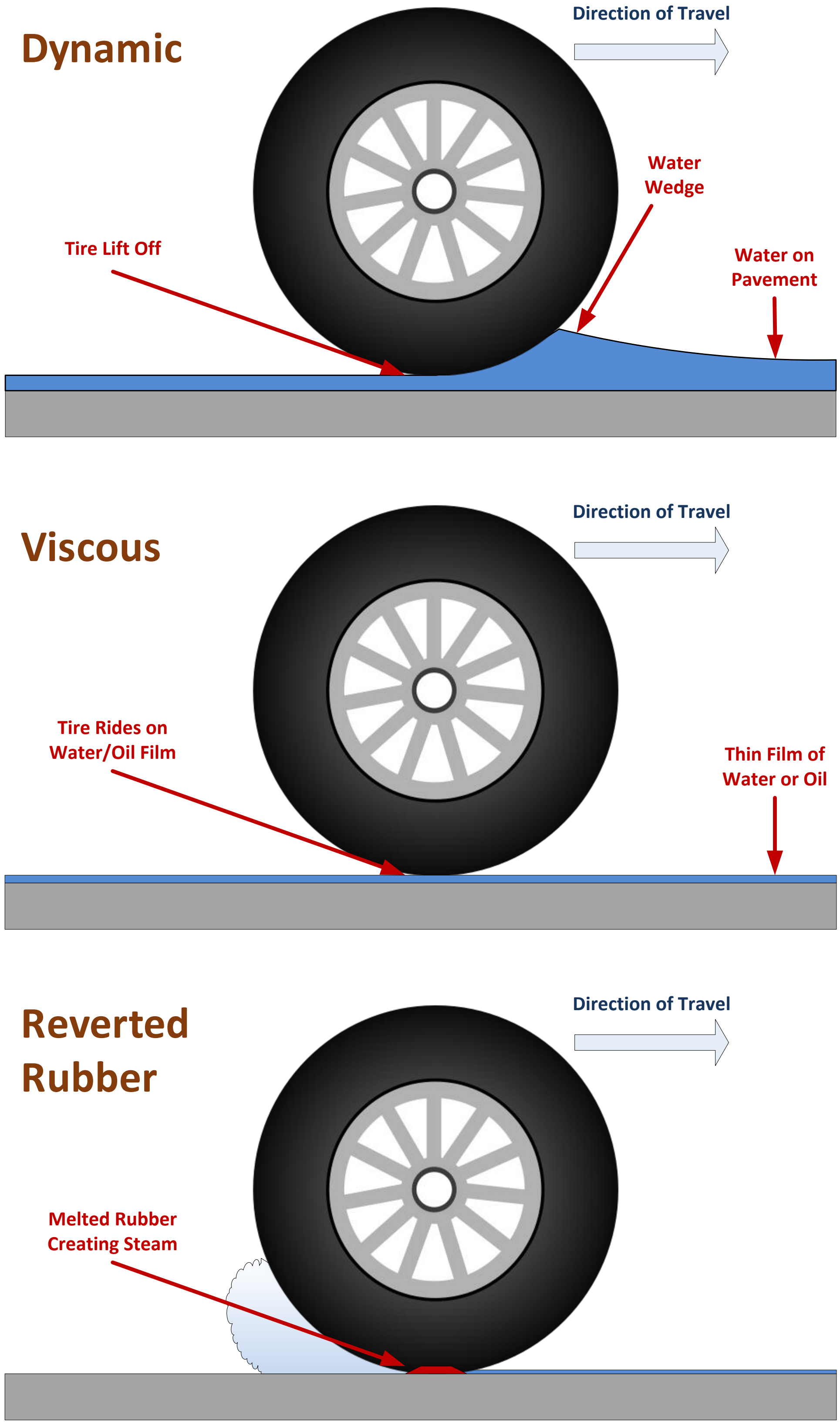


Figure 2. Three categories of hydroplaning.

1.1.2. Factors Affecting Hydroplaning

The factors that influence hydroplaning can be grouped into four categories: (1) roadway and pavement parameters, (2) environmental factors, (3) driver factors, and (4) vehicle factors. Table 1 lists the various factors in each category. Among these, the factors related to the roadway and pavement parameters are considered to be within a state highway agency's (SHA) control and should be considered in the pavement design phase or during pavement evaluation for safety.

Table 1. Factors affecting hydroplaning.

Roadway and Pavement Parameters	Environmental Factors	Driver Factors	Vehicle Factors
• Surface type • Rut depth • Permeability of pavement surface • Pavement micro- and macro-textures • Cross-slope (to include locations of superelevation) • Longitudinal grade (to include sag vertical curves) • Pavement width • Roadway curvature • Depressions	• Rainfall intensity • Rainfall duration • Temperature	• Speed • Accelerating or braking • Steering maneuvers	• Tire tread design • Tire tread wear (tread depth) • Tire pressure • Vehicle type • Vehicle (or axle) weight • Tire tread design (aqua tread for example)

1.2. RESEARCH OBJECTIVES

The primary objective of this research project is to enhance FDOT's existing Hydroplaning Prediction (HP) program. At a minimum, these enhancements should include:

- Assessing the hydroplaning potential in a continuous manner. The user should be able to input roadway geometric design parameters as well as continuous data (e.g., pavement cross-slope, grade, and rut depth) collected using a multi-purpose survey vehicle (MPSV) and pavement texture data for the analysis.

- Analyzing multiple scenarios effectively and efficiently. The program should be capable of making batch runs for different lane widths (or number of lanes, currently referred to as planes in the current HP software) and rainfall intensities.

- Integrating the software with geographic information system (GIS) applications for displaying the computed hydroplaning potential on a map.

2. REVIEW OF EMPIRICAL HYDROPLANING MODELS

In order to verify if the models built into the existing HP tool are correct, the empirical models for Water Film Thickness (WFT) and hydroplaning speed identified from their original sources (i.e., reports and papers) are reviewed herein. To avoid any confusion over the units (SI vs. English) of the input and output variables, the empirical equations shown in this section will adhere to the specific units used in the respective reports or papers unless noted otherwise.

2.1. WATER FILM THICKNESS MODELS

It is noted that some researchers (e.g., Chesterton et al, 2006) have used the terms WFT and the thickness of total water flow (*y*) interchangeably, while some others (e.g., Gallaway et al., 1979) have only used the term WFT to represent the thickness of the water flow. To avoid more confusion over these terms and to ensure more clarity, this report will adhere to the definition that was used by the developers of PAVDRN (Anderson et al., 1998; Huebner et al., 1997). The variables are graphically defined in Figure 3.

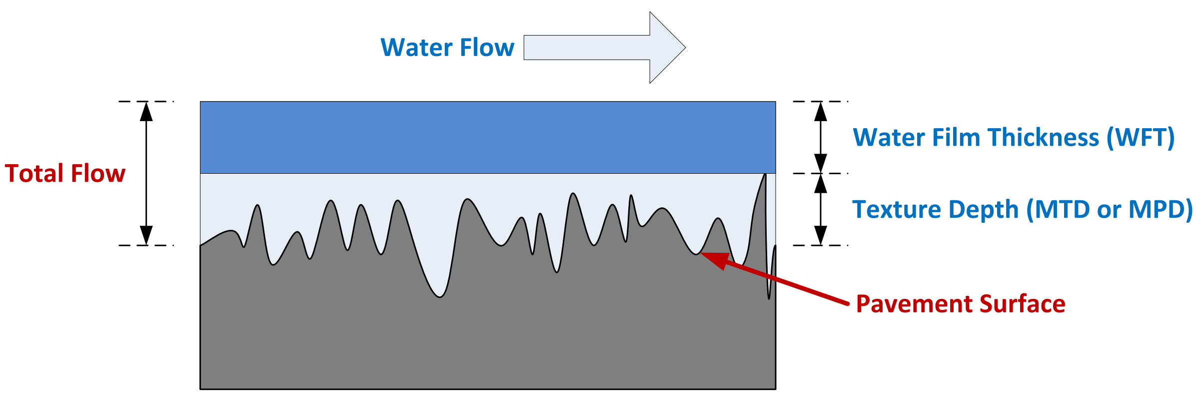


Figure 3. Definition of water film thickness, mean texture depth, and total flow.

The thickness of total water flow (*y*) is defined as the thickness of the water flow measured from the bottom of the pavement texture, whereas the WFT is defined as the thickness of water measured from the top of the pavement texture asperities (in terms of Mean Texture Depth, MTD, or Mean Profile Depth, MPD). According to these definitions, WFT and *y* are related to each other by the following equation.

$$WFT = y - MTD \tag{1}$$

2.1.1. <u>Characterization of Input Parameters</u>

Many of the WFT models to be presented below share common input parameters such as pavement slope, rainfall intensity, drainage path length, etc. As such, it is important to define and understand the input parameters needed for these models.

Rainfall intensity is one of the input parameters used by all of the empirical models. Therefore, it is important to define the relationship between excess rainfall intensity (*I*), actual rainfall intensity (*RI*), and infiltration rate or permeability (*k*) of the pavement surface. It is also necessary to clarify which intensity value should be used in predicting the WFT. For this purpose, the relationship provided by Anderson et al. (1998) is adopted herein and is written as the following.

$$I = RI - k \tag{2}$$

Some researchers in the past have not accounted for the effect of permeability (*k*) or assumed it to be zero (e.g., Gallaway et al., 1979; Chesterton et al, 2006). As such, they were able to use the terms *I* and *RI* interchangeably. However, FDOT's previous hydroplaning study incorporated the pavement permeability (Gunaratne et al., 2012) and hence, the two terms will not be used interchangeably. Consequently, the excess rainfall rate, *I*, should be used in all of the WFT models shown below.

It is also beneficial to identify the pavement slope and the drainage path inputs to be used with the WFT models. The relationship between the pavement cross slope, longitudinal grade, pavement width, and the drainage path length was first provided by Gallaway et al. (1979). This relationship has been adopted by many researchers including FDOT and is given as the following (Mraz and Nazef, 2008; FDOT, 2016).

$$DP_i = W_i \sqrt{1 + \left(\frac{S_{G,i}}{S_{C,i}} \right)^2} \tag{3}$$

where,

DP_i	=	Drainage path length for i^{th} lane (ft or m)
W_i	=	Width of i^{th} lane (same unit as DP_i)
$S_{G,i}$	=	Longitudinal grade of i^{th} lane (ft/ft or m/m). Typically, a single value is used for all lanes at a given location.
$S_{C,i}$	=	Cross slope of i^{th} lane (ft/ft or m/m)

The resultant slope of the pavement surface is calculated from the longitudinal grade and cross slope using the following equation.

$$S_i = \sqrt{{S_{G,i}}^2 + {S_{C,i}}^2} \tag{4}$$

where,

S_i	=	Resultant pavement slope of i^{th} lane (ft/ft or m/m)

It is also noted that Equations (3) and (4) can still be used for multiple lanes if the longitudinal grade and cross slope of the roadway do not vary from lane to lane. In this case, the only variable that needs to be changed is the lane width in Equation (3), e.g., W_i =12 ft. for the first lane and W_i =24 ft. for the second lane.

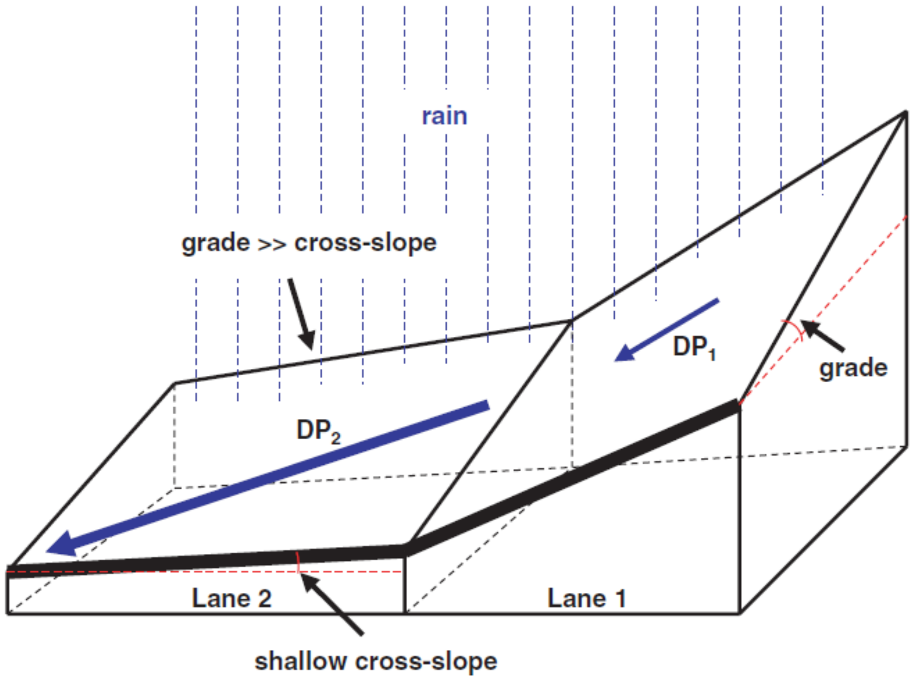


Figure 4. Illustration of drainage path for multiple lanes (after Mraz and Nazef, 2008).

However, as conceptually illustrated in Figure 4, it is possible that the cross slope, longitudinal grade, and lane width may be different from one lane to the next. In this case, the drainage path length for each lane should be calculated separately and then summed up to yield the maximum flow path length:

$$L_i = \sum_{j=1}^{i} DP_j = DP_1 + DP_2 + \cdots + DP_i \tag{5}$$

where,

L_i	=	Maximum flow or drainage path length for i^{th} lane (ft or m)
DP_j	=	Drainage path length for j^{th} lane (same unit as L_i)

The above equation simply indicates that the rainfall droplet entering the pavement at the top-right corner of the pavement in Figure 4 would follow the drainage path of Lane 1 (DP_1) and then the drainage path of Lane 2 (DP_2) before exiting the pavement.

The above equation can also be used to calculate the total amount of water exiting the pavement after the flow. Since the amount of water collected at the bottom of a given drainage path, DP_i, can be written as:

$$q_i = DP_i \cdot I \tag{6}$$

where,

q_i = Total water flow per unit width and time at the bottom of DP_i (ft^3/s/ft)

The total amount of water flow can be obtained as the sum of water flow over the maximum flow path length.

$$\begin{aligned} Q_i &= \sum_{j=1}^{i} q_j = q_1 + q_2 + \cdots + q_i \\ &= I \cdot \sum_{j=1}^{i} DP_j = I \cdot \left(DP_1 + DP_2 + \cdots + DP_i \right) \\ &= I \cdot L_i \end{aligned} \tag{7}$$

where,

Q_i = Total flow of water per unit width and time over the path L_i (ft^3/s/ft)

The empirical WFT models will be presented in the following paragraphs. It should be noted that the pavement slope (S_i) from Equation (4) and the drainage path length (L_i) from Equation (5) should be used as inputs into these models, regardless of the total number of lanes to be analyzed. However, in order to present the equations in the form similar to what was shown in the literature, the subscript (i) will not be used in presentation of these models.

2.1.2. Gallaway WFT Model

The Gallaway model for WFT was derived based on a comprehensive experiment that produced a total of 1,059 data points. The equation is given as the following.

$$WFT = \frac{0.003726 \cdot MTD^{0.125} \cdot L^{0.519} \cdot I^{0.562}}{S^{0.364}} - MTD \tag{8}$$

where,

WFT	=	Water film thickness (in)
MTD	=	Mean texture depth (in)
L	=	Drainage path length (ft)
I	=	Excess rainfall intensity (in/hr)
S	=	Slope of the pavement (dimensionless)

2.1.3. U.K. Road Research Laboratory (RRL) WFT Model

The RRL model was originally developed under a research conducted by the U.K's Ministry of Transport (Ross and Russam, 1968). The equation from the original research is only given for the thickness of the total flow as the following.

$$y = \frac{0.015 \cdot (L \cdot I)^{0.5}}{S^{0.2}} \quad (9)$$

where,

y	=	Thickness of total water flow (cm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (cm/hr)
S	=	Slope of the pavement (dimensionless)

Converting the units of *y* and *I* and incorporating into Equation (1) results in the following equation, which is form more frequently referenced in other literatures (Gunaratne et al., 2012; Chesterton et al, 2006; Oakden, 1977).

$$WFT = \frac{0.046 \cdot (L \cdot I)^{0.5}}{S^{0.2}} - MTD \quad (10)$$

where,

WFT	=	Water film thickness (mm)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

2.1.4. New Zealand (NZ) Modified WFT Model

The NZ-Modified equation takes the same form as the Gallaway equation (Equation (8)) but uses different coefficients and units. The equation is written as the following (Chesterton et al, 2006).

$$WFT = \frac{0.001485 \cdot MTD^{0.110} \cdot L^{0.430} \cdot I^{0.590}}{S^{0.420}} - MTD \quad (11)$$

where,

WFT	=	Water film thickness (mm)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

2.1.5. PAVDRN WFT Model

The PAVDRN model was developed under an NCHRP study (Anderson et al., 1998; Huebner et al., 1997). The model is given as the following.

$$WFT = \left(\frac{n \cdot L \cdot I}{36.1 \cdot S^{0.5}} \right)^{0.6} - MTD \tag{12}$$

where,

WFT	=	Water film thickness (mm)
n	=	Manning's *n* value (dimensionless)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

The Manning's *n* value in the above equation is calculated in the following manner, depending on the pavement surface type.

1. Portland Cement Concrete (PCC) surfaces:

$$n = \begin{cases} = \dfrac{0.388}{N_R^{0.535}} & (N_R < 240) \\ = \dfrac{0.345}{N_R^{0.502}} & (N_R < 500) \\ = \dfrac{0.319}{N_R^{0.480}} & (N_R < 1000) \\ = 0.017 & (N_R \geq 1000) \end{cases} \tag{13}$$

2. Dense-Graded Friction Courses (DGFC):

$$n = 0.0823 \cdot N_R^{-0.174} \tag{14}$$

3. Open-Graded Friction Courses (OGFC):

$$n = \frac{1.490 \cdot S^{0.306}}{N_R^{0.424}} \tag{15}$$

where N_R is the dimensionless Reynold's Number calculated as the following.

$$N_R = \frac{L \cdot I}{\upsilon} \qquad (16)$$

The parameter ν in the above equation represents the kinematic viscosity of water.

2.2. HYDROPLANING SPEED MODELS

Three (3) hydroplaning speed models were incorporated into the existing hydroplaning tool. These models are described in the following paragraphs.

2.2.1. <u>Gallaway Hydroplaning Model</u>

The Hydroplaning Speed (HPS) model by Gallaway et al. (1979) is given by the following equation.

$$HPS = SD^{0.04} \cdot p_t^{\,0.3} \cdot (1 + TD)^{0.06} \cdot A \qquad (17)$$

where,

HPS	=	Hydroplaning speed (mph)
SD	=	Spindown of the tire rotational speed at the initiation of hydroplaning (Percent), typically 10 percent.
p_t	=	Tire pressure (psi)
TD	=	Tire tread depth (in 32nds of an inch)

and,

$$A = Max\left(\frac{10.409}{WFT^{0.06}} + 3.507, \left[\frac{28.952}{WFT^{0.06}} - 7.817\right] \cdot MTD^{0.14}\right) \qquad (18)$$

where,

WFT	=	Water film thickness (in)
MTD	=	Mean texture depth (in)

It is important to note that in Equation (17), the value of *SD* should be inputted as a percentage rather than a fraction (i.e., if the spindown is 10 percent then 10 should be used directly rather than 0.1). Furthermore, the *TD* should be inputted in units of 32nds of an inch (i.e., if the tread depth is 2/32 inch then *TD* = 2). This *TD* value can also be calculated as the actual tread depth in inches multiplied by 32.

2.2.2. <u>PAVDRN Hydroplaning Model</u>

The PAVDRN model for HPS is provided for two levels of WFT.

1. For WFT < 2.4 mm (0.094 in):

$$HPS = 26.04 \cdot WFT^{-0.259} \tag{19}$$

where,

HPS	=	Hydroplaning speed (mph)
WFT	=	Water film thickness (in)

2. For WFT ≥ 2.4 mm (0.094 in):

$$HPS = 3.09 \cdot A \tag{20}$$

where A was previously defined in Equation (18).

It is also noted that Equation (20) is a special case of the Gallaway HPS model shown in Equation (17). For example, if the values of SD = 10 percent, p_t = 30 psi, and TD = 0.3 (actual tread depth = 0.01 in) are inputted into Equation (17), the equation simplifies and reduces to Equation (20).

It should also be made very clear that although the PAVDRN equation for the WFT (Equation (12)) is provided using SI units, the PAVDRN model for HPS uses English units (Equations (18), (19), and (20)).

2.2.3. USF Model

The University of South Florida (USF) model for HPS (Gunaratne et al., 2012) was developed by fitting an empirical equation to the Finite Element (FE) simulation results provided by Ong and Fwa (2007). The model takes the following form.

$$HPS = WL^{0.2} \cdot p_t^{0.5} \cdot \left(\frac{0.82}{WFT^{0.06}} + 0.49 \right) \tag{21}$$

where,

HPS	=	Hydroplaning speed (km/h)
WL	=	Wheel load (N)
p_t	=	Tire pressure (kPa)
WFT	=	Water film thickness (mm)

3. REVIEW OF EXISTING HYDROPLANING TOOL

FDOT’s current HP tool was developed by Gunaratne et al. (2012). This chapter contains a detailed review of FDOT’s current version of the HP tool. The functionality of the tool in terms of inputs, models and outputs was evaluated using both the program interface as well as the underlying Matlab code. In addition, sensitivity analysis of the existing HP tool was conducted to identify any further discrepancies or invalid assumptions.

3.1. USER INTERFACE, INPUTS, AND OUTPUTS OF CURRENT HP TOOL

The user interface of the existing HP tool was developed using the Graphical User Interface (GUI) Toolbox provided with Matlab programming language. A screenshot of this interface is shown in Figure 5.

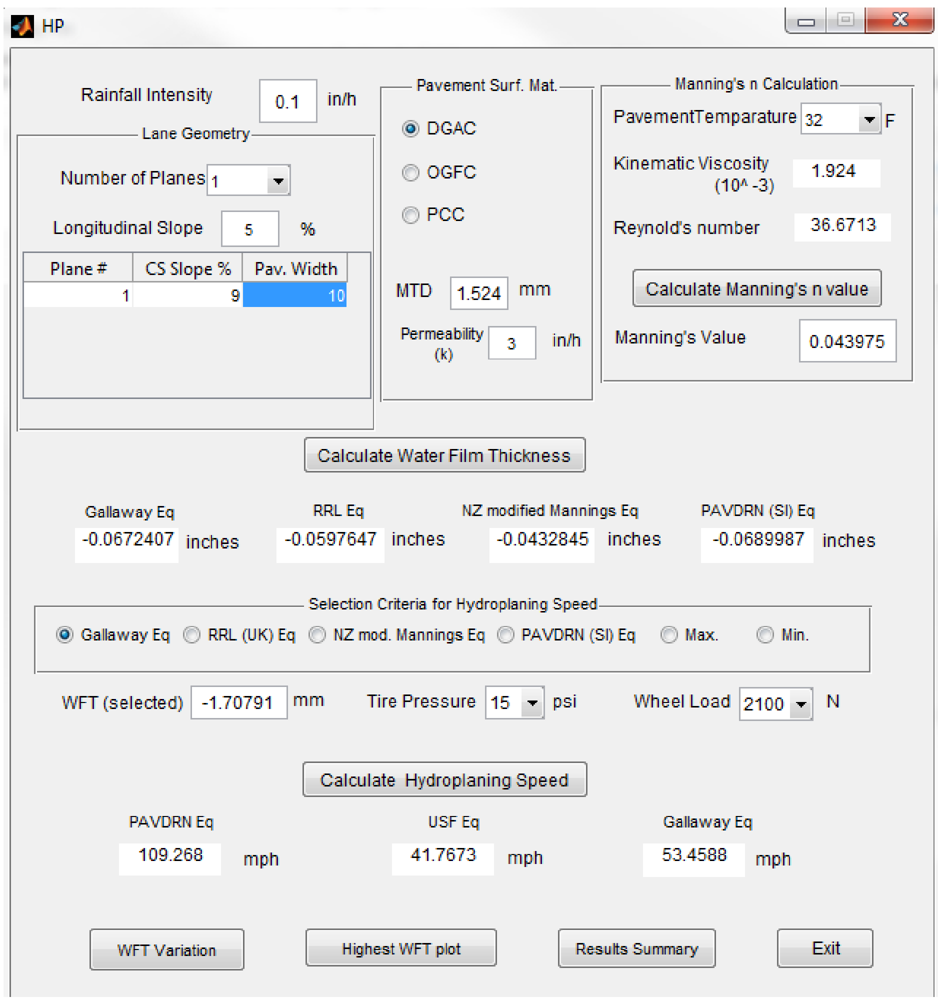


Figure 5. User interface of existing Hydroplaning tool.

The use of the existing HP tool interface is straightforward. The interface is divided into multiple panels that obtain user inputs, contain buttons to perform calculations when clicked, and display results on the screen. Once all the inputs are entered either as numerical values or selected from the drop-down boxes, the user can proceed to calculate the WFT using four different models. Upon selection of the WFT from one of the six options (four models, minimum, or maximum WFT), the user can ask the program to calculate the HPS based on three different prediction models.

Although the user interface is simple and the analysis procedure is straightforward, the researchers' evaluation of the current HP tool revealed several deficiencies that include the following.

- The units used in the interface (Figure 5) are not consistent (i.e., SI and English units are used simultaneously).
- Some of the continuous variables (i.e., temperature, tire pressure, and wheel load) are inputted using drop-down boxes.
- No check is made on the user-inputted values (e.g., rainfall intensity, cross-slope, MTD, etc.). The user is allowed to provide unreasonable input values (e.g., negative values or even complex numbers for rainfall intensity and other variables). In this case, the program will calculate unreasonable outputs without any warning.
- Some of the variables (e.g., lane width and kinematic viscosity) are provided without any units.
- The maximum flow path length is calculated incorrectly for multiple planes in the current HP program. This provides incorrect results for predicted WFT and HPS.
- The input requirements are not specific to the WFT and HPS prediction models. For example, Manning's *n* value, tire pressure, and wheel load inputs are not needed for HP speed prediction using Gallaway model. The current HP program does not clarify which of the inputs are needed for the specific models selected by the user.

Table 2 shows additional details regarding the HP tool interface, program inputs and outputs, along with the identified deficiencies.

Table 2. List of input and output variables in HP tool

Interface Panels	Variable	Input/ Output	Units*	Comments and Drawbacks
General	Rainfall intensity	Input	in/hr	Value inputted by user**.
Lane geometry	Number of planes	Input	N/A	Up to 7 planes can be selected from drop-down box.
	Longitudinal slope of entire pavement	Input	Percent	Value inputted by user**.
	CS (cross-sectional) slope for each plane	Input	Percent	Value inputted by user**.
	Pavement width for each plane	Input	feet	Value inputted by user**.
Pavement Surf. Mat.	Pavement surface material – selection of material between DGAC, OGFC and PCC	Input	N/A	Provides the default MTD value for each surface type upon selection.
	Mean texture depth, MTD	Input	mm	Value inputted by user**.
	Permeability (*k*)	Input	in/hr	Value inputted by user**.
Manning's *n* Calculation	Pavement temperature	Input	°F	Continuous variable selected from a drop-down box.
	Kinematic viscosity	Output	10^{-5} ft^2/s	Shown with wrong multiplier (10^{-3}) and no units.
	Reynold's number	Output	N/A	Calculated output.
	Manning's *n* value	Output	N/A	Calculated output. Can be overwritten by user**.
Calculate Water Film Thickness	WFT – Gallaway Eq.	Output	inch	Calculated output.
	WFT – RRL (UK) Eq.	Output	inch	
	WFT – NZ mod. Manning's Eq.	Output	inch	
	WFT – PAVDRN (SI) Eq.	Output	inch	
Selection criteria for hydroplaning speed	WFT (selected)	Input	mm	Defaulted to Gallaway WFT.
	Tire pressure	Input	psi	Continuous variable selected from a drop-down box.
	Wheel load	Input	Newton	Continuous variable selected from a drop-down box.
Calculate Hydroplaning Speed	Hydroplaning speed – PAVDRN Eq.	Output	in/hr	Calculated output.
	Hydroplaning speed – USF Eq.	Output	in/hr	Must select tire pressure and wheel load from drop-down to display the output.
	Hydroplaning speed – Gallaway Eq.	Output	in/hr	Must select tire pressure from drop-down to display the output.

Note*: N/A indicates that the variable is dimensionless

Note**: Double asterisk indicates that no check is done on the user inputted value. The user can input negative values as well as complex numbers.

3.2. MODELS IMPLEMENTED IN EXISTING HYDROPLANING TOOL

As mentioned above, the existing HP tool does not provide any warning messages for any of the unreasonable inputs provided by the user. Furthermore, the example input/output previously shown in Figure 5 indicates that the program may have mathematical bugs as it predicted positive hydroplaning speed based on negative WFT.

In order to identify the mathematical bugs existing in the current HP tool, the Matlab source code provided with the tool was reviewed extensively. Tables 3 and 4 provide the mathematical equations for WFT and HPS obtained directly from the Matlab source code. These equations were then compared to the correct equations documented in the previous section of the report and the mathematical deficiencies were identified. The detailed deficiencies are provided in the tables. The following is a brief summary of the deficiencies.

- Among the four WFT models, only the Gallaway model is implemented correctly (Table 3).
    - The other three models have incorrect unit conversion built in for the rainfall intensity.
    - The equation form for the NZ Modified model is incorrect.
- Among the three HPS models, only the USF model is implemented correctly (Table 4).
    - Incorrect unit conversion is built in for the parameter *A* used for Gallaway and PAVDRN models. However, it is noted that these are minor errors and do not affect the predicted hydroplaning speed nor FDOT's previous designs in any significant manner.
    - The Gallaway model has incorrect inputs built in for spindown and tire tread depth.
    - Incorrect WFT threshold was implemented for the PAVDRN models.
- The Reynold's number is calculated using 12 ft. lane widths, regardless of the user-inputted lane widths. Furthermore, the pavement slope is hard-coded at 2.0 percent for calculation of OGFC Manning's *n*. These deficiencies affect the PAVDRN WFT model (Table 3).

In summary, the above deficiencies indicate that among the twelve combinations of WFT and HPS models (four WFT models and three HPS models) implemented in the existing HP tool, only one combination (Gallaway WFT model & USF HPS model) calculates the output correctly.

The above mathematical bugs, however, do not explain how positive HPS values were obtained from negative WFT values (Figure 5). It was also noticed that if the WFT is negative (regardless of its magnitude), the HPS results were calculated as 109 mph, 42 mph, and 53 mph from the PAVDRN, USF, and Gallaway models, respectively (using a tire pressure of 15 psi and 2100 N wheel load). This suggested that the program may assume a certain minimum value for the WFT when it is calculated to be negative. However, this value could not identified from the source code. Therefore, a sensitivity analysis of the existing HP tool was conducted to identify any additional features or deficiencies not revealed from the source code.

Table 3. WFT equations and models built into existing HP program.

Variable	Material / Model	Equation	Comments
Water Film Thickness	Gallaway Eq.	$WFT = \dfrac{0.003726 \cdot MTD^{0.125} \cdot L^{0.519} \cdot I^{0.562}}{(S/100)^{0.364}} - MTD$	Units: *WFT* [in], *MTD* [in], *L* [ft], *I* [in/hr], *S*[%]
	UK RRL Eq.	$WFT = \dfrac{\dfrac{0.046 \cdot ([0.3048 \cdot L] \cdot [25.5 \cdot I])^{0.5}}{S^{0.2}} - [25.4 \cdot MTD]}{25.4}$	Units: *WFT* [in], *MTD* [in], *L* [ft], *I* [in/hr], *S*[%] **Incorrect unit conversion for *I***
	NZ Modified Eq.	$WFT = \dfrac{\dfrac{0.06354 \cdot [0.3048 \cdot L]^{0.366} \cdot [25.5 \cdot I]^{0.3288}}{(S/100)^{0.3}} - [25.4 \cdot MTD]}{25.4}$	Units: *WFT* [in], *MTD* [in], *L* [ft], *I* [in/hr], S[%] **Incorrect unit conversion for *I*** **Incorrect coefficient and exponents, MTD missing in calculation of *y*.**
	PAVDRN Eq.	$WFT = \dfrac{\left(\dfrac{n \cdot [0.3048 \cdot L] \cdot [25.5 \cdot I]}{55.955 \cdot (S/100)^{0.5}}\right)^{0.6} - [25.4 \cdot MTD]}{25.4}$	Units: *WFT* [in], *MTD* [in], *L* [ft], *I* [in/hr], *S*[%] **Incorrect unit conversion for *I***
Reynolds No.		$N_R = \left(\dfrac{[12 \cdot n_l] \cdot [I/43200]}{\upsilon/10^5}\right)$	n_l = Lane number Units: *I* [in/hr], ν[10^5 ft^2/s] **Assumes 12 ft. lane width for N_R calculation**
Manning's *n* value	PCC	$n = \dfrac{0.345}{N_R^{0.502}}$	Both *n* and N_R are dimensionless
	DGFC	$n = 0.0823 \cdot N_R^{-0.174}$	Both *n* and N_R are dimensionless
	OGFC	$n = \dfrac{1.490 \cdot (0.02)^{0.306}}{N_R^{0.424}}$	***S* is fixed to 2%**

Table 4. Hydroplaning speed models built into existing HP program.

Variable	Model	Equation	Comments
Hydroplaning Speed	Gallaway Eq.	$HPS = (0.1)^{0.04} \cdot [0.145038 \cdot p_t]^{0.3} \cdot (1.02)^{0.06} \cdot A$	Units: HPS [mph], p_t [kPa] Assumes SP = 10% and actual tread depth of 0.02 in.(according to Gunaratne et al., 2012) **Incorrect input for SP and TD**
	PAVDRN Eq.	$HPS = 26.04 \cdot \left[\frac{WFT}{25.5}\right]^{-0.259}$ (if WFT < 2.54 mm)	Units: HPS [mph], *WFT* [mm] **Incorrect threshold for WFT,** **Incorrect unit conversion for *WFT***
		$HPS = 3.09 \cdot A$ (if $WFT \geq 2.54$ mm)	Units: HPS [mph] **Incorrect threshold for WFT**
	USF Eq.	$HPS = 0.6213 \cdot WL^{0.2} \cdot p_t^{0.5} \cdot \left(\frac{0.82}{WFT^{0.06}} + 0.49\right)$	Units: HPS [mph], WL [N], *WFT* [mm]
Parameter *A*		$A = Max\left(\frac{10.409}{\left[\frac{WFT}{25.5}\right]^{0.06}} + 3.507, \left[\frac{28.952}{\left[\frac{WFT}{25.5}\right]^{0.06}} - 7.817\right] \cdot MTD^{0.14}\right)$	Units: *WFT* [mm], MTD [in] **Incorrect unit conversion for *WFT***

3.3. SENSITIVITY ANALYSIS OF EXISTING HP TOOL

Since it was already found that eleven of the twelve WFT & HPS combinations are incorrectly implemented in the existing HP tool, it was concluded that a meaningful sensitivity study (i.e., the effects of the inputs on the outputs) cannot be accomplished using the current HP tool. As such, the objective of the sensitivity analysis herein was to identify any features or bugs that were not found from the source code. To ensure that all potential bugs are identified, the sensitivity study was conducted for single plane analysis and extended to multiple plane analysis. The analysis involved running the HP tool to calculate WFT and HPS values and comparing them to those obtained from external calculations. The external calculations were carried out using Microsoft Excel® spreadsheet by implementing the equations shown in Tables 3 and 4.

The approach for conducting the sensitivity analysis and the findings are documented in the following section.

3.3.1. Sensitivity Analysis Procedure

The sensitivity analysis was carried out in five steps described below.

Step 1: Select values for each input variable that can be entered/changed by the user.

A range of input values for the sensitivity analysis were determined after consultation with FDOT personnel. Table 5 shows the list of input variables and their values used for the sensitivity analysis.

Table 5. Input variables for sensitivity analysis

Variable	Values							Number of Values
Rainfall intensity, in/hr	0.1	0.5	1	3	5	9	12	7
Permeability, in/hr	0	3	6	10	50	100	180	3
MTD, mm	0.25	0.5	1.5	2	2.5	3.8	5	6
Pavement temperature, F	32	50	70	90	110	130		6
Tire pressure, psi	15	27	33	60	80	100		6
Wheel load, N	2100	3000	3600	4800				4
Longitudinal slope, %	0	1	2	3	4	5		6
Cross-sectional slope, %	1	3	5	7	9	10		6
Pavement width, ft.	10	12	14	16				4
Number of Planes	1	2	3	4				4

Step 2: Develop a full factorial of runs using the selected inputs.

Using the input values shown in Table 5, full factorial designs were developed separately for single plane and multiple plane analyses. For the single plane analysis (i.e., Number of Planes = 1), the full factorial yielded over 7 million runs of the HP program. Since the single plane analysis resulted in such a large number of runs, it was anticipated that the full factorial for the multiple planes would yield an unreasonably large number. Therefore, for multiple plane analysis, the pavement longitudinal slope was limited to 0, 2, and 5 percent, while the cross-slope was limited to 1, 3, and 5 percent. In addition, the cross-slope values for multiple planes were set up such that the plane farther from the median had an equal or higher cross-slope compared to the adjacent inside plane. The full factorial obtained in this manner yielded more than 12 million runs of the HP program for multiple planes.

Step 3: Select reduced dataset for sensitivity analysis

As mentioned previously, the objective of this sensitivity analysis was to find any additional bugs not identified from the source code. However, the full factorials yielded a very large number of runs, which is deemed highly inefficient and considered to be unnecessary for this objective. Therefore, it was decided to extract a reduced set of input values from the full factorial design for this analysis. As a result, a total of 300 sets of inputs (200 sets for single plane and 100 sets for multiple planes) were randomly extracted.

Step 4: Run the HP tool with the reduced datasets as input

The reduced set of inputs determined above was used to run the HP tool. The outputs from the HP tool were manually recorded in Excel because the tool does not provide an option to save the calculated results into an output file. The output parameters that were recorded from the HP tool interface included the following.

- Kinematic viscosity of water (10^{-5} ft^2/sec)
- Reynold's number
- Manning's *n* coefficient
- WFT calculated using all four models as displayed (inch and mm)
- HPS predicted using all three models for each WFT (mph), resulting in a total of 12 hydroplaning speed values were recorded for each run.

Figure 6 shows a screenshot that illustrates the format used to record output data from the HP tool.

Run No.	Mat'l	Kin Visc	Reynolds	Mannings		WFT Gall	WFT RRL	WFT NZ	WFT Pav
1	DGAC	1.924	36.6713	0.043975	Inches	-0.003514	0.0008841	0.003698	-0.004506
					mm	-0.089253	0.0224561	0.0939296	-0.114457
					V Pavdrn	109.268	109.268	109.268	109.268
					V USF	66.5318	66.5318	66.5318	66.5318
					V Gallaway	52.6994	50.5116	47.1078	52.6994
	OGFC			0.09773	Inches				-0.001153
					mm				-0.029291
					V Pavdrn				109.268
					V USF				66.5318
					V Gallaway				52.6994
	PCC			0.056562	Inches				-0.003617
					mm				-0.091869
					V Pavdrn				109.268
					V USF				66.5318
					V Gallaway				52.6994

Figure 6. Screenshot – data template for recording HP tool output

Step 5: Compare HP tool output values to external calculations

For the external calculations, separate spreadsheets were setup for single and multiple plane analyses. All intermediate and final output calculations were performed using the equations shown in Tables 3 and 4. Same input values used to run the HP tool in step 4 were used again for the external calculations to allow direct comparison of the results.

3.3.2. <u>Findings from Sensitivity Analysis</u>

Initial results from the sensitivity analysis showed that the external calculations matched the HP tool outputs for all cases when the calculated WFT values were positive. This indicated that the equations shown in Tables 3 and 4 with all the mathematical deficiencies are implemented in the HP tool.

However, the initial, external calculations could not be completed under the following conditions.

1. When the WFT from Equation (1) was calculated to be negative. i.e.:

$$WFT = y - MTD < 0 \quad \text{or} \quad y < MTD \tag{22}$$

2. When the excess rainfall intensity (I) from Equation (2) was calculated to be negative. i.e.:

$$I = RI - k < 0 \quad \text{or} \quad RI < k \tag{23}$$

The reason that the external calculations could not be completed for the above conditions was simple. It was due to the empirical equations (Tables 3 and 4) that included the terms in which WFT and I values are raised to a non-integer power. Further evaluation of the empirical equations and the external calculations revealed that the HP program is apparently handling the above conditions in the following manner.

1. If the WFT is calculated to be negative (Equation (22)):

    - The WFT value is adjusted to 0.039 inch (0.1 mm) for the PAVDRN and USF hydroplaning models. .
    - The WFT value is adjusted to 0.0039 inch (0.01 mm) for the Gallaway hydroplaning model.

2. If the excess rainfall intensity (I) is calculated to be negative (Equation (23)):

    - The Matlab still uses the negative value of I and raises it to a non-integer power, resulting in a complex number for the predicted WFT. The tool then reports the real part of the complex WFT number on the user interface and continues to calculate the HPS which is also a complex number (real part reported only).

With the above findings on how the Matlab code is handling the negative values for WFT and *I*, the external calculations were updated to match the HP outputs for all 300 datasets. However, it is noted that the above manner of handling negative values lacks consistency. Furthermore, it should be noted that none of the empirical equations (Tables 3 and 4) were developed for any complex algebra and hence, the tool needed further error-proofing in order to avoid abusing the mathematical capabilities of Matlab.

4. SUMMARY OF GAP ANALYSIS

In this chapter, the drawbacks of the existing HP tool are summarized in terms of model discrepancies, functionalities, features, and user friendliness.

4.1. MODEL ERRORS IN EXISTING HYDROPLANING TOOL

The sensitivity analysis conducted on the existing HP tool showed that the models used for WFT and HPS prediction are made in accordance with the equations and the implementation errors shown in Tables 3 and 4. As mentioned in the previous section, among the twelve combinations of WFT and HPS models (four WFT models and three HPS models), only one combination (Gallaway WFT model & USF HPS model) is implemented correctly in the HP tool. Although a few minor bugs were identified for the models used by FDOT (i.e., Gallaway WFT and PAVDRN HPS models), these bugs were found to have insignificant effects on the predicted hydroplaning speed. The details regarding the implementation deficiencies for the other models were discussed in the previous section. As such, the following is a broad summary of the errors found during this study.

- The NZ Modified WFT model as implemented in the HP tool is not in agreement with the equation documented in the literature.

- The PAVDRN HPS model consists of two equations (one for WFT < 2.4 mm and the other for WFT ≥ 2.4 mm) [See Equations (19) and (20)]. However, the existing HP tool has this threshold hard-coded at 2.54 mm.

- The existing HP tool has numerous built-in errors for unit conversion, especially for the conversion between inches and millimeters. The correct constant for this conversion is 25.4. The HP program uses 25.4 in some of the code and 25.5 in some other lines of the code without any consistency. Such errors were found in both the WFT equations and HPS equations. Although this may be considered to have a minor effect on the overall results, it is recommended that such unnecessary discrepancies be fixed in the next generation of the HP tool.

- The existing HP tool has various inputs that are incorrectly built into the code. These inputs include tire spin down (for Gallaway HPS), lane width (for Reynold’s number), tire tread depth (Gallaway HPS), and pavement slope (for Manning’s n calculation).

- No limits (lower and upper bounds) are implemented into the HP tool that prevent users from entering erroneous inputs such as negative or extremely large values. No checks are made for negative values of the intermediate variable (e.g., excess rainfall). In addition, inconsistent limits are used for the WFT before HPS calculation (WFT ≥ 0.1 mm for the PAVDRN and USF HPS models; WFT ≥ 0.01 mm for the Gallaway HPS model).

- The maximum flow path length is calculated incorrectly for multiple planes, causing incorrect results for predicted WFT and HPS.

4.2. ADDITIONAL SHORTCOMINGS OF EXISTING HYDROPLANING TOOL

In addition to the above model errors, several deficient features and functionalities of the existing HP tool were identified during the review. These are summarized in the following.

- The existing HP tool lacks user-friendliness and flexibility.
    - Some of the continuous variables (e.g., pavement temperature, tire pressure, and wheel load) can only be selected from a list of options provided in the drop-down list and cannot be entered as numeric values.
    - Some of the intermediate outputs such as Manning's *n* coefficient and WFT values cannot be saved to an external file for analysis or documentation. It is only possible to save the hydroplaning speed predictions to an image file, which also makes it difficult to obtain the output in a numerical format.
    - Some inputs (e.g., tire tread depth and spin down) are hard-coded and the user is not allowed to change these variables. While the use of default values is considered acceptable, it is desirable to make the users aware of these default values and allow them to modify the values if needed.
    - The existing HP tool loads a default value of one for the number of planes. However, it does not allow user to enter the cross-slope and pavement width for the plane until the number of planes is changed (i.e., the default value is not taken automatically). Similarly, kinematic viscosity and Reynolds number values are not displayed until the temperature is changed by the user. Hydroplaning speed using the USF equation is not displayed until both tire pressure and wheel load values are changed. Hydroplaning speed using the Gallaway (TXDOT) equation is not displayed until tire pressure is changed.
    - The existing HP tool is not consistent in units. E.g., while some variables are displayed in SI units (e.g., MTD, selected WFT, and wheel load), other variables are provided in English units (e.g., permeability, WFT, and HPS).

- The existing program was developed using Matlab programming language.
    - Although Matlab is a powerful language for sophisticated mathematical operations, it requires an expensive license fee as well as knowledge and experience for coding.
    - The empirical equations for WFT and HPS are simple equations that do not require such a sophisticated mathematical package capable of handling complex algebra.
    - Owing to the above, it is recommended that the new HP program be built in Excel spreadsheet and Visual Basic for Applications (VBA) environment. FDOT has access to Excel and has sufficient experience in VBA language.

- The existing HP program lacks efficiency for analyzing multiple scenarios or large amount of inputs.
    - The tool only allows for analyzing a single set of inputs, without any flexibility to analyze multiple scenarios through batch processing.

    - The tool does not allow for automated processing of cross-slope, grade, and rut depth data from FDOT's Multi-Purpose Survey Vehicle (MPSV) which may be useful for forensic investigation and other case studies.

- The existing program only takes the MTD as the texture input while FDOT is frequently measuring the texture in terms of the mean profile depth (MPD).
    - Although MTD is a 3-dimensional estimate of pavement texture, the associated test (i.e., sand patch test per ASTM E 965) is time consuming and labor intensive.
    - FDOT's high speed, 64 kHz lasers mounted on locked wheel testers are capable of outputting the MPD along the entire length of the roadway with GPS coordinates. Automated processing of such MPD data along with the MPSV data may allow for a more streamlined analysis of existing roadways.

- FDOT's output files from both the MPSV and locked wheel tester (for pavement texture) include GPS coordinates that could be used for GIS application. However, because the current HP programs only take manual user inputs, the GIS application is not feasible.

5. TEXTURE AND PERMEABILITY INPUTS FOR HYDROPLANING SPEED PREDICTION

As discussed in the previous chapter of the report, one of the major shortcomings of the current HP program is that it only takes the MTD as the necessary texture input. Although this is mainly because the empirical WFT equations were developed using MTD, FDOT is primarily measuring the pavement texture in terms of MPD as part of their pavement friction protocol. As such, it is desirable to establish a relationship between the MTD and MPD for use with the hydroplaning tool. This will also allow FDOT to convert the MPD measured from either the high speed laser (mounted under FDOT's locked wheel testers) or from a circular texture meter (CTM) to an equivalent MTD.

Based on recommendations of the current HP user guide, the permeability input in the current HP program is defaulted to zero regardless of the surface type. Considering that the pavement surfaces may deteriorate over time due to rutting, ravelling, depressions, and other distresses that affect the flow of water at the pavement surface, it is believed that this recommendation is reasonable for a more conservative hydroplaning analysis during the design stage. However, it is also believed that FDOT may want to use non-zero permeability values and utilize the full functionality of the HP program for special occasions (e.g., forensic analysis) in the future.

In this section of the report, the texture and permeability data collected by FDOT are reviewed in an attempt to develop the necessary relationship between MTD and MPD, and to provide a means for estimating the permeability of in-service pavement surfaces (for special cases).

5.1. TEST SECTIONS

Tables 6, 7, and 8 show the list of sections tested with rigid surfaces, dense-graded friction courses (DGFC), and open-graded friction courses (OGFC), respectively. As shown in the tables, 10 sections were selected and tested for each surface type, for a grand total of 30 test sections.

Table 6. Rigid pavement and bridge deck test sections

Site	Construction Year	Surface*	Location	Project ID	Beginning Milepost	Ending Milepost	Tested Lane
1	2016	LGD	SR 9B	72002027	3.000	3.538	SBL3
2	2017	LGD	SR 400	79110000	17.005	17.700	NBL3
3	2016	LGD	SR 45	01010000	4.000	4.600	SBTL
4	2014	LGD	SR 600	10130000	11.114	11.700	NBL3
5	2016	LGD	Apollo Blvd Bridge	70017500	2.200	2.390	NBL
6	2013	LGD	SR - 228	72120000	4.114	4.714	EBTL
7	2013	LGD	SR 600/US 92	79060000	7.716	8.300	EBL2
8	2012	BD	SR 600/US 92	79060000	4.300	4.900	WBL2
9	2016	LGD-TGV	SR 9B - Bridge Deck	72002027	2.693	2.910	SBL3
10	NA	LGD-TGV	SR-417 Bridge	77470000	7.310	7.910	NBTL

Table 7. Dense-graded asphalt surface test sections

Site	Construction Year	Mix Type	Location	Material	Project ID	Beginning Milepost	Ending Milepost	Tested Lane
1	2011	FC125MR	SR 10	Limestone	27010000	15.000	15.600	SBTL
2	2015	FC125MR	SR 51	Limestone	33040000	20.673	21.200	NB
3	2017	FC95MR	SR 81	Granite	52040000	5.097	5.700	NBTL
4	2011	FC125MR	SR 10	Limestone	27010000	11.863	12.232	EBTL
5	2005	FC125	SR 16	Limestone	28030001	6.943	7.469	WBTL
6	2015	FC125MR	SR 121	Granite	39020000	10.589	11.789	NB
7	2011	FC125	SR 363	Granite	55040000	0.400	0.968	NB
8	2004	FC125	US 41	Granite	29040000	3.300	3.868	NB
9	2009	FC125	SR 47	Granite	29020000	2.300	2.868	NBTL
10	2004	FC125	SR 90	Limestone	87120000	2.601	3.100	WBTL

Table 8. Open-graded asphalt surface test sections

Site	Construction Year	Mix Type	Location	Material	Project ID	Beginning Milepost	Ending Milepost	Tested Lane
1	2010	FC5M	US 19,	Granite	34050000	26.807	27.375	NBTL
2	2017	FC5M	SR 200	Granite	26060000	27.000	27.538	NBTL
3	2008	FC5	SR 24	Limestone	26050000	12.145	12.540	NBPL
4	2008	FC5M	US 441	Granite	26010000	1.100	1.700	SBPL
5	2000	FC5	US 301	Limestone	28010000	3.007	3.575	SBTL
6	2016	FC5A	SR 415	Granite	79120000	1.002	1.600	NBTL
7	2014	FC5AW	SR5	Limestone	73010000	1.408	2.000	NBTL
8	2006	FC5M	US 1	Limestone	73010000	22.666	23.234	SBTL
9	2015	FC5M	SR 589	Granite	08470000	9.134	9.702	NBTL
10	2010	FC5	SR 25	Limestone	86060000	8.098	8.700	SBTL

Table 6 shows that there were a total of 3 bridge decks surveyed, 2 of which were treated with longitudinal grinding (LGD) and transverse grooving (TGV) finish, in accordance with FDOT's standard practice. The other bridge deck (i.e., Apollo Blvd. Bridge) was only treated with LGD finish as part of an FDOT's experimental study and was excluded from the analysis. Furthermore, the table also shows that there was only one rigid pavement section finished with burlap drag (BD) which was excluded from the analysis. Although this pavement section could have been included, the results with and without this section practically made no difference.

The data for the above 30 sections were gathered as part of FDOT's broader effort of harmonizing different equipment for pavement friction and texture. The tests performed in each of the above 30 sections are listed in Table 9. As shown in the table, numerous site-specific and high-speed tests were conducted. Furthermore, the site-specific tests were conducted at least 5 different locations with each location tested both in the wheel path and at the lane center (i.e., non-wheel path).

Table 9. Tests performed for FDOT's friction/texture harmonization

Tested Variable	Test Methods
Mean Texture Depth (MTD)	• Sand Patch (SP) testing per ASTM E 965

Mean Profile Depth (MPD)	• Circular Texture Meter (CTM) testing per ASTM E 2157
	• TM2 Walking Texture Meter per ASTM E 1845
	  o In longitudinal and transverse directions
	• High Speed 64kHz per ASTM E 1845
	  o With point and line lasers

Pavement Friction Number (FN)	• Locked wheel friction testing per ASTM E 274
	  o With ribbed (ASTM E 501) and smooth (ASTM E 524) tires
	  o At various speeds ranging from 30 mph to 60 mph.
	• Dynamic Friction Tester (DFT) testing per ASTM E 1911

Outflow Time (OFT)	• Outflow Meter testing per ASTM E 2380

Although a lot of data was collected as part of the above effort, development of the harmonized equations for pavement friction and texture is beyond the scope of this study. As the purpose of this particular effort was to develop the relationships between MTD, MPD, and permeability for hydroplaning analysis, only the following tests (and results) are studied for this purpose.

- MTD from the Sand Patch Testing
- MPD from the Circular Texture Meter
- OFT from the Outflow Meter

The results and findings from the analysis are presented in the following sections.

5.2. ESTIMATION OF SURFACE PERMEABILITY

The Outflow Meter testing standardized in ASTM E 2380 is a commonly used procedure for assessing the drainage capability of a pavement surface through its texture and subsurface voids. The device measured the Outflow Time (OFT) which is the time taken by a known quantity of water to escape through the pavement texture and voids under gravitational pull.

ASTM E 2380 also states that the OFT is related to pavement texture (or MTD to be more specific) and provides an equation of the following form for the correlation.

$$MTD = \frac{C_1}{OFT} + C_2 \tag{24}$$

where C_1 and C_2 are the regression coefficients. Rewriting the above equation for OFT results in the following.

$$OFT = \frac{C_1}{MTD - C_2}\text{, for } (MTD\text{-}C_2) > 0 \text{ and } OFT > 0 \tag{25}$$

Provided that reasonable coefficients (C_1 and C_2) are made available, Equation (25) can be used to estimate the OFT from pavement texture. As such, the regression equation shown in Equation (24) was fitted to the dataset for determining C_1 and C_2 coefficients. The equation was fitted separately for each surface type as well as for all surfaces merged together. Figure 7 graphically shows these results while Table 10 summarizes the coefficients and R^2 determined from the regression analysis. For reference purposes, the coefficients provided in ASTM E 2380 are also shown in Table 10.

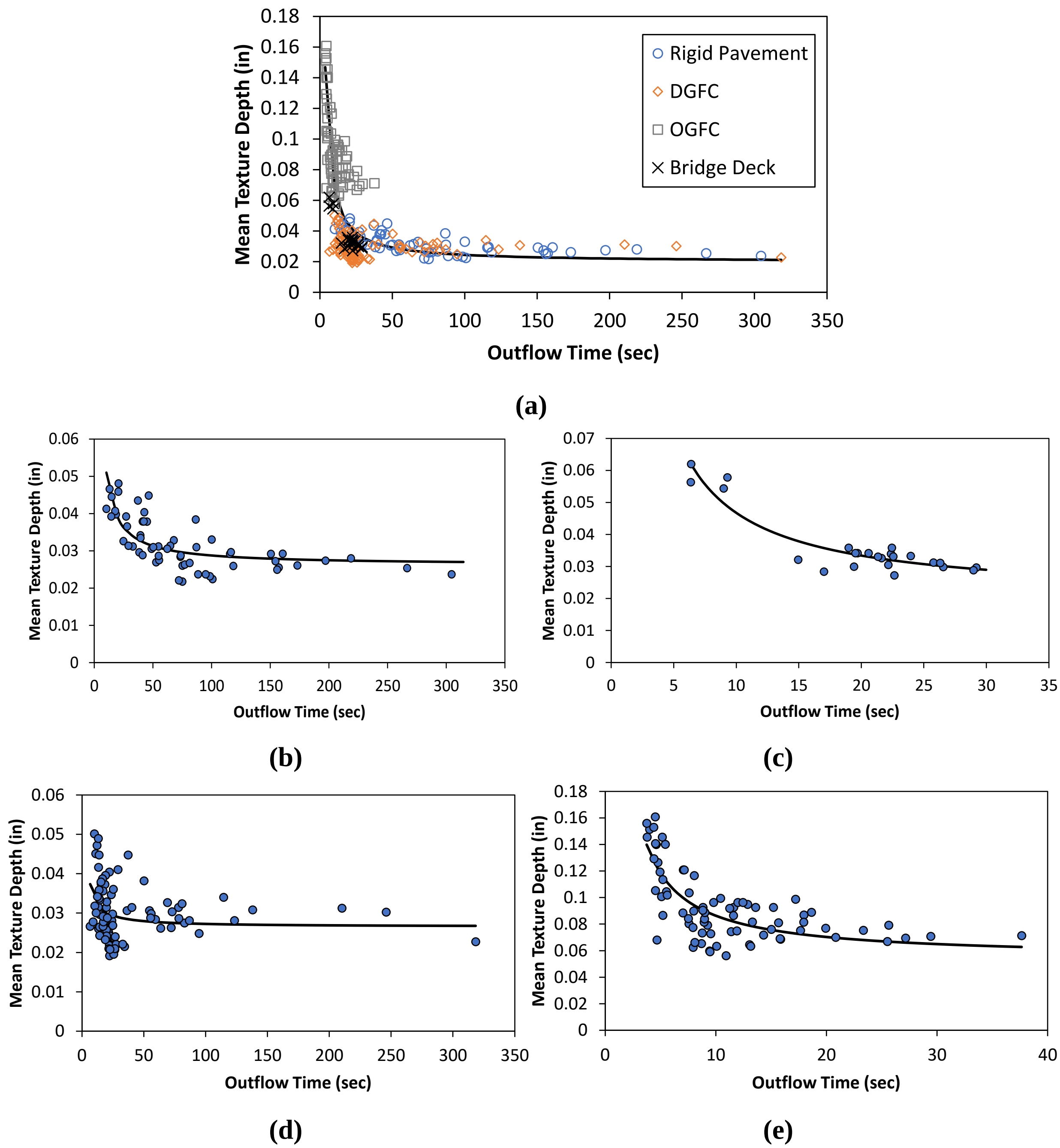


Figure 7. MTD vs. OFT for (a) all surfaces, (b) rigid pavements [LGD], (c) bridge decks [LGD-TGV], (d) DGFC, and (e) OGFC

Table 10. Regression coefficients for relating MTD and OFT [Equations (24) and (25)]

Surface Type	Regression Coefficients*		R^2 Value
	C_1	C_2	
All	0.477	0.020	0.71
Rigid Pavement (LGD and BD)	0.256	0.026	0.54
Bridge Deck (LGD-TGV)	0.267	0.020	0.87
DGFC	0.072	0.027	0.07
OGFC	0.321	0.054	0.58
ASTM E 2380	0.123	0.025	N/A

Note: These coefficients correspond to English units [*MTD* in inches and OFT in seconds]. The original equation in ASTM E 2380 was provided for SI units [*MTD* in mm].

However, ASTM E 2380 does not provide any guidance on estimating the surface permeability from the OFT. As such, the simple and well-known Darcy's law will be utilized herein for developing the relationship between OFT and permeability. Figure 8 shows the schematics of the falling-head permeability test which was originally developed for permeability testing of soils. For a one-dimensional flow, the Darcy's law for the falling-head test can be written as the following (Holtz and Kovacs, 1981).

$$k = \frac{a \cdot H}{A \cdot \Delta t} \cdot \ln\left(\frac{h_0}{h_T}\right), \quad \Delta t = t_T - t_0 \tag{26}$$

where a and A are the cross sectional areas of the test tubes (cm^2), H is the height (or thickness) of the sample (cm), h_0 and h_T are the energy heads of the water (cm) at the beginning ($t = t_0$) and ending ($t = t_T$) times (in seconds) of the test. For the Outflow Meter used by FDOT, the two cross sectional areas a and A are equal to each other and the above equation simplified further. In addition, the Δt term can be replaced by the OFT measured by the Outflow Meter. As a result, Equation (26) can be rewritten as the following.

$$k = \frac{H}{OFT} \cdot \ln\left(\frac{h_0}{h_T}\right) \tag{27}$$

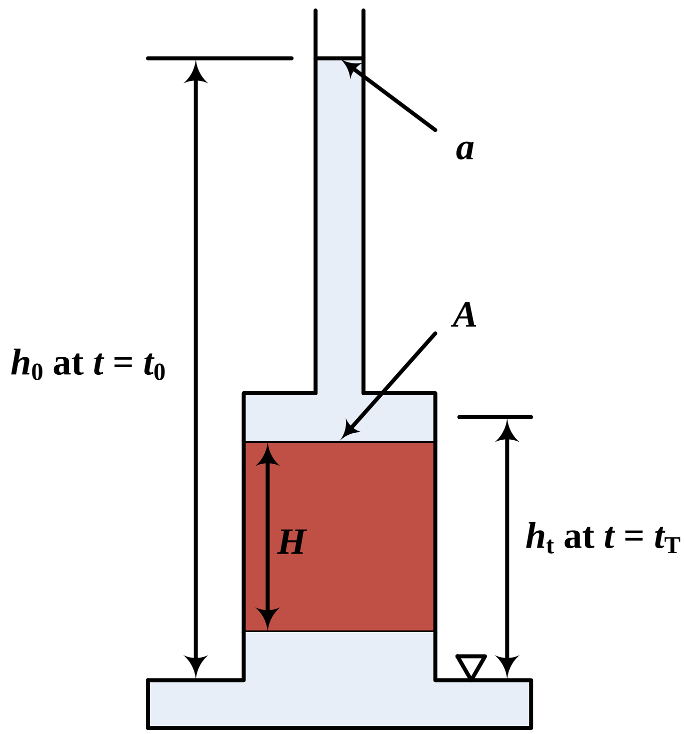


Figure 8. Schematics of falling-head permeability test

Although the simple equation shown above has not been standardized as a Florida Method (FM) of Test, it is currently being used by the researchers at the State Materials Office (SMO) for field permeability tests with the Outflow Meter. As such, Equation (27) was used in this study for calculating the permeability based on the OFT values measured from the 30 test sections.

However, it should be noted that Equation (27) requires the thickness (*H*) of the surface layer as an input, which was not available for this study. Therefore, the following assumptions were made in using Equation (27).

1. For OGFC surfaces, the thickness of the porous layer was assumed to be 0.75 in. which is typical for Florida pavements.
2. For DGFC and rigid surfaces, it was assumed that the layers are essentially impermeable and the water is only allowed to escape through the texture of the pavement surface. With this assumption, the variable *H* in Equation (25) was set equal to the MTD measured from the Sand Patch testing.

Figure 9 shows the plot between the MTD and the permeability calculated with the above assumptions for all surface types. The figure shows that there is reasonable relationship between the MTD and the permeability calculated from Equation (27) [note that this equation is independent of MTD]. Therefore, regression equations of the following form were fitted to the data shown in Figure 9.

$$k = C_3 \cdot MTD - C_4 \tag{28}$$

where C_3 and C_4 are regression coefficients. The resulting coefficients and the R^2 values are summarized in Table 11.

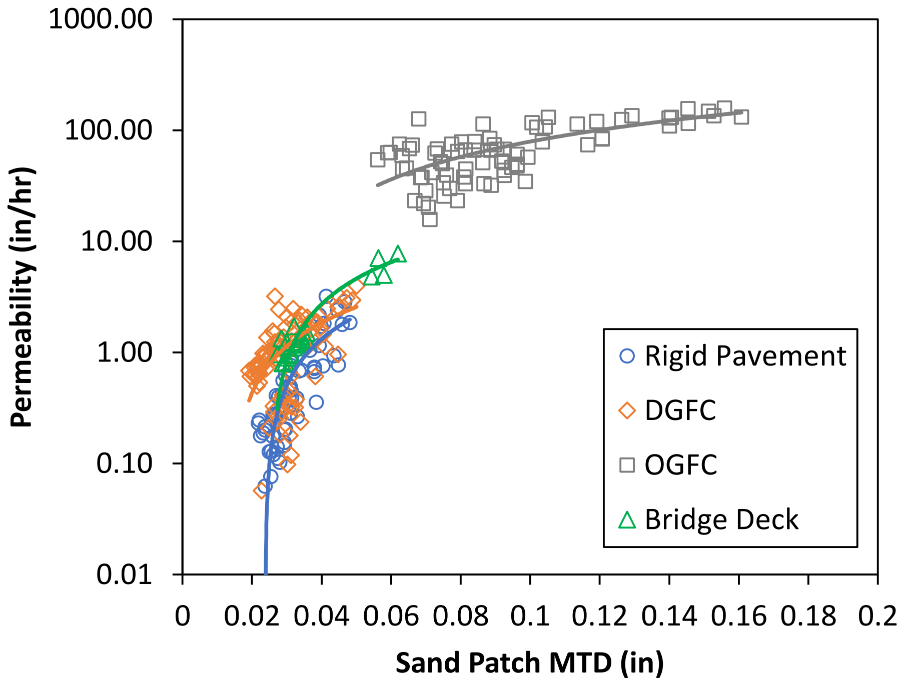


Figure 9. Permeability vs. Mean Texture Depth

Table 11. Regression coefficients for relating MTD and permeability [Equation (28)]

Surface Type	Regression Coefficients		R^2 Value
	C_3	C_4	
Rigid Pavement (LGD)	81.49	1.94	0.63
Bridge Deck (LGD-TGV)	189.27	4.84	0.93
DGFC	71.20	0.99	0.38
OGFC	1076.45	28.43	0.58

Note: These coefficients correspond to English units [*MTD* in inches and *k* in in/hr].

5.3. TEXTURE RELATIONSHIPS

To develop the relationship between MTD and MPD, the texture data obtained from the Sand Patch testing was plotted against those from the CTM. Figures 10 through 13 show these relationships for different surface types with the linear regression equation of the following form fitted to all data shown in the respective plots.

$$MTD = C_5 \cdot MPD + C_6 \tag{29}$$

where the coefficients C_5 and C_6 are shown in the respective plots, and also summarized in Table 12 with the corresponding R^2 values.

The figures generally show good correlation between MTD and MPD, with the exception of OGFC as shown in Figure 13(a). This figure shows that MTD obtained from the Sand Patch testing is significantly higher than the MPD results from the CTM. Furthermore, the data points shown in this figure can be categorized into two groups: (1) the data points below the trend line and closer to the line of equality and (2) the points above the trend line (corresponding to much higher MTD values when compared to MPD).

Further examination of the data set indicated that the data points corresponding to the second group were from OGFC sites 1, 2, 4 and 9, all of which included granite aggregates (Table 8). In addition, all of the Outflow meter tests from these locations resulted in OFT values less than 5.5 seconds. While it is unclear why all these data points correspond to OGFCs with granite aggregates, the OFT results clearly indicate that these sections were highly permeable likely due to the high air voids. It is believed that these high air voids may have caused challenges with the Sand Patch testing procedure (i.e., the small spheres or sand particles used for the testing may have been dropped into the larger air voids before the operator could spread them over the OGFC surface). Therefore, these data points (corresponding to OFT < 5.5 seconds) were removed from the plot and the MTD vs MPD relationship was re-obtained as shown in Figure 13(b).

At this time, it is recommended that the linear regression corresponding to Figure 13(b) be used for converting MPD to MTD for a more conservative hydroplaning analysis. It is also recommended that further tests (Sand Patch and CTM) be conducted on OGFCs with high air voids for better understanding and characterization of the MTD/MPD relationship.

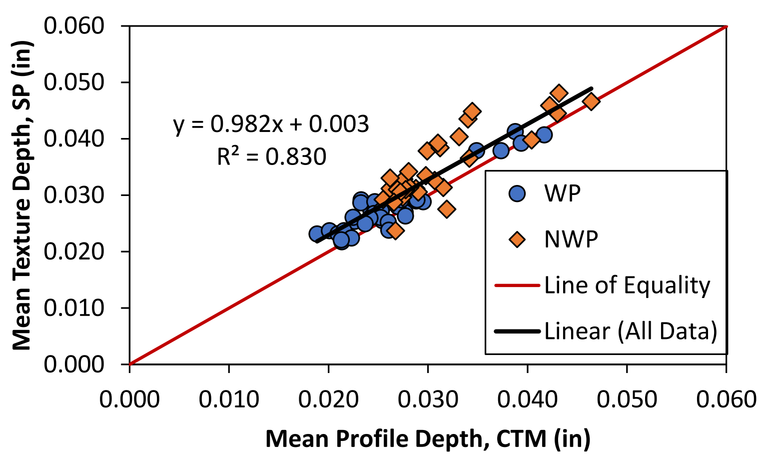


Figure 10. MPD (CTM) vs. MTD (Sand Patch) for rigid pavement surfaces (LGD)

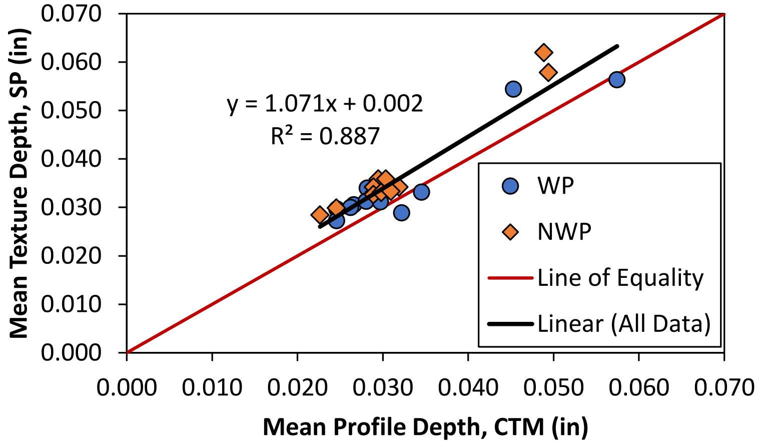


Figure 11. MPD (CTM) vs. MTD (Sand Patch) for bridge deck surfaces (LGD-TGV)

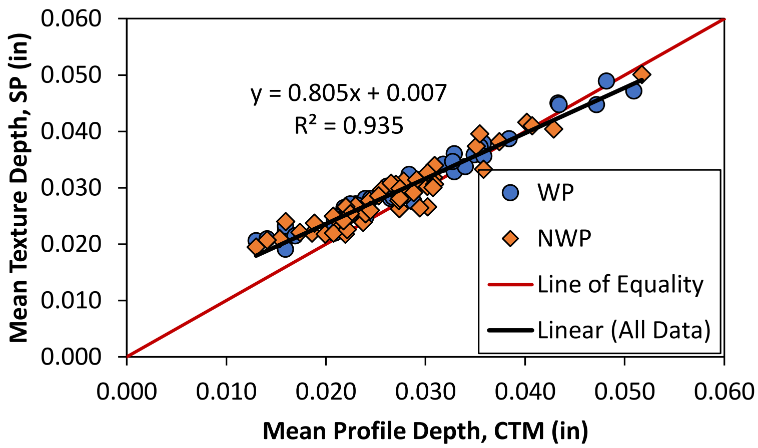
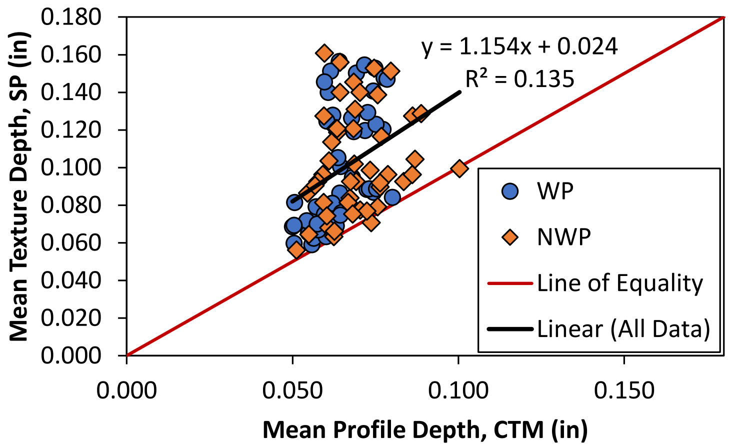
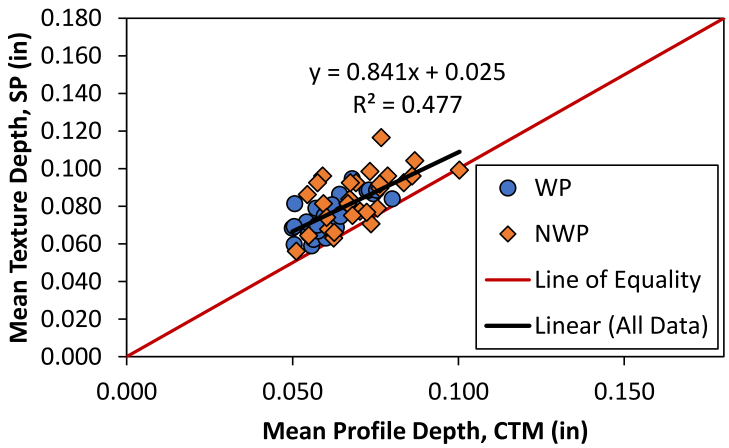


Figure 12. MPD (CTM) vs. MTD (Sand Patch) for DGFC



(a)



(b)

Figure 13. MPD (CTM) vs. MTD (Sand Patch) for OGFC (a) with and (b) without OFT less than 5.5 seconds

Table 12. Regression coefficients for relating MTD and MPD [Equation (29)]

Surface Type		Regression Coefficients		R^2 Value
		C_5	C_6	
Rigid Pavement (LGD)		0.982	0.003	0.83
Bridge Deck (LGD-TGV)		1.071	0.002	0.89
DGFC		0.805	0.007	0.94
OGFC	All Data	1.154	0.024	0.14
	Without OFT < 5.5 sec	0.841	0.025	0.48

Note: These coefficients correspond to English units [both *MTD* and MPD are in inches].

5.4. DEFAULT TEXTURE AND PERMEABILITY INPUTS FOR HYDROPLANING ANALYSIS

In order to determine the default texture (MPD and MTD) values for hydroplaning analysis, the MPD values collected from FDOT's roadway network were studied. Table 13 summarizes some percentile (i.e., 5th, 10th, 15th, 50th, and 90th) values of the Statewide MPD collected between 2014 and 2018 from in-service pavements as well as newly constructed pavements (Wang and Holzschuher, 2019). Table 14 shows the MTD values obtained from the MPD values in Table 13 using Equation (29). The tables show that for flexible surfaces (i.e., DGFC and OGFC), the MPD values obtained from newly constructed surfaces are generally lower than those of existing pavements.

Upon discussion with FDOT's technical experts, it was recommended that conservative texture values be used for hydroplaning analysis at the pavement design phase. As such, the default texture values for DGFC and OGFC surfaces were chosen to be the 5th percentile values in Table 13 and Table 14. It is also noted that insufficient MPD values were available for newly constructed rigid pavement (i.e., LGD) and bridge deck surfaces. Therefore, the default values for these surfaces remain unchanged from those recommended from the previous study (Gunaratne et al., 2012). In summary, Table 15 shows the new default texture values for the hydroplaning analysis.

Table 13. Percentiles of mean profile depth for FDOT's roadways (Wang and Holzschuher, 2019)

Percentile	In Service Pavements				New Pavements			
	DGFC	OGFC	LGD	Bridge Deck (LGD+TTN)	DGFC	OGFC	LGD	Bridge Deck (LGD+TTN)
5%	0.015	0.051	0.020	0.041	0.014	0.050	N/A	N/A
10%	0.017	0.054	0.021	0.043	0.015	0.052	N/A	N/A
15%	0.020	0.055	0.022	0.043	0.016	0.054	N/A	N/A
50%	0.025	0.063	0.025	0.045	0.018	0.061	N/A	N/A
90%	0.039	0.075	0.040	0.065	0.023	0.070	N/A	N/A

Table 14. Percentiles of mean texture depth for FDOT's roadways

Percentile	In Service Pavements				New Pavements			
	DGFC	OGFC	LGD	Bridge Deck (LGD+TTN)	DGFC	OGFC	LGD	Bridge Deck (LGD+TTN)
5%	0.020	0.067	0.022	0.046	0.018	0.067	N/A	N/A
10%	0.022	0.070	0.024	0.048	0.020	0.068	N/A	N/A
15%	0.024	0.070	0.024	0.048	0.021	0.069	N/A	N/A
50%	0.028	0.077	0.028	0.050	0.022	0.075	N/A	N/A
90%	0.039	0.087	0.042	0.071	0.027	0.083	N/A	N/A

Table 15. New default texture values for hydroplaning analysis

Surface Type	Default Values	
	MTD (in.)	MPD (in.)
Dense Graded Friction Course (DGFC)*	0.018	0.014
Open Graded Friction Course (OGFC)*	0.067	0.050
Rigid Pavements – (LGD**)	0.035	0.033

Note*: These MTD and MPD values are different from the default values documented in the old version of the Hydroplaning Guidance. These default values have been updated based on a recent FDOT study (FDOT, 2019; Wang and Holzschuher, 2019).

Note**: LGD = Longitudinal Grinding

As mentioned, FDOT's current recommendation is to assume an impermeable surface (i.e., zero permeability) for the hydroplaning analysis, regardless of the surface type. At this time, it is believed that assuming an impermeable surface (even for OGFCs) is reasonable for hydroplaning analysis during the pavement design phase due to the following reasons.

1. The permeability values for OGFC shown in Figure 9 are significantly greater than the typical rainfall intensity used for the hydroplaning analysis. This is consistent with what was reported by the developers of PAVDRN (Anderson et al., 1998; Huebner et al., 1997). Per the recommendation by PAVDRN developers, using a lower OGFC permeability value would allow for a more conservative hydroplaning analysis for the worst conditions (Anderson et al., 1998; Huebner et al., 1997).
2. Pavement distresses such as rutting, ravelling, depressions, bleeding, and other sources of contamination may have a significant effect on pavement permeability.
3. For locations with excessively long drainage path (e.g., > 100 ft), hydroplaning may occur on any pavement surfaces (including OGFCs), regardless of the effective permeability.
4. Many of the empirical WFT equations (i.e., Gallaway, RRL, and NZ Modified models) were developed without considering the permeability of the pavement surface directly. However, the effect of pavement permeability may have been incorporated indirectly due to the inherent nature of pavement surfaces.

Based on the above reasoning, current recommendation is to use FDOT's existing default value of zero permeability for hydroplaning analysis in the design phase. However, it is noted that FDOT may want to carry out the hydroplaning analysis using input values that are different from their defaults for special cases (such as forensic evaluation).

6. DEVELOPMENT OF ENHANCED HYDROPLANING TOOL

6.1. INTRODUCTION

In previous chapters of this report, the relevant literature was reviewed for the empirical Water Film Thickness (WFT) and Hydroplaning Speed (HPS) models. These models were implemented into the new hydroplaning program (HP).

This chapter documents the development of the new HP and describes its features. Validation examples based on sample problems made available in literature are provided in the next chapter. A detailed hydroplaning guidance and user manual of the new HP tool are provided in Appendix A and Appendix B of this report, respectively.

6.2. DEVELOPMENT OF NEW HYDROPLANING PROGRAM

The new HP tool was implemented in a macro-enabled Excel spreadsheet environment. Since all of the WFT and HPS equations are empirical and simple, the calculations within the HP tool are carried out using Excel's standard equations. However, the HP tool also includes macros or code written in Visual Basic for Application (VBA) language, primarily for the user to navigate through the spreadsheet, run advanced analysis (e.g., importing continuous data and exporting .kml files), and to generate output tables and plots as appropriate.

Figure 14 shows the interface of the new HP tool. As shown in this figure, the new program is composed of six major parts. These are:

1. General Inputs
2. Analysis Options
3. Model Selection
4. Pavement Inputs
5. Environmental Inputs
6. Vehicle Inputs
7. Analysis Results

Additional description on the above major parts and the flow of the new program is provided below.

6.3. GENERAL INPUTS

These inputs are the general project-related information that defines the location of the project as well as other information pertaining to the project (i.e., similar project information as included in FDOT's nondestructive testing reports). These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts.

FDOT

Hydroplaning Analysis Tool

General Inputs

FPID	123456-7	Roadway Section Number	12345
District No.	2	Milepost	0.800 to 4.000
County	Alachua	Direction	North

General Inputs

Analysis Options

Select Analysis Option: Deterministic (Default) : Show intermediate outputs? No

Risk Analysis? (Per FDOT's Design Guidance): No

Continuous Data? No : For Rut depth, Cross Slope, and/or Texture

Analysis Options

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway	Y		Y
UK RRL			
NZ Mod.			
PAVDRN			

Notes on WFT and HPS Models

Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Model Selection

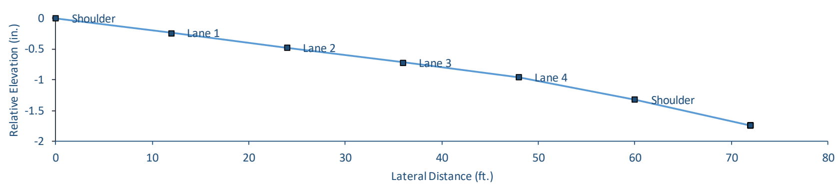
Pavement Inputs

Deterministic Analysis

Longitudinal Grade (%): 3
Surface Type: Dense Graded Friction Course
Permeability (in/hr): 0

Pavement Texture (Please Select MTD or MPD below)
Mean Texture Depth (in.): 0.035

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Description	Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Cross Slope (%)	2	2	2	2	3	3.5						
Width (ft.)	12	12	12	12	12	12						



Pavement Inputs

Environmental Inputs

Deterministic Analysis

Rainfall Intensity (in/hr): 2.00

Environmental Inputs

Vehicle Inputs

Deterministic Analysis

Tire Pressure (psi): 30 <-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%): 10 <-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in): 0.02 <-- Note: Tread Depth is only needed for Gallaway HPS Model

Vehicle Inputs

Analysis Results

Deterministic Analysis

Water Film Thickness (WFT) Table

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Model	Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Gallaway	0.015	0.037	0.054	0.069	0.074	0.081						

Hydroplaning Speed (HPS) Table

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Hydroplaning Speed													
HPS	WFT												
PAVDRN	Gallaway	76.7	61.0	55.4	52.1	51.1	50.0						
Gallaway	Gallaway	57.5	53.8	52.3	51.3	51.0	50.7						

Analysis Results

Figure 14. New hydroplaning program user interface.

6.4. ANALYSIS OPTIONS

The analysis options implemented into the new HP tool are schematically shown in Figure 15. As indicated in the figure, the user needs to choose from the following analysis types.

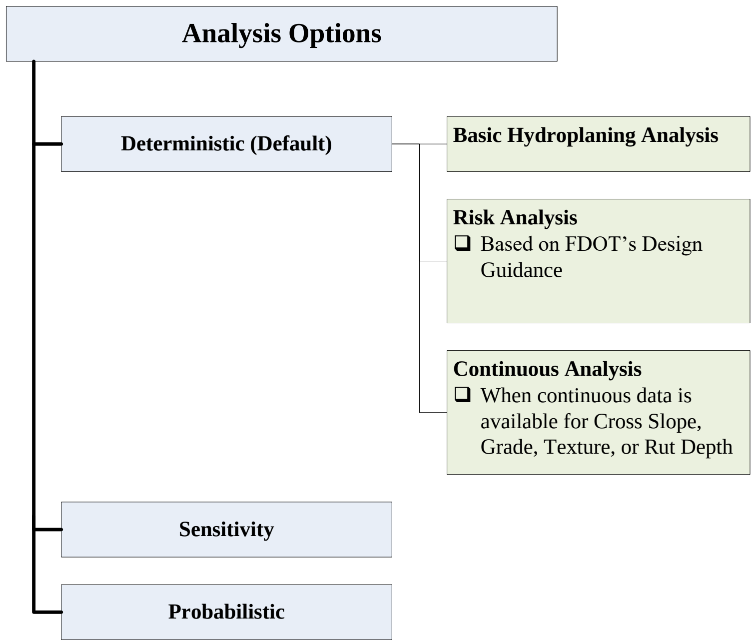


Figure 15. Analysis options implemented in the new HP tool.

6.4.1. <u>Deterministic Analysis</u>

The deterministic analysis is a simple calculation of the intermediate and output variables based on a given set of known input parameters. There are three analysis options under this analysis category.

1. **Basic Hydroplaning Analysis**: This is the most basic and default mode of hydroplaning analysis. The user may select multiple models (up to 3 WFT models × 4 HPS models = 12 model combinations) and view the results in the same worksheet.

2. **Risk Analysis**: The risk analysis is based on FDOT's Design Guidance on the analysis of hydroplaning risk assessment using the HP program. The risk analysis is conducted by comparing the expected driver speed during rainfall events (Jayasooriya and Gunaratne, 2014) and the expected hydroplaning speed. Note that in accordance with FDOT's Design Guidance, the Risk Analysis is always based on the Gallaway WFT model and the PAVDRN HPS model.

3. **Continuous Analysis**: The user may run this analysis option if one or more of the continuous data files are available for Cross Slope, Grade, Texture, or Rut Depth. If the GPS coordinates are available in the data, the user may export the results into a .kml file for viewing in Google Earth.

6.4.2. Sensitivity Analysis

The sensitivity analysis option allows the user to simulate a variety of conditions, which may be useful during the pavement design phase. The user is allowed to vary one or more of the input variables (e.g., rainfall intensity, temperature, cross-slope, tire pressure, etc.) at desired intervals. For each sensitivity variable, the user must provide Min., Max., and Interval values, e.g., if the user specified the rainfall intensity input such that Min. = 1.0 in/hr, Max. = 4.0 in/hr, and Interval = 1.0 in/hr, then the program will run the hydroplaning analysis for rainfall intensities of 1.0 in/hr, 2.0 in/hr, 3.0 in/hr, and 4.0 in/hr.

6.4.3. Probabilistic Analysis

The probabilistic analysis option allows the user to characterize the uncertainties associated with certain variables (e.g., rainfall intensity, pavement temperature, axle weight, tire pressure, etc.). The probabilistic input variables must be defined in terms of a distribution (i.e., mean and standard deviation), rather than a fixed value. The output variables are calculated using the Monte Carlo simulation methodology using a set of randomly generated input parameters in accordance with the given distribution (i.e., mean and standard deviation).

6.5. MODEL SELECTION

The user may select one or more WFT and HPS models for the analysis. The available models are:

- Water Film Thickness: Gallaway, UK RRL, NZ Mod., and PAVDRN models
- Hydroplaning Speed: PAVDRN, USF, and Gallaway models

The new HP program has the above list of models organized in a matrix form (Figure 14), and the user needs to type in “Y” in the cell corresponding to the desired WFT and HPS model combination.

Two of the analysis options are exceptions to the above (i.e., multiple models cannot be used). These options are:

- Risk Analysis Option
  - The analysis always uses Gallaway WFT and PAVDRN HPS models (regardless of user-selected models).
- Continuous Analysis Option
  - Due to the large amount of data associated with continuous data, only one model combination (WFT and HPS) is used with this analysis option. If the user selects multiple model combinations, the one corresponding to the leftmost column and top row in the model selection matrix is used.

6.6. PAVEMENT INPUTS

The user must provide the necessary pavement or roadway related inputs needed for the hydroplaning analysis, which include the following:

- Longitudinal pavement grade.
- Pavement surface type. Note that for the deterministic analysis, changing the surface type fills in the default values for pavement texture and permeability. The available surface types and their default values are:
  - DGFC: MTD = 0.018 in. (MPD = 0.014 in.) and Permeability = 0.0 in/hr.
  - OGFC: MTD = 0.067 in. (MPD = 0.050 in.) and Permeability = 0.0 in/hr.
  - PCC (LGD): MTD = 0.035 in. (MPD = 0.033 in.) and Permeability = 0.0 in/hr.
- Pavement Texture
  - The user may override the default MTD value. The user may also select to provide texture in terms of MPD rather than MTD.
- Permeability of pavement surface.
  - The recommendation is to use 0.0 in/hr permeability for the hydroplaning analysis. However, the user may override the default permeability value if desired.
- Pavement cross-slope.
- Pavement width.

6.7. ENVIRONMENTAL INPUTS

The environmental inputs needed for the hydroplaning analysis are:

- Rainfall Intensity (Required for all analyses).
- Temperature. Note that temperature is only used for PAVDRN WFT model. Therefore, the temperature input is only visible when the PAVDRN WFT model is selected.

6.8. VEHICLE INPUTS

It is noted that the vehicle inputs are needed only for the Gallaway and USF HPS models. Therefore, if these HPS models are not selected, the vehicle inputs are not visible to the user. In addition, each vehicle input becomes visible when it is needed for the selected model(s). The vehicle inputs and the associated HPS models are:

- Axle Weight: Needed for USF HPS model.
- Tire Pressure: Needed for Gallaway and USF HPS models.
- Spindown: Needed for Gallaway HPS model.
- Tread Depth: Needed for Gallaway HPS model.

6.9. ANALYSIS RESULTS

Analysis of hydroplaning involves calculation of the intermediate and the output variables. The user can decide to show or hide the intermediate variables at any time. The output variables are displayed at all times.

6.9.1. Intermediate Variables

Prior to calculating the predicted hydroplaning speed, it is necessary to calculate all of the intermediate variables. These intermediate variables include the following.

- Drainage Path (DP) Length.
  - The drainage path values are calculated for all models and are displayed if the user chooses to view the intermediate variables.
- Mean Texture Depth.
  - If the user inputted texture values in terms of MPD, the computed MTD value is displayed as an intermediate variable.
- Kinematic viscosity, Reynold's number, and Manning's *N* value.
  - These intermediate variables are only used by PAVDRN WFT model, and are displayed if this WFT model is selected and the user chooses to view the intermediate output.

6.9.2. Output Variables

Upon completing calculation of the intermediate variables, the hydroplaning program calculates the final output variables. These variables are:

- Water film thickness.
  - The water film thickness is calculated and displayed for all of the WFT and HPS model combinations.
- Hydroplaning speed.
  - The hydroplaning speed will be calculated from the intermediate variables and the water film thickness calculated above. The user will be able to use one or more (or all) models.
- Water depth due to rutting.
  - Hydroplaning analysis due to rut depth is only available under continuous analysis option. The user may provide a continuous rut data file or provide a fixed value for rut depth. In accordance with Figure 16, the depth of water ponding in a rutted pavement is calculated as:

$$WD = d - L \cdot s \tag{30}$$

where WD is the maximum water depth, d is the measured rut depth, L is the distance between the lower side of rut to the position of the maximum rut, and s is the measured cross-slope.

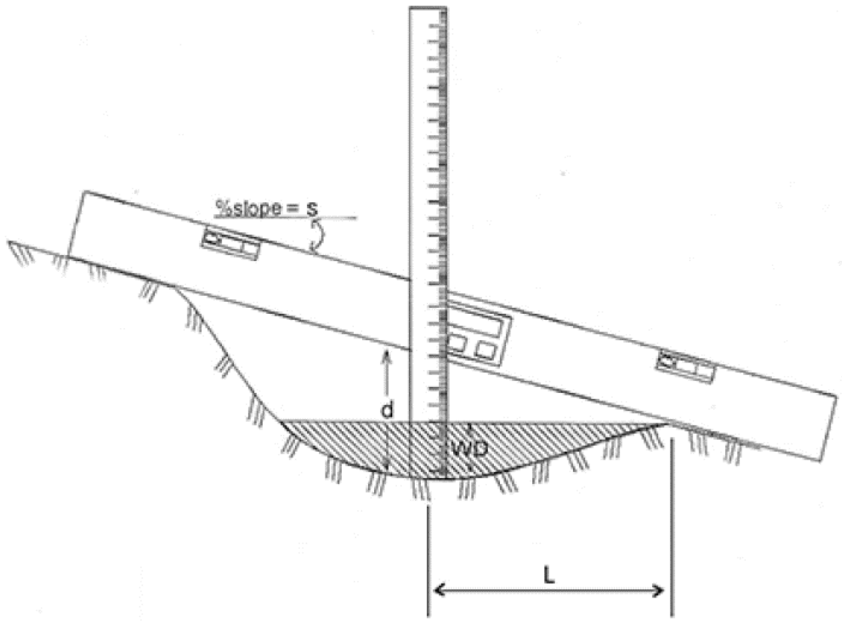


Figure 16. Illustration of water depth due to pavement rutting and cross-slope.

7. VALIDATION OF FDOT'S NEW HYDROPLANING TOOL

In order to ensure that the equations in the new HP tool are correctly implemented, the newly developed tool has been validated. However, since any field validation effort is beyond the scope of this study and the implemented equations were brought directly from literature, the validation effort was limited to replicating the available examples in the literature.

7.1. GALLAWAY EXAMPLE

Gallaway et al. (1979) provided two examples for the equations they developed. The first example, as seen in Figure 17, shows the relationship between WFT and the drainage path length while other input variables remain fixed. The necessary input variables are shown in the figure. Noted that the figure shows two curves denoted as "Combined Data (Eq. 19)" and "Old Equation (Eq. 16)". The equation implemented into the new HP tool corresponds to Gallaway's new equation or the one denoted as "Combined Data (Eq. 19)".

Figure 18 shows the results reproduced using the equations implemented into FDOT's new HP tool. The figure shows that the results are in agreement with those obtained by Gallaway et al. (1979).

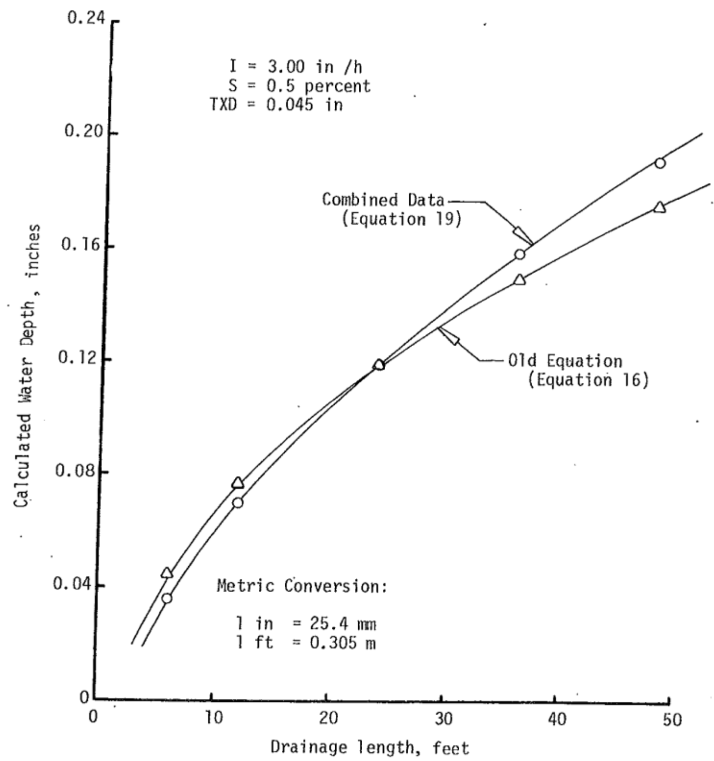


Figure 17. Gallaway water film thickness example (Gallaway et al., 1979, p. 83)

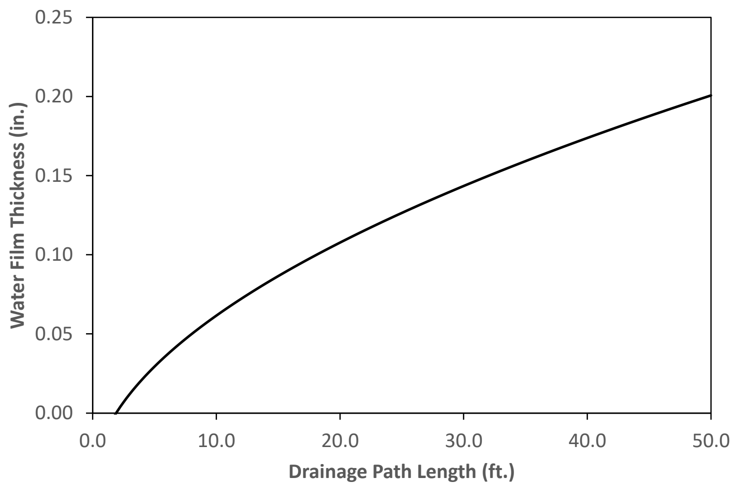


Figure 18. Gallaway's water film thickness example simulated with new HP tool

Gallaway's second example is given for the hydroplaning speed equation, as shown in Figure 19. These plots were generated by calculating the hydroplaning speed by changing spindown variable and one additional variable. The inputs used for creating these plots are directly shown in the figure. Figure 20 shows the corresponding results reproduced using the equations implemented in the new HP tool.

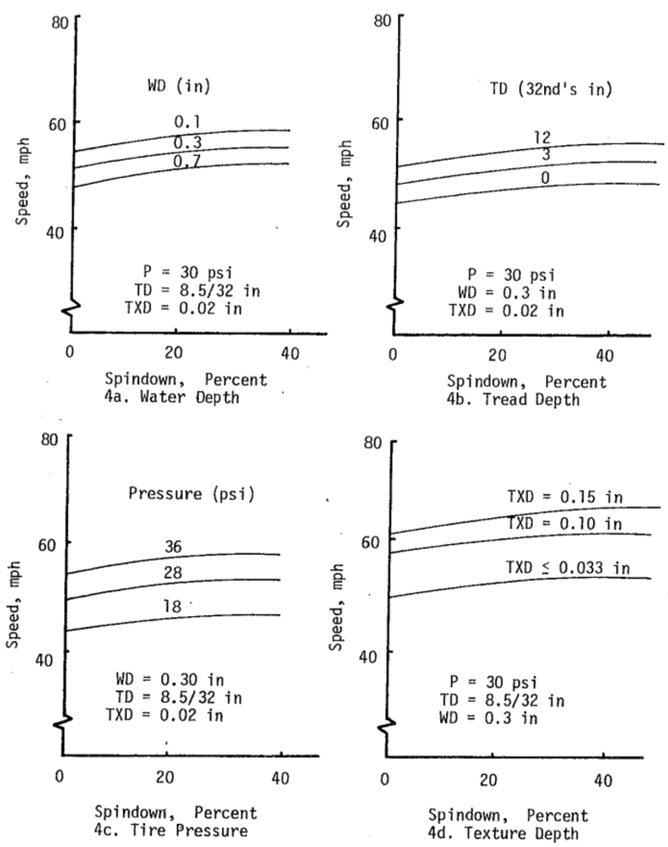


Figure 19. Gallaway hydroplaning speed example (Gallaway et al., 1979, p. 12)

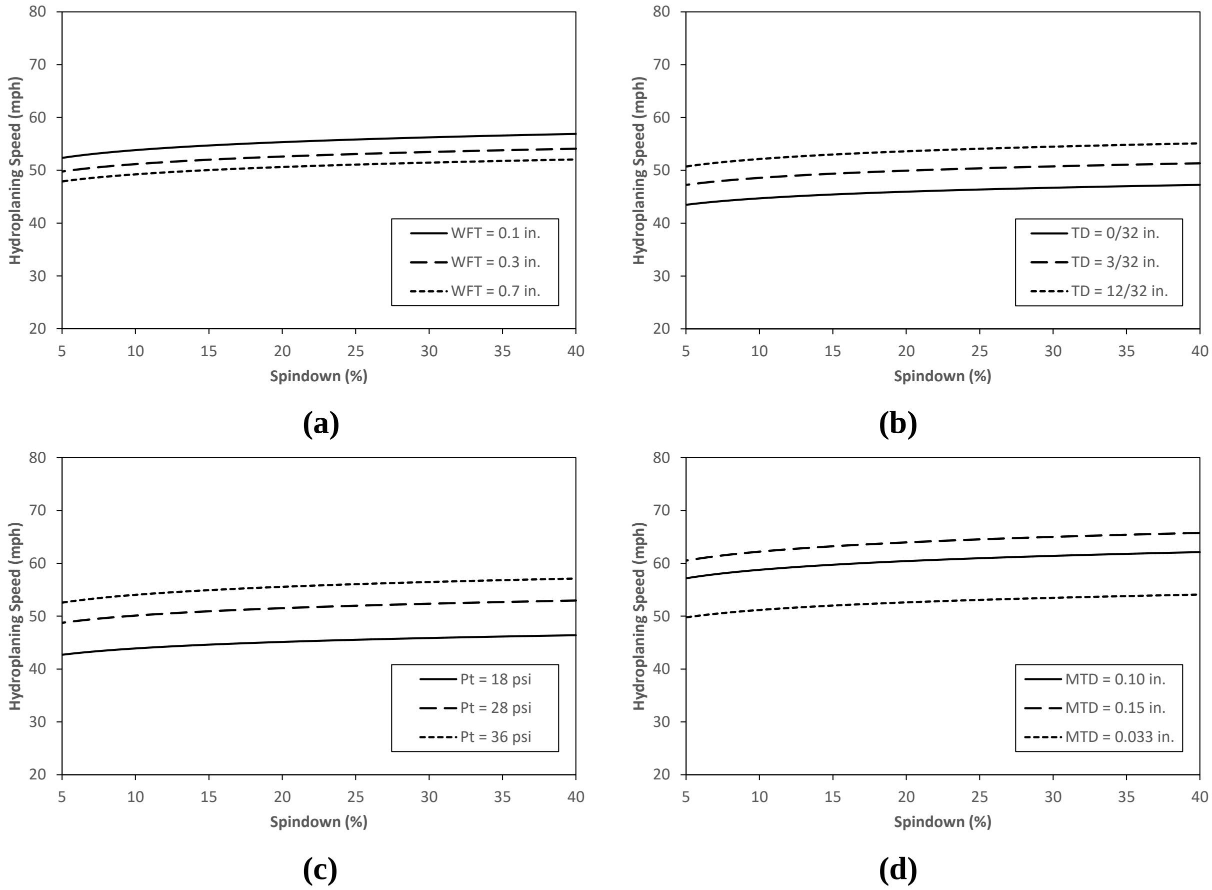


Figure 20. Gallaway's hydroplaning speed example simulated with new HP tool

7.2. PAVDRN EXAMPLE

The developers of PAVDRN equations provided one example that was made using their software (Anderson et al., 1998; Huebner et al., 1997). The inputs for this example are shown in Table 16.

Table 16. Inputs for PAVDRN example (Anderson et al., 1998; Huebner et al., 1997)

Property /Variable		Value
Rainfall Intensity		80 mm/hr
Temperature		10 ^{o}C
Total Number of Planes		3
Pavement Grade		2.0 %
Width of Each Plane		4.0 m
Pavement Type		PCC
Mean Texture Depth		0.50 mm
Cross Slope	Plane 1	1.5 %
	Plane 2	2.5 %
	Plane 3	3.5 %

The WFT and HPS outputs documented in the literature (Anderson et al., 1998; Huebner et al., 1997) are compared to those obtained using the new HP tool in Table 17. As shown in the table, the new HP tool was not able to reproduce the results documented by Huebner et al. (1997). The differences were observed both in the WFT (up to 3 mm difference) and HPS (up to 6 km/hr difference).

Table 17. Comparison of PAVDRN and FDOT's new HP outputs

Plane Number	Water Film Thickness (mm)		Hydroplaning Speed (km/hr)	
	Huebner et al. (1997)	New HP	Huebner et al. (1997)	New HP
1	1.3	1.0	90	95.8
2	1.5	1.2	88	91.6
3	1.6	1.3	86	90.4

To investigate the reason behind the discrepancies seen in Table 17, the equations for drainage path and pavement slope are revisited. As documented earlier, the equation for the resultant pavement slope is calculated from the longitudinal grade and cross slope using Equation (4) [repeated below for convenience].

$$S_i = \sqrt{S_{G,i}{}^2 + S_{C,i}{}^2} \tag{4}$$

where,

S_i = Resultant pavement slope of i^{th} lane (ft/ft or m/m)
$S_{G,i}$ = Longitudinal grade of i^{th} lane (ft/ft or m/m).
$S_{C,i}$ = Cross slope of i^{th} lane (ft/ft or m/m)

The resultant pavement slope calculated from the above equation is then inputted into the equations for WFT.

On the other hand, given the pavement width, cross slope, and grade, the equation for calculating the drainage path was given in Equation (3) [repeated below for convenience].

$$DP_i = W_i \sqrt{1 + \left(\frac{S_{G,i}}{S_{C,i}} \right)^2} \tag{3}$$

where,

DP_i = Drainage path length for i^{th} lane (ft or m)
W_i = Width of i^{th} lane (same unit as DP_i)

The new HP results shown in Table 17 were obtained using the drainage path equation shown in Equation (3).

However, after numerous trial-and-error, it was discovered that if the following equation is used to calculate the drainage path, then the results by Huebner et al. (1997) could be reproduced.

$$DP_i = W_i \sqrt{1 + \left(\frac{S_{G,i}}{S_i}\right)^2} = W_i \sqrt{1 + \left(\frac{S_{G,i}}{\sqrt{S_{G,i}^{\ 2} + S_{C,i}^{\ 2}}}\right)^2} \tag{31}$$

The above equation was obtained by replacing the cross slope variable in Equation (3) by the resultant slope of the pavement surface [i.e., replacing $S_{C,i}$ in Equation (3) by S_i given in Equation (4)].

The results WFT and HPS results obtained using Equation (31) are shown in Table 18 which shows the WFT values were reproduced exactly while the HPS results showed some minor variation, possibly due to rounding effects and unit conversion.

Table 18. Comparison of PAVDRN and FDOT's new HP outputs

Plane Number	Water Film Thickness (mm)		Hydroplaning Speed (km/hr)	
	Huebner et al. (1997)	New HP	Huebner et al. (1997)	New HP
1	1.3	1.3	90	90.7
2	1.5	1.5	88	87.0
3	1.6	1.6	86	85.7

As seen from the above table, the PAVDRN results could be reproduced if Equation (31) is used for calculating the drainage path, rather than Equation (3). However, it should be noted that the correct equation for drainage path is Equation (3) [NOT Equation (31)], and the new HP tool is implemented with the correct equations.

7.3. UK RRL AND NZ MOD. EXAMPLE

Chesterton et al. (2006) provides a simple example in which they compared the NZ Mod. WFT equation to the UK RRL WFT equation. Figure 21 shows this comparison with the inputs used for this analysis. It should be noted that in this figure, the model denoted as "Gallaway" corresponds to the NZ Mod. WFT model (i.e., the NZ Mod. Model is essentially the Gallaway WFT model with coefficients updated for New Zealand conditions).

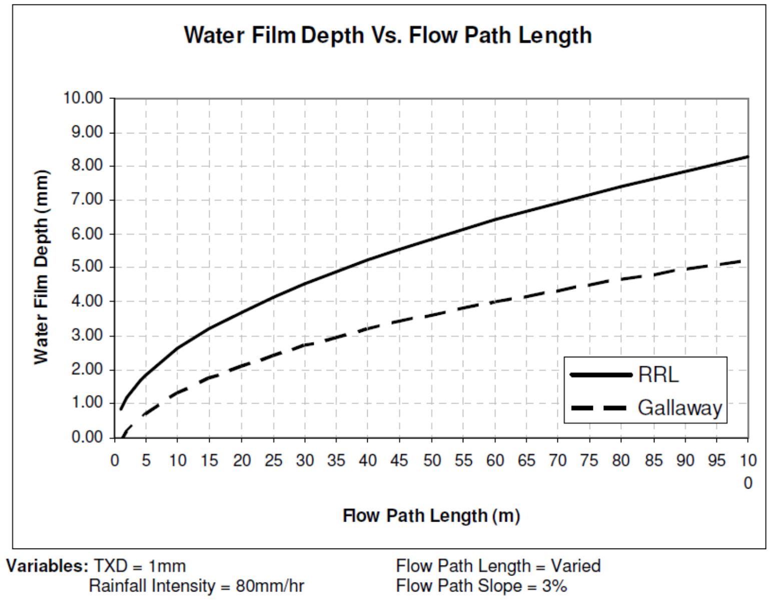


Figure 21. UK RRL and NZ Mod. water film thickness example (Chesterton et al., 2006, p. 15)

Figure 22 shows the corresponding results reproduced using the equations implemented in the new HP tool. This WFT curves in this plot are in excellent agreement with those shown in Figure 21.

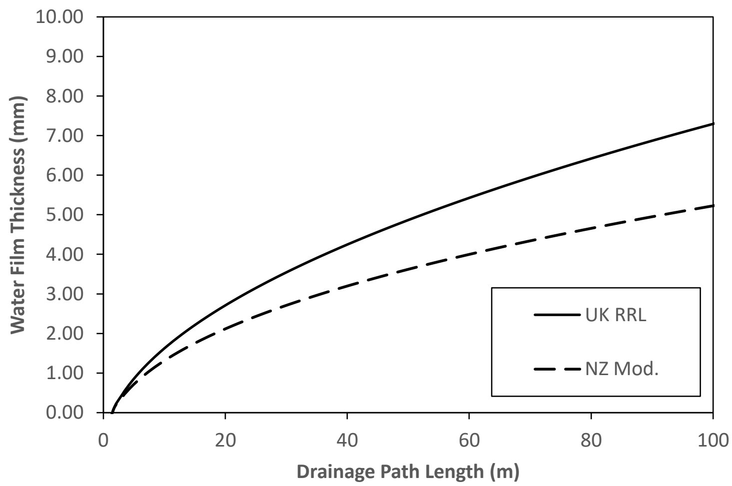


Figure 22. UK RRL and NZ Mod. water film thickness example simulated with new HP tool

8. SUMMARY AND CONCLUSIONS

In this study, relevant literature was gathered and reviewed to support implementation of empirical WFT and HPS models in FDOT's new hydroplaning tool. The existing tool was also reviewed extensively to identify any bugs or shortcomings that were built into the program. It was found that the existing hydroplaning tool included many minor bugs (e.g., incorrect unit conversions) as well as major deficiencies (e.g. incorrectly built-in inputs).

In addition, a gap analysis conducted on the current tool indicated that the program is lacking many features that may be useful to the users. The next generation hydroplaning tool should take care of all these deficiencies.

The texture and permeability data collected by FDOT have been reviewed in an attempt to develop the necessary relationship between MTD and MPD and to characterize the permeability of in-service pavement surfaces. Recommendations were provided based on the results and findings.

FDOT's new Hydroplaning Program (HP) was implemented in a macro-enabled Excel spreadsheet environment. The new program allows for three different WFT models and four different HPS models (i.e., total of twelve combination of WFT and HPS models).

In addition to the basic hydroplaning analysis that was implemented in FDOT's old HP tool, the new tool also allows for studying the effect of certain variables on WFT and HPS (i.e., sensitivity analysis) or for studying the uncertainties associated with the input variables (i.e., probabilistic analysis). The new tool was validated against the examples provided in previously published literature. The validation results showed that the WFT and HPS equations are correctly implemented in the new HP tool.

9. IMPLEMENTATION RECOMMENDATIONS

9.1. RESEARCH PRODUCTS AND OUTCOMES

This chapter identifies the minimum items or products and outcomes from this project that should be included in the implementation plan for future use by FDOT to implement the hydroplaning tool. These outcomes include the following:

- FDOT's Enhanced Hydroplaning Prediction (HP) Tool: This is the primary outcome of this research effort and is planned to replace FDOT's old HP tool. Development of the new HP and describes its features are documented in previous chapters and appendices of this report. In addition, the report provides validation examples based on sample problems made available in literature.

- FDOT Hydroplaning Guidance (Appendix A): This document serves as a quick reference document for those that will be using FDOT's new HP tool. The document provides background information on hydroplaning phenomenon as well as the models for predicting the hydroplaning speed.

- FDOT Hydroplaning Computer Based Training (CBT): This is a PowerPoint file that is proposed for training the Department personnel that are new to analysis of hydroplaning and the associated risk. The learning objectives for this computer based training are:
    - To understand the different types of hydroplaning and their causes
    - To understand the factors affecting hydroplaning
    - To understand the features of FDOT's Hydroplaning prediction tool
    - To understand the inputs for hydroplaning prediction

- FDOT Hydroplaning CBT Script: This is the script that describes each slide in the CBT course. This script is to be used with the above PowerPoint file for developing the actual CBT.

Execution of the implementation plan provided herein is not within the scope of work for this project. However, it is suggested that FDOT use the plan to complete a pilot project to ensure all details have been considered and addressed.

9.2. RECOMMENDED ACTIVITIES FOR IMPLEMENTATION

The expected audience for the above implementation products should be the practicing FDOT engineers or representatives required to implement the design and safety recommendations on FDOT projects. In addition, FDOT's Pavement Materials Office should be included in the expected audience as they are involved with forensic investigation and continuous pavement analysis methodologies.

The recommended activities for implementation include the following:

1. Modify current FDOT manuals, specifications, and standards to incorporate the newly developed HP tool and hydroplaning analysis into engineering practice. In other words, prepare documents and written procedures and policies that apply directly to determining the predicted hydroplaning speed and applying it to pavement engineering practice.

2. Further distribute hydroplaning guidance and the recommendations of this research. The guidance can also serve as a starting point for producing best practices manual for FDOT.

3. Prepare a PowerPoint presentation and other marketing/educational materials, and conduct webinar sessions to ensure technology transfer to the FDOT design, materials, and safety personnel and also consultants working on FDOT projects. These materials can be used to disseminate the new HP tool and educate agency and contractor personnel to ensure an understanding of the newly developed procedure.

4. Conduct demonstration/pilot projects that will put the new technology into practice.

5. Monitor crash rates due to hydroplaning to ensure FDOT's Hydroplaning Design guides are validated and satisfactory. This product includes identification of a site with high crash risk, as well as determination of the cause of crashes. If the causes are determined to be hydroplaning, validate the HP tool based on observed crashes and perform appropriate restoration work. Then the section should be monitored for future hydroplaning crashes.

9.3. POTENTIAL IMPEDIMENTS TO IMPLEMENTATION

The implementation plan may face some impediments depending on whether there is a good understanding of the results or the recommendations require further data to confidently implement the study results. The following provides a brief discussion on potential impediments to the implementation of the products from this project:

- A major impediment to successful implementation is a change from existing practice. The change or any new process deviating from the existing ones should be justified by the positive benefits. The primary goal of the recommended strategies will be to get "buy in" from different offices and contractors involved with hydroplaning and safety.

- The criteria that will be provided for judging the progress and consequences of implementation should be based on Florida's safety improvement program and data included in the crash database. That information should be used during the project to demonstrate the benefit in terms of reduced number of crashes and added benefit. This process should be summarized in a written report so that Florida and industry can continue to track the results in the future.

9.4. ANTICIPATED DURATION FOR IMPLEMENTATION

It is envisioned that implementation of the products will be executed by Florida over 2 to 3 years of effort, considering the time needed for the pilot project results to become available and marketing materials to be developed and disseminated.

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APPENDIX A: FDOT HYDROPLANING GUIDANCE

A.1. INTRODUCTION

A.1.1. BACKGROUND

Weather-related crashes are defined as those that occur during adverse weather conditions (e.g., rain, sleet, snow, fog, severe crosswinds, blowing snow/sand/debris, etc.) or during conditions when the pavement surface is slippery (e.g., wet pavement, snowy/slushy pavement, or icy pavement). According to the National Highway Traffic Safety Administration (NHTSA) 10-year average data from 2005 to 2014, over 5,748,000 vehicle crashes occur in the U.S. each year (FHWA, 2017). Among these crashes, approximately 22 percent (or nearly 1,259,000 crashes) are weather-related. Each year, almost 6,000 people are killed and over 445,000 people are injured due to these weather-related crashes.

The 10-year averages of NHTSA data also revealed that 73 percent of weather-related crashes occur on wet pavement surfaces and 46 percent during rainfall (FHWA, 2017). A much smaller percentage of weather-related crashes occur during winter conditions: 17 percent during snow or sleet and 13 percent on icy pavements. These numbers clearly indicate that the vast majority of weather-related crashes happen on wet pavement and during rainfall.

The primary outcome of a wet pavement surface is reduction in pavement friction due to water acting as a lubricant between the pavement surface and the vehicle tires. Normally, the vehicle tires are designed to push away the undesired substances (due to standing water, rain, snow, and mud), but under severe circumstances, a tire may encounter more water than it can push aside. When a tire can no longer move the water aside, the water pressure in front of the wheel causes the tire to lift from the road surface. This phenomenon, known as aquaplaning or hydroplaning, may occur when a layer of water builds between the wheels of the vehicle and the pavement surface.

In order for a vehicle to respond to a driver's controlling or maneuvering inputs, the vehicle tires must be in contact with the pavement surface. In other words, the vehicle tires enable a driver to start, stop, change speed, and make turning maneuvers only if the tires are in contact with the pavement and if sufficient friction is provided at the tire/pavement interface. However, when hydroplaning occurs, the vehicle tires become separated from the pavement surface and skate on a sheet of water with little to no traction, compromising the driver's ability to steer, brake, or accelerate. Furthermore, when all tires of a vehicle undergo hydroplaning, the driver may lose control of the vehicle and slide until it either collides with an obstacle, or slows down enough such that one or more tires contact the pavement and friction is regained.

A.1.2. OBJECTIVE AND SCOPE

The objective of this document is to serve as a quick reference document for those that will be using FDOT's new Hydroplaning Prediction Tool. The document provides background information on hydroplaning phenomenon as well as the models for predicting the hydroplaning speed. In addition, the document describes the options and features that were made available in the new tool, with some examples that the users can replicate. The document also includes an Appendix, which is the User Manual for the Hydroplaning Tool.

A.1.3. ORGANIZATION OF GUIDELINE

Including this introductory Chapter, this guidance document is composed of 4 Chapters and an Appendix as outlined in Figure A-1. While it is advised that the first-time users of the Hydroplaning Tool go through this entire document in order, advanced users may want to skip some of the contents herein.

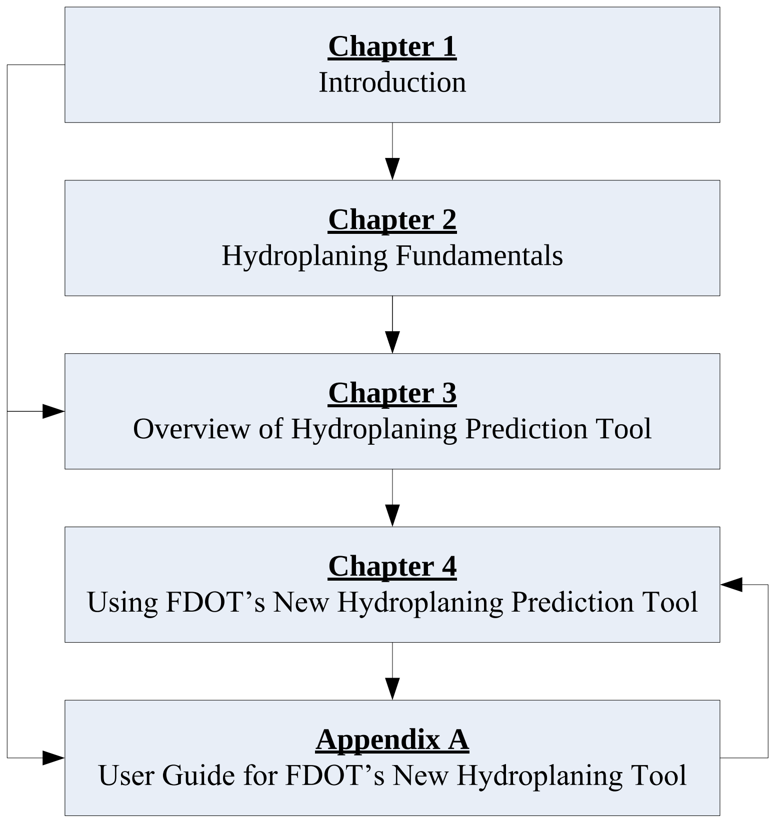


Figure A-1. Organization of Guidance Document.

A.1.4. SYMBOLS AND ABBREVIATIONS

This guidance is written such that all symbols and abbreviations are defined the first time it appears. However, as the readers go through the document and are not clear on symbols and/or abbreviations, they may revisit the list below to find out the corresponding definitions.

DGFC:	Dense Graded Friction Course
DP_i:	Drainage path length for i^{th} lane
HPS:	Hydroplaning Speed
HP Tool:	Hydroplaning Prediction Tool
I:	Excess Rainfall Intensity
k:	Infiltration rate or permeability of pavement surface
LGD:	Longitudinal Grinding
L_i:	Maximum flow or drainage path length for i^{th} lane

MPD: Mean Profile Depth
MTD: Mean Texture Depth
n: Manning's coefficient
N_R: Dimensionless Reynold's Number
OGFC: Open Graded Friction Course
PCC: Portland Cement Concrete
p_t: Tire pressure
RI: Actual rainfall intensity
$S_{C,i}$: Cross slope of i^{th} lane
SD: Spindown of tire rotational speed at the initiation of hydroplaning
$S_{G,i}$: Longitudinal grade of i^{th} lane
S_i: Resultant pavement slope of i^{th} lane
TD: Tire tread depth
VBA: Visual Basic for Applications
WFT: Water Film Thickness
W_i: Width of i^{th} lane
y: Thickness of Total Water Flow
ν: Kinematic viscosity of water

A.2. HYDROPLANING FUNDAMENTALS

A.2.1. DEFINITION OF HYDROPLANING

According to Horne (1968), hydroplaning is defined as the condition that exists when a film of water or other contaminant is present at the tire/pavement interface and completely separates the tire from the pavement surface, as shown in Figure A-2.

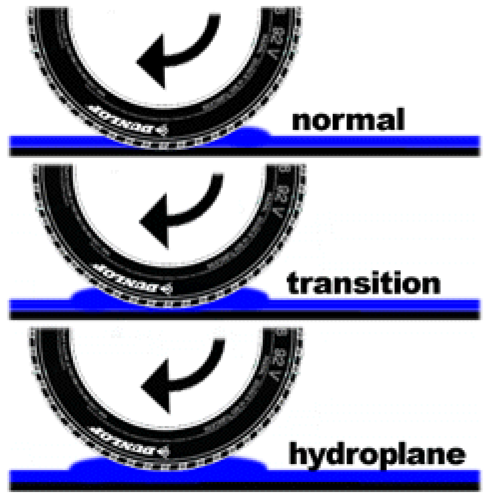


Figure A-2. Simplified diagram of forces acting on a rotating wheel.

🕮 When hydroplaning occurs, the vehicle tire is **NOT in contact** with the pavement!

Along with the above definition, Horne (1968) also categorized the hydroplaning phenomenon into three categories as shown in Figure A-3. These categories are dynamic, viscous, and reverted-rubber hydroplaning.

- Dynamic Hydroplaning is the most frequent type of hydroplaning encountered in roadways. It occurs when a moving tire runs over wet pavement with more water than it can push away and becomes completely separated from the pavement. Dynamic hydroplaning usually occurs at high speeds (typically above 45 mph).

- Viscous Hydroplaning only occurs on pavement with little or no micro-texture. The typical example is pavement with significant amount of bleeding where the asphalt completely covers the pavement surface. Viscous hydroplaning can also occur on pavement that has been polished smooth by traffic. Under these conditions, even a very thin film of water may separate the moving tire from pavement because of insufficient micro-texture to break down the water film. Viscous hydroplaning can occur at any speed.

- Reverted-rubber hydroplaning occurs when the friction between the tire and the pavement generates excessive heat to the point where the tire rubber has melted and reverted to its uncured state (therefore closing all the treads). This type of hydroplaning typically does not occur on roadways but occurs rarely on runways with high speed aircrafts.

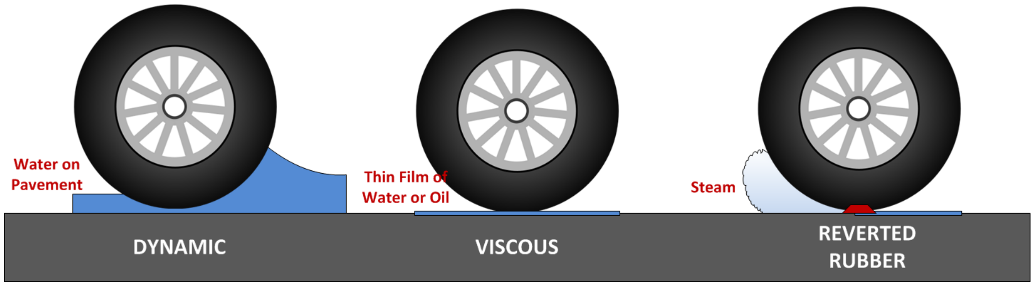


Figure A-3. Three categories of hydroplaning.

> 🕮 FDOT's Hydroplaning Tool was developed for predicting the **Dynamic Hydroplaning** phenomenon.

A.2.2. FACTORS AFFECTING HYDROPLANING

The factors that influence hydroplaning can be grouped into four categories: (1) roadway and pavement geometry, (2) environmental conditions, (3) driver behavior, and (4) vehicle condition. Table A-1 lists the various factors in each category. Among these, the factors related to the roadway and pavement parameters are considered to be within a highway agency's control and should be considered in the pavement design phase or during pavement evaluation for safety.

Table A-1. Factors affecting hydroplaning.

Roadway and Pavement Geometry	Environmental Conditions	Driver Behavior	Vehicle Condition
• Rut depth • Pavement micro- and macro-textures • Cross-slope (to include locations of superelevation) • Longitudinal grade (to include sag vertical curves) • Pavement width • Roadway curvature • Depressions	• Rainfall intensity • Rainfall duration • Temperature	• Speed • Accelerating or braking • Steering maneuvers	• Tire tread wear (tread depth) • Tire pressure • Vehicle type • Vehicle (or axle) weight • Tire tread design (aqua tread for example)

A.2.3. HYDROPLANING PREDICTION MODELS

Two of the most important parameters in hydroplaning analysis are Water Film Thickness (WFT) and Hydroplaning Speed (HPS). The Hydroplaning Prediction (HP) Tool offers four different empirical models for WFT and three different models for HPS. These models are:

- Water Film Thickness Models

  - Gallaway Model
  - U.K. Road Research Laboratory (RRL) Model
  - New Zealand Modified Model (NZ Mod.) Model
  - PAVDRN Model

- Hydroplaning Speed Models
  - PAVDRN Model
  - University of South Florida (USF) Model
  - Gallaway Model

Among the above, the FDOT recommended models are the Gallaway WFT Model (Gallaway et al., 1979) and the PAVDRN HPS Model (Anderson et al., 1998). These options (i.e., the Gallaway WFT model together with the PAVDRN HPS model) were found to be the best predictor of Florida's wet weather crash data (Gunaratne et al., 2012).

All of the above WFT and HPS models are briefly reviewed in the remaining section of this Chapter, along with the inputs needed for their calculation. Advanced hydroplaning analysts that are already familiar with these models or elementary users of the HP tool that are not seeking for mathematical background of these models may skip this Chapter and jump directly to Chapter 3.

> 🕮 FDOT recommends **Gallaway Water Film Thickness Model** and **PAVDRN Hydroplaning Speed Model** for hydroplaning analysis.

> 🕮 If you do not need the mathematical equations for hydroplaning prediction, you may skip this Chapter.

A.2.3.1. <u>Input Parameters</u>

Figure A-4 schematically shows the definition of WFT. The thickness of total water flow (*y*) is defined as the thickness of the water flow measured from the bottom of the pavement texture, whereas the WFT is defined as the thickness of water measured from the top of the pavement texture asperities. According to these definitions, WFT and *y* are related to each other by the following equation.

$$WFT = y - MTD \tag{1}$$

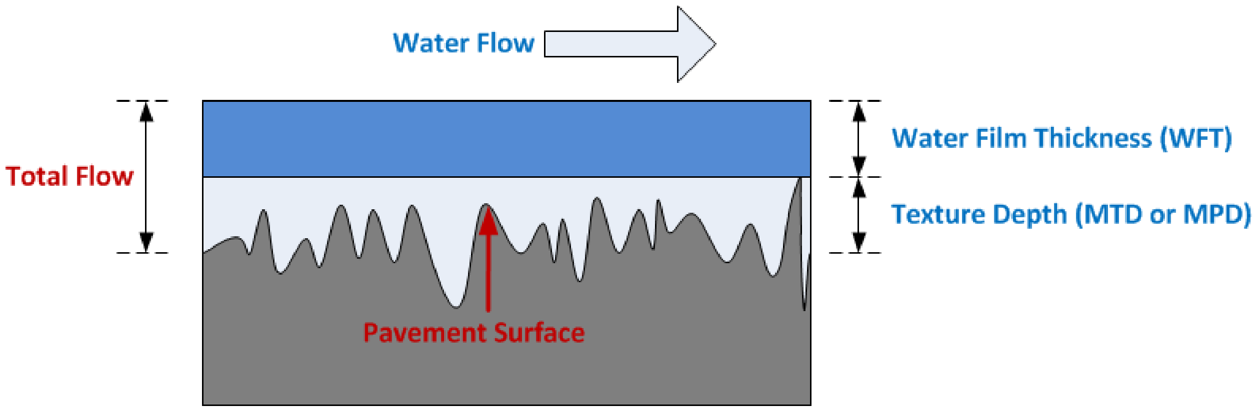


Figure A-4. Definition of water film thickness, mean texture depth, and total flow.

🕮 Thickness of total flow (*y*) is the thickness of the water flow measured from the bottom of the pavement texture. **Water Film Thickness (WFT)** is the thickness of water measured from the top of pavement texture asperities. The **WFT** is used for predicting the hydroplaning speed (**NOT the Thickness of Total Flow**).

Rainfall intensity is another crucial input parameter needed for the hydroplaning analysis. The excess rainfall intensity, *I*, which is to be used with the Gallaway WFT model is defined as (Anderson et al., 1998):

$$I = RI - k \tag{2}$$

where *RI* is the actual rainfall intensity and *k* is the infiltration rate or permeability of the pavement surface.

It is also beneficial to identify the pavement slope and the drainage path inputs to be used with the WFT model. The relationship between the pavement cross slope, longitudinal grade, pavement width, and the drainage path length was first provided by Gallaway et al. (1979). This relationship has been adopted by many researchers including FDOT and is given as the following (Mraz and Nazef, 2008; FDOT, 2016).

$$DP_i = W_i \sqrt{1 + \left(\frac{S_{G,i}}{S_{C,i}}\right)^2} \tag{3}$$

where,

DP_i	=	Drainage path length for i^{th} lane (ft or m)
W_i	=	Width of i^{th} lane (same unit as DP_i)
$S_{G,i}$	=	Longitudinal grade of i^{th} lane (ft/ft or m/m). Typically, a single value is used for all lanes at a given location.
$S_{C,i}$	=	Cross slope of i^{th} lane (ft/ft or m/m)

The resultant slope of the pavement surface is calculated from the longitudinal grade and cross slope using the following equation.

$$S_i = \sqrt{S_{G,i}^{\;2} + S_{C,i}^{\;2}} \tag{4}$$

where,

S_i = Resultant pavement slope of i^{th} lane (ft/ft or m/m)

It is also noted that Equations (3) and (4) can still be used for multiple lanes if the longitudinal grade and cross slope of the roadway do not vary from lane to lane. In this case, the only variable that needs to be changed is the lane width in Equation (3), e.g., W_i =12 ft. for the first lane and W_i =24 ft. for the second lane.

However, as conceptually illustrated in Figure A-5, it is possible that the cross slope, longitudinal grade, and lane width may be different from one lane to the next. In this case, the drainage path length for each lane should be calculated separately and then summed up to yield the maximum flow path length:

$$L_i = \sum_{j=1}^{i} DP_j = DP_1 + DP_2 + \cdots + DP_i \tag{5}$$

where,

L_i = Maximum flow or drainage path length for i^{th} lane (ft or m)
DP_j = Drainage path length for j^{th} lane (same unit as L_i)

The above equation simply indicates that the rainfall droplet entering the pavement at the top-right corner of the pavement in Figure A-5 would follow the drainage path of Lane 1 (DP_1) and then the drainage path of Lane 2 (DP_2) before exiting the pavement.

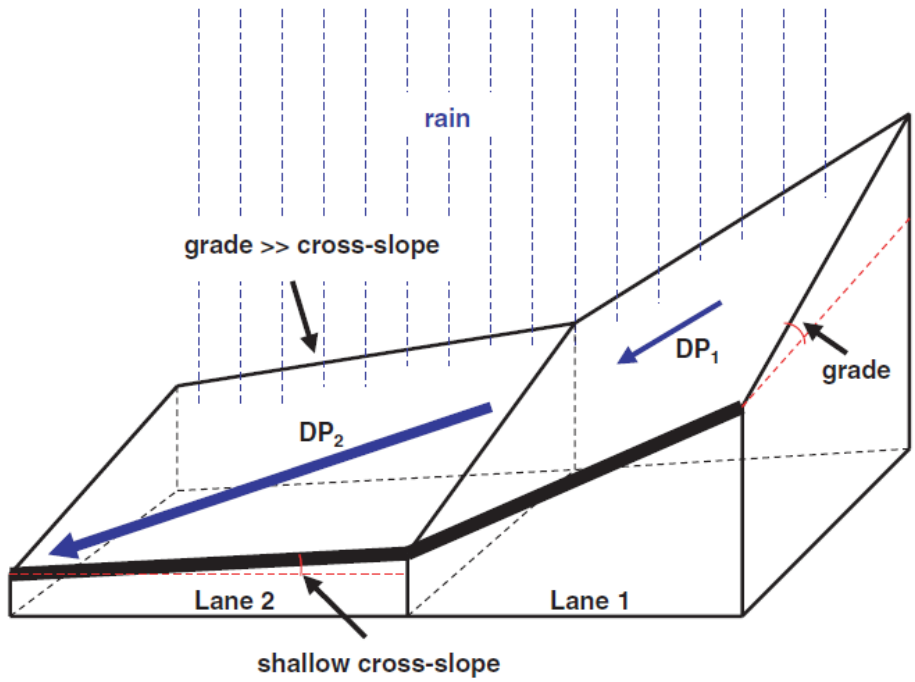


Figure A-5. Illustration of drainage path for multiple lanes (after Mraz and Nazef, 2008).

📖 The **Excess Rainfall Intensity** (*I*), Pavement Texture in terms of **Mean Texture Depth** (MTD), **Resultant Slope** (*S*), and the **Maximum Drainage Path Length** (*L*) are used for predicting WFT.

A.2.3.2. Models for Water Film Thickness

The WFT models will be presented in the following section. It should be noted that the pavement slope (S_i) from Equation (4) and the drainage path length (L_i) from Equation (5) should be used as inputs into these models, regardless of the total number of lanes to be analyzed. However, in order to present the equations in the form similar to what was shown in the literature, the subscript (*i*) will not be used in presentation of these models.

Gallaway WFT Model

The Gallaway model for WFT was derived based on a comprehensive experiment that produced a total of 1,059 data points. The equation is given as the following.

$$WFT = \frac{0.003726 \cdot MTD^{0.125} \cdot L^{0.519} \cdot I^{0.562}}{S^{0.364}} - MTD \tag{6}$$

where,

WFT = Water film thickness (in)

MTD	=	Mean texture depth (in)
L	=	Drainage path length (ft)
I	=	Excess rainfall intensity (in/hr)
S	=	Slope of the pavement (dimensionless)

U.K. Road Research Laboratory (RRL) WFT Model

The RRL model was originally developed under a research conducted by the U.K's Ministry of Transport (Ross and Russam, 1968). The equation from the original research is only given for the thickness of the total flow as the following.

$$y = \frac{0.015 \cdot (L \cdot I)^{0.5}}{S^{0.2}} \tag{7}$$

where,

y	=	Thickness of total water flow (cm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (cm/hr)
S	=	Slope of the pavement (dimensionless)

Converting the units of *y* and *I* and incorporating into Equation (1) results in the following equation, which is form more frequently referenced in other literatures (Gunaratne et al., 2012; Chesterton et al, 2006; Oakden, 1977).

$$WFT = \frac{0.046 \cdot (L \cdot I)^{0.5}}{S^{0.2}} - MTD \tag{8}$$

where,

WFT	=	Water film thickness (mm)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

New Zealand (NZ) Modified WFT Model

The NZ-Modified equation takes the same form as the Gallaway equation (Equation (6)) but uses different coefficients and units. The equation is written as the following (Chesterton et al, 2006).

$$WFT = \frac{0.001485 \cdot MTD^{0.110} \cdot L^{0.430} \cdot I^{0.590}}{S^{0.420}} - MTD \tag{9}$$

where,

WFT	=	Water film thickness (mm)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

PAVDRN WFT Model

The PAVDRN model was developed under an NCHRP study (Anderson et al., 1998; Huebner et al., 1997). The model is given as the following.

$$WFT = \left(\frac{n \cdot L \cdot I}{36.1 \cdot S^{0.5}} \right)^{0.6} - MTD \tag{10}$$

where,

WFT	=	Water film thickness (mm)
n	=	Manning's *n* value (dimensionless)
MTD	=	Mean texture depth (mm)
L	=	Drainage path length (m)
I	=	Excess rainfall intensity (mm/hr)
S	=	Slope of the pavement (dimensionless)

The Manning's *n* value in the above equation is calculated in the following manner, depending on the pavement surface type.

1. Portland Cement Concrete (PCC) surfaces:

$$n = \begin{cases} = \dfrac{0.388}{N_R^{\,0.535}} & (N_R < 240) \\ = \dfrac{0.345}{N_R^{\,0.502}} & (N_R < 500) \\ = \dfrac{0.319}{N_R^{\,0.480}} & (N_R < 1000) \\ = 0.017 & (N_R \geq 1000) \end{cases} \tag{11}$$

2. Dense-Graded Friction Courses (DGFC):

$$n = 0.0823 \cdot N_R^{-0.174} \tag{12}$$

3. Open-Graded Friction Courses (OGFC):

$$n = \frac{1.490 \cdot S^{0.306}}{N_R^{\ 0.424}} \tag{13}$$

where N_R is the dimensionless Reynold's Number calculated as the following.

$$N_R = \frac{L \cdot I}{\upsilon} \tag{14}$$

The parameter ν in the above equation represents the kinematic viscosity of water.

A.2.3.3. Hydroplaning Speed Models

The HPS models takes the WFT values and other inputs for calculating the hydroplaning speed. Three (3) hydroplaning speed models were incorporated into the hydroplaning tool. These models are described in the following paragraphs.

Gallaway Hydroplaning Model

The Hydroplaning Speed (HPS) model by Gallaway et al. (1979) is given by the following equation.

$$HPS = SD^{0.04} \cdot p_t^{\ 0.3} \cdot (1 + TD)^{0.06} \cdot A \tag{15}$$

where,

HPS	=	Hydroplaning speed (mph)
SD	=	Spindown of the tire rotational speed at the initiation of hydroplaning (Percent), typically 10 percent.
p_t	=	Tire pressure (psi)
TD	=	Tire tread depth (in 32nds of an inch)

and,

$$A = Max\left(\frac{10.409}{WFT^{0.06}} + 3.507, \left[\frac{28.952}{WFT^{0.06}} - 7.817 \right] \cdot MTD^{0.14} \right) \tag{16}$$

where,

WFT	=	Water film thickness (in)
MTD	=	Mean texture depth (in)

It is important to note that in Equation (15), the value of *SD* should be inputted as a percentage rather than a fraction (i.e., if the spindown is 10 percent then 10 should be used directly rather than 0.1). Furthermore, the *TD* should be inputted in units of 32nds of an inch (i.e., if the tread depth is 2/32 inch then TD = 2). This TD value can also be calculated as the actual tread depth in inches multiplied by 32.

PAVDRN Hydroplaning Model

The PAVDRN model for HPS is provided for two levels of WFT.

1. For WFT < 2.4 mm (0.094 in):

$$HPS = 26.04 \cdot WFT^{-0.259} \tag{17}$$

   where,

HPS	=	Hydroplaning speed (mph)
WFT	=	Water film thickness (in)

2. For WFT ≥ 2.4 mm (0.094 in):

$$HPS = 3.09 \cdot A \tag{18}$$

   where A was previously defined in Equation (16).

It is also noted that Equation (18) is a special case of the Gallaway HPS model shown in Equation (15). For example, the PAVDRN Hydroplaning Model uses values of SD = 10 percent, p_t = 30 psi, and TD = 0.3 (actual tread depth = 0.01 in) and when these values are entered into Equation (15), the equation simplifies and reduces to Equation (18).

It should also be made very clear that although the PAVDRN equation for the WFT (Equation (10)) is provided using SI units, the PAVDRN model for HPS uses English units (Equations (16), (17), and (18)).

USF Model

The University of South Florida (USF) model for HPS (Gunaratne et al., 2012) was developed by fitting an empirical equation to the Finite Element (FE) simulation results provided by Ong and Fwa (2007). The model takes the following form.

$$HPS = WL^{0.2} \cdot p_t^{0.5} \cdot \left(\frac{0.82}{WFT^{0.06}} + 0.49 \right) \tag{19}$$

where,

HPS	=	Hydroplaning speed (km/h)
WL	=	Wheel load (N)
p_t	=	Tire pressure (kPa)
WFT	=	Water film thickness (mm)

🕮 **You do NOT need to know all of the above equations** or models in great detail. The new Hydroplaning Prediction Tool is developed for that purpose. However, if you are new to hydroplaning analysis, you must become familiar with the inputs and outputs of the hydroplaning tool, and the tool itself. This is discussed in the next Chapter. Let's proceed!

A.3. OVERVIEW OF HYDROPLANING PREDICTION TOOL

The new HP tool is implemented in a macro-enabled Excel spreadsheet environment. The HP tool also includes macros or code written in Visual Basic for Application (VBA) language, primarily for the user to navigate through the spreadsheet, run advanced analysis (e.g., importing continuous data and exporting .kml files), and to generate output tables and plots as appropriate.

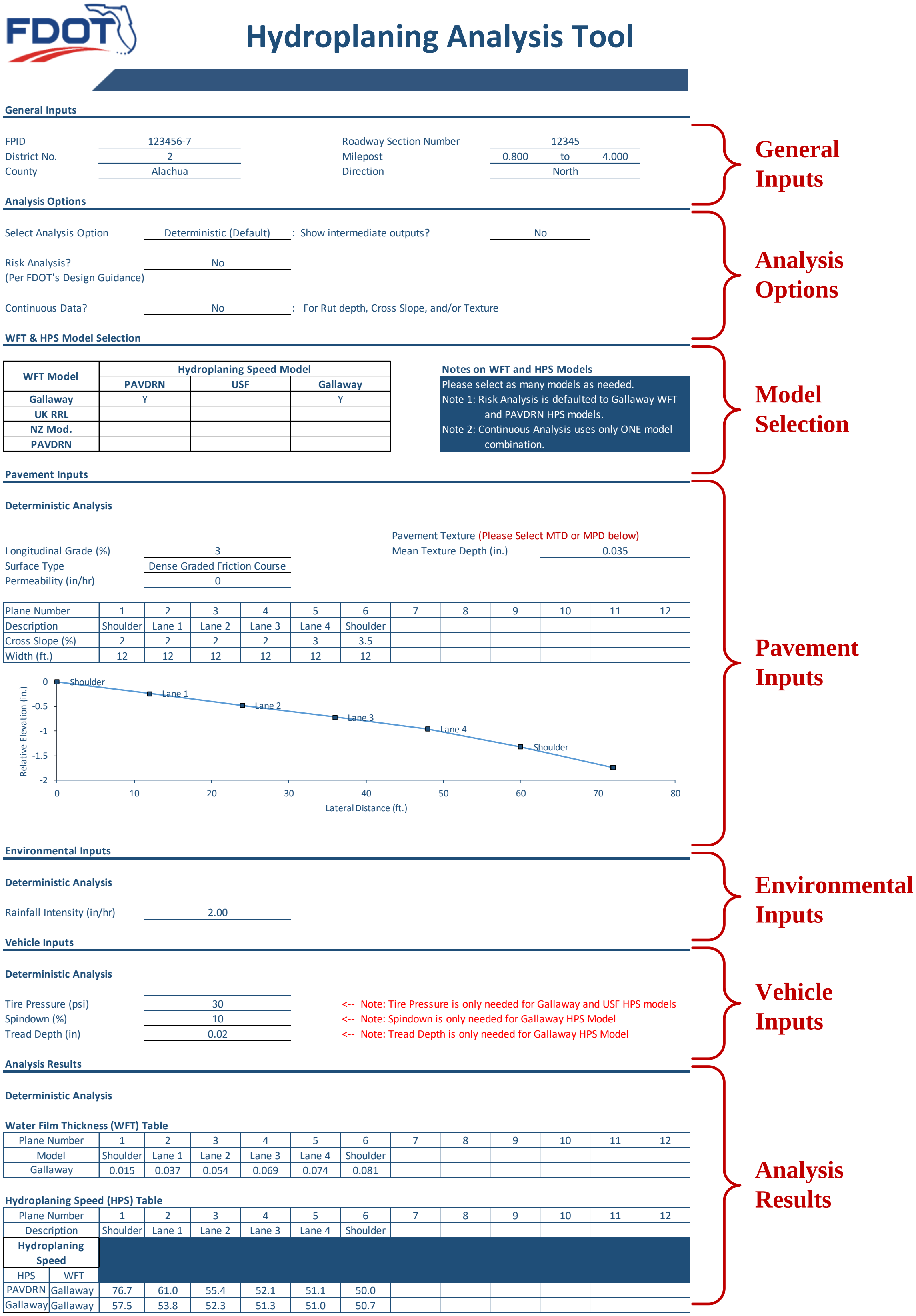
Figure A-6 shows the interface of the new HP tool. As shown in this figure, the new program is composed of six major parts. These are:

1. General Inputs
2. Analysis Options
3. Model Selection
4. Pavement Inputs
5. Environmental Inputs
6. Vehicle Inputs
7. Analysis Results

Additional description on the above major parts and the flow of the new program is provided below.

A.3.1. GENERAL INPUTS

These inputs are the general project-related information that defines the location of the project as well as other information pertaining to the project (i.e., similar project information as included in FDOT's nondestructive testing reports). These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts.



FDOT

Hydroplaning Analysis Tool

General Inputs

FPID	123456-7	Roadway Section Number	12345
District No.	2	Milepost	0.800 to 4.000
County	Alachua	Direction	North

Analysis Options

Select Analysis Option: Deterministic (Default) : Show intermediate outputs? No

Risk Analysis? (Per FDOT's Design Guidance): No

Continuous Data? No : For Rut depth, Cross Slope, and/or Texture

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway	Y		Y
UK RRL			
NZ Mod.			
PAVDRN			

Notes on WFT and HPS Models
Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Pavement Inputs

Deterministic Analysis

Longitudinal Grade (%): 3
Surface Type: Dense Graded Friction Course
Permeability (in/hr): 0

Pavement Texture (Please Select MTD or MPD below)
Mean Texture Depth (in.): 0.035

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Description	Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Cross Slope (%)	2	2	2	2	3	3.5						
Width (ft.)	12	12	12	12	12	12						

Environmental Inputs

Deterministic Analysis

Rainfall Intensity (in/hr): 2.00

Vehicle Inputs

Deterministic Analysis

Tire Pressure (psi): 30 <-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%): 10 <-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in): 0.02 <-- Note: Tread Depth is only needed for Gallaway HPS Model

Analysis Results

Deterministic Analysis

Water Film Thickness (WFT) Table

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Model	Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Gallaway	0.015	0.037	0.054	0.069	0.074	0.081						

Hydroplaning Speed (HPS) Table

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Shoulder	Lane 1	Lane 2	Lane 3	Lane 4	Shoulder						
Hydroplaning Speed													
HPS	WFT												
PAVDRN	Gallaway	76.7	61.0	55.4	52.1	51.1	50.0						
Gallaway	Gallaway	57.5	53.8	52.3	51.3	51.0	50.7						

General Inputs

Analysis Options

Model Selection

Pavement Inputs

Environmental Inputs

Vehicle Inputs

Analysis Results

Figure A-6. New hydroplaning program user interface.

A.3.2. ANALYSIS OPTIONS

The analysis options implemented into the new HP tool are schematically shown in Figure A-7. As indicated in the figure, the user needs to choose from the following analysis types.

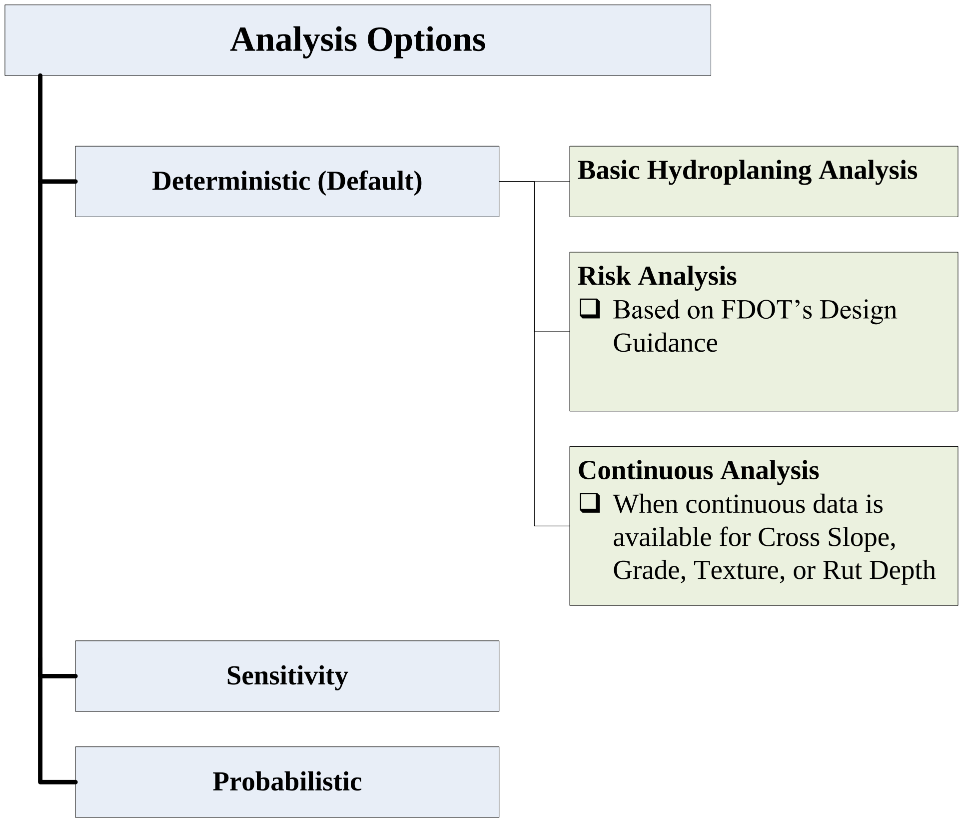


Figure A-7. Analysis options implemented in the new HP tool.

A.3.2.1. <u>Deterministic Analysis</u>

The deterministic analysis is a simple calculation of the intermediate and output variables based on a given set of known input parameters. There are three analysis options under this analysis category.

4. **Basic Hydroplaning Analysis**: This is the most basic and default mode of hydroplaning analysis. The user may select multiple models (up to 3 WFT models × 4 HPS models = 12 model combinations) and view the results in the same worksheet.

5. **Risk Analysis**: The risk analysis is based on FDOT's Design Guidance on the analysis of hydroplaning risk assessment using the HP program. The risk analysis is conducted by comparing the expected driver speed during rainfall events (Jayasooriya and Gunaratne, 2014) and the expected hydroplaning speed. Note that in accordance with FDOT's Design Guidance, the Risk Analysis is always based on the Gallaway WFT model and the PAVDRN HPS model.

6. **Continuous Analysis**: The user may run this analysis option if one or more of the continuous data files are available for Cross Slope, Grade, Texture, or Rut Depth. If the GPS coordinates are available in the data, the user may export the results into a .kml file for viewing in Google Earth.

> 🕮 **Deterministic analysis is a simple calculation** of the intermediate and output variables based on a given set of known input parameters. In other words, it is nothing more than a "**Plug and Chug**" of the equations presented in the previous Chapter.

A.3.2.2. Sensitivity Analysis

The sensitivity analysis option is to allow the user to simulate a variety of conditions, which may be useful during the pavement design phase. The user is allowed to vary one or more of the input variables (e.g., rainfall intensity, temperature, cross-slope, tire pressure, etc.) at desired intervals. For each sensitivity variable, the user must provide Min., Max., and Interval values. E.g., if the user specified the rainfall intensity input such that Min. = 1.0 in/hr, Max. = 4.0 in/hr, and Interval = 1.0 in/hr, then the program will run the hydroplaning analysis for rainfall intensities of 1.0 in/hr, 2.0 in/hr, 3.0 in/hr, and 4.0 in/hr.

> 🕮 **Sensitivity Analysis is equivalent to running the Deterministic Analysis multiple times.** You can vary one or more of the input variables (e.g., rainfall intensity, temperature, cross-slope, tire pressure, etc.) at desired intervals.

A.3.2.3. Probabilistic Analysis

The probabilistic analysis option allows the user to characterize the uncertainties associated with certain variables (e.g., rainfall intensity, pavement temperature, axle weight, tire pressure, etc.). The probabilistic input variables must be defined in terms of a distribution (i.e., mean and standard deviation), rather than a fixed value. The output variables are calculated using the Monte-Carlo simulation methodology using a set of randomly generated input parameters in accordance with the given distribution (i.e., mean and standard deviation).

> 🕮 Are you sure that your rainfall intensity is always and consistently 2.0 in/hr? If you answered "No", you are probably ready to run the **Probabilistic Analysis, which can take care of the uncertainties of your inputs.** Probabilistic Analysis is for more advanced users, and assumes that you understand the concept of distribution (i.e., mean and standard deviation).

A.3.3. MODEL SELECTION

The Hydroplaning Prediction (HP) Tool offers four different empirical models for WFT and three different models for HPS. The user may select one or more WFT and HPS model combinations for the analysis. The available models are:

- Water Film Thickness: Gallaway, UK RRL, NZ Mod., and PAVDRN models
- Hydroplaning Speed: PAVDRN, USF, and Gallaway models

It is obvious that the ultimate (final) output of all these models are the Hydroplaning Speed. However, with a total of 12 WFT and HPS model combinations to choose from, the user may easily become confused with what inputs are needed and what intermediate outputs are produced from each model. Tables A-2 and A-3 are intended to clarify this.

Table A-2. Necessary Inputs and Intermediate Outputs of Water Film Thickness Models.

Inputs for Water Film Thickness Models					
Input Type	**Input Variable**	**Water Film Thickness Model**			
		Gallaway	**UK RRL**	**NZ Mod.**	**PAVDRN**
Pavement Inputs	Surface Type	✓	✓	✓	✓
	Permeability	✓	✓	✓	✓
	Pavement Texture	✓	✓	✓	✓
	Longitudinal Grade	✓	✓	✓	✓
	Cross Slope	✓	✓	✓	✓
	Width	✓	✓	✓	✓
Environmental Inputs	Rainfall Intensity	✓	✓	✓	✓
	Temperature				✓
Intermediate Outputs from Water Film Thickness Models					
Output Type	**Output Variable**	**Water Film Thickness Model**			
		Gallaway	**UK RRL**	**NZ Mod.**	**PAVDRN**
Pavement Related	Total Slope	✓	✓	✓	✓
	Drainage Path	✓	✓	✓	✓
Water Related	Kinematic Viscosity of Water				✓
	Reynold's Number				✓
	Manning's *n* value				✓

Table A-3. Necessary Inputs for Hydroplaning Speed Models.

Input Type	**Input Variable**	**Hydroplaning Speed Model**		
		PAVDRN	**USF**	**Gallaway**
Water Film Thickness		✓	✓	✓
Pavement Inputs	Pavement Texture	✓		✓
Vehicle Inputs	Axle Weight		✓	
	Tire Pressure		✓	✓
	Spindown			✓
	Tread Depth			✓

The new HP program has the above list of models organized in a matrix form (Figure A-6), and the user needs to type in "Y" in the cell corresponding to the desired WFT and HPS model combination.

Two of the analysis options are exceptions to the above (i.e., multiple models cannot be used). These options are:

- Risk Analysis Option.
  - The analysis always uses Gallaway WFT and PAVDRN HPS models (regardless of user selected models).
- Continuous Analysis Option.
  - Due to the large amount of data associated with continuous data, only one model combination (WFT and HPS) is used with this analysis option. If the user selects multiple model combinations, the one corresponding to the leftmost column and top row in the model selection matrix is used.

🕮 Still confused? No worries. The new **Hydroplaning Tool will guide you** with the inputs needed for the selected models and the options available for the selected analysis method. I.e., **if you do not see an input box for a particular input (e.g., temperature), it simply means that the input is not needed** for the analysis and/or model you selected. So, if you don't see it, then don't worry about it!

A.3.4. PAVEMENT INPUTS

The user must provide the necessary pavement or roadway related inputs needed for the hydroplaning analysis, which include the following:

- Longitudinal pavement grade.
- Pavement surface type. Note that for the deterministic analysis, changing the surface type fills in the default values for pavement texture and permeability. The available surface types and their default texture values are shown in Table A-4.
- Pavement Texture
  - The user may override the default MTD value. The user may also select to provide texture in terms of MPD rather than MTD.
- Permeability of pavement surface.
  - The recommended default permeability value is 0.0 in/hr for hydroplaning analysis. However, the user may override the default permeability value if desired.
- Pavement cross-slope and width.
  - The cross-slope and width must be provided for each pavement lane.

Table A-4. Default Texture Values for Hydroplaning analysis

Surface Type	Default Values	
	MTD (in.)	MPD (in.)
Dense Graded Friction Course (DGFC)*	0.018	0.014
Open Graded Friction Course (OGFC)*	0.067	0.050
Rigid Pavements – (LGD**)	0.035	0.033

Note*: These MTD and MPD values are different from the default values documented in the old version of the Hydroplaning Guidance. These default values have been updated based on a recent FDOT study (FDOT, 2019; Wang and Holzschuher, 2019).
Note**: LGD = Longitudinal Grinding

📖 The above Pavement Inputs are needed, regardless of analysis methodology or model selection.

A.3.5. ENVIRONMENTAL INPUTS

The environmental inputs needed for the hydroplaning analysis are:

- Rainfall Intensity
  - Required for all analysis types.
- Temperature
  - Note again that temperature is only used for PAVDRN WFT model (Table A-2). Therefore, the temperature input is only visible when the PAVDRN WFT model is selected.

📖 **Rainfall Intensity is the only critical input for all models**. If you are not using PAVDRN WFT model, you do not need to worry about pavement temperature. As a reminder, **FDOT's recommended WFT model is Gallaway** Model.

A.3.6. VEHICLE INPUTS

Note that the vehicle inputs are needed only for the Gallaway and USF HPS models (Table A-3). Therefore, if these HPS models are not selected, the vehicle inputs are not visible to the user. In addition, each vehicle input becomes visible when it is needed for the selected model(s). The vehicle inputs and the associated HPS models are:

- Axle Weight: Needed for USF HPS model.
- Tire Pressure: Needed for Gallaway and USF HPS models.
- Spindown: Needed for Gallaway HPS model.
- Tread Depth: Needed for Gallaway HPS model.

📖 If you are not using Gallaway or USF models for HPS, you do not need to worry about vehicle inputs at all. As a reminder, **FDOT's recommended HPS model is PAVDRN** Model.

A.3.7. ANALYSIS RESULTS

Analysis of hydroplaning involves calculation of the intermediate and the output variables. The user can decide to show or hide the intermediate variables at any time. The output variables are displayed at all times.

A.3.7.1. <u>Intermediate variables</u>

Prior to calculating the predicted hydroplaning speed, it is necessary to calculate all of the intermediate variables. These intermediate variables include the following.

- Drainage Path (DP) Length.

    - The drainage path values are calculated for all models and are displayed if the user chooses to view the intermediate variables.
- Mean Texture Depth.
    - If the user inputted texture values in terms of MPD, the computed MTD value is displayed as an intermediate variable.
- Kinematic viscosity, Reynold's number, and Manning's *n* value.
    - These intermediate variables are only used by PAVDRN WFT model, and are displayed if this WFT model is selected and the user chooses to view the intermediate output.

> 🕮 In the new HP Tool, you can choose to view or hide all of the above Intermediate Variables.

A.3.7.2. <u>**Output variables**</u>

Upon completing calculation of the intermediate variables, the hydroplaning program calculates the final output variables. These variables are:

- Water film thickness.
    - The water film thickness is calculated and displayed for all of the WFT and HPS model combinations.
- Hydroplaning speed.
    - The hydroplaning speed will be calculated from the intermediate variables and the water film thickness calculated above. The user will be able to use one or more (or all) models.
- Water depth due to rutting.
    - Hydroplaning analysis due to rut depth is only available under continuous analysis option. The user may provide a continuous rut data file or provide a fixed value for rut depth. In accordance with Figure A-8, the depth of water ponding in a rutted pavement is calculated as:

$$WD = d - L \cdot s \tag{1}$$

where *WD* is the maximum water depth, *d* is the measured rut depth, *L* is the distance between the lower side of rut to the position of the maximum rut, and *s* is the measured cross-slope.

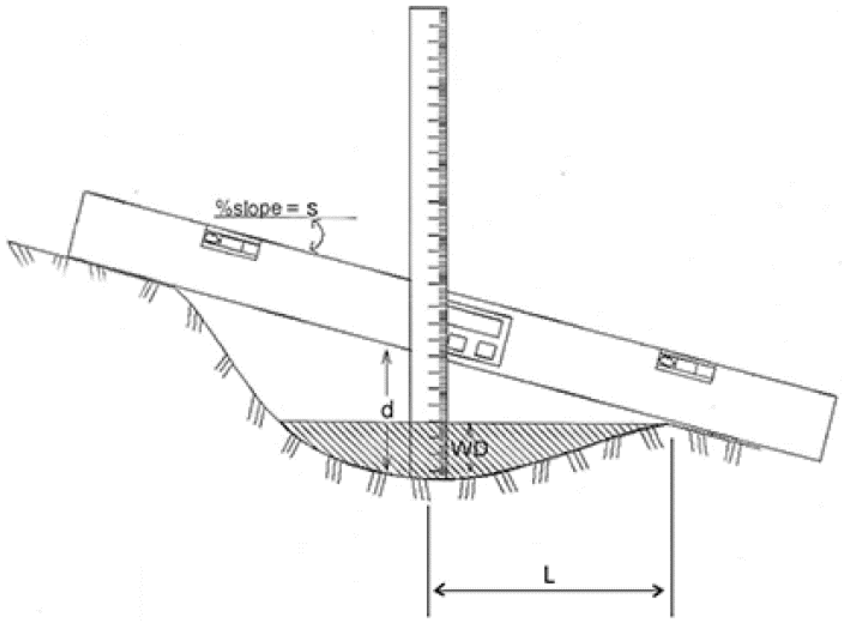


Figure A-8. Illustration of water depth due to pavement rutting and cross-slope.

🕮 Water Film Thickness and Hydroplaning Speed are the ultimate (final) outputs from the HP Tool.

A.4. USING FDOT'S NEW HYDROPLANING PREDICTION TOOL

A.4.1. GENERAL

In previous Chapters, the models built into FDOT's new HP Tool were reviewed and features of the HP tool were described. The objective of this Chapter is to further explain and demonstrate the use of this new tool by providing practical examples (where applicable). Note that a detailed User Manual for the HP tool is included in Appendix B, and the first-time users are recommended to visit Appendix B for more information on setting up the tool and for step-by-step procedures for running the hydroplaning analysis using different options.

A.4.2. RISK ANALYSIS EXAMPLE (FDOT DESIGN USING PAVDRN AND GALLAWAY EQUATIONS)

The risk analysis is based on FDOT's Design Guidance on the analysis of hydroplaning risk assessment using the HP program. The risk analysis is conducted by comparing the expected driver speed during rainfall events (Jayasooriya and Gunaratne, 2014) and the expected hydroplaning speed.

The predicted driver speed during rainfall events is calculated according to Table A-5. As an example, a driver is expected to drive at a speed 8 mph less than the design speed during a rainfall event with 1.0 in/hr intensity. However, the risk analysis is primarily conducted for high speed facilities and it is assumed that the risk is minimal when the vehicle speed is less than 45 mph. As such, the minimum predicted driver speed is set to 45 mph. For example, the predicted driver speed at a rainfall intensity of 1.0 in/hr for the Ramp is calculated to be 38 mph based on Table A-5. Since this value is less than 45 mph, the predicted driver speed is fixed at 45 mph.

Table A-5. Predicted Driver Speed Reductions

Intensity (in/hr)	Predicted Driver Speed* (mph)
0.1	Design Speed – 0
0.25	Design Speed – 0
0.5	Design Speed – 6
1	Design Speed – 8
2	Design Speed – 12
3	45 mph
4	

Note*: Hydroplaning risk analysis is conducted for high speed facilities and it is assumed that the hydroplaning risk is minimal when the vehicle speed is less than 45 mph. As such, if any of the predicted driver speed is calculated to be less than 45 mph, it is brought back to 45 mph.

📖 **Risk Analysis** is primarily conducted for **High Speed Facilities**. The minimum predicted driver speed for this analysis is 45 mph.

A.4.2.1. Inputs

Since the risk analysis is always based on Gallaway WFT and PAVDRN HPS models, the user is not allowed to select any other models for this analysis. Furthermore, since these models do not require any vehicle related inputs and temperature input, these inputs are not displayed (and not used).

🕮 **Reminder: Risk Analysis** is always based on the **Gallaway WFT** model and the **PAVDRN HPS** model. The HP tool does not provide an option for using other models for this analysis.

For the risk analysis, the user must provide the pavement or roadway related inputs that include longitudinal grade, surface type, permeability, texture, lane description, cross slope, lane width, and design speed. Note that the user may input the design speed, cross slope, and width for each plane (up to 12 planes).

Consider a pavement having four 12-ft lanes and a ramp with shoulders on both side of the pavement as well as buffer and gore areas. All the inputs are shown in Figure A-9. Note that the design speed is left blank for the shoulder and gore areas, because these areas are typically not analyzed for hydroplaning risk. The risk analysis will not be conducted for the planes with missing design speed information.

Pavement Inputs

Deterministic Analysis

Pavement Texture (Please Select MTD or MPD below)

Longitudinal Grade (%)	3
Surface Type	Open Graded Friction Course
Permeability (in/hr)	0
Mean Texture Depth (in.)	0.067

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Description	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Design Speed (mph)		70	70	70	65	65		50				
Cross Slope (%)	2	2	2	2	3	3.5	3.5	3.5	6			
Width (ft.)	12	12	12	4	12	12	12	12	12			

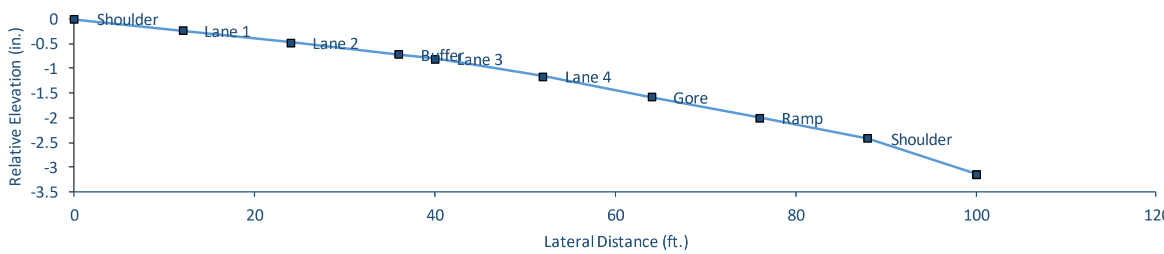


Figure A-9. Pavement inputs for Risk analysis

🕮 **Question:** Shoulder and gore areas are not analyzed for hydroplaning risk. So, why are we including these areas in the analysis?

Answer: Because water still flows over these areas. As an example, the rain drop that landed in the left shoulder will flow over all of the above planes before exiting through the right shoulder. In other words, the water film thickness is affected by all planes even if some planes are not specifically analyzed for hydroplaning risk.

A.4.2.2. <u>Results</u>

Figure A-10 shows the output for the risk analysis based on the inputs shown in Figure A-9. The outputs include three tables:

- The first table shows the WFT calculated using Gallaway WFT model.
- The second table provides the predicted driver speed at various rainfall intensities.
- The final table shows the predicted hydroplaning speed based on PAVDRN HPS model.

As shown in the figure, if the hydroplaning speed is less than or equal to the predicted driver speed, the corresponding cells in both tables are highlighted for further evaluation. More specifically, the results show that for this particular example, Lanes 2 and 4 as well as the buffer areas are not meeting FDOT's design requirements for hydroplaning risk. Therefore mitigating solutions should be considered (e.g., increasing the cross slope, etc.) to minimize the hydroplaning potential. Coordinate closely with your local district to determine how to properly evaluate mitigating solutions.

Risk Analysis Results

(Based on Gallaway WFT and PAVDRN HPS Models)

Predicted Water Film Thickness (in.)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
0.1		-0.050	-0.046	-0.045	-0.043	-0.042		-0.038				
0.25		-0.038	-0.031	-0.029	-0.027	-0.025		-0.019				
0.5		-0.024	-0.014	-0.011	-0.009	-0.005		0.004				
1		-0.004	0.011	0.015	0.019	0.024		0.037				
2		0.026	0.048	0.054	0.060	0.068		0.087				
3		0.050	0.077	0.085	0.093	0.102		0.127				
4		0.070	0.102	0.112	0.121	0.132		0.161				

Predicted Driver Speed (mph)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
0.1		70.0	70.0	70.0	65.0	65.0		50.0				
0.25		70.0	70.0	70.0	65.0	65.0		50.0				
0.5		64.0	64.0	64.0	59.0	59.0		45.0				
1		62.0	62.0	62.0	57.0	57.0		45.0				
2		58.0	58.0	58.0	53.0	53.0		45.0				
3		45.0	45.0	45.0	45.0	45.0		45.0				
4		45.0	45.0	45.0	45.0	45.0		45.0				

Predicted Hydroplaning Speed (mph)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
0.1		999.0	999.0	999.0	999.0	999.0		999.0				
0.25		999.0	999.0	999.0	999.0	999.0		999.0				
0.5		999.0	999.0	999.0	999.0	999.0		110.5				
1		999.0	84.4	77.2	72.4	68.3		61.0				
2		67.1	57.3	55.4	53.9	52.3		49.0				
3		56.7	50.6	49.3	48.2	53.7		52.8				
4		51.8	53.7	53.3	53.0	52.7		51.8				

Figure A-10. Risk analysis results

A.4.3. BASIC HYDROPLANING ANALYSIS EXAMPLE (WITH OPTIONS FOR WFT AND HYDROPLANING SPEED FORMULAS)

This mode of hydroplaning analysis allows for calculating WFT and HPS with different models. The user may select multiple models (up to 3 WFT models × 4 HPS models = 12 model combinations) and view the results in the same worksheet.

A.4.3.1. <u>WFT and HPS Model Selection</u>

The user can select one or more Water Film Thickness (WFT) and Hydroplaning Speed (HPS) models for the basic hydroplaning analysis (Figure A-11). If the cells are left blank or includes "N", then the corresponding model combination is not selected.

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway	Y	Y	Y
UK RRL	Y	Y	Y
NZ Mod.	Y	Y	Y
PAVDRN	Y	Y	Y

Notes on WFT and HPS Models

Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Figure A-11. WFT and HPS model selection

A.4.3.2. <u>Analysis Inputs</u>

Similar to the Risk Analysis, the user must provide the pavement or roadway related inputs that include longitudinal grade, surface type, permeability, texture, lane description, cross slope, lane width, and design speed. Note that the user may input the cross slope and width for each plane (up to 12 planes).

Question: What is the **difference between Risk Analysis and Basic Hydroplaning Analysis**?

Answer: Basic Hydroplaning Analysis does NOT require Design Speed (which was required for Risk Analysis). Also, you may select **up to 12 model combinations** (3 WFT models × 4 HPS models) under the basic analysis option.

Consider the same pavement section shown in the previous example for Risk Analysis. Again, the pavement is composed of four 12-ft lanes and a ramp with shoulders on both side of the pavement as well as buffer and gore areas. The pavement related inputs for this analysis option are shown in Figure A-12. Note that the Design Speed is not an input for this analysis option.

Pavement Inputs

Deterministic Analysis

Pavement Texture (Please Select MTD or MPD below)

Mean Texture Depth (in.): 0.067

Longitudinal Grade (%): 3

Surface Type: Open Graded Friction Course

Permeability (in/hr): 0

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Description	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Cross Slope (%)	2	2	2	2	3	3.5	3.5	3.5	6			
Width (ft.)	12	12	12	4	12	12	12	12	12			

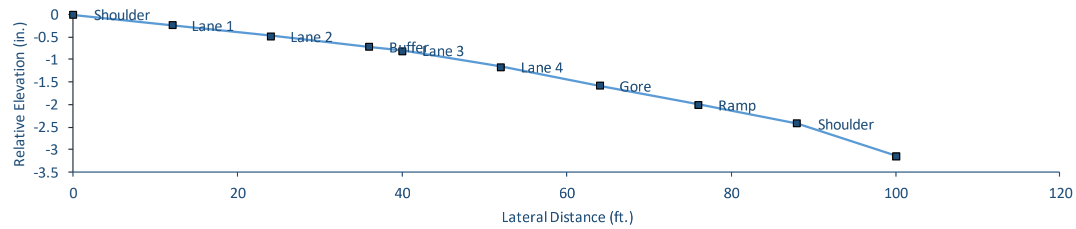


Figure A-12. Pavement inputs for Basic Hydroplaning analysis

Figure A-13 shows the input screen for the environmental and vehicle related inputs for the basic hydroplaning analysis. Note again that not all of the WFT and HPS models require the inputs shown in this figure. Therefore, these inputs are displayed only when the associated WFT or HPS models are selected. The rainfall intensity is required for all models.

Environmental Inputs

Deterministic Analysis

Rainfall Intensity (in/hr): 2.00

Temperature (deg. F): 70.0 <-- Note: Temperature is only needed for PAVDRN WFT Model

Vehicle Inputs

Deterministic Analysis

Axle Weight (lbs): 472.1 <-- Note: Axle Weight is only needed for USF HPS Model

Tire Pressure (psi): 30 <-- Note: Tire Pressure is only needed for Gallaway and USF HPS models

Spindown (%): 10 <-- Note: Spindown is only needed for Gallaway HPS Model

Tread Depth (in): 0.02 <-- Note: Tread Depth is only needed for Gallaway HPS Model

Figure A-13. Environmental and Vehicle inputs for Basic Hydroplaning analysis

🕮 **Question:** Why are we seeing the Environmental and Vehicle related inputs? Why do we need them?

Answer: Because every model is slightly different. Some models require vehicle related inputs while others do not. Refer to **TablesA- 2 and A-3** for the inputs related to different WFT and HPS models. Again, the HP tool will display these inputs if and only if you select a model or models that need these inputs. Therefore, **if you do not see an input box for a particular input (e.g., temperature), it simply means that the input is not needed** for the analysis and/or model you selected. So, if you do not see it, then do not worry about it!

A.4.3.3. <u>Analysis Results</u>

The hydroplaning analysis results for the above example inputs are shown in Figure A-14. Note that this figure also shows the intermediate variables (drainage path, total slope, viscosity, etc.) above the final WFT and HPS results.

Analysis Results

Deterministic Analysis

Intermediate Variables

Drainage Path Length (in feet)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Param \ Lane	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Total Slope (%)	3.6	3.6	3.6	3.6	4.2	4.6	4.6	4.6	6.7			
DP / Lane (ft.)	21.6	21.6	21.6	7.2	17.0	15.8	15.8	15.8	13.4			
Total DP (ft.)	21.6	43.3	64.9	72.1	89.1	104.9	120.7	136.5	149.9			

Intermediate Variables

Kin. Viscosity (ft^2/s)	1.052E-05	<-- Note: Viscosity is only used by PAVDRN WFT Model
Mean Texture Depth (in.)	0.067	

Reynold's Number and Manning's Table <-- Note: Reynold's Number and Manning's N value are only used by PAVDRN WFT Model

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Param \ Lane	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Reynold's No.	95	190	285	317	392	461	531	600	659			
Manning's N	3.5E-02	2.5E-02	2.0E-02	1.9E-02	1.7E-02	1.6E-02	1.6E-02	1.5E-02	1.4E-02			

Water Film Thickness (WFT) Table (Units: in.)

Gallaway WFT

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Model	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Gallaway	-0.002	0.026	0.048	0.054	0.060	0.068	0.078	0.087	0.074			
UK RRL	-0.003	0.024	0.045	0.051	0.060	0.068	0.078	0.087	0.083			
NZ Mod.	-0.010	0.010	0.025	0.029	0.031	0.035	0.041	0.047	0.034			
PAVDRN	-0.013	0.000	0.008	0.011	0.012	0.014	0.020	0.024	0.017			

Hydroplaning Speed (HPS) Table (Units: mph)

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
A Parameter													
WFT	Gallaway	0.00	19.34	18.45	18.27	18.11	17.96	17.76	17.60	17.82			
	UK RRL	0.00	19.44	18.54	18.36	18.13	17.95	17.76	17.60	17.67			
	NZ Mod.	0.00	20.79	19.41	19.17	19.07	18.91	18.67	18.47	18.93			
	PAVDRN	0.00	0.00	21.04	20.65	20.50	20.27	19.69	19.45	20.00			
Hydroplaning Speed		**PAVDRN HPS using Gallaway WFT**											
HPS	WFT												
PAVDRN	Gallaway	999.0	67.1	57.3	55.4	53.9	52.3	50.5	49.0	51.1			
	UK RRL	999.0	68.3	58.3	56.4	54.1	52.2	50.4	49.0	49.6			
	NZ Mod.	999.0	85.8	67.9	65.2	64.0	62.2	59.6	57.5	62.4			
	PAVDRN	999.0	999.0	89.5	83.9	81.8	78.7	71.3	68.5	75.2			
USF	Gallaway	999.0	54.9	53.7	53.4	53.2	53.0	52.7	52.5	52.8			
	UK RRL	999.0	55.1	53.8	53.6	53.2	53.0	52.7	52.5	52.6			
	NZ Mod.	999.0	57.0	55.0	54.7	54.5	54.3	54.0	53.7	54.3			
	PAVDRN	999.0	999.0	57.3	56.8	56.6	56.2	55.4	55.1	55.9			
Gallaway	Gallaway	999.0	60.6	57.8	57.2	56.8	56.3	55.7	55.2	55.9			
	UK RRL	999.0	60.9	58.1	57.5	56.8	56.2	55.6	55.2	55.4			
	NZ Mod.	999.0	65.1	60.8	60.1	59.7	59.3	58.5	57.9	59.3			
	PAVDRN	999.0	999.0	65.9	64.7	64.2	63.5	61.7	61.0	62.7			

Figure A-14. Intermediate variables and results of Basic Hydroplaning analysis

Note again, that the results shown in Figure A-14 were obtained using a rainfall intensity of 2.0 in/hr. As such, the Gallaway WFT and PAVDRN HPS results shown in this figure are identical to those obtained from the risk analysis (shown in Figure A-9) for the same rainfall intensity.

Figure A-14 also shows how different WFT and HPS models compare in terms of the results. As an example, the water film thickness for Lane 2 ranged from 0.008 in. (from PAVDRN model) to 0.054 in. (from Gallaway Model). These water film thicknesses result in hydroplaning speeds of 57.3 mph and 83.9 mph when combined with the PAVDRN HPS model. These different models are made available for comparison purposes only. The models recommended for FDOT's hydroplaning analysis are Gallaway WFT and PAVDRN HPS models.

A.4.4. CONTINUOUS ANALYSIS (WITH CONTINUOUS INPUT DATA)

The user may run the Continuous Analysis option if one or more of the continuous data files are available for cross slope, grade, texture, or rut depth. If the GPS coordinates are available in the data, the user may export the results into a .kml file for viewing in Google Earth.

The analysis methodology and interpretation of results for the Continuous Analysis is not different from the Basic Analysis. The continuous data files are entered into the WFT and HPS models to produce the hydroplaning speed results. The primary difference is that Continuous Analysis does not assume all the inputs are constant, and is capable of using measured data for cross slope, grade, texture, and/or rut depth. Therefore, the drainage path, WFT, and HPS results may vary with milepost or station.

A.4.4.1. <u>Analysis Inputs</u>

Figure A-15 shows the input screen for the Continuous analysis option. The user is referred to Appendix B for a detailed description of input requirements and step-by-step procedures for running the Continuous Analysis.

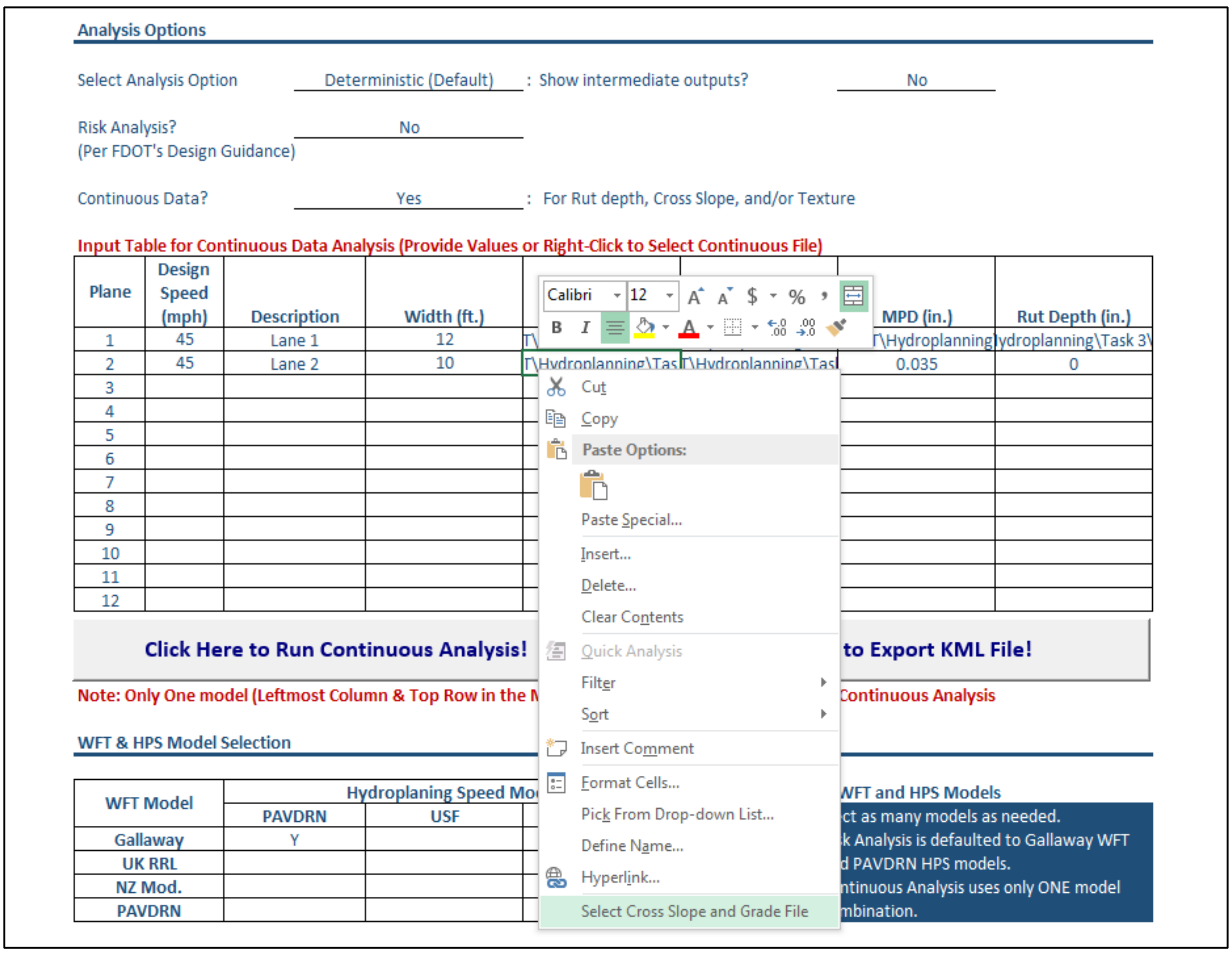


Figure A-15. Selecting continuous data file

📖 **Continuous Analysis** is nothing more than a **simple extension of the Basic Hydroplaning Analysis.** It is capable of calculating the hydroplaning results for cross slope, grade, texture, and/or rut depth values that may vary along the road.

A.4.4.2. <u>Analysis Results</u>

Figure A-16 is a sample of the output plots generated from the Continuous Analysis. The first two plots (cross slope and longitudinal grade) are the inputs that varies along the roadway. The third plot shows the intermediate variable (i.e., drainage path) calculated from these inputs. The last two plots are the outputs (WFT and HPS).

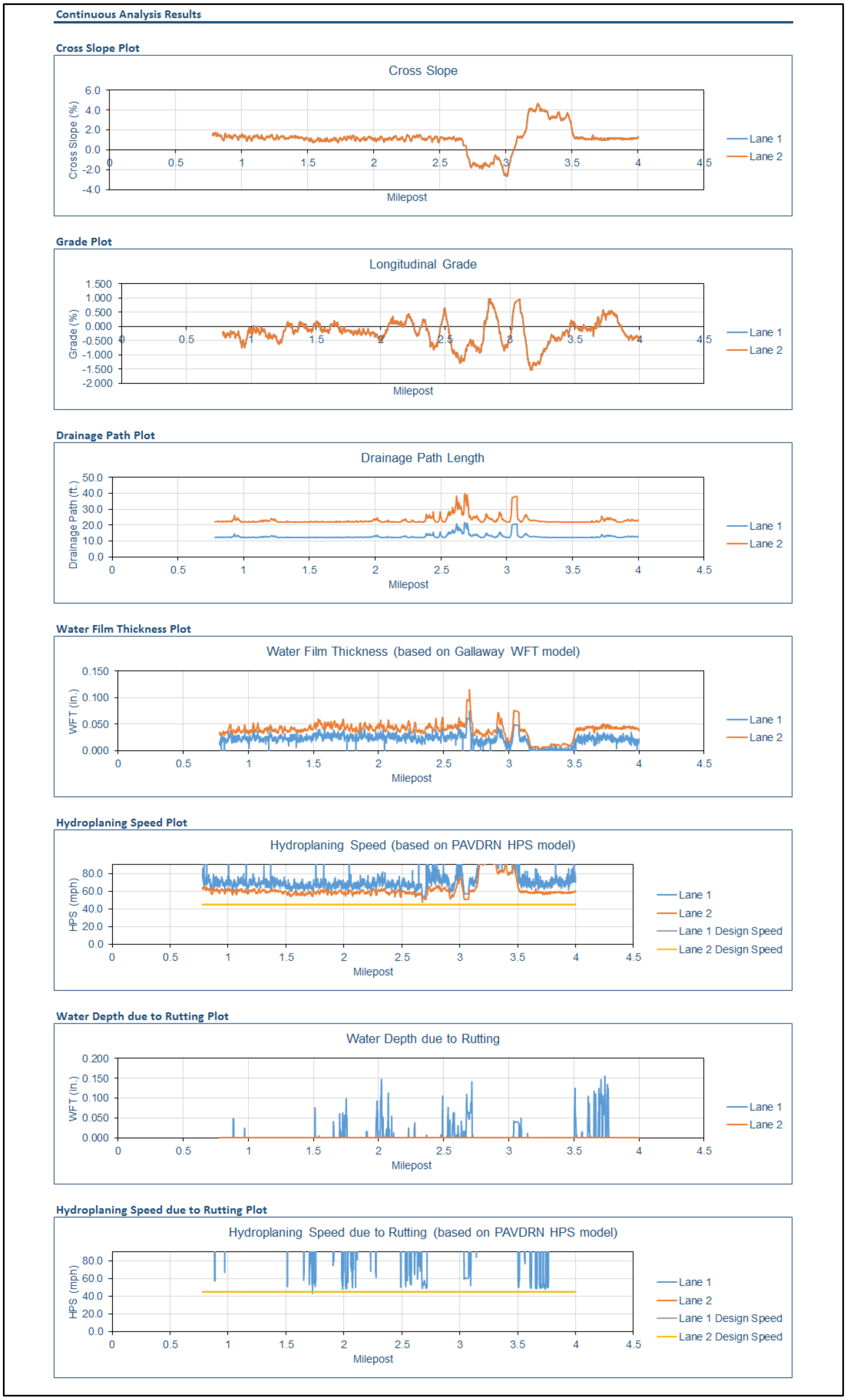


Figure A-16. Continuous analysis results

A.4.5. SENSITIVITY ANALYSIS (BATCH MODE FOR BASIC ANALYSIS)

The sensitivity analysis option allows the user to simulate a variety of conditions, which may be useful during the pavement design phase. The user may vary one or more of the input variables (e.g., rainfall intensity, temperature, cross-slope, tire pressure, etc.) at desired intervals.

As a conceptual example shown in Figure A-17, consider the situation where the user needs to run the Deterministic Analysis multiple times with different inputs (48 runs in this specific example). Rather than running the program 48 times repeatedly, a single Sensitivity Analysis Run can be made to get the results for all 48 scenarios.

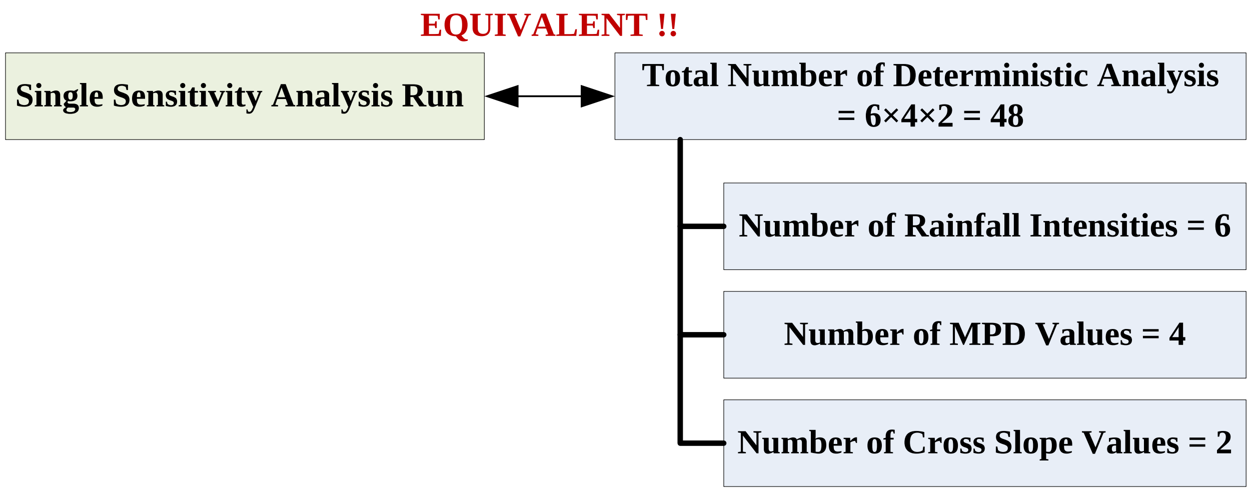


Figure A-17. Concept of Sensitivity Analysis

A.4.5.1. <u>Analysis Inputs</u>

Figure A-18 shows a sample input screen for Sensitivity Analysis.

This screen shows for the rainfall intensity input, the minimum, maximum, and increment are specified to be 0.5 in/hr, 3.0 in/hr, and 0.5 in/hr, respectively. This means the analysis will be conducted for 6 rainfall intensities (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 in/hr).

At the same time, pavement texture (MPD) is specified to vary from 0.02 in. to 0.05 in. at an increment of 0.01 in. Consequently, the Sensitivity Analysis will be run for all possible combinations of rainfall intensity and MPD.

> 🕮 Have a lot of inputs for hydroplaning analysis? Then consider running the **Sensitivity Analysis Option**!

Pavement Inputs

Sensitivity Analysis

Select Surface Type (Y/N)

Dense Graded Friction Course	Y
Open graded Friction Course	
PCC (LGD)	
PCC (LGD+TGV)	

	Min	Max	Inc.
Longitudinal Grade (%)	1	2	
Permeability (in/hr)	0		
Mean Profile Depth (in.)	0.02	0.05	0.01

(Please Select MTD or MPD from above Cell)

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
Cross Slope (%)	Min	1	1										
	Max	2	2										
	Inc.	1											
Width (ft.)	Min	12	12										
	Max	14	14										
	Inc.												

Environmental Inputs

Sensitivity Analysis

	Min	Max	Inc.
Rainfall Intensity (in/hr)	0.5	3	0.5
Temperature (deg. F)	70	80	

Click Here to Run Sensitivity Analysis!

<-- Note: Temperature is only needed for PAVDRN WFT Model

Vehicle Inputs

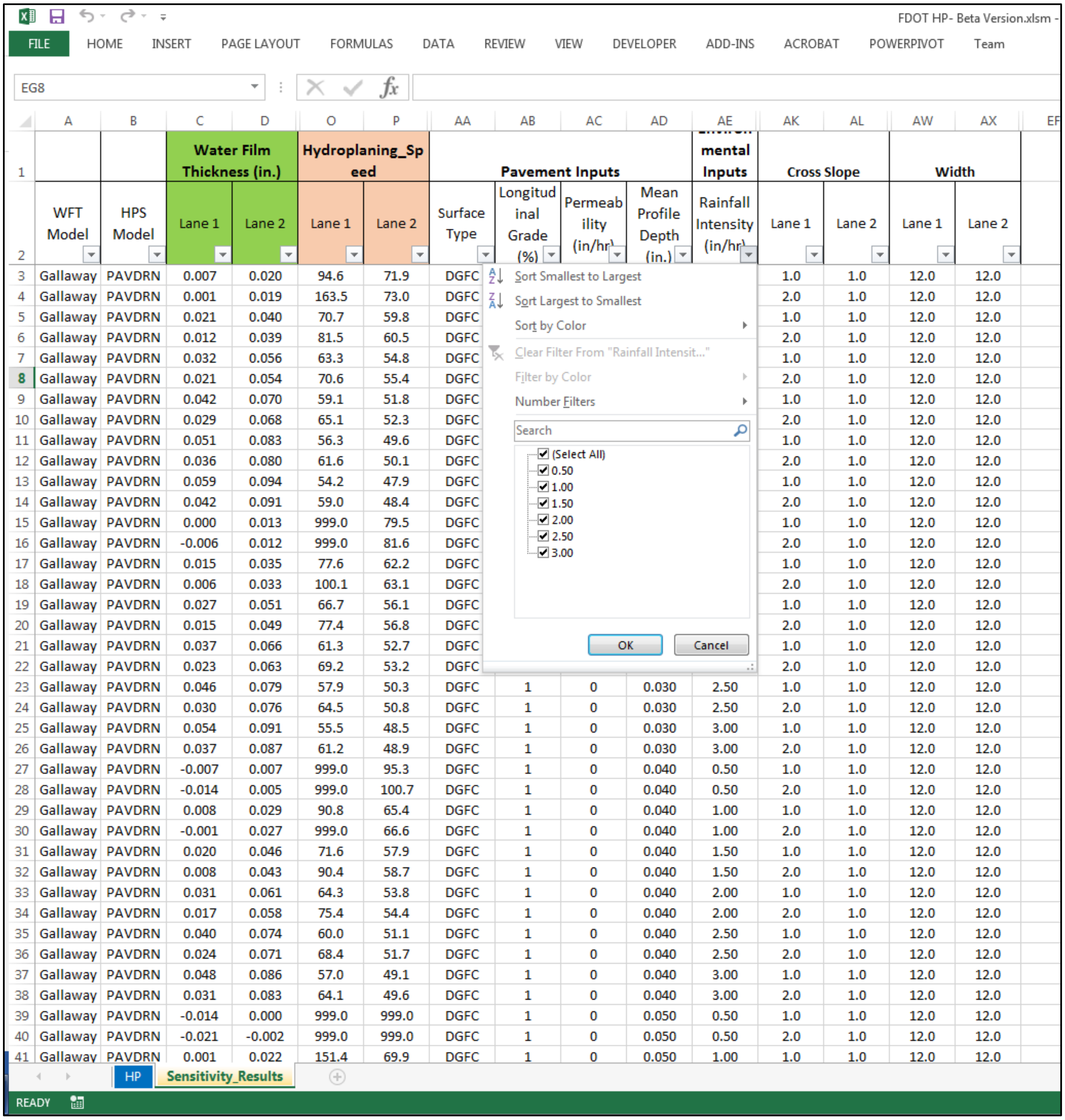
Sensitivity Analysis

	Min	Max	Inc.	
Axle Weight (lbs)	450	550		<-- Note: Axle Weight is only needed for USF HPS Model
Tire Pressure (psi)	20	30		<-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%)	10	10	0	<-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in)	0.02	0.02	0	<-- Note: Tread Depth is only needed for Gallaway HPS Model

Figure A-18. Input Screen for Sensitivity analysis

A.4.5.2. <u>Analysis Results</u>

Figure A-19 shows an example output from the Sensitivity Analysis. Due to the large amount of outputs, the results are provided in a separate Excel tab. The user may use Excel's standard filtering feature to sort through the desired outputs.



	A	B	C	D	O	P	AA	AB	AC	AD	AE	AK	AL	AW	AX
1			Water Film Thickness (in.)		Hydroplaning_Speed		Pavement Inputs				Environmental Inputs	Cross Slope		Width	
2	WFT Model	HPS Model	Lane 1	Lane 2	Lane 1	Lane 2	Surface Type	Longitudinal Grade (%)	Permeability (in/hr)	Mean Profile Depth (in.)	Rainfall Intensity (in/hr)	Lane 1	Lane 2	Lane 1	Lane 2
3	Gallaway	PAVDRN	0.007	0.020	94.6	71.9	DGFC					1.0	1.0	12.0	12.0
4	Gallaway	PAVDRN	0.001	0.019	163.5	73.0	DGFC					2.0	1.0	12.0	12.0
5	Gallaway	PAVDRN	0.021	0.040	70.7	59.8	DGFC					1.0	1.0	12.0	12.0
6	Gallaway	PAVDRN	0.012	0.039	81.5	60.5	DGFC					2.0	1.0	12.0	12.0
7	Gallaway	PAVDRN	0.032	0.056	63.3	54.8	DGFC					1.0	1.0	12.0	12.0
8	Gallaway	PAVDRN	0.021	0.054	70.6	55.4	DGFC					2.0	1.0	12.0	12.0
9	Gallaway	PAVDRN	0.042	0.070	59.1	51.8	DGFC					1.0	1.0	12.0	12.0
10	Gallaway	PAVDRN	0.029	0.068	65.1	52.3	DGFC					2.0	1.0	12.0	12.0
11	Gallaway	PAVDRN	0.051	0.083	56.3	49.6	DGFC					1.0	1.0	12.0	12.0
12	Gallaway	PAVDRN	0.036	0.080	61.6	50.1	DGFC					2.0	1.0	12.0	12.0
13	Gallaway	PAVDRN	0.059	0.094	54.2	47.9	DGFC					1.0	1.0	12.0	12.0
14	Gallaway	PAVDRN	0.042	0.091	59.0	48.4	DGFC					2.0	1.0	12.0	12.0
15	Gallaway	PAVDRN	0.000	0.013	999.0	79.5	DGFC					1.0	1.0	12.0	12.0
16	Gallaway	PAVDRN	-0.006	0.012	999.0	81.6	DGFC					2.0	1.0	12.0	12.0
17	Gallaway	PAVDRN	0.015	0.035	77.6	62.2	DGFC					1.0	1.0	12.0	12.0
18	Gallaway	PAVDRN	0.006	0.033	100.1	63.1	DGFC					2.0	1.0	12.0	12.0
19	Gallaway	PAVDRN	0.027	0.051	66.7	56.1	DGFC					1.0	1.0	12.0	12.0
20	Gallaway	PAVDRN	0.015	0.049	77.4	56.8	DGFC					2.0	1.0	12.0	12.0
21	Gallaway	PAVDRN	0.037	0.066	61.3	52.7	DGFC					1.0	1.0	12.0	12.0
22	Gallaway	PAVDRN	0.023	0.063	69.2	53.2	DGFC					2.0	1.0	12.0	12.0
23	Gallaway	PAVDRN	0.046	0.079	57.9	50.3	DGFC	1	0	0.030	2.50	1.0	1.0	12.0	12.0
24	Gallaway	PAVDRN	0.030	0.076	64.5	50.8	DGFC	1	0	0.030	2.50	2.0	1.0	12.0	12.0
25	Gallaway	PAVDRN	0.054	0.091	55.5	48.5	DGFC	1	0	0.030	3.00	1.0	1.0	12.0	12.0
26	Gallaway	PAVDRN	0.037	0.087	61.2	48.9	DGFC	1	0	0.030	3.00	2.0	1.0	12.0	12.0
27	Gallaway	PAVDRN	-0.007	0.007	999.0	95.3	DGFC	1	0	0.040	0.50	1.0	1.0	12.0	12.0
28	Gallaway	PAVDRN	-0.014	0.005	999.0	100.7	DGFC	1	0	0.040	0.50	2.0	1.0	12.0	12.0
29	Gallaway	PAVDRN	0.008	0.029	90.8	65.4	DGFC	1	0	0.040	1.00	1.0	1.0	12.0	12.0
30	Gallaway	PAVDRN	-0.001	0.027	999.0	66.6	DGFC	1	0	0.040	1.00	2.0	1.0	12.0	12.0
31	Gallaway	PAVDRN	0.020	0.046	71.6	57.9	DGFC	1	0	0.040	1.50	1.0	1.0	12.0	12.0
32	Gallaway	PAVDRN	0.008	0.043	90.4	58.7	DGFC	1	0	0.040	1.50	2.0	1.0	12.0	12.0
33	Gallaway	PAVDRN	0.031	0.061	64.3	53.8	DGFC	1	0	0.040	2.00	1.0	1.0	12.0	12.0
34	Gallaway	PAVDRN	0.017	0.058	75.4	54.4	DGFC	1	0	0.040	2.00	2.0	1.0	12.0	12.0
35	Gallaway	PAVDRN	0.040	0.074	60.0	51.1	DGFC	1	0	0.040	2.50	1.0	1.0	12.0	12.0
36	Gallaway	PAVDRN	0.024	0.071	68.4	51.7	DGFC	1	0	0.040	2.50	2.0	1.0	12.0	12.0
37	Gallaway	PAVDRN	0.048	0.086	57.0	49.1	DGFC	1	0	0.040	3.00	1.0	1.0	12.0	12.0
38	Gallaway	PAVDRN	0.031	0.083	64.1	49.6	DGFC	1	0	0.040	3.00	2.0	1.0	12.0	12.0
39	Gallaway	PAVDRN	-0.014	0.000	999.0	999.0	DGFC	1	0	0.050	0.50	1.0	1.0	12.0	12.0
40	Gallaway	PAVDRN	-0.021	-0.002	999.0	999.0	DGFC	1	0	0.050	0.50	2.0	1.0	12.0	12.0
41	Gallaway	PAVDRN	0.001	0.022	151.4	69.9	DGFC	1	0	0.050	1.00	1.0	1.0	12.0	12.0

Figure A-19. Sensitivity analysis results

A.4.6. PROBABILISTIC ANALYSIS

The Probabilistic Analysis option is another variation of running the Deterministic Analysis multiple times. It allows the user to characterize the uncertainties associated with certain variables (e.g., rainfall intensity, pavement temperature, axle weight, tire pressure, etc.). The probabilistic input variables must be defined in terms of a distribution (i.e., mean and standard deviation), rather than a fixed value. The output variables are calculated using the Monte-Carlo simulation methodology using a set of randomly generated input parameters in accordance with the given distribution (i.e., mean and standard deviation). Figure A-20 shows a schematic illustration behind this concept.

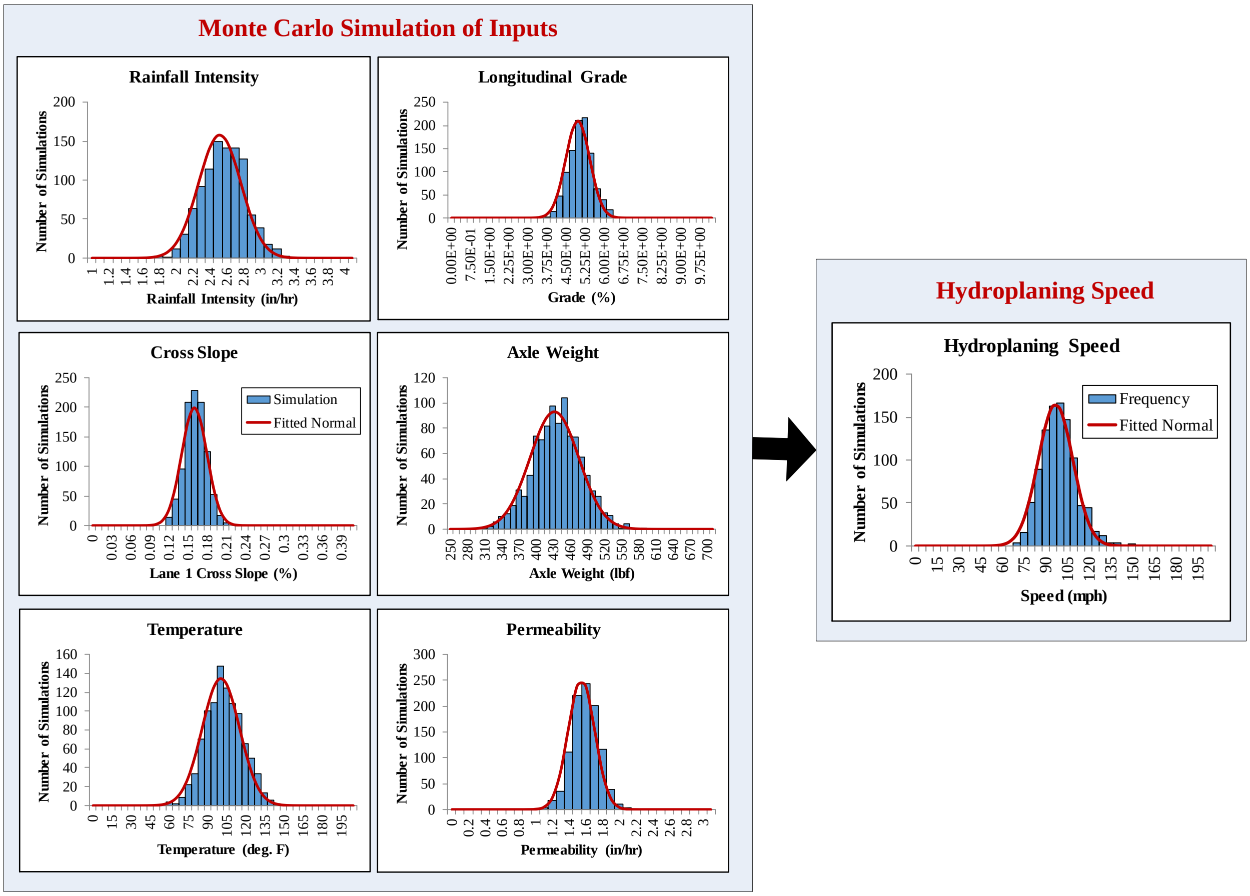


Figure A-20. Concept of Probabilistic analysis

📖 **Question**: Both the **Sensitivity Analysis and Probabilistic Analysis** Options are designed to run the hydroplaning analysis multiple times. **What is the difference**?

Answer: In the **Sensitivity Analysis, you specify the exact inputs** (e.g., Rainfall Intensities at 0.5, 1.0, and 1.5 in/hr). In the **Probabilistic Analysis, the HP tool generates random inputs** in accordance with the **Distribution** you specify (e.g., Rainfall Intensity with a mean of 1.0 in/hr and a standard deviation of 0.3 in/hr).

A.4.6.1. Analysis Inputs

Figure A-21 shows a sample input screen for the Probabilistic Analysis. For each probabilistic variable, the user must provide Average and Coefficient of Variation (COV) values. E.g., if the user specified the rainfall intensity input such that Avg. = 2.0 in/hr, COV = 10.0 percent, then the program will run the hydroplaning analysis with rainfall intensities having a normal distribution with mean of 2.0 in/hr and a standard deviation of 0.2 in/hr.

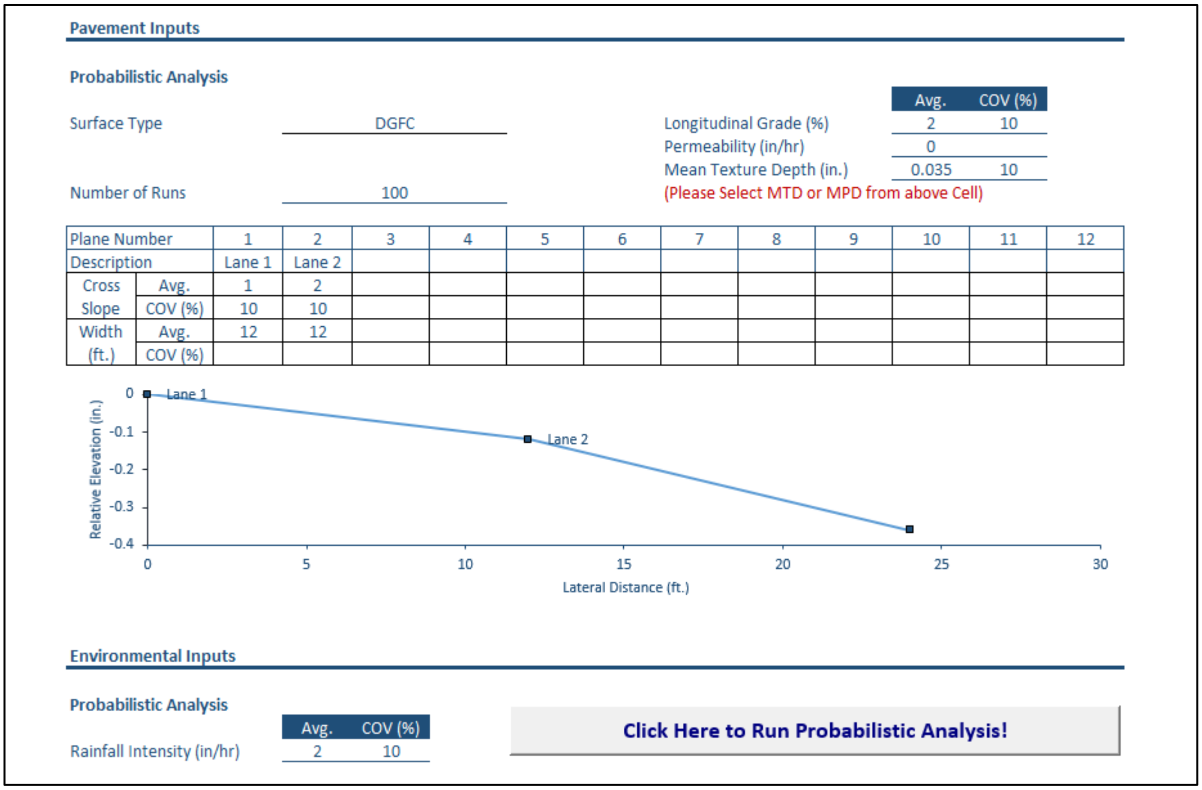


Figure A-21. Selecting Probabilistic analysis option

A.4.6.2. <u>Analysis Results</u>

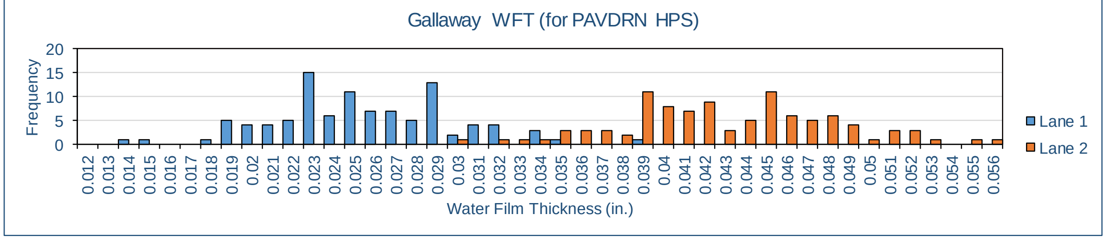
Figure A-22 shows a sample output from the Probabilistic Analysis. Similar to the inputs, the WFT and HPS results are also in terms of a distribution.

More specifically, this example output shows that for Lane 1, the WFT from Gallaway model is 0.025 in. on average but can be as low as 0.014 in. and as high as 0.034 in. Similarly, the HPS predicted by the PAVDRN model is 68 mph on average, but can be as low as 61 mph and as high as 80 mph.

Probabilistic Analysis Results

Water Film Thickness (WFT) Results

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
HPS	WFT												
PAVDRN	Gallaway												
Mean (in.)		0.025	0.043										
Stdev (in.)		0.004	0.005										
COV (%)		17.4	12.1										



Hydroplaning Speed (HPS) Results

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
HPS	WFT												
PAVDRN	Gallaway												
Mean (mph)		68.0	59.1										
Stdev (mph)		3.2	1.9										
COV (%)		4.7	3.2										

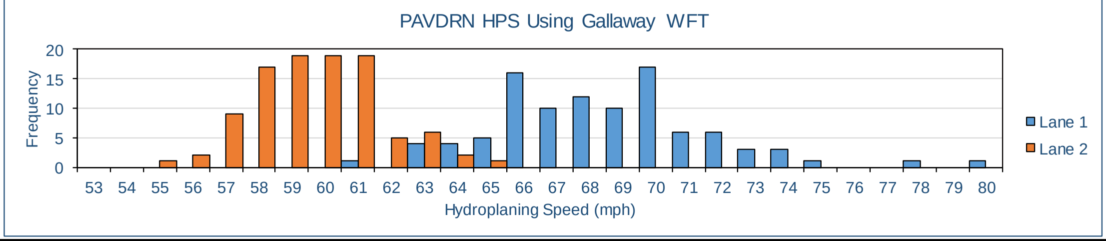


Figure A-22. Summary of probabilistic results

A.5. REFERENCES AND FURTHER READING

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APPENDIX B: USER GUIDE FOR FDOT'S NEW HYDROPLANING PROGRAM

B.1. BEFORE GETTING STARTED

FDOT's new Hydroplaning Prediction (HP) tool is available for download from FDOT's Roadway Drainage Office website:
https://www.fdot.gov/roadway/drainage/manualsandhandbooks.shtm

The new HP tool is implemented in a macro-enabled Excel spreadsheet environment. As such, it is important that the macros or code written in Visual Basic for Application (VBA) language be enabled for the HP tool to function properly.

Figure B-1 shows the Excel window in which a security warning is displayed due to the embedded macros. If the user sees such a message, the user has to click the "Enable Content" button to enable the macros within the HP tool.

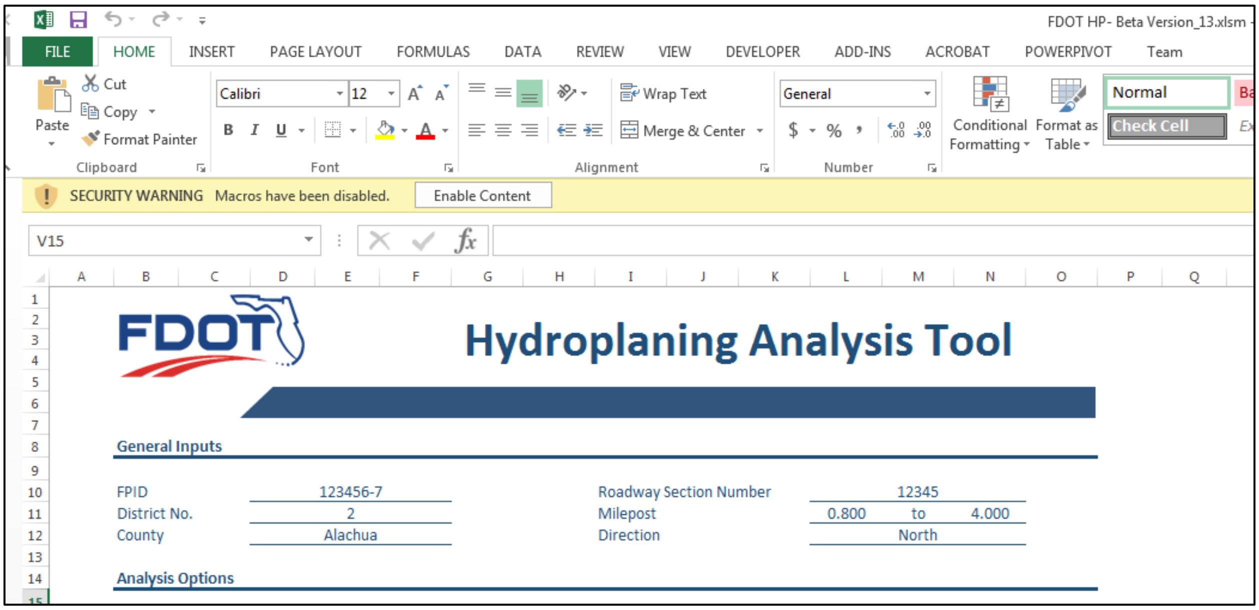


Figure B-1. Security warning message in Excel

Furthermore, it is recommended that the user enables all macros within the Excel environment. To do so, the user needs to follow the steps outlined below.

1. Click on the "Developer" tab of the Excel Ribbon
   a. If the "Developer" tab is not visible, go to File → Options → Customize Ribbon, and select the check box next to "Developer".
2. Select "Macro Security" in the "Developer" tab
3. In the new pop up window, select "Enable All Macros" option and then click "OK" (Figure B-2).

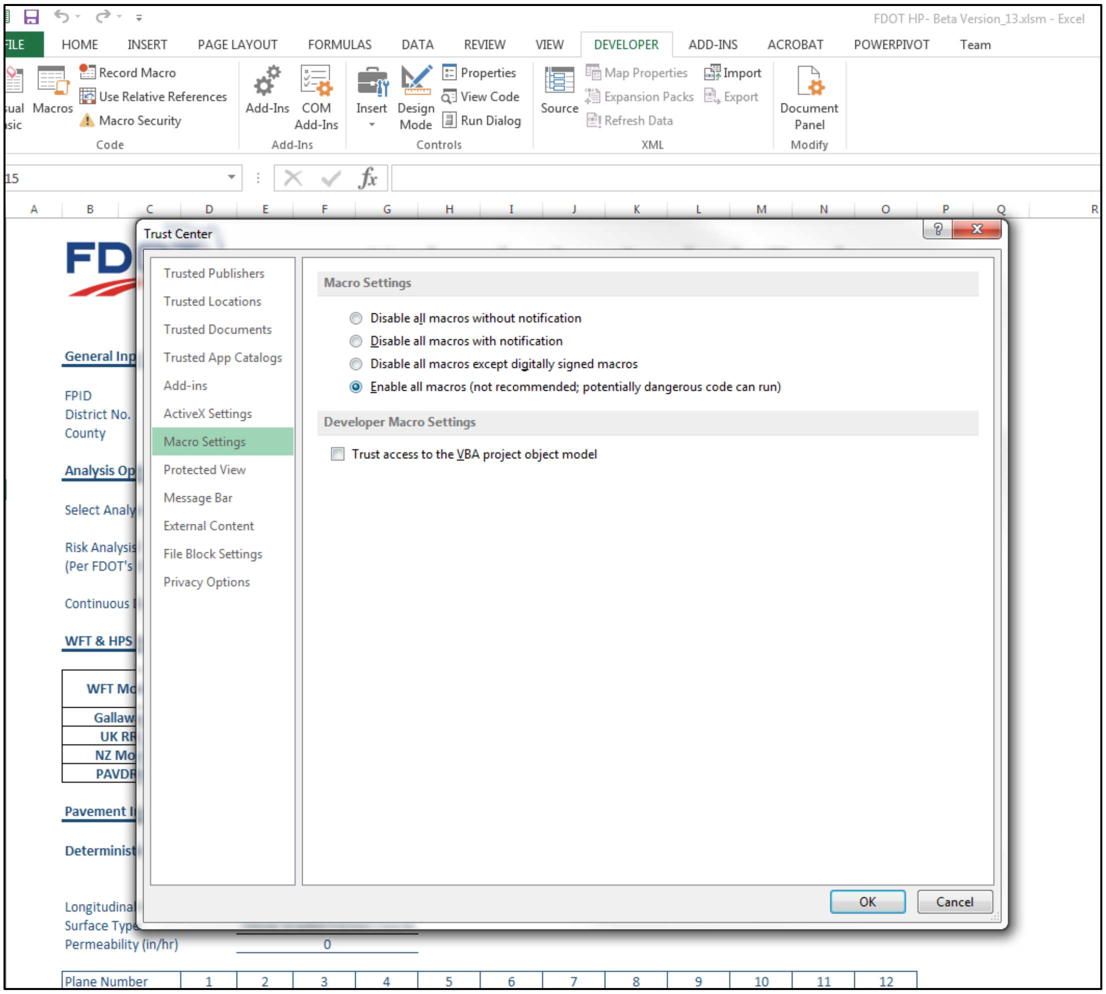


Figure B-2. Enabling all macros in Excel

With the above settings in Excel, the user is ready to run the new HP tool. The remainder of this manual describes how the user can run each mode of analysis.

B.1.1. RISK ANALYSIS (FDOT DESIGN USING PAVDRN AND GALLAWAY EQUATIONS)

The risk analysis is based on FDOT's Design Guidance on the analysis of hydroplaning risk assessment using the HP program. The risk analysis is conducted by comparing the expected driver speed during rainfall events (Jayasooriya and Gunaratne, 2014) and the expected hydroplaning speed. Note that in accordance with FDOT's Design Guidance, the Risk Analysis is always based on the Gallaway WFT model and the PAVDRN HPS model.

B.1.1.1. General Inputs

Before running the analysis, the user needs to fill out the general inputs. Figure B-3 shows the general input screen. These inputs are not necessarily used for the hydroplaning analysis, but are designed to record the general project-related information. These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts. As shown in Figure B-3, the user may choose between milepost and stations for the linear referencing system.

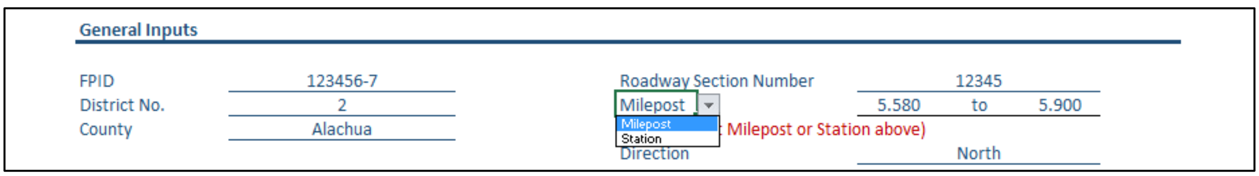


Figure B-3. General inputs

B.1.1.2. Analysis Options

To run the risk analysis (typical for FDOT Design), the user must select the "Deterministic (Default)" analysis option (Figure B-4) if not already selected. Then, select "Yes" for the "Risk Analysis" option.

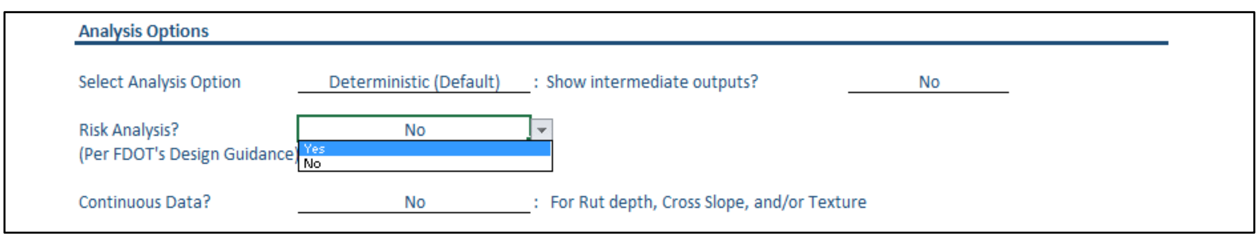


Figure B-4. Selecting Risk analysis option

B.1.1.3. Analysis Inputs

Since the risk analysis is always based on Gallaway WFT and PAVDRN HPS models, the user does not see the model selection window. Furthermore, since these models do not require any vehicle related inputs and temperature input, these inputs are not displayed (and not used).

For the risk analysis, the user must provide the pavement or roadway related inputs as shown in Figure B-5. These pavement related inputs include longitudinal grade, surface type, permeability, texture, lane description, cross slope, lane width, and design speed. Note that the user may input the design speed, cross slope, and width for each plane (up to 12 planes) in the provided table (Figure B-5).

<u>Note 1</u>: Upon selection of the “Surface Type”, the texture input is updated to show the default Mean Texture Depth (MTD) value for that surface. If the user wants to use Mean Profile Depth (MPD), the texture type must be updated (See Figure B-5). Upon selection of MPD option, the texture value is updated to the default MPD value for the selected surface type. The user can override the MTD or MPD values for the analysis.

<u>Note 2</u>: The MTD is the volumetric texture obtained from Sand Patch Testing in accordance with per ASTM E 965. On the other hand, the MPD is the 2-dimensional texture obtained using laser technologies in accordance with ASTM E 1911. The default values of MTD and MPD for Florida’s roadways were determined based on the analysis of statewide texture data (FDOT, 2019), and are shown in Table B-1.

<u>Note 3</u>: The new HP tool only accepts English units. For example, texture (MTD or MPD) has to be in inches, design speed in mph, and pavement width in ft.

<u>Note 4</u>: Shoulder and gore areas are typically not analyzed for hydroplaning risk. For these areas, the user may leave the design speed cells blank as shown in Figure B-5. The risk analysis will not be conducted for the planes with missing design speed information.

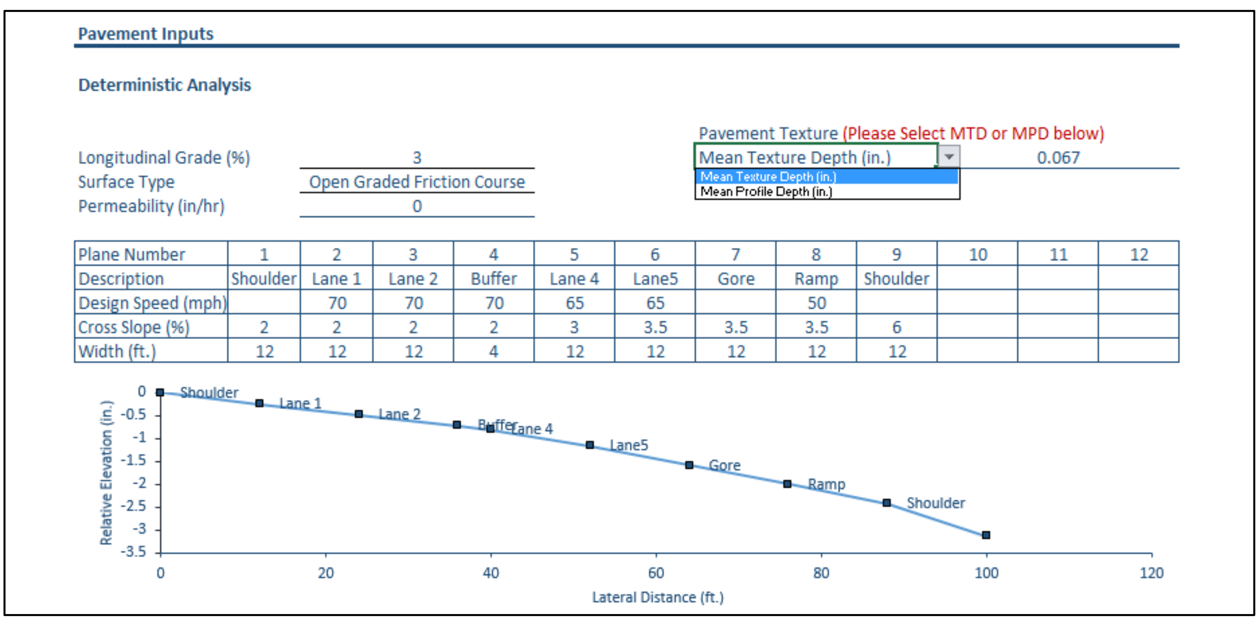


Figure B-5. Pavement inputs for Risk analysis

Table B-1. Default texture values for Hydroplaning analysis

Surface Type	Default Values	
	MTD (in.)	MPD (in.)
Dense Graded Friction Course (DGFC)	0.018	0.014
Open Graded Friction Course (OGFC)	0.067	0.050
PCC (LGD*) – Rigid Pavements	0.035	0.033

Note*: LGD = Longitudinal Grinding

B.1.1.4. Analysis Results

The risk analysis results are displayed as soon as the inputs are filled out (i.e., no button to click) and are automatically updated when any changes are made to the input.

Figure B-6 shows a sample output for the risk analysis based on the sample inputs shown in Figure B-5. The outputs include three tables. The first table shows the WFT calculated using Gallaway WFT model. The second table provides the predicted driver speed at various rainfall intensities. The final table shows the predicted hydroplaning speed based on PAVDRN HPS model. As shown in the figure, if the hydroplaning speed is less than or equal to the predicted driver speed, the corresponding cells in both tables are highlighted for further evaluation.

Risk Analysis Results

(Based on Gallaway WFT and PAVDRN HPS Models)

Predicted Water Film Thickness (in.)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 4	Lane5	Gore	Ramp	Shoulder			
0.1		-0.050	-0.046	-0.045	-0.043	-0.042		-0.038				
0.25		-0.038	-0.031	-0.029	-0.027	-0.025		-0.019				
0.5		-0.024	-0.014	-0.011	-0.009	-0.005		0.004				
1		-0.004	0.011	0.015	0.019	0.024		0.037				
2		0.026	0.048	0.054	0.060	0.068		0.087				
3		0.050	0.077	0.085	0.093	0.102		0.127				
4		0.070	0.102	0.112	0.121	0.132		0.161				

Predicted Driver Speed (mph)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 4	Lane5	Gore	Ramp	Shoulder			
0.1		70.0	70.0	70.0	65.0	65.0		50.0				
0.25		70.0	70.0	70.0	65.0	65.0		50.0				
0.5		64.0	64.0	64.0	59.0	59.0		45.0				
1		62.0	62.0	62.0	57.0	57.0		45.0				
2		58.0	58.0	58.0	53.0	53.0		45.0				
3		45.0	45.0	45.0	45.0	45.0		45.0				
4		45.0	45.0	45.0	45.0	45.0		45.0				

Predicted Hydroplaning Speed (mph)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Intensity (in/hr)	Shoulder	Lane 1	Lane 2	Buffer	Lane 4	Lane5	Gore	Ramp	Shoulder			
0.1		999.0	999.0	999.0	999.0	999.0		999.0				
0.25		999.0	999.0	999.0	999.0	999.0		999.0				
0.5		999.0	999.0	999.0	999.0	999.0		110.5				
1		999.0	84.4	77.2	72.4	68.3		61.0				
2		67.1	57.3	55.4	53.9	52.3		49.0				
3		56.7	50.6	49.3	48.2	53.7		52.8				
4		51.8	53.7	53.3	53.0	52.7		51.8				

Figure B-6. Risk analysis results

Note 5: Because the design speed was not provided for the shoulder and gore areas (Figure B-5), the analysis was not conducted for these planes. Hence, the columns corresponding to these planes are left blank in Figure B-6.

Note 6: The predicted driver speed during rainfall events is calculated according to Table B-2. As an example, a driver is expected to drive at a speed 8 mph less than the design speed during a rainfall event with 1.0 in/hr intensity. However, the risk analysis is primarily conducted for high speed facilities and it is assumed that the risk is minimal when the vehicle speed is less than 45 mph. As such, the minimum predicted driver speed is set to 45 mph. For example, the predicted driver speed at a rainfall intensity of 1.0 in/hr for the Ramp is calculated to be 38 mph based on Table B-2. Since this value is less than 45 mph, the predicted driver speed is fixed at 45 mph (see Figure B-6).

Table B-2. Predicted Driver Speed Reductions

Intensity (in/hr)	Predicted Driver Speed* (mph)
0.1	Design Speed – 0
0.25	Design Speed – 0
0.5	Design Speed – 6
1	Design Speed – 8
2	Design Speed – 12
3	45 mph
4	

Note*: Hydroplaning risk analysis is conducted for high speed facilities and it is assumed that the hydroplaning risk is minimal when the vehicle speed is less than 45 mph. As such, if any of the predicted driver speed is calculated to be less than 45 mph, it is brought back to 45 mph.

B.1.2. BASIC HYDROPLANING ANALYSIS (WITH OPTIONS FOR WFT AND HYDROPLANING SPEED FORMULAS)

This mode of hydroplaning analysis allows for calculating WFT and HPS with different models. The user may select multiple models (up to 3 WFT models × 4 HPS models = 12 model combinations) and view the results in the same worksheet.

B.1.2.1. General Inputs

Before running the analysis, the user needs to fill out the general inputs. Figure B-7 shows the general input screen. These inputs are not necessarily used for the hydroplaning analysis, but are designed to record the general project-related information. These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts. As shown in Figure B-7, the user may choose between milepost and stations for the linear referencing system.

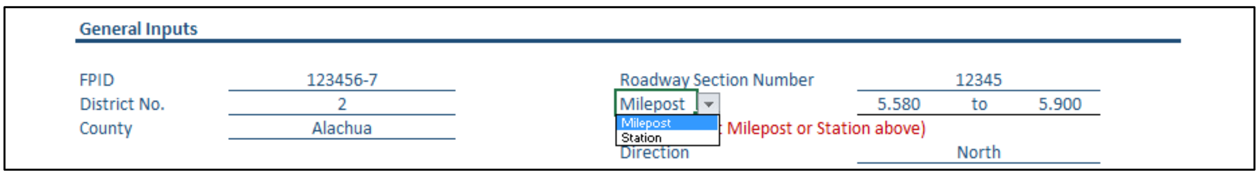


Figure B-7. General inputs

B.1.2.2. Analysis Options

In order to run the basic hydroplaning analysis, the user must select the "Deterministic (Default)" analysis option (Figure B-8). In addition, the "Risk Analysis" and "Continuous Data" options must be set to "No".

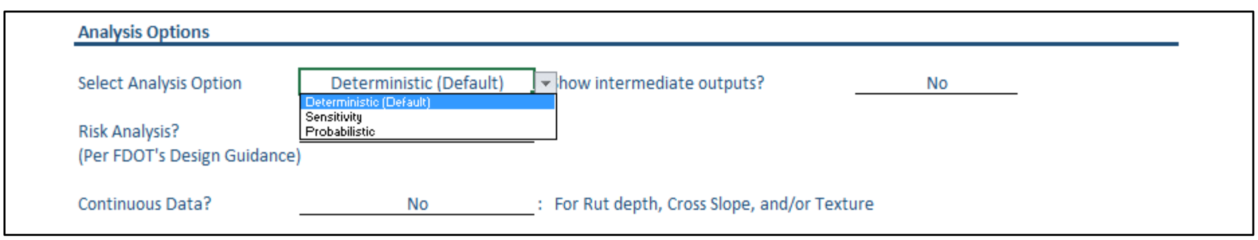


Figure B-8. Selecting Deterministic analysis option

The user may also choose to show or hide the intermediate outputs which include the following.

- Total Slope
- Drainage Path Length
- Kinematic Viscosity (Only if PAVDRN WFT model is selected)
- Mean Texture Depth (if Mean Profile Depth was inputted)
- Reynold's Number (Only if PAVDRN WFT model is selected)
- Manning's *n* value (Only if PAVDRN WFT model is selected)

B.1.2.3. <u>WFT and HPS Model Selection</u>

The user can select one or more WFT and HPS models for the basic hydroplaning analysis (Figure B-9). Selecting "Y" in these cells indicated that the model is selected. If the cells are left blank or includes "N", then the corresponding model is not selected.

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway	Y	Y	Y
UK RRL	Y	Y	Y
NZ Mod.	Y	Y	Y
PAVDRN	Y	Y	Y

Notes on WFT and HPS Models

Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Figure B-9. WFT and HPS model selection

B.1.2.4. <u>Analysis Inputs</u>

For the basic analysis, the user must provide the pavement or roadway related inputs as shown in Figure B-10. These pavement related inputs include longitudinal grade, surface type, permeability, texture, lane description, cross slope, lane width, and design speed. Note that the user may input the cross slope and width for each plane (up to 12 planes) in the provided table (Figure B-10).

<u>Note 1</u>: Upon selection of the "Surface Type", the texture input is updated to show the default Mean Texture Depth (MTD) value for that surface. If the user wants to use Mean Profile Depth (MPD), the texture type must be updated (See Figure B-10). Upon selection of MPD option, the texture value is updated to the default MPD value for the selected surface type. The user can override the MTD or MPD values for the analysis.

<u>Note 2</u>: The MTD is the volumetric texture obtained from Sand Patch Testing in accordance with per ASTM E 965. On the other hand, the MPD is the 2-dimensional texture obtained using laser technologies in accordance with ASTM E 1911. The default values of MTD and MPD for Florida's roadways were determined based on the analysis of statewide texture data (FDOT, 2019), and are shown in Table B-1 (this table was shown previously under the risk analysis manual, but shown again below Figure B-10 for convenience).

<u>Note 3</u>: The new HP tool only accepts English units. For example, texture (MTD or MPD) has to be in inches and pavement width has to be in feet.

Pavement Inputs

Deterministic Analysis

Pavement Texture (Please Select MTD or MPD below)
Mean Texture Depth (in.) 0.067

Longitudinal Grade (%) 3
Surface Type Open Graded Friction Course
Permeability (in/hr) 0

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Description	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Cross Slope (%)	2	2	2	2	3	3.5	3.5	3.5	6			
Width (ft.)	12	12	12	4	12	12	12	12	12			

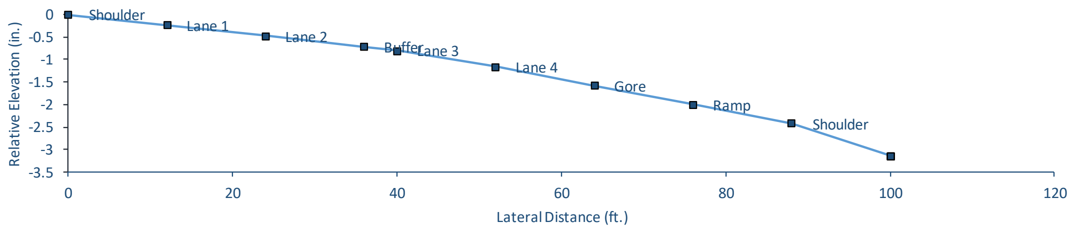


Figure B-10. Pavement inputs for Basic Hydroplaning analysis

Table B-1. Default texture values for Hydroplaning analysis

Surface Type	Default Values	
	MTD (in.)	MPD (in.)
Dense Graded Friction Course (DGFC)	0.018	0.014
Open Graded Friction Course (OGFC)	0.067	0.050
PCC (LGD*) – Rigid Pavements	0.035	0.033

Note*: LGD = Longitudinal Grinding

Figure B-11 shows the input screen for the environmental and vehicle related inputs for the basic hydroplaning analysis. It should be noted that not all of the WFT and HPS models require the inputs shown in this figure. As such, these inputs are displayed only when the associated WFT or HPS models are selected. The rainfall intensity is required for all models.

Environmental Inputs

Deterministic Analysis

Rainfall Intensity (in/hr) 2.00
Temperature (deg. F) 70.0 <-- Note: Temperature is only needed for PAVDRN WFT Model

Vehicle Inputs

Deterministic Analysis

Axle Weight (lbs) 472.1 <-- Note: Axle Weight is only needed for USF HPS Model
Tire Pressure (psi) 30 <-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%) 10 <-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in) 0.02 <-- Note: Tread Depth is only needed for Gallaway HPS Model

Figure B-11. Environmental and Vehicle inputs for Basic Hydroplaning analysis

B.1.2.5. Analysis Results

The hydroplaning analysis results are displayed as soon as the inputs are filled out (i.e., no button to click) and are automatically updated when any changes are made to the input.

Figure B-12 shows the results of the basic hydroplaning analysis. Note that the user may choose to show or hide the intermediate variables by selecting "Yes" or "No" in the Analysis Options window. The WFT and HPS results for the selected models are displayed at all times for the basic analysis option.

Analysis Results

Deterministic Analysis

Intermediate Variables

Drainage Path Length (in feet)

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Param \ Lane	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Total Slope (%)	3.6	3.6	3.6	3.6	4.2	4.6	4.6	4.6	6.7			
DP / Lane (ft.)	21.6	21.6	21.6	7.2	17.0	15.8	15.8	15.8	13.4			
Total DP (ft.)	21.6	43.3	64.9	72.1	89.1	104.9	120.7	136.5	149.9			

Intermediate Variables

Kin. Viscosity (ft^2/s) 1.052E-05 <-- Note: Viscosity is only used by PAVDRN WFT Model

Mean Texture Depth (in.) 0.067

Reynold's Number and Manning's Table <-- Note: Reynold's Number and Manning's N value are only used by PAVDRN WFT Model

Plane Number	1	2	3	4	5	6	7	8	9	10	11	12
Param \ Lane	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
Reynold's No.	95	190	285	317	392	461	531	600	659			
Manning's N	3.5E-02	2.5E-02	2.0E-02	1.9E-02	1.7E-02	1.6E-02	1.6E-02	1.5E-02	1.4E-02			

Water Film Thickness (WFT) Table (Units: in.)

Gallaway WFT

Plane Number	1	2	3	4	5	6				10	11	12
Model	Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4						
Gallaway	-0.002	0.026	0.048	0.054	0.060	0.068	0.078	0.087	0.074			
UK RRL	-0.003	0.024	0.045	0.051	0.060	0.068	0.078	0.087	0.083			
NZ Mod.	-0.010	0.010	0.025	0.029	0.031	0.035	0.041	0.047	0.034			
PAVDRN	-0.013	0.000	0.008	0.011	0.012	0.014	0.020	0.024	0.017			

Hydroplaning Speed (HPS) Table (Units: mph)

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Shoulder	Lane 1	Lane 2	Buffer	Lane 3	Lane 4	Gore	Ramp	Shoulder			
A Parameter													
WFT	Gallaway	0.00	19.34	18.45	18.27	18.11	17.96	17.76	17.60	17.82			
	UK RRL	0.00	19.44	18.54	18.36	18.13	17.95	17.76	17.60	17.67			
	NZ Mod.	0.00	20.79	19.41	19.17	19.07	18.91	18.67	18.47	18.93			
	PAVDRN	0.00	0.00	21.04	20.65	20.50	20.27	19.69	19.45	20.00			
Hydroplaning Speed		PAVDRN HPS using Gallaway WFT											
HPS	WFT												
PAVDRN	Gallaway	999.0	67.1	57.3	55.4	53.9	52.3	50.5	49.0	51.1			
	UK RRL	999.0	68.3	58.3	56.4	54.1	52.2	50.4	49.0	49.6			
	NZ Mod.	999.0	85.8	67.9	65.2	64.0	62.2	59.6	57.5	62.4			
	PAVDRN	999.0	999.0	89.5	83.9	81.8	78.7	71.3	68.5	75.2			
USF	Gallaway	999.0	54.9	53.7	53.4	53.2	53.0	52.7	52.5	52.8			
	UK RRL	999.0	55.1	53.8	53.6	53.2	53.0	52.7	52.5	52.6			
	NZ Mod.	999.0	57.0	55.0	54.7	54.5	54.3	54.0	53.7	54.3			
	PAVDRN	999.0	999.0	57.3	56.8	56.6	56.2	55.4	55.1	55.9			
Gallaway	Gallaway	999.0	60.6	57.8	57.2	56.8	56.3	55.7	55.2	55.9			
	UK RRL	999.0	60.9	58.1	57.5	56.8	56.2	55.6	55.2	55.4			
	NZ Mod.	999.0	65.1	60.8	60.1	59.7	59.3	58.5	57.9	59.3			
	PAVDRN	999.0	999.0	65.9	64.7	64.2	63.5	61.7	61.0	62.7			

Figure B-12. Intermediate variables and results of Basic Hydroplaning analysis

Note 1: The results shown in Figure B-12 was obtained using a rainfall intensity of 2.0 in/hr. As such, the Gallaway WFT and PAVDRN HPS results shown in Figure B-12 are identical to those obtained from the risk analysis (shown in Figure B-6) for the same rainfall intensity.

B.1.3. CONTINUOUS ANALYSIS (WITH CONTINUOUS INPUT DATA)

The user may run the Continuous Analysis option if one or more of the continuous data files are available for cross slope, grade, texture, or rut depth. If the GPS coordinates are available in the data, the user may export the results into a .kml file for viewing in Google Earth.

B.1.3.1. <u>General Inputs</u>

Before running the analysis, the user needs to fill out the general inputs. Figure B-13 shows the general input screen. These inputs are not necessarily used for the hydroplaning analysis, but are designed to record the general project-related information. These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts.

Figure B-13 shows that the user may choose between milepost and stations for the linear referencing system. However, it should be noted that the "Station" option is not available for continuous analysis and "Milepost" must be selected for the analysis to run.

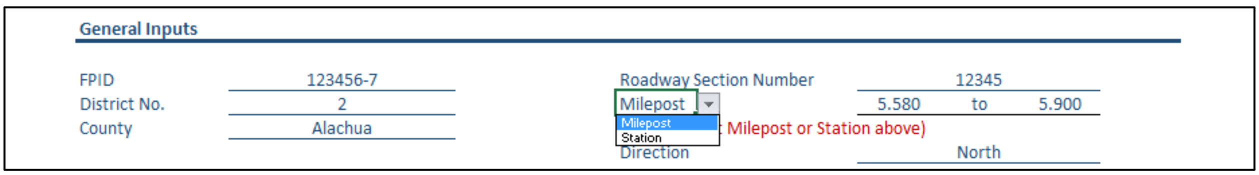


Figure B-13. General inputs

B.1.3.2. <u>Analysis Options</u>

To run the continuous analysis, the user must select the "Deterministic (Default)" analysis option (Figure B-14) if not already selected. Then, select "No" for the "Risk Analysis" option and select "Yes" for the "Continuous Data" option (Figure B-14).

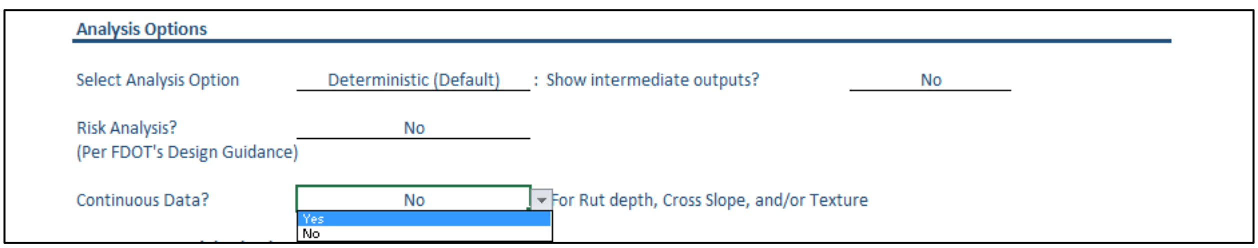


Figure B-14. Selecting Continuous analysis option

B.1.3.3. <u>Analysis Inputs</u>

Figure B-15 shows the input screen for the Continuous analysis option. The user should fill in the lane description and the width columns. In addition, the user may provide the design speed for each lane.

For this analysis, the user can choose to import continuous data or use fixed values for cross slope, grade, MPD, and rut depth. The continuous data can be imported by right-clicking on the appropriate cell and selecting the file selection option. If continuous data file is selected, the cell will show the location and file name. If fixed value is inputted, the cell simply shows the numerical value.

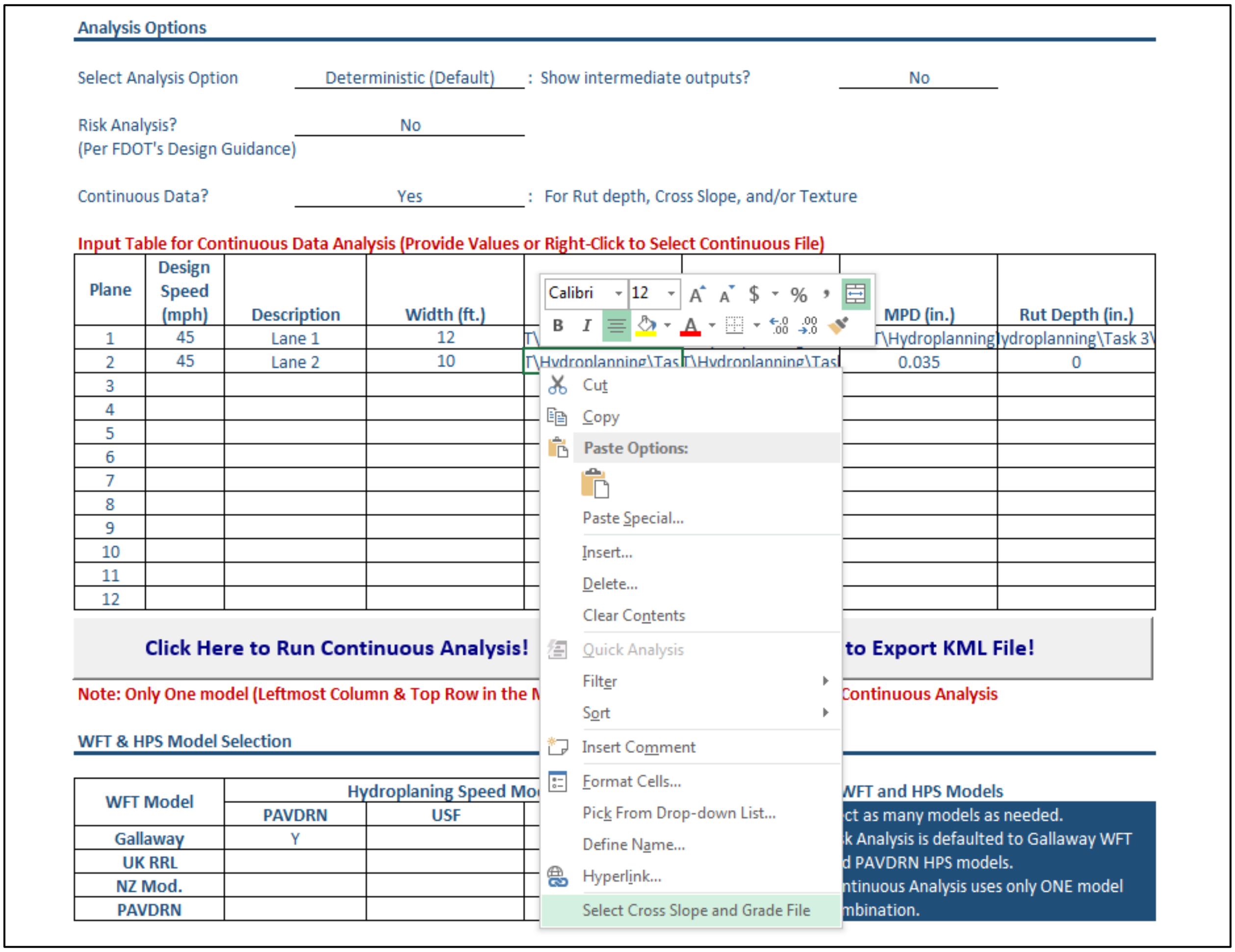


Figure B-15. Selecting continuous data file

<u>Note 1</u>: The continuous Cross Slope file must be in a .CSV format with column headers at the first row. The order of the columns is not important but the file must include headers of the following: “RefPost” (for milepost), “Slope”, “Grade”, “Longitude”, and “Latitude”.

<u>Note 2</u>: The continuous Rut Depth file must be in a .CSV format with column headers at the first row. The order of the columns is not important but the file must include headers of the following: “From” (for milepost), “AvgRut” (for Rutting), “Longitude”, and “Latitude”.

<u>Note 3</u>: The continuous Texture file must be in an “A-file” format used by FDOT for continuous texture. A sample of the “A-file” is shown in Figure B-16. When open in Excel, the data must start at row number 14 with milepost in column “B” and MPD data in column “F”. Also note that the MPD data must be provided in mm (NOT in INCHES).

	A	B	C	D	E	F	G	H
1	FILENAME	D:\2011\D	STUDY\26130.P02					
2	DATE	COLLECTEI	#########	TIME	COLLECTEI	11:08:45		
3	UNITS:	ENGLISH	COUNTY:	ALACHUA				
4	ROUTE:	26	LANE:	1				
5	DIRECTIOI	East(+)	USER	REF	1:00			
6	USER	REF	2:00	USER	REF	3:00		
7	OPERATOI	RAD	DRIVER:	CRM				
8	VEHICLE:	DOT31602	EQUIPMEI	FDOT	UNIT-			
9	WEATHER	COND:	CLOUDY	AIR	TEMPERAT	74		
10		MILES	MPH	MM				
11		INTERV	%					
12		FROM	TO	DIST	SPEED	MPD	Error	
13	------------	------------	-------	-----	-------	-------		
14		0.078	0.079	0.001	12.2	0.629	0	
15		0.079	0.08	0.001	12.3	0.901	0	
16		0.08	0.081	0.001	12.4	2.087	0.16	
17		0.081	0.082	0.001	12.5	0.772	0	
18		0.082	0.083	0.001	12.7	0.556	0	
19		0.083	0.084	0.001	12.8	0.578	0.24	
20		0.084	0.085	0.001	12.9	0.328	0	

Figure B-16. Continuous Texture data file

Figure B-17 shows the input screen for the remainder of the pavement related inputs (Surface Type and Permeability) as well as environmental and vehicle related inputs for the continuous hydroplaning analysis. It should be noted that not all of the WFT and HPS models require the inputs shown in this figure. As such, these inputs are displayed only when the associated WFT or HPS models are selected. The rainfall intensity is required for all models.

Pavement Inputs

Deterministic Analysis

Surface Type	Dense Graded Friction Course	
Permeability (in/hr)	0	

Environmental Inputs

Deterministic Analysis

Rainfall Intensity (in/hr)	2.00	
Temperature (deg. F)	70.0	<-- Note: Temperature is only needed for PAVDRN WFT Model

Vehicle Inputs

Deterministic Analysis

Axle Weight (lbs)	472.1	<-- Note: Axle Weight is only needed for USF HPS Model
Tire Pressure (psi)	30	<-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%)	10	<-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in)	0.02	<-- Note: Tread Depth is only needed for Gallaway HPS Model

Figure B-17. Environmental and Vehicle inputs for Basic Hydroplaning analysis

B.1.3.4. WFT and HPS Model Selection

Figure B-18 shows the model selection window. It should be noted that only one model combination (WFT and HPS) is used with the continuous analysis option. If the user selects multiple model combinations, the one corresponding to the leftmost column and top row in the model selection matrix is used. For the example shown in Figure B-18, only the Gallaway WFT and USF HPS model will be used for continuous analysis.

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway		Y	
UK RRL			
NZ Mod.		Y	
PAVDRN			Y

Notes on WFT and HPS Models

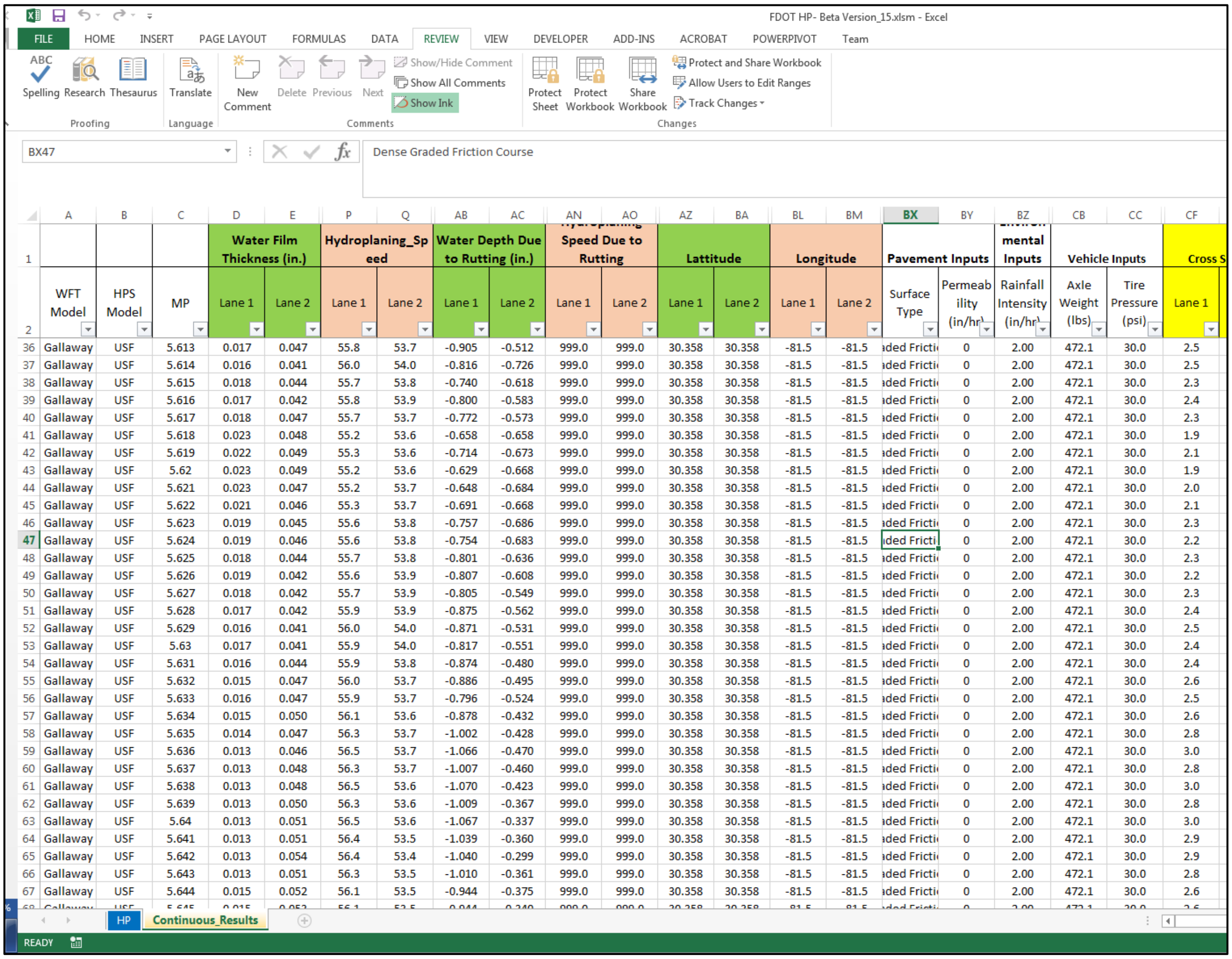
Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Figure B-18. WFT and HPS model selection for Continuous analysis

B.1.3.5. Analysis Results

Once the user fills in all of the pavement, environmental, and vehicle related inputs and click on the analysis button (with caption "Click Here to Run Continuous Analysis!"), the HP tool imports the continuous data into a separate worksheet named "Continuous Results" (Figure B-19). The user may filter through the results using the Excel's built-in filter, if desired. In addition, summary plots are created at the bottom of the "HP" worksheet (Figure B-20).

After running the continuous analysis, the user can export the results into a Google Earth file (.kml). The .kml file is automatically given a name with County name, roadway section number, and limiting mileposts. Figure B-21 shows a screenshot of the .kml file open in Google Earth.

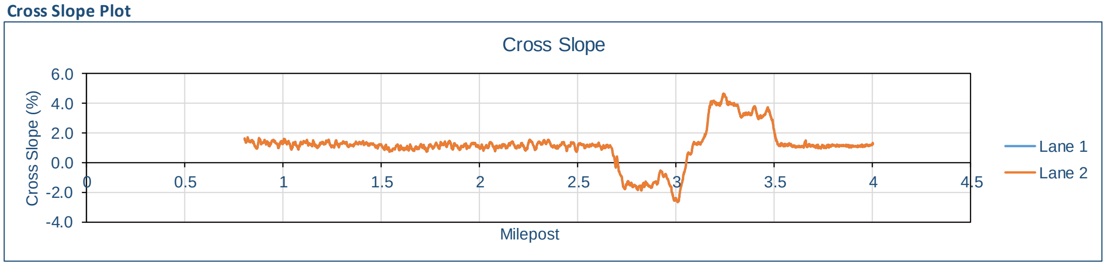


	A	B	C	D	E	P	Q	AB	AC	AN	AO	AZ	BA	BL	BM	BX	BY	BZ	CB	CC	CF
1				Water Film Thickness (in.)		Hydroplaning_Speed		Water Depth Due to Rutting (in.)		Speed Due to Rutting		Lattitude		Longitude		Pavement Inputs		mental Inputs	Vehicle Inputs		Cross S
2	WFT Model	HPS Model	MP	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2	Surface Type	Permeability (in/hr)	Rainfall Intensity (in/hr)	Axle Weight (lbs)	Tire Pressure (psi)	Lane 1
36	Gallaway	USF	5.613	0.017	0.047	55.8	53.7	-0.905	-0.512	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.5
37	Gallaway	USF	5.614	0.016	0.041	56.0	54.0	-0.816	-0.726	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.5
38	Gallaway	USF	5.615	0.018	0.044	55.7	53.8	-0.740	-0.618	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.3
39	Gallaway	USF	5.616	0.017	0.042	55.8	53.9	-0.800	-0.583	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.4
40	Gallaway	USF	5.617	0.018	0.047	55.7	53.7	-0.772	-0.573	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.3
41	Gallaway	USF	5.618	0.023	0.048	55.2	53.6	-0.658	-0.658	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	1.9
42	Gallaway	USF	5.619	0.022	0.049	55.3	53.6	-0.714	-0.673	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.1
43	Gallaway	USF	5.62	0.023	0.049	55.2	53.6	-0.629	-0.668	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	1.9
44	Gallaway	USF	5.621	0.023	0.047	55.2	53.7	-0.648	-0.684	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.0
45	Gallaway	USF	5.622	0.021	0.046	55.3	53.7	-0.691	-0.668	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.1
46	Gallaway	USF	5.623	0.019	0.045	55.6	53.8	-0.757	-0.686	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.3
47	Gallaway	USF	5.624	0.019	0.046	55.6	53.8	-0.754	-0.683	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.2
48	Gallaway	USF	5.625	0.018	0.044	55.7	53.8	-0.801	-0.636	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.3
49	Gallaway	USF	5.626	0.019	0.042	55.6	53.9	-0.807	-0.608	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.2
50	Gallaway	USF	5.627	0.018	0.042	55.7	53.9	-0.805	-0.549	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.3
51	Gallaway	USF	5.628	0.017	0.042	55.9	53.9	-0.875	-0.562	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.4
52	Gallaway	USF	5.629	0.016	0.041	56.0	54.0	-0.871	-0.531	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.5
53	Gallaway	USF	5.63	0.017	0.041	55.9	54.0	-0.817	-0.551	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.4
54	Gallaway	USF	5.631	0.016	0.044	55.9	53.8	-0.874	-0.480	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.4
55	Gallaway	USF	5.632	0.015	0.047	56.0	53.7	-0.886	-0.495	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.6
56	Gallaway	USF	5.633	0.016	0.047	55.9	53.7	-0.796	-0.524	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.5
57	Gallaway	USF	5.634	0.015	0.050	56.1	53.6	-0.878	-0.432	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.6
58	Gallaway	USF	5.635	0.014	0.047	56.3	53.7	-1.002	-0.428	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.8
59	Gallaway	USF	5.636	0.013	0.046	56.5	53.7	-1.066	-0.470	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	3.0
60	Gallaway	USF	5.637	0.013	0.048	56.3	53.7	-1.007	-0.460	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.8
61	Gallaway	USF	5.638	0.013	0.048	56.5	53.6	-1.070	-0.423	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	3.0
62	Gallaway	USF	5.639	0.013	0.050	56.3	53.6	-1.009	-0.367	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.8
63	Gallaway	USF	5.64	0.013	0.051	56.5	53.6	-1.067	-0.337	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	3.0
64	Gallaway	USF	5.641	0.013	0.051	56.4	53.5	-1.039	-0.360	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.9
65	Gallaway	USF	5.642	0.013	0.054	56.4	53.4	-1.040	-0.299	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.9
66	Gallaway	USF	5.643	0.013	0.051	56.3	53.5	-1.010	-0.361	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.8
67	Gallaway	USF	5.644	0.015	0.052	56.1	53.5	-0.944	-0.375	999.0	999.0	30.358	30.358	-81.5	-81.5	aded Fricti	0	2.00	472.1	30.0	2.6

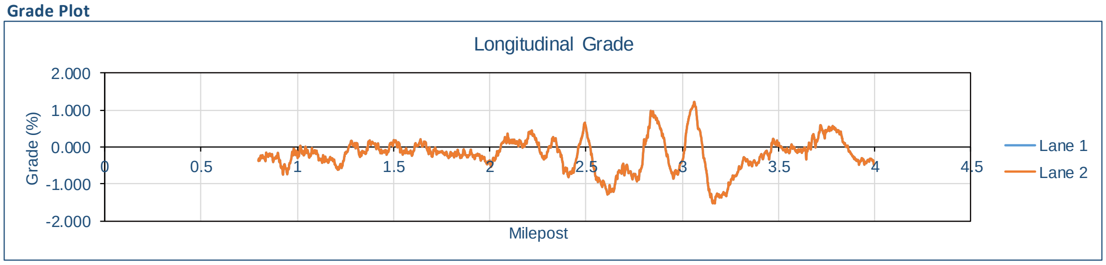
Figure B-19. Continuous analysis results worksheet

Continuous Analysis Results

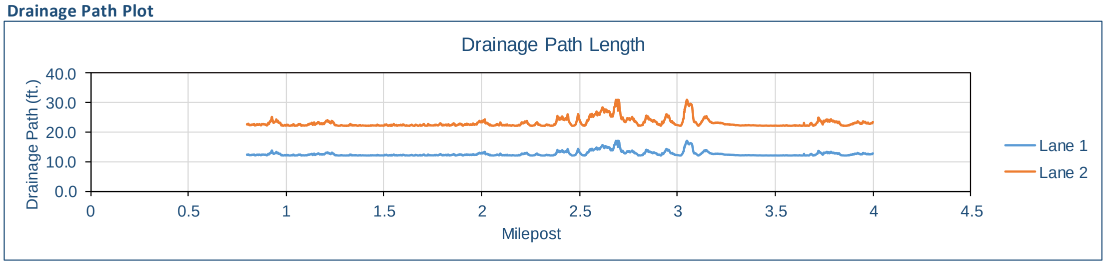
Cross Slope Plot



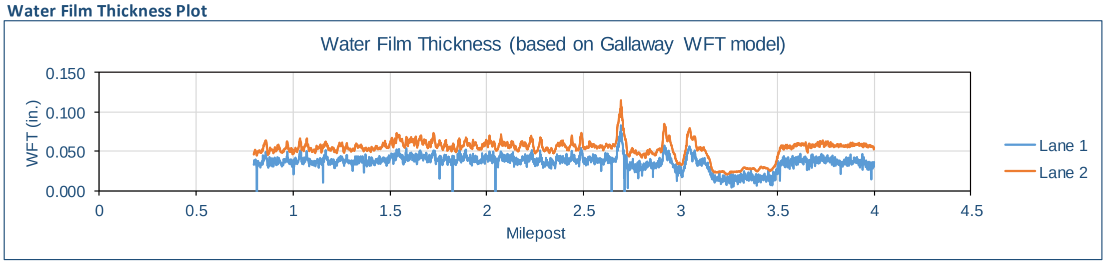
Grade Plot



Drainage Path Plot



Water Film Thickness Plot



Hydroplaning Speed Plot

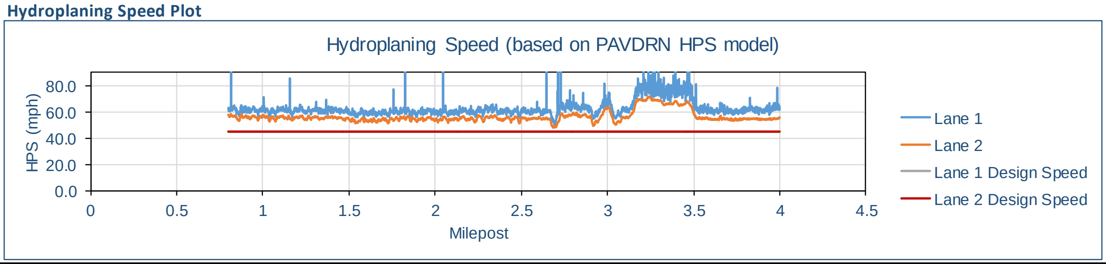


Figure B-20. Continuous analysis results

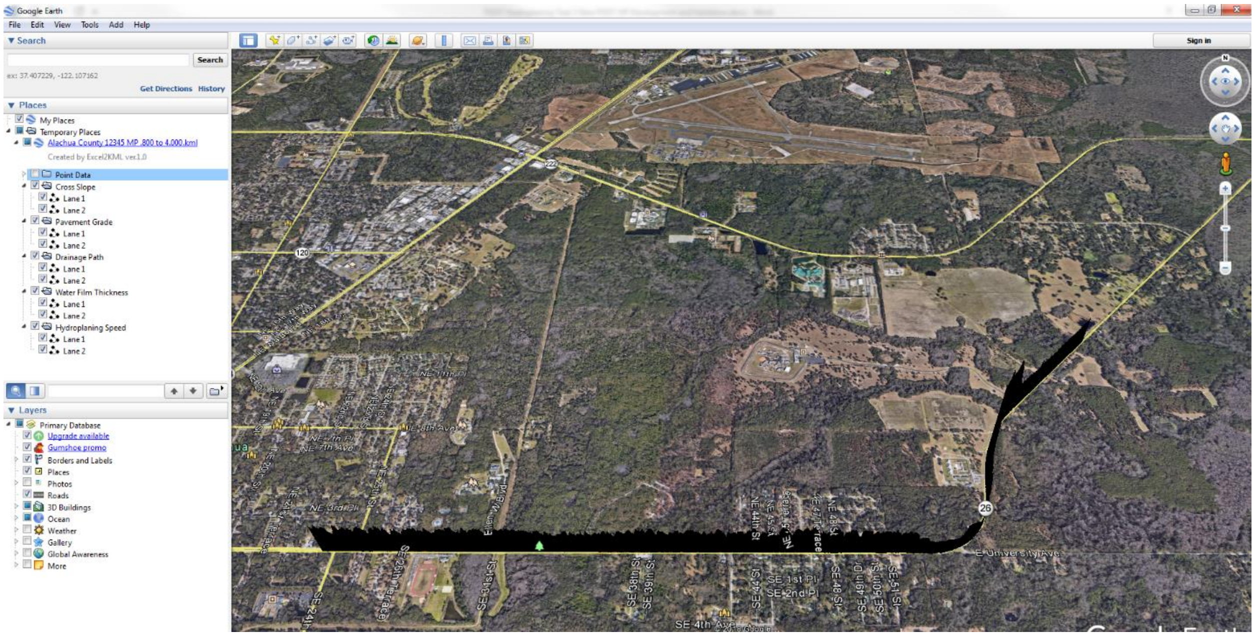


Figure B-21. Continuous analysis results opened in Google Earth

B.1.4. SENSITIVITY ANALYSIS (BATCH MODE FOR BASIC ANALYSIS)

The sensitivity analysis option is to allow the user to simulate a variety of conditions, which may be useful during the pavement design phase. The user is be allowed to vary one or more of the input variables (e.g., rainfall intensity, temperature, cross-slope, tire pressure, etc.) at desired intervals.

B.1.4.1. <u>General Inputs</u>

Before running the analysis, the user needs to fill out the general inputs. Figure B-22 shows the general input screen. These inputs are not necessarily used for the hydroplaning analysis, but are designed to record the general project-related information. These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts. As shown in Figure B-22, the user may choose between milepost and stations for the linear referencing system.

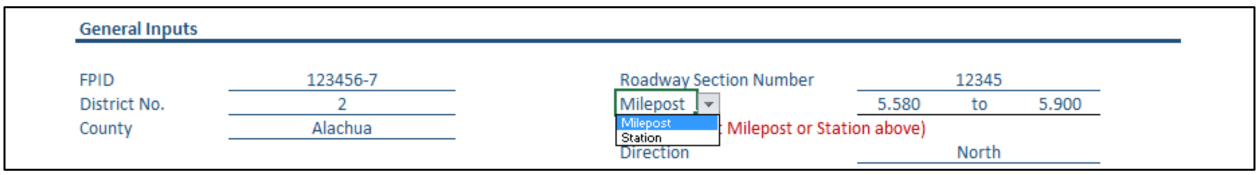


Figure B-22. General inputs

A.5.1.1. <u>Analysis Options</u>

To run the sensitivity analysis, the user must select the "Sensitivity" analysis option (Figure B-23).

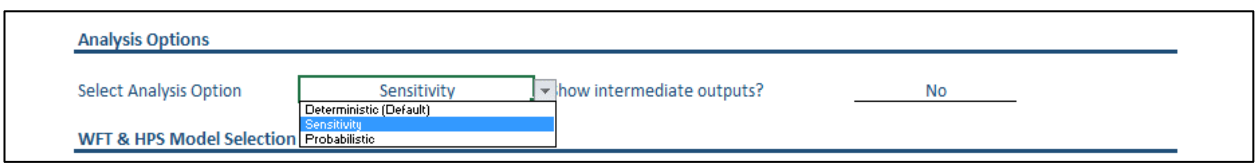


Figure B-23. Selecting Sensitivity analysis option

B.1.4.2. <u>WFT and HPS Model Selection</u>

The user can select one or more Water Film Thickness (WFT) and Hydroplaning Speed (HPS) models for the basic hydroplaning analysis (Figure B-24). Selecting "Y" in these cells indicated that the model is selected. If the cells are left blank or includes "N", then the corresponding model is not selected.

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway		Y	
UK RRL			
NZ Mod.		Y	
PAVDRN			Y

Notes on WFT and HPS Models

Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Figure B-24. WFT and HPS model selection for Sensitivity analysis

B.1.4.3. <u>Analysis Inputs</u>

Figure B-25 shows the input screen for Sensitivity Analysis. For each sensitivity variable, the user must provide Min., Max., and Interval values. E.g., if the user specified the rainfall intensity input such that Min. = 1.0 in/hr, Max. = 4.0 in/hr, and Interval = 1.0 in/hr, then the program will run the hydroplaning analysis for rainfall intensities of 1.0 in/hr, 2.0 in/hr, 3.0 in/hr, and 4.0 in/hr.

Pavement Inputs

Sensitivity Analysis

Select Surface Type (Y/N)

Dense Graded Friction Course	Y
Open graded Friction Course	
PCC (LGD)	
PCC (LGD+TGV)	

	Min	Max	Inc.
Longitudinal Grade (%)	1	2	
Permeability (in/hr)	0		
Mean Profile Depth (in.)	0.02	0.05	0.01

(Please Select MTD or MPD from above Cell)

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
Cross Slope (%)	Min	1	1										
	Max	2	2										
	Inc.	1											
Width (ft.)	Min	12	12										
	Max	14	14										
	Inc.												

Environmental Inputs

Sensitivity Analysis

	Min	Max	Inc.
Rainfall Intensity (in/hr)	0.5	3	0.5
Temperature (deg. F)	70	80	

Click Here to Run Sensitivity Analysis!

<-- Note: Temperature is only needed for PAVDRN WFT Model

Vehicle Inputs

Sensitivity Analysis

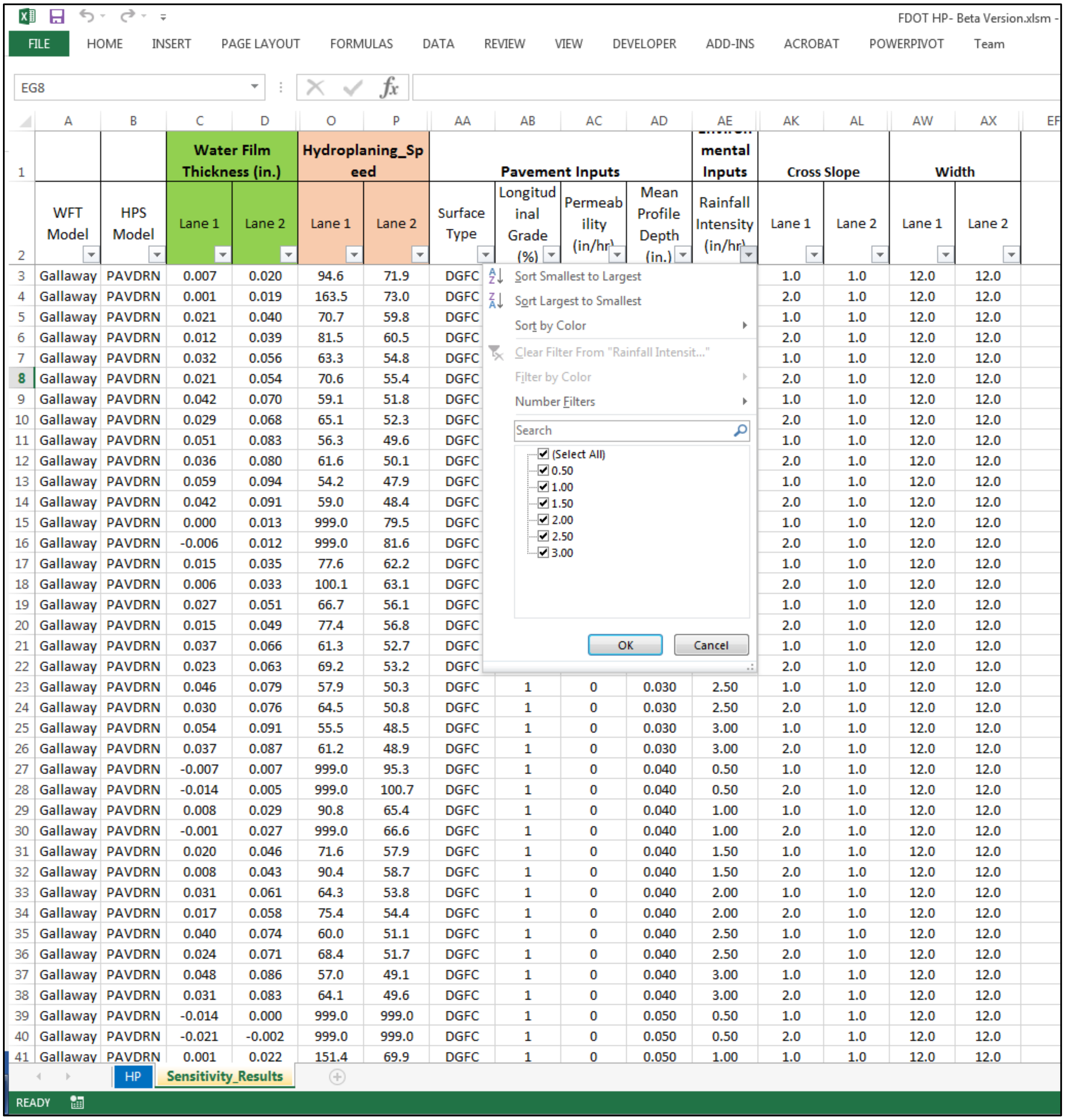
	Min	Max	Inc.	
Axle Weight (lbs)	450	550		<-- Note: Axle Weight is only needed for USF HPS Model
Tire Pressure (psi)	20	30		<-- Note: Tire Pressure is only needed for Gallaway and USF HPS models
Spindown (%)	10	10	0	<-- Note: Spindown is only needed for Gallaway HPS Model
Tread Depth (in)	0.02	0.02	0	<-- Note: Tread Depth is only needed for Gallaway HPS Model

Figure B-25. Input Screen for Sensitivity analysis

<u>Note 1</u>: For an input to be identified as a sensitivity variable, all three values (Min., Max., and Increment) must be provided. If the Max. or Increment value is missing, the HP tool will assume that the variable is fixed and use the value provided in the Min. cell. If the Min. cell is missing for any variable, the HP tool will display and error message and will not run the analysis.

B.1.4.4. Analysis Results

Once the user fills in all of the pavement, environmental, and vehicle related inputs and click on the analysis button (with caption “Click Here to Run Sensitivity Analysis!”), the HP tool generates the results in a separate worksheet named “Sensitivity Results”. The user may filter the inputs and outputs and display only those that are desired (Figure B-26).



	A	B	C	D	O	P	AA	AB	AC	AD	AE	AK	AL	AW	AX
1			Water Film Thickness (in.)		Hydroplaning_Speed		Pavement Inputs				Environmental Inputs	Cross Slope		Width	
2	WFT Model	HPS Model	Lane 1	Lane 2	Lane 1	Lane 2	Surface Type	Longitudinal Grade (%)	Permeability (in/hr)	Mean Profile Depth (in.)	Rainfall Intensity (in/hr)	Lane 1	Lane 2	Lane 1	Lane 2
3	Gallaway	PAVDRN	0.007	0.020	94.6	71.9	DGFC					1.0	1.0	12.0	12.0
4	Gallaway	PAVDRN	0.001	0.019	163.5	73.0	DGFC					2.0	1.0	12.0	12.0
5	Gallaway	PAVDRN	0.021	0.040	70.7	59.8	DGFC					1.0	1.0	12.0	12.0
6	Gallaway	PAVDRN	0.012	0.039	81.5	60.5	DGFC					2.0	1.0	12.0	12.0
7	Gallaway	PAVDRN	0.032	0.056	63.3	54.8	DGFC					1.0	1.0	12.0	12.0
8	Gallaway	PAVDRN	0.021	0.054	70.6	55.4	DGFC					2.0	1.0	12.0	12.0
9	Gallaway	PAVDRN	0.042	0.070	59.1	51.8	DGFC					1.0	1.0	12.0	12.0
10	Gallaway	PAVDRN	0.029	0.068	65.1	52.3	DGFC					2.0	1.0	12.0	12.0
11	Gallaway	PAVDRN	0.051	0.083	56.3	49.6	DGFC					1.0	1.0	12.0	12.0
12	Gallaway	PAVDRN	0.036	0.080	61.6	50.1	DGFC					2.0	1.0	12.0	12.0
13	Gallaway	PAVDRN	0.059	0.094	54.2	47.9	DGFC					1.0	1.0	12.0	12.0
14	Gallaway	PAVDRN	0.042	0.091	59.0	48.4	DGFC					2.0	1.0	12.0	12.0
15	Gallaway	PAVDRN	0.000	0.013	999.0	79.5	DGFC					1.0	1.0	12.0	12.0
16	Gallaway	PAVDRN	-0.006	0.012	999.0	81.6	DGFC					2.0	1.0	12.0	12.0
17	Gallaway	PAVDRN	0.015	0.035	77.6	62.2	DGFC					1.0	1.0	12.0	12.0
18	Gallaway	PAVDRN	0.006	0.033	100.1	63.1	DGFC					2.0	1.0	12.0	12.0
19	Gallaway	PAVDRN	0.027	0.051	66.7	56.1	DGFC					1.0	1.0	12.0	12.0
20	Gallaway	PAVDRN	0.015	0.049	77.4	56.8	DGFC					2.0	1.0	12.0	12.0
21	Gallaway	PAVDRN	0.037	0.066	61.3	52.7	DGFC					1.0	1.0	12.0	12.0
22	Gallaway	PAVDRN	0.023	0.063	69.2	53.2	DGFC					2.0	1.0	12.0	12.0
23	Gallaway	PAVDRN	0.046	0.079	57.9	50.3	DGFC	1	0	0.030	2.50	1.0	1.0	12.0	12.0
24	Gallaway	PAVDRN	0.030	0.076	64.5	50.8	DGFC	1	0	0.030	2.50	2.0	1.0	12.0	12.0
25	Gallaway	PAVDRN	0.054	0.091	55.5	48.5	DGFC	1	0	0.030	3.00	1.0	1.0	12.0	12.0
26	Gallaway	PAVDRN	0.037	0.087	61.2	48.9	DGFC	1	0	0.030	3.00	2.0	1.0	12.0	12.0
27	Gallaway	PAVDRN	-0.007	0.007	999.0	95.3	DGFC	1	0	0.040	0.50	1.0	1.0	12.0	12.0
28	Gallaway	PAVDRN	-0.014	0.005	999.0	100.7	DGFC	1	0	0.040	0.50	2.0	1.0	12.0	12.0
29	Gallaway	PAVDRN	0.008	0.029	90.8	65.4	DGFC	1	0	0.040	1.00	1.0	1.0	12.0	12.0
30	Gallaway	PAVDRN	-0.001	0.027	999.0	66.6	DGFC	1	0	0.040	1.00	2.0	1.0	12.0	12.0
31	Gallaway	PAVDRN	0.020	0.046	71.6	57.9	DGFC	1	0	0.040	1.50	1.0	1.0	12.0	12.0
32	Gallaway	PAVDRN	0.008	0.043	90.4	58.7	DGFC	1	0	0.040	1.50	2.0	1.0	12.0	12.0
33	Gallaway	PAVDRN	0.031	0.061	64.3	53.8	DGFC	1	0	0.040	2.00	1.0	1.0	12.0	12.0
34	Gallaway	PAVDRN	0.017	0.058	75.4	54.4	DGFC	1	0	0.040	2.00	2.0	1.0	12.0	12.0
35	Gallaway	PAVDRN	0.040	0.074	60.0	51.1	DGFC	1	0	0.040	2.50	1.0	1.0	12.0	12.0
36	Gallaway	PAVDRN	0.024	0.071	68.4	51.7	DGFC	1	0	0.040	2.50	2.0	1.0	12.0	12.0
37	Gallaway	PAVDRN	0.048	0.086	57.0	49.1	DGFC	1	0	0.040	3.00	1.0	1.0	12.0	12.0
38	Gallaway	PAVDRN	0.031	0.083	64.1	49.6	DGFC	1	0	0.040	3.00	2.0	1.0	12.0	12.0
39	Gallaway	PAVDRN	-0.014	0.000	999.0	999.0	DGFC	1	0	0.050	0.50	1.0	1.0	12.0	12.0
40	Gallaway	PAVDRN	-0.021	-0.002	999.0	999.0	DGFC	1	0	0.050	0.50	2.0	1.0	12.0	12.0
41	Gallaway	PAVDRN	0.001	0.022	151.4	69.9	DGFC	1	0	0.050	1.00	1.0	1.0	12.0	12.0

Figure B-26. Sensitivity analysis results

B.1.5. PROBABILISTIC ANALYSIS

The probabilistic analysis option allows the user to characterize the uncertainties associated with certain variables (e.g., rainfall intensity, pavement temperature, axle weight, tire pressure, etc.). The probabilistic input variables must defined in terms of a distribution (i.e., mean and standard deviation), rather than a fixed value. The output variables are calculated using the Monte-Carlo simulation methodology using a set of randomly generated input parameters in accordance with the given distribution (i.e., mean and standard deviation).

B.1.5.1. <u>General Inputs</u>

Before running the analysis, the user needs to fill out the general inputs. Figure B-26 shows the general input screen. These inputs are not necessarily used for the hydroplaning analysis, but are designed to record the general project-related information. These inputs include the financial project number (FPN), District, County, roadway section number, direction, and limiting mileposts. As shown in Figure B-27, the user may choose between milepost and stations for the linear referencing system.

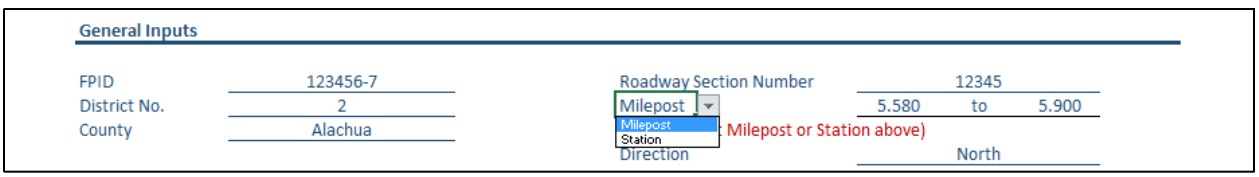


Figure B-27. General inputs

B.1.5.2. <u>Analysis Options</u>

To run the sensitivity analysis, the user must select the "Probabilistic" analysis option (Figure B-28).

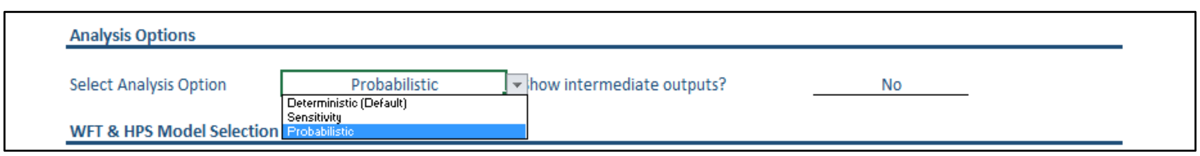


Figure B-28. Selecting Sensitivity analysis option

B.1.5.3. <u>WFT and HPS Model Selection</u>

The user can select one or more Water Film Thickness (WFT) and Hydroplaning Speed (HPS) models for the basic hydroplaning analysis (Figure B-29). Selecting "Y" in these cells indicated that the model is selected. If the cells are left blank or includes "N", then the corresponding model is not selected.

WFT & HPS Model Selection

WFT Model	Hydroplaning Speed Model		
	PAVDRN	USF	Gallaway
Gallaway	Y		
UK RRL			
NZ Mod.			
PAVDRN			

Notes on WFT and HPS Models

Please select as many models as needed.
Note 1: Risk Analysis is defaulted to Gallaway WFT and PAVDRN HPS models.
Note 2: Continuous Analysis uses only ONE model combination.

Figure B-29. WFT and HPS model selection for Sensitivity analysis

B.1.5.4. Analysis Inputs

Figure B-30 shows the input screen for the Probabilistic Analysis. For each probabilistic variable, the user must provide Average and Coefficient of Variation (COV) values. For example, if the user specified the rainfall intensity input such that Avg. = 2.0 in/hr, COV = 10.0 percent, then the program will run the hydroplaning analysis with rainfall intensities having a normal distribution with mean of 2.0 in/hr and a standard deviation of 0.2 in/hr.

Note 1: If the COV value is missing, the HP tool will assume that the variable is fixed and use the value provided in the Avg. cell. If the Avg. cell is missing for any variable, the HP tool will display and error message and will not run the analysis.

Note 2: The "Number of Runs" for the probabilistic analysis corresponds to the total number of runs per model. For example, if the number of runs was 100 and two models are selected, the probabilistic analysis will be run for a total of 200 simulations (100 simulations per model).

Pavement Inputs

Probabilistic Analysis

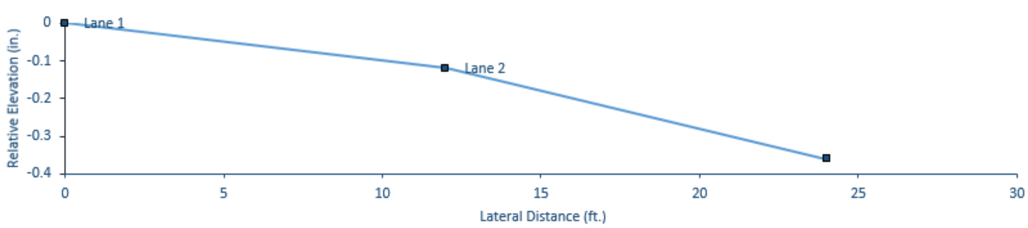
Surface Type: DGFC

Number of Runs: 100

	Avg.	COV (%)
Longitudinal Grade (%)	2	10
Permeability (in/hr)	0	
Mean Texture Depth (in.)	0.035	10

(Please Select MTD or MPD from above Cell)

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
Cross	Avg.	1	2										
Slope	COV (%)	10	10										
Width	Avg.	12	12										
(ft.)	COV (%)												



Environmental Inputs

Probabilistic Analysis

	Avg.	COV (%)
Rainfall Intensity (in/hr)	2	10

Click Here to Run Probabilistic Analysis!

Figure B-30. Selecting Probabilistic analysis option

B.1.5.5. Analysis Results

Once the user fills in all of the pavement, environmental, and vehicle related inputs and click on the analysis button (with caption "Click Here to Run Probabilistic Analysis!"), the HP tool generates the results in a separate worksheet named "Probabilistic Results" (Figure B-31). Similar to the sensitivity results, the user may use Excel's filter to show/hide the inputs and outputs. In addition, summary tables and plots for the probabilistic analysis are created at the bottom of the "HP" worksheet (Figure B-32).

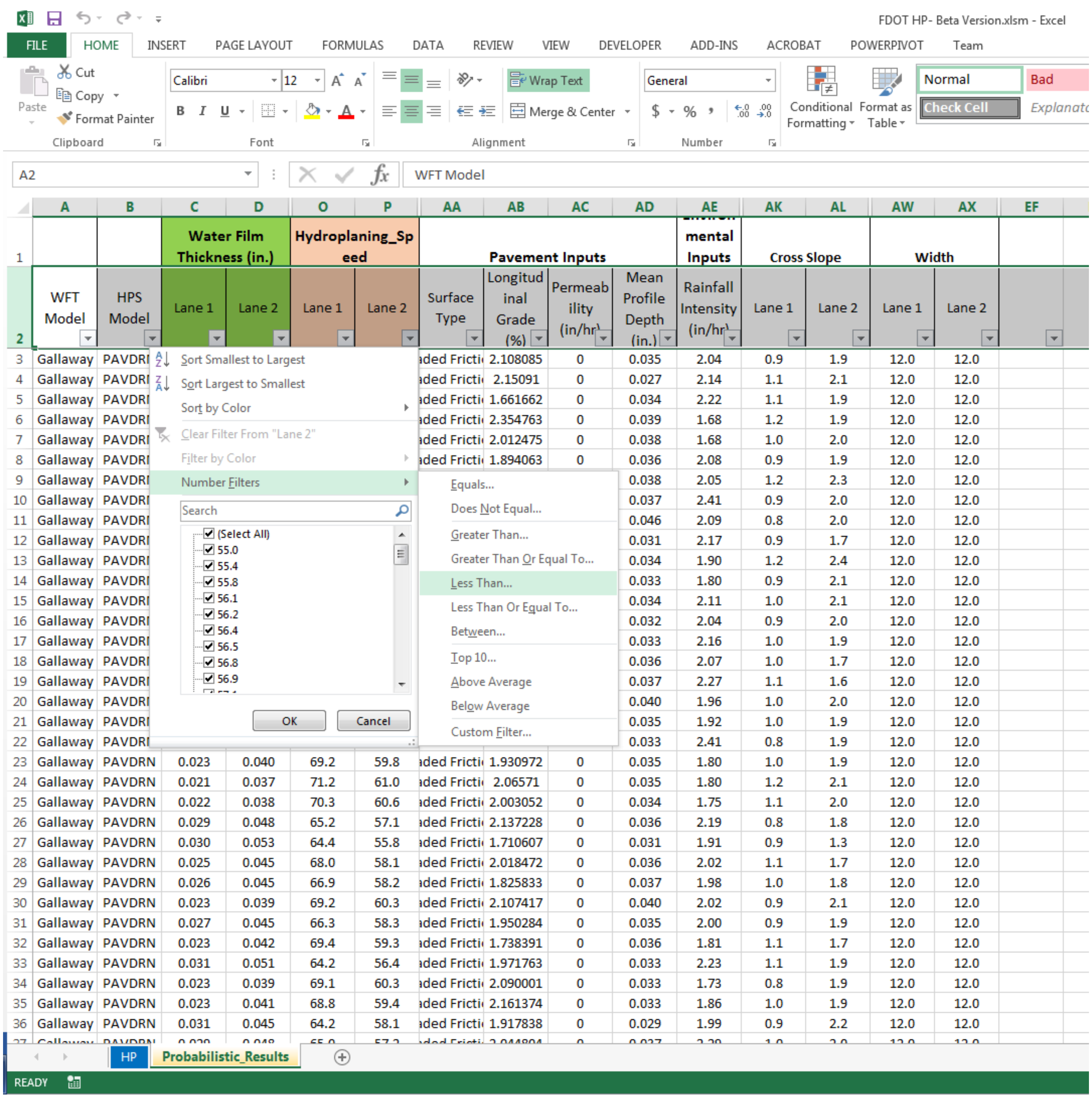
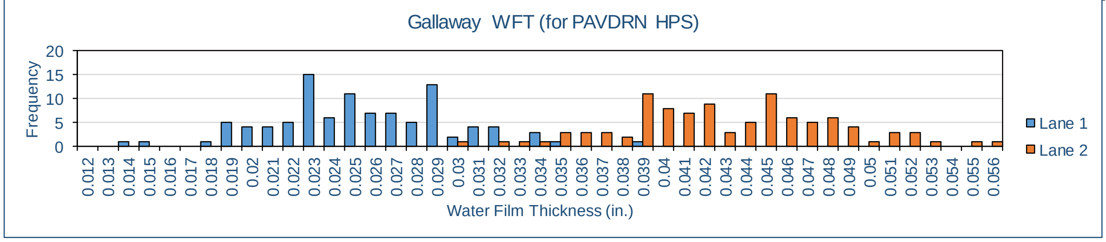


Figure B-31. Probabilistic analysis results

Probabilistic Analysis Results

Water Film Thickness (WFT) Results

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
HPS	WFT												
PAVDRN	Gallaway												
Mean (in.)		0.025	0.043										
Stdev (in.)		0.004	0.005										
COV (%)		17.4	12.1										



Hydroplaning Speed (HPS) Results

Plane Number		1	2	3	4	5	6	7	8	9	10	11	12
Description		Lane 1	Lane 2										
HPS	WFT												
PAVDRN	Gallaway												
Mean (mph)		68.0	59.1										
Stdev (mph)		3.2	1.9										
COV (%)		4.7	3.2										

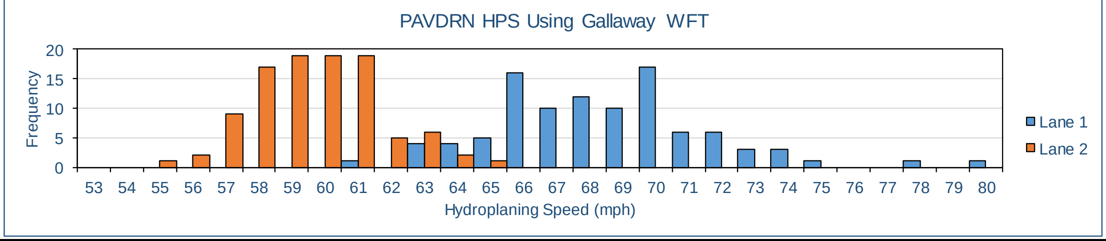


Figure B-32. Summary of probabilistic results