A Procedure for Modeling Tire Behavior on Wet Surfaces in HVE

by

William Blythe
William Blythe, Inc.

ABSTRACT

A method to account for tire-roadway friction changes due to wet road conditions is presented. The method is empirical and is based upon flat-bed tire test data. The procedure is being incorporated into the "hydroplaning" model in HVE, for use initially in SIMON and possibly later in EDSMAC4 and is known as the *Blythe-Day* model.

INTRODUCTION

Tire friction is reduced on wet surfaces. The lower limit of this reduction is full hydroplaning, with the tire supported by a water film and with essentially no contact between the tire and the underlying road surface. This change in tire-surface friction is not a step function, but rather a continuous decrease dependent upon several variables, including water depth, tread depth and speed, as well as tire tread design, tire construction details, tire contact patch dimensions (dependent on tire pressure and load) and road surface texture.

The procedure presented is limited to including the effects on tire-road friction due to speed, water depth and tread depth. A table look-up technique is employed, using data base or user-supplied empirical data relating tire longitudinal and lateral friction and effective cornering stiffness to water depth, tread depth and speed.

GENERAL DESCRIPTION

Tire-roadway friction has an obvious effect on vehicle dynamics. Wet roadway surfaces are a major contributor to reduced friction. The ability to model changes in tire-roadway friction during a simulation, as a vehicle tire encounters wet areas on the road, is highly desirable. To do this, it is necessary to model the wet surface and to have information on tire performance on a wet surface.

MODELING THE WET SURFACE

Obviously, to model water on the roadway requires information about the location and dimensions of the water area and the water depth. Water location and dimensions sometimes are available from photographs of the area of loss of control, or from records taken at the site. Water depth usually is changing fairly rapidly with time, and may only be able to be approximated. Hydrologic data (and hydrology experts) may be helpful in estimating water depth at particular locations at specific times.

The ability to model the wet surface is present in HVE Version 7. The terrain polygon database has been changed to include a terrain type "Water". Two water depth procedures are available: "static" and "dynamic".

If the water depth method selected (in the Environment Editor's Object Attributes dialog) is "dynamic", the user creates a water surface above the road surface, whose vertices are independent of the underlying road surface. The location and height of the vertices of the water surface allow any variation in location and depth of water to be modeled, and the water depth employed in the calculation is the difference in elevation between the water surface so constructed and the road surface under a tire at any time step.

If the water depth method selected is "static", the user still creates a water surface above the road surface, but a value for water depth is input, in the Environment Editor's Object Attributes dialog, for each polygon or group of polygons of that water surface, and that input water depth is used whenever a tire is on that particular polygon or group of polygons, *regardless* of the actual distance of the constructed water surface above the road surface.

In each case, the program utilizes the water depth under each tire at each integration time step and searches tables for the appropriate friction and effective cornering stiffness values, based upon the speed and tread depth of the tire.

FLAT-BED TIRE TEST DATA

Flat-bed wet-surface tire tests on passenger car tires were conducted at Calspan Corporation, Buffalo, New York, in 2000-2001, in 2008 and also in 2010. These tests have been reported in [1] and [2]. The results of these tests are the basis for the data-base-supplied tables used in the look-up procedure. A user may supply data in tabular form as well[1].

The tires tested are illustrated in Figures 1 and 2.

Figure 1: Tread Configuration

Both braking and cornering tests for normalized longitudinal and lateral friction forces were conducted. Effective cornering stiffness also was evaluated. Variables were water depth, tread depth and speed.

Friction variations in braking and in cornering due to water and tread depth have been found to be very similar [1].

[1] It is desirable, of course, to have test data, such as that reported here, for the specific tires in question in a particular investigation. The data given, however, are considered to be typical of the general behavior of tires under wet conditions. See [1].

The specific tires tested are identified in Table 1. The tire preparation procedures are detailed in the references [1, 2]. The desired tread depths were obtained by shaving on an Amermac Tire Truer. Before testing each tire was subjected to a warm-up period of three minutes at 50 mph under the specified vertical load of 800 pounds.

A typical graph of flat-bed test results for lateral friction is shown in Figure 3. The tires represented here are Michelin Symmetry. These results are tabulated in Table 2.

Michelin Destiny
Figure 2: Tread Configuration

Brand	Model	Size
Michelin	Symmetry	P215/75R15
Michelin	Destiny	P205/70R15
Michelin	Destiny	P205/65R15
Michelin	Destiny	P205/60R15

Table 1: Tires Tested

Typical results for effective cornering stiffness are shown in Figure 4 and are tabulated in Table 3. These results also are for the Michelin Symmetry tire.

Similar results for longitudinal peak and slide friction for the same tires are presented in Figures 5 and 6 and in Tables 4 and 5.

Longitudinal peak and slide friction test values, as well as lateral peak friction and effective cornering stiffness values, are available for water depths of 0.15, 0.10 and 0.05 inches [1]. Lateral peak friction values and cornering stiffness values are available for water depths of 0.04, 0.03, 0.02 and 0.01 inches [2]. Data similar to those presented in Tables 2, 3, 4 and 5 will be incorporated into the data base to be available in HVE.

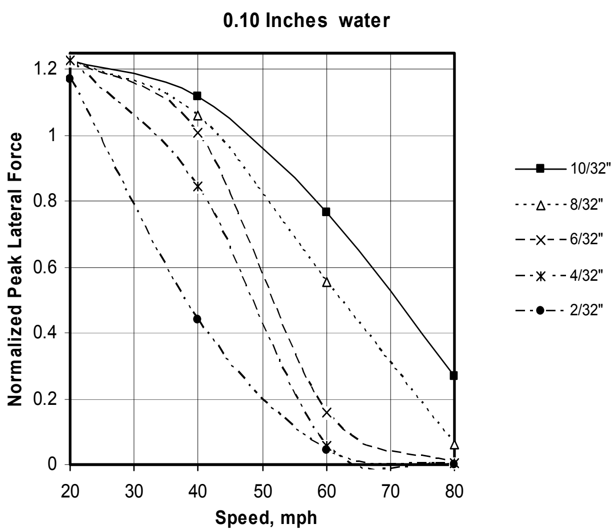

Figure 3: Lateral Friction, Michelin Symmetry

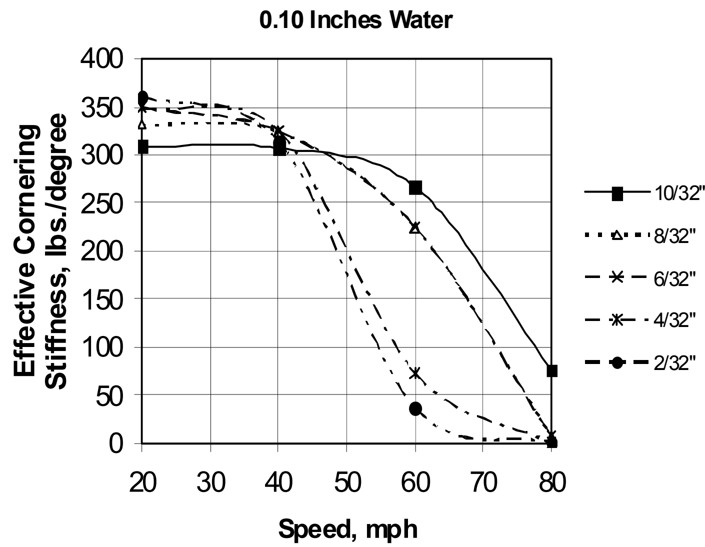

Figure 4: Effective Cornering Stiffness, Michelin Symmetry

Speed, mph	Tread Depth, Inches	Lateral Friction
20	2/32	1.17
	4/32	1.23
	6/32	1.23
	8/32	1.23
	10/32	1.23
40	2/32	0.44
	4/32	0.84
	6/32	1.01
	8/32	1.06
	10/32	1.12
60	2/32	0.04
	4/32	0.06
	6/32	0.16
	8/32	0.56
	10/32	0.76
80	2/32	0
	4/32	0
	6/32	0.01
	8/32	0.06
	10/32	0.27

Table 2: Lateral Friction (from Fig. 3)

Speed, mph	Tread Depth, Inches	Effective Cornering Stiffness, lbs./deg.
20	2/32	361
	4/32	349
	6/32	349
	8/32	332
	10/32	309
40	2/32	314
	4/32	325
	6/32	325
	8/32	324
	10/32	307
60	2/32	37
	4/32	73
	6/32	225
	8/32	225
	10/32	267
80	2/32	1
	4/32	0
	6/32	7
	8/32	7
	10/32	76

Table 3: Effective Cornering Stiffness (from Fig. 4)

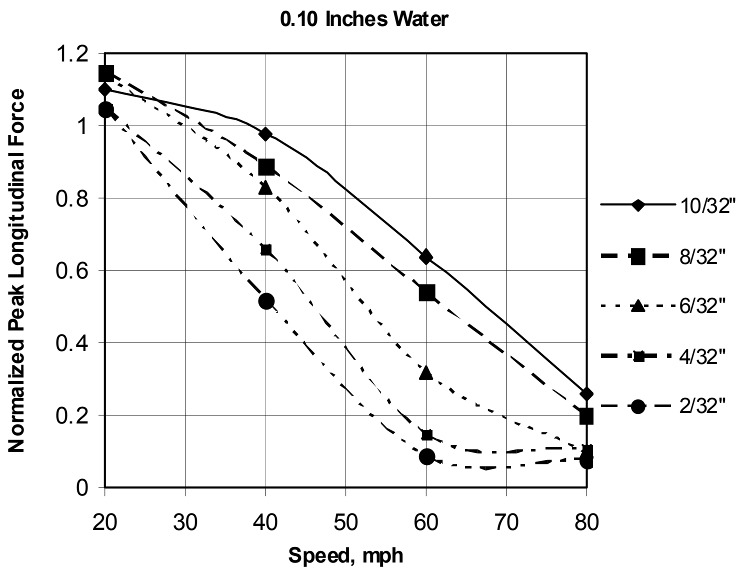

Figure 5: Peak Longitudinal Friction, Michelin Symmetry

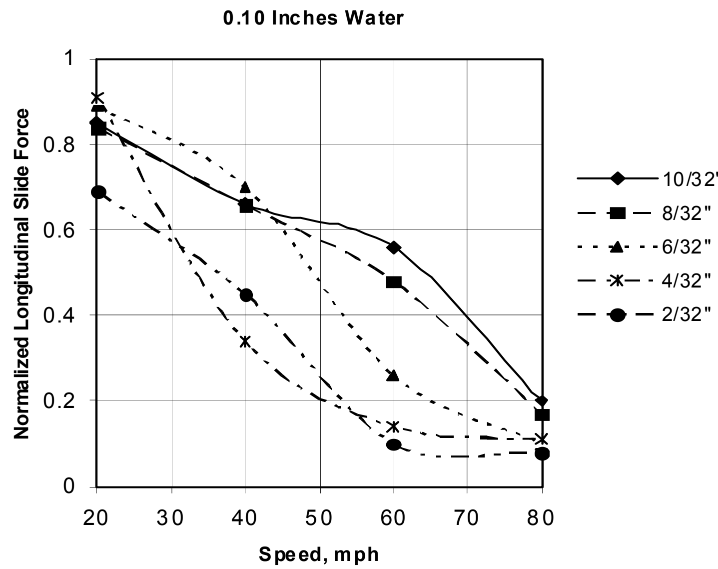

Figure 6: Longitudinal Slide Friction, Michelin Symmetry

Speed, mph	Tread Depth, Inches	Friction
20	2/32	1.05
	4/32	1.05
	6/32	1.14
	8/32	1.15
	10/32	1.10
40	2/32	0.52
	4/32	0.66
	6/32	0.83
	8/32	0.89
	10/32	0.98
60	2/32	0.09
	4/32	0.15
	6/32	0.32
	8/32	0.54
	10/32	0.64
80	2/32	0.08
	4/32	0.11
	6/32	0.10
	8/32	0.20
	10/32	0.26

Table 4: Peak Longitudinal Friction (from Fig. 5)

Speed, mph	Tread Depth, Inches	Friction
20	2/32	0.69
	4/32	0.91
	6/32	0.89
	8/32	0.84
	10/32	0.85
40	2/32	0.45
	4/32	0.34
	6/32	0.70
	8/32	0.66
	10/32	0.66
60	2/32	0.10
	4/32	0.14
	6/32	0.26
	8/32	0.48
	10/32	0.56
80	2/32	0.08
	4/32	0.11
	6/32	0.10
	8/32	0.17
	10/32	0.2

Table 5: Longitudinal Slide Friction (from Fig. 6)

Figure 7: The Test Surface

The test surface of the flat-bed tire test machine is rather aggressive. A photograph is given in Figure 7. It is 80 grit polycut Regalite, manufactured by 3M Corporation.

This material is a polyester with ceramic particles that are controlled in size and shape by the manufacturer in a patented process. The skid number (SN) [4] of this material dry is in the range 80 to 85.[2] Skid numbers for well-textured, dry pavement typically will be in the range of 70 and above [5].[3]

The expected dry-surface friction at the tire-roadway interface for any particular roadway, as always, must be estimated by the analyst, and the "in-use" factor for the tires, or the basic dry-surface tire friction data, must be adjusted accordingly in the HVE vehicle editor.

THE COMPUTATIONAL PROCEDURE

At this time (March, 2010) work is proceeding on the implementation of this process. When completed, it is expected generally to follow the description given below.

First, the user will enter the individual tire *average* tread depth in the Vehicle Editor. Next, in the Environment Editor, the water surface is established, either by the *dynamic* or the *static* method, as briefly described earlier. Then, in the Event Editor from the Options Menu the user chooses *Calculation Options* and selects the *Blythe-Day Hydroplane Model.*

OBTAINING TIRE-SURFACE FRICTION AT ANY TIME-STEP

Data-base tables like the examples presented here will be available for discrete water depths as previously listed. See the Appendix for additional data. The user may insert values in such tables to provide data similar to that contained in the data base, if such data are available, similar to the user-constructed steer, throttle and brake tables currently available. HVE, at each time step, will determine the water depth under each tire and go to the appropriate table for the friction factor (both longitudinal and lateral) and the cornering stiffness applicable, based upon tire tread depth and the speed at that moment.

Linear interpolation will be used for values of water depth, tread depth and speed not explicitly available in the tables.

Lateral and longitudinal friction values will be combined by a friction circle based on the tire slip angle, as is done presently.

CONSIDERATION OF "FOLLOWING" TIRES

An issue not fully addressed in research to date is the potential for following tires to see less water depth than leading tires, due to possible "clearing" of water by the leading tires. See, for example, reference [3].

Water clearing is not accounted for currently in this proposed procedure. The following discussion is intended to raise awareness of this issue, and to give some indication of its possible effect.

For essentially straight travel, where tires are tracking, it is likely that water clearing decreases with decreasing initial water depth, since, at zero water depth the reduction for following tires would be zero. A reasonable first-order approximation *may be* that the percent reduction in water depth for following tires is linear with initial water depth.

For example, if, at an initial water depth d_1 of 0.40 inches, tests indicate that a following tire may have the same friction as if on a dry surface [3], then the percent reduction in water depth for a following tire might be $\frac{d_1}{0.40}(100)$. This is illustrated in Figure 8.

[2] Personal communication: David Gentz, Tire Research Facility (TIRF), Calspan Corporation, Buffalo, New York.
[3] Skid numbers typically are reported at 40 mph.

Then, subtracting this reduction ratio from the initial water depth, the effective water depth at a following tire (d_2) might be approximated as

$$d_2 = d_1(1 - \frac{d_1}{0.40}) = d_1 - 2.5d_1^2$$

where d_1, the initial water depth, is always ≤ 0.40. Then $d_2 = 0$ when $d_1 = 0.40$ and $d_2 = 0$ when $d_1 = 0$.

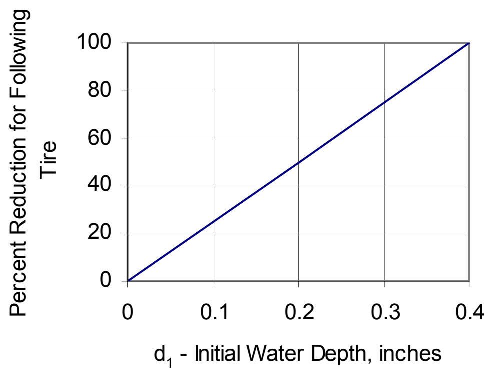

Figure 8: Possible Percent Reduction in Water Depth For Following Tire

In standard form, this parabola is

$$(d_1 - 0.2)^2 = 4(-0.1)(d_2 - 0.1)$$

where the focus is at (0.2, 0) and the vertex is at (0.2, 0.1).

This is illustrated in Figure 9.

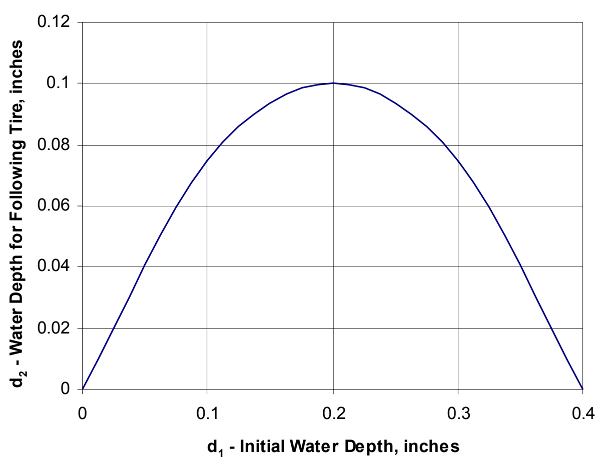

Figure 9: Possible Relation between Initial Water Depth and Water Depth for Following Tire

For example, if $d_1 = 0.10$ inches, then $d_2 = d_1(1 - \frac{1}{4}) = 0.10(.75) = 0.075$ inches, or a reduction of 25 percent. If $d_1 = 0.20$ inches, then $d_2 = d_1(1 - 0.5) = 0.2(.5) = 0.1$ inches, or a reduction of 50 percent.

In turns, water clearing likely decreases with decreasing track overlap, or increasing off-tracking. This might be accounted for by a term proportional to the off-tracking, added to the depth d_2 calculated above. For example, if $d_2^{'}$ is the water depth seen by the following tire when accounting for off-tracking, then

$$d_2^{'} = d_2 + (d_1 - d_2)C$$

where C is an off-tracking factor, being zero for no off-tracking and 1.0 for full off-tracking. Then $d_2^{'} = d_2$ when C = 0 and $d_2^{'} = d_1$ when C = 1.

Clearly, there likely also will be a velocity effect as well.[4] As speeds increase, below the front tire hydroplaning speed, the clearing effect of the front tires might be expected to be greater than at low speeds, where more time is available for water to return to the rear tire path after having been displaced by the front tires.

More research is needed to clarify the issue of path clearing by leading tires.

CONCLUSION

The procedure described herein is a work in progress. When implemented, HVE users will have at their disposal a tool to account for tire - wet surface decreases in friction leading up to and including hydroplaning[5], based upon empirical data. Either data-base values or user-supplied values can be the basis for calculation.

[4] The tests referred to above, from [3], were done at 40 mph.

[5] "Hydroplaning" is, for these tests, assumed to be equivalent to friction values below 0.10.

REFERENCES

1. Blythe, W. and Day, T., "Single Vehicle Wet Road Loss of Control; Effects of Tire Tread Depth and Placement", SAE International Technical Paper No. 2002-01-0553, SAE 2002 World Congress, March 4-7, 2002. Also in *Accident Reconstruction 2002*, SP-1666, pp. 161-185, SAE International.

2. Blythe, W., "Friction, Tread Depth and Water; Laboratory Investigations of Passenger Car Tire Performance under Minimally-wet Conditions", submitted for review. Expected to be published in 2010.

3. Metz, L.D., Kinney, J.R., Herling, D., "Realistic Rear Axle Hydroplaning during Forward Motion", SAE International Technical Paper No. 2006-01-1560, SAE 2006 World Congress, April 2006.

4. ASTM E-274-06, "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire," ASTM International, 100 Barr Harbor Drive, P.O. Box C-700, West Conshohocken, Pennsylvania 19428-2959.

5. Hegmon, R.R., "Tire-Pavement Interaction." SAE Technical Paper No. 870241, Society of Automotive Engineers, Annual Meeting, Detroit, Michigan, February, 1987

CONTACT

William Blythe, P.E., Ph.D.
William Blythe, Inc.
1545 University Avenue
Palo Alto, CA 94301-3140
650-323-2062
wbinc8831@sbcglobal.net

APPENDIX

A: DATA FOR 0.15 INCHES WATER DEPTH
All results are for Michelin Symmetry

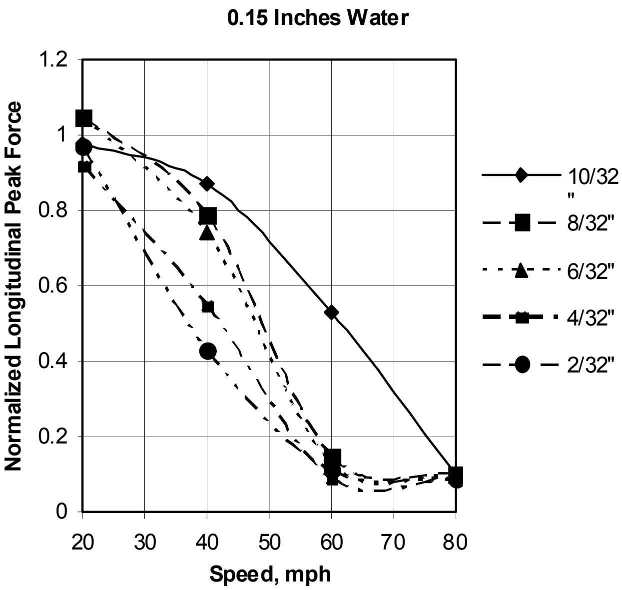

Figure A-1: Longitudinal Peak Friction

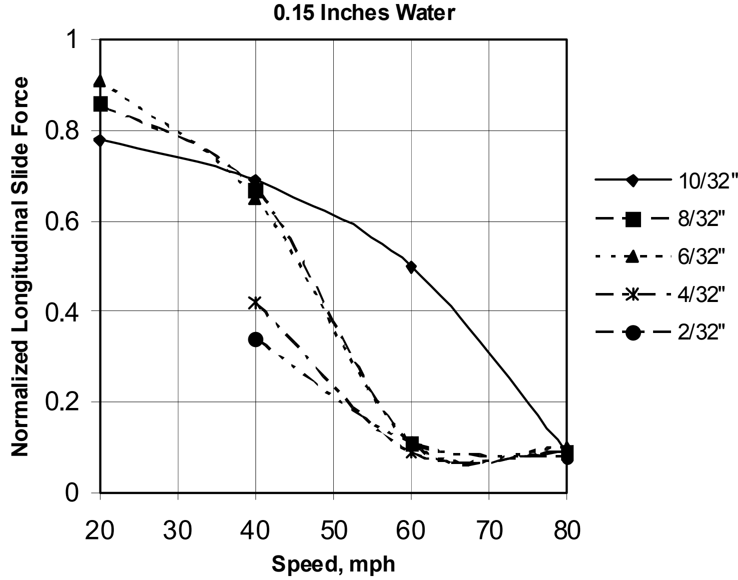

Figure A-2: Longitudinal Slide Friction

Speed, mph	Tread Depth, Inches	Friction
20	2/32	0.97
	4/32	0.92
	6/32	1.05
	8/32	1.05
	10/32	0.98
40	2/32	0.43
	4/32	0.55
	6/32	0.74
	8/32	0.79
	10/32	0.87
60	2/32	0.11
	4/32	0.09
	6/32	0.13
	8/32	0.15
	10/32	0.53
80	2/32	0.09
	4/32	0.09
	6/32	0.10
	8/32	0.10
	10/32	0.10

Table A-1: From Figure A-1

Speed, mph	Tread Depth, Inches	Friction
20	2/32	--
	4/32	--
	6/32	0.91
	8/32	0.86
	10/32	0.78
40	2/32	0.34
	4/32	0.42
	6/32	0.65
	8/32	0.67
	10/32	0.69
60	2/32	0.11
	4/32	0.09
	6/32	0.11
	8/32	0.11
	10/32	0.50
80	2/32	0.08
	4/32	0.09
	6/32	0.10
	8/32	0.09
	10/32	0.09

Table A-2: From Figure A-2

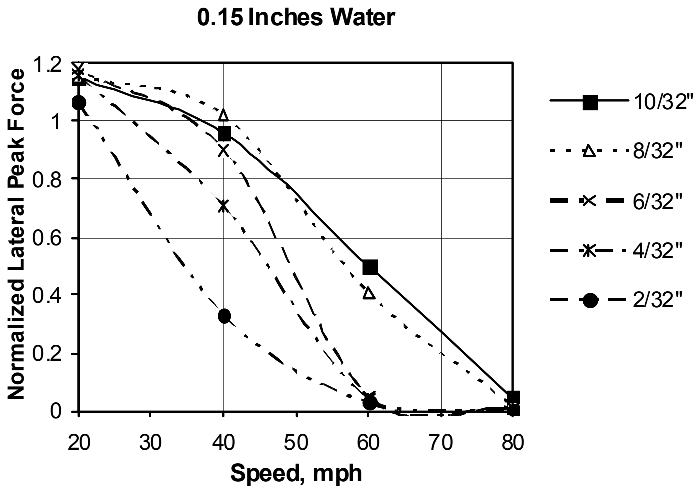

Figure A-3: Lateral Friction

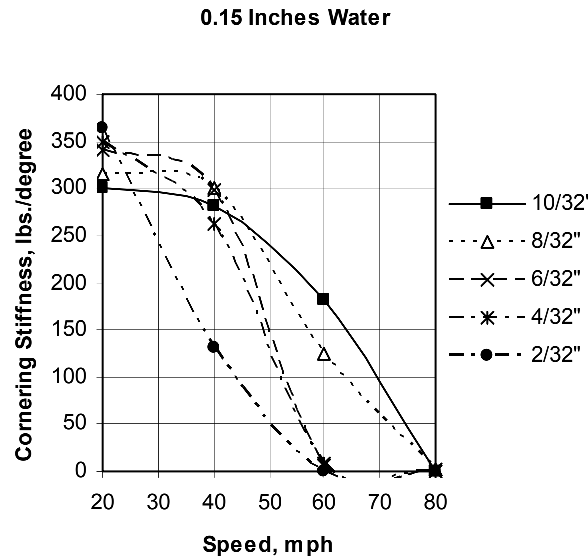

Figure A-4: Effective Cornering Stiffness

Speed, mph	Tread Depth, Inches	Lateral Friction
20	2/32	1.07
	4/32	1.16
	6/32	1.18
	8/32	1.16
	10/32	1.15
40	2/32	0.33
	4/32	0.71
	6/32	0.90
	8/32	1.02
	10/32	0.96
60	2/32	0.03
	4/32	0.04
	6/32	0.05
	8/32	0.41
	10/32	0.50
80	2/32	0.00
	4/32	0.01
	6/32	0.01
	8/32	0.02
	10/32	0.05

Table A-3: From Fig. A-3

Speed, mph	Tread Depth, Inches	Cornering Stiffness, lbs./degree
20	2/32	365
	4/32	350
	6/32	340
	8/32	316
	10/32	300
40	2/32	131
	4/32	262
	6/32	299
	8/32	300
	10/32	281
60	2/32	0
	4/32	8
	6/32	6
	8/32	124
	10/32	181
80	2/32	1
	4/32	0
	6/32	2
	8/32	2
	10/32	1

Table A-4: From Fig. A-4

B. DATA FOR 0.05 INCHES WATER DEPTH
All results are for Michelin Symmetry

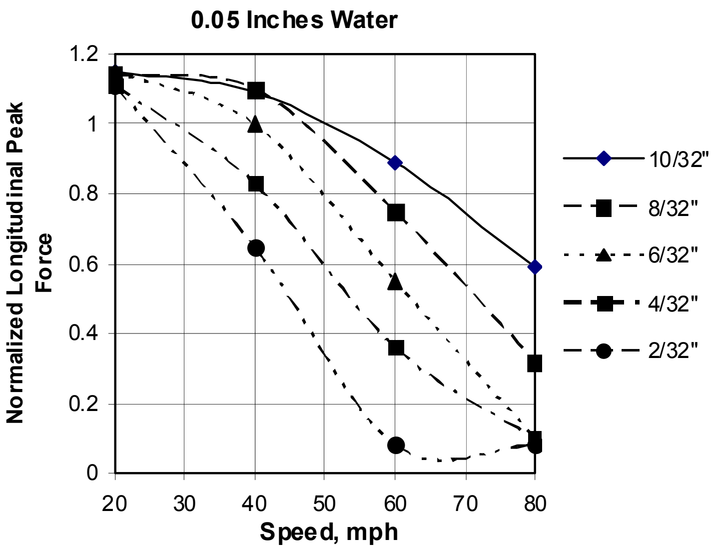

Figure B-1: Longitudinal Peak Friction

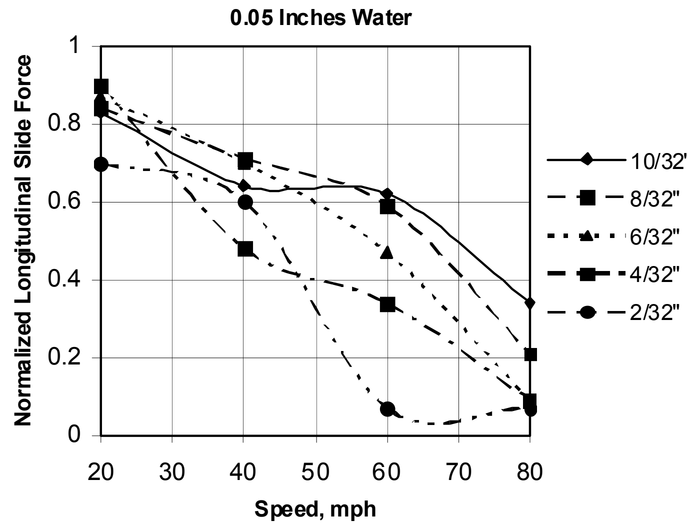

Figure B-2: Longitudinal Slide Friction

Speed, mph	Tread Depth, Inches	Friction
20	2/32	1.11
	4/32	1.11
	6/32	1.15
	8/32	1.14
	10/32	1.15
40	2/32	0.65
	4/32	0,83
	6/32	1.0
	8/32	1.11
	10/32	1.15
60	2/32	0.08
	4/32	0.36
	6/32	0.55
	8/32	0.75
	10/32	0.89
80	2/32	0.08
	4/32	0.10
	6/32	0.10
	8/32	0.32
	10/32	0.59

Table B-1: From Fig. B-1

Speed, mph	Tread Depth, Inches	Friction
20	2/32	0.70
	4/32	0.90
	6/32	0.87
	8/32	0.84
	10/32	0.83
40	2/32	0.60
	4/32	0.48
	6/32	0.70
	8/32	0.71
	10/32	0.64
60	2/32	0.07
	4/32	0.34
	6/32	0.47
	8/32	0.59
	10/32	0.62
80	2/32	0.07
	4/32	0.09
	6/32	0.09
	8/32	0.21
	10/32	0.34

Table B-2: From Fig. B-2

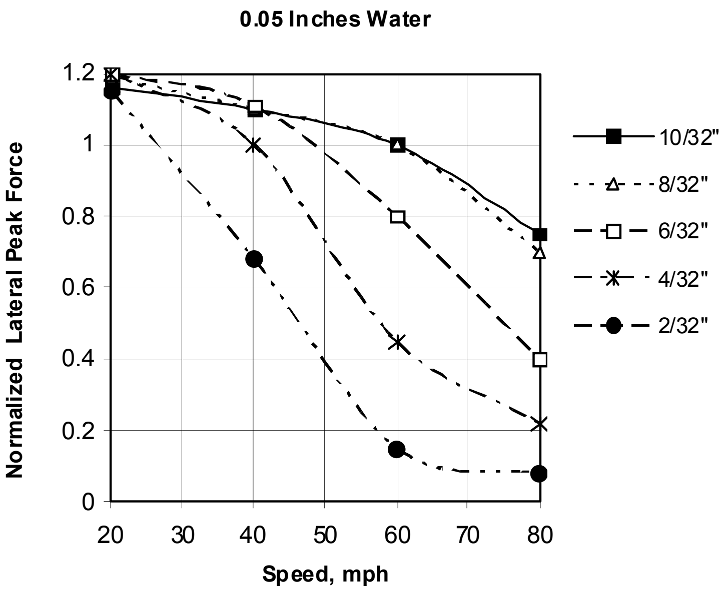

Figure B-3: Lateral Friction

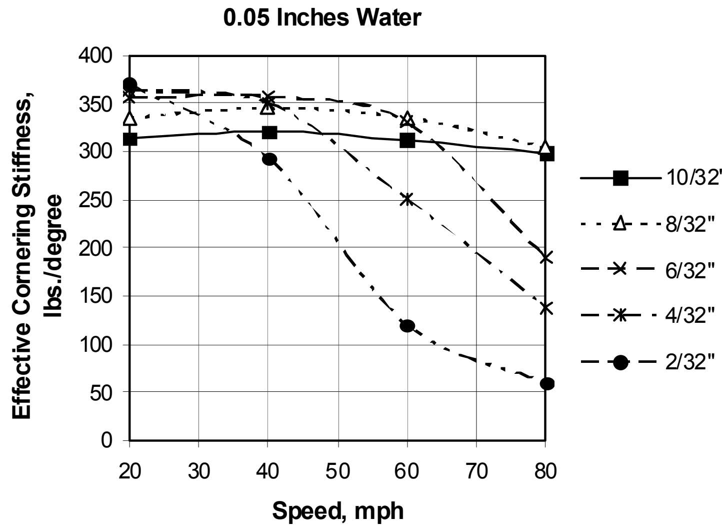

Figure B-4: Effective Cornering Stiffness

Speed, mph	Tread Depth, Inches	Lateral Friction
20	2/32	1.15
	4/32	1.20
	6/32	1.20
	8/32	1.19
	10/32	1.16
40	2/32	0.68
	4/32	1.00
	6/32	1.11
	8/32	1.10
	10/32	1.10
60	2/32	0.15
	4/32	0.45
	6/32	0.80
	8/32	1.0
	10/32	1.0
80	2/32	0.08
	4/32	0.22
	6/32	0.40
	8/32	0.70
	10/32	0.75

Table B-3: From Fig. B-3

Speed, mph	Tread Depth, Inches	Cornering Stiffness, lbs./degree
20	2/32	370
	4/32	364
	6/32	356
	8/32	335
	10/32	314
40	2/32	293
	4/32	350
	6/32	357
	8/32	345
	10/32	321
60	2/32	120
	4/32	251
	6/32	331
	8/32	335
	10/32	312
80	2/32	60
	4/32	138
	6/32	190
	8/32	305
	10/32	298

Table B-4: From Fig. B-4