2006-01-0559

Measurement and Modeling of Tire Forces on a Low Coefficient Surface

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Abstract

There exists a fairly extensive set of tire force measurements performed on dry pavement. But in order to develop a low-coefficient of friction tire model, a set of tire force measurements made on wet pavement is required. Using formulations and parameters obtained on dry roads, and then reducing friction level to that of a wet road is not sufficient to model tire forces in a high fidelity simulation. This paper describes the process of more accurately modeling low coefficient tire forces on the National Advanced Driving Simulator (NADS). It is believed that the tire model improvements will be useful in many types of NADS simulations, including ESC and other advanced vehicle technology studies.

In order to produce results that would come from a road surface that would be sufficiently slippery, a set of tires were shaved to 4/32 inches and sent to a tire-testing lab for measurement. Shaving a tire does not produce the same effects that would come about by allowing a tire to wear down to 4/32 inches through normal use. However, for this study, only the coefficient of friction needed to be reduced. The aging effects of rubber are ignored. Tire forces were measured on a tire test machine, using a water-coated surface to approximate the frictional properties of wet pavement. These tests, which included cornering, braking, and driving, were performed at five loading conditions. They showed a decrease in tire effective lateral stiffness as well as a drop in longitudinal force as the tire speed increased. The data set from these tests was used to create a tire model for a dynamic simulation. The paper concludes by displaying the model's longitudinal and lateral forces versus loading condition and tire slip angle.

Introduction

The purpose of this research was to develop a low coefficient of friction tire model. The model was used on the National Advanced Driving Simulator (NADS) for a study to investigate the safety benefits of Electronic Stability and Control (ESC) systems. The research was not to develop ESC systems, but rather to use an existing ESC system to study drivers' performances from a human factors perspective. The low coefficient of friction tire model was needed to increase the incidences of ESC activation as test subjects drove through the various NADS scenarios. The vehicle modeled was a 2002 Oldsmobile Intrigue with Goodyear Eagle RSA P225/60R16 tires. To make the NADS study realistic and useful, the vehicle dynamics model must be of high fidelity; that is, the physics predicted through the simulation should be very close to real-world experiences.

NADS vehicle dynamics have been validated with various vehicles (1994 Ford Taurus, 1998 Chevrolet Malibu, 1997 Jeep Cherokee, and 1991 GM-Volvo heavy truck with 1992 Fruehauf trailer), but not with cases involving low coefficients of friction, like driving on wet roads and ice. In order to properly model the low coefficient surface, tire tests were performed under low friction conditions. Modeling tire mechanics for vehicle dynamics relies heavily on tire testing, and most models are dominated by empirical formulations.

Using formulations and parameters obtained on dry roads, and then simply scaling the friction level and associated forces and moments to that of a lower coefficient road, is not sufficient to accurately replicate tire forces, particularly when the vehicle is operating at highway speeds. Therefore, this research involved measuring tire forces at different speeds on a low friction, wet test surface, and to developing a tire model with speed dependency. The tire model based on these measurements provides realistic forces in the linear and nonlinear range, and the peak friction is at a level where ESC engages during driving tasks specified by the NADS ESC study testing protocol.

For the NADS ESC study, the goal was to have the peak tire coefficient of friction be less than 0.6 to ensure ESC activation. This condition can be produced in the "tire-laboratory" with a shaved tire running on a wet test surface. Variations of tread depth, water depth, tire pressure, tire construction, surface texture, and tread patterns were not addressed. These properties were fixed for this study, and speed was the only parameter affecting tire-force generation capabilities that was varied. Wet tire testing was performed at the CALSPAN Tire Research Facility (TIRF). The tire test conditions specified were selected to provide a peak tire coefficient of friction of about 0.5 at 50 mph, with decreasing friction as speed increases. The tire model was developed based on TIRF data with speed-dependent properties like peak coefficient of friction and effective lateral and longitudinal stiffnesses.

The tire data presented were obtained on a flatbed test machine, so variations in roadway micro and macro textures, which are a significant factor in real world tire performance on wet roads, were not accounted for in this study. Open road macro-texture facilitates gross drainage and micro-harshness produces sharp points that can penetrate the remaining water film. Nonetheless, the tire measurements made were quite useful for the purpose of developing the low friction tire model.

The tire model developed in this research was used with the existing Oldsmobile Intrigue model for the NADS ESC study. The low friction model simulation predictions were compared and validated with vehicle field experiments on the wet Jennite surface with ASTM-measured peak and sliding friction values of 40-45 and 15-20 respectively, at the Transportation Research Center, Inc. (TRC). Likewise, simulation predictions using the normal tire model were validated using vehicle field tests on the dry asphalt surfaces at TRC. For the case of the wet Jennite, slight adjustments of the peak coefficient of friction were made to narrow the differences between simulation predictions and field measurements. The validation procedures and results will be documented separately.

Figure 1 was generated from data compiled by Blythe and Day [1] from wet tire testing that was performed at the CALSPAN Tire Research Facility (TIRF). We used the graph in Figure 1 to select the tread depth (4/32"). Figure 2 shows peak longitudinal coefficient of friction data from the 4/32" tread depth tire. The curves in Figure 2 bound our target peak friction value of about 0.5 at 50 mph. We selected a water depth of 0.05" for our tests, with the expectation that we would get similar peak longitudinal force values from our tests, suiting the needs of our driving simulator research. A tread depth of 4/32" represents a moderately well worn tire. NHTSA studies have indicated that the average tread depth for in-service tires, based on measurements made on 11,530 vehicles, to be 7/32" [2]. Shaving a tire does not produce the same effects that would come about by allowing a tire to wear down to 4/32 inches through normal use. However, for this study, only the coefficient of friction needed to be reduced.

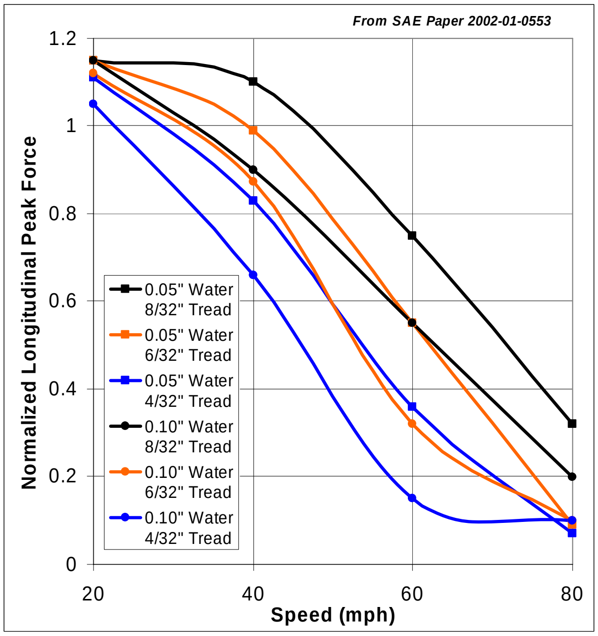

Figure 1. Peak Longitudinal Coefficient of Friction

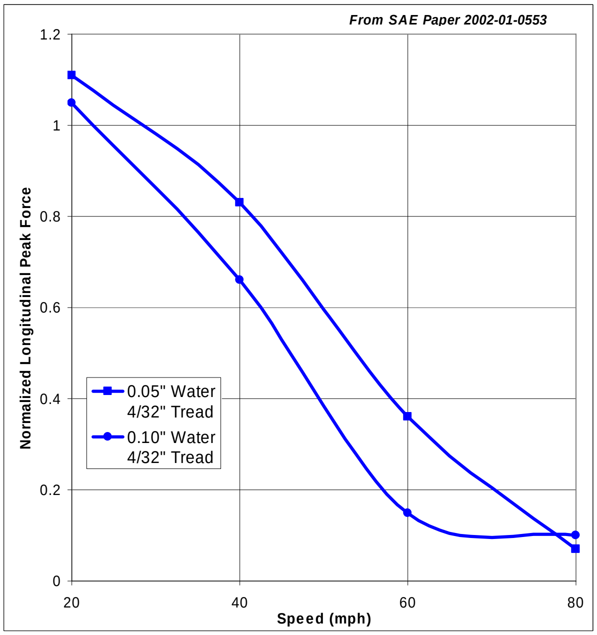

Figure 2. Peak Longitudinal Coefficient of Friction

Tire Testing

The testing included wet and dry cambering, cornering, and braking/driving test procedures. The wet and dry test programs included four test procedures: two free rolling test procedures (one cambering and one steering) and two braking/driving test procedures (one straight-line and one combined with steering). The tires used were all shaved to a tread depth of 4/32", and all had the same DOT number as indicated on Table 1. A constant water depth of 0.050" and regulated test inflation pressure of 34 psi were used throughout the test program. Each wet test was performed at four velocity conditions of 30, 45, 60 and 75 mph. All of the dry tests were performed at a single velocity of 30 mph. A reference load of 1150 lbs was used for the entire test program. The maximum test load was 200% of the reference, or 2300 lbs. Figure 3 shows a test in progress.

Table 1. Tires For CALSPAN Testing

Goodyear Eagle RSA P225/60R16 All Tires Shaved to 4/32" Tread Depth All Tire Pressures at 34 psi		
Tire No.	**Reference**	**Description**
1	GY1381-DOT4304	Testing
2	GY1382-DOT4304	
3	GY1383-DOT4304	
4	GY1384-DOT4304	
5	GY1380-DOT2404	Reserve

Figure 3. Tire Test at CALSPAN

The testing included 16 wet runs and 4 dry runs as follows:

Discrete Cambering At Zero Slip Angle
Inclination angles: -10, -8, -6, -4, -2, 0, 2, 4, 6, 8 and 10°
Normal loads: 40, 80, 120, 160 and 200% of reference load.

Wet test speeds: 30, 45, 60 and 75 mph (4 tests)
Dry test speed: 30 mph (1 test)

Quasi-Static Steering / Cornering
Inclination angle: 0°
Slip angle sweep: 0 to -20 to +20 to 0° at a rate of 3 deg/sec
Normal loads: 40, 80, 120, 160 and 200% of reference load.

Wet test speeds: 30, 45, 60 and 75 mph (4 tests)
Dry test speed: 30 mph (1 test)

Quasi-Static Braking / Driving
Inclination angle: 0°
Slip ratio sweep: 0 to -50% to +50% to 0
Ramp time (0 to 50%) of 1.5 sec
Normal loads: 40, 80, 120, 160 and 200% of reference load.

Wet test speeds: 30, 45, 60 and 75 mph (4 tests)
Dry test speed: 30 mph (1 test)

Quasi-Static Combined Steering / Braking / Driving
Inclination angle: 0°
Normal loads: 100% of reference load.
Steady state slip angles: -6, -4, -2, 0, 2, 4, and 6°
Slip ratio sweep: 0 to -50% to +50% to 0
Ramp time (0 to 50%) of 1.5 sec
Wet test speeds: 30, 45, 60 and 75 mph (4 tests)
Dry test speed: 30 mph (1 test)

Fundamental Mechanical Tire Properties

The tire model used in this research is a modified version of the Systems Technology, Inc. tire model [3, 4]. The tire model parameters are obtained at four different speeds: 30, 45, 60, and 75 mph. Linear interpolation of basic tire properties was performed to generate values between these speeds. Using linear interpolation of the peak coefficient of friction and effective stiffnesses will be shown to give good approximations and be a valid approach. The tire stiffness on wet roads at different speeds is basically the effective stiffness, and decreases as speed increases on wet roads due to hydroplaning effects, and it is not due to tire rubber/carcass structure.

At low speed, the presence of water affects the boundary conditions of the tire contact surface. This is a boundary layer lubricated frictional contact that produces a lower coefficient of friction when compared to dry contact. Yet the frictional force is fairly large, and the differences between dry and wet tire forces are not large. As speed increases, the front edge of the tire starts to ride on a film of fluid. This film is formed due to inertia and viscosity-induced retardation of water displacement. With a further increase in speed, the fluid film extends backward into the contact area, as shown in Figure 4. This phenomenon is very similar to elastohydrodynamic lubrication, a terminology used in tribology science to refer to rolling bodies in contact. At a particular speed, the fluid film extends to cover the entire contact area, and the tire consequently makes no direct contact with the surface, and the normal force is totally born by fluid pressure. The tangential shear force from water film is small. Fluids like water do not sustain shear forces comparable to direct tire contact and tire asperity deformation. Their viscous nature is not strong enough.

The loss of shear force capabilities at high speed on flooded roads is referred in vehicle dynamics as tire hydroplaning. It is a process where water acts like a bearing between the road and the tire contact area. Tread pattern and surface macro and micro texture are very important in wet surface contact. The surface used for this project at CALSPAN is coated with 3M 80-grit-polycut sandpaper. This surface texture is different from road surfaces and the concrete surface used at TRC. Therefore, adjustments and caution should be used when using CALSPAN data to validate field dynamic tests, in particular when tire forces are close to saturation, or in sliding mode.

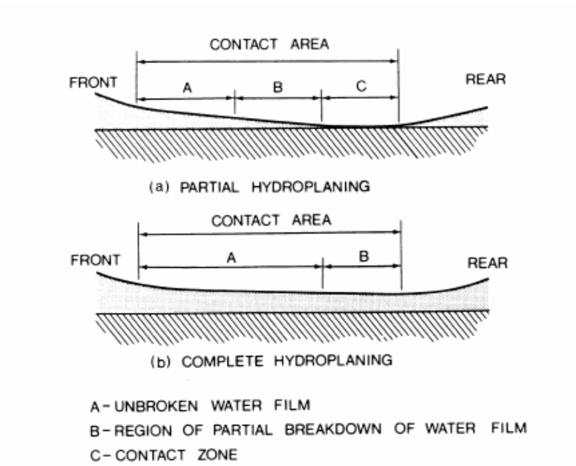

Figure 4. Hydroplaning of a Tire on a Flooded Surface [5]

The goal of this research is not to simulate complete hydroplaning of four tires, but to simulate conditions that vary from boundary wet friction to partial hydroplaning. The partial hydroplaning should be enough to activate ESC, which will demonstrate its vital role in maintaining vehicle stability.

Tire Coefficients

Figure 5 shows the measured peak lateral coefficient of friction at different test speeds, and Figure 6 shows the measured peak longitudinal coefficient of friction (A problem related to the quality of the TIRF belt control occurred during the 45-mph longitudinal test, so data from this test was not used.) The symbols on the graphs indicate the measured data points, while the curves represent the tire model based on curve fits of the test data. The longitudinal peak coefficient of friction values shown in Figure 5 compare well with the targeted range shown in Figure 2.

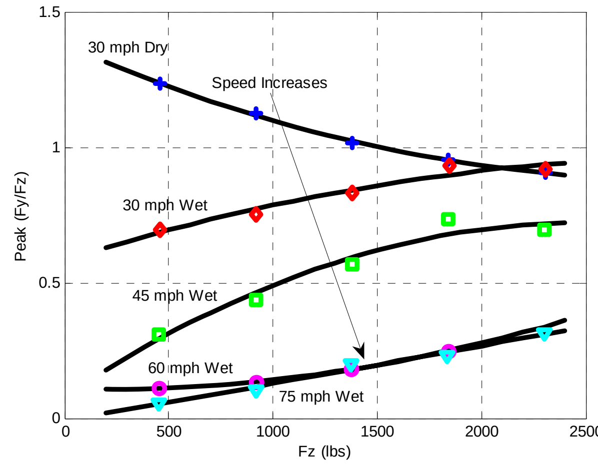

Figure 5. Lateral Peak Coefficient of Friction

For the longitudinal data measured at CALSPAN we encountered the following drawbacks:

At the higher test speeds, longitudinal forces increase as slip ratio increases up to a maximum force at full sliding. Current research and tire/wet road testing do not indicate this phenomenon. This might be due the surface texture of the surface used on the CALSPAN TIRF.

The test conditions are not precisely defined for different vertical loads. The TIRF machine was controlled with a longitudinal slip formulation that uses the ratio of wheel spin velocity, based on the tire free-rolling radius determined during the lightest vertical load, to belt speed. The tire free-rolling radius was not updated for different loads and as a result the longitudinal tire data has large longitudinal slip offsets.

The measured longitudinal stiffness values from all of the longitudinal tire testing were found to be considerably higher than expected for these wet and dry tests using shaved tires. Longitudinal stiffness values from the current wet and dry shaved tire testing were found to be about three times higher than longitudinal stiffness values for unshaved Goodyear Eagle P255/60R16 tires measured on a dry surface at a different facility.

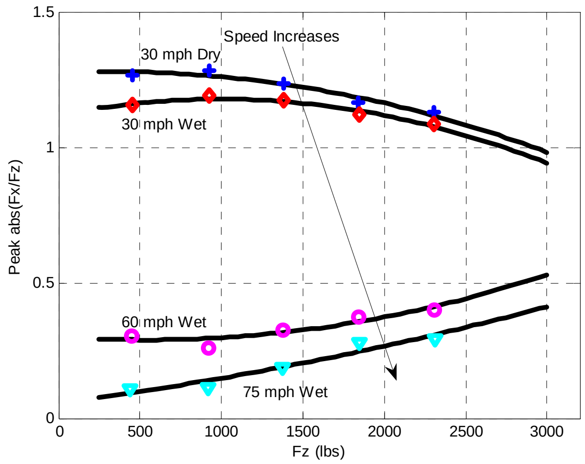

Figure 6. Longitudinal Peak Coefficient of Friction

The effective tire lateral stiffness at different speeds is shown in Figure 7, the effective aligning moment stiffness in Figure 8, and the effective overturning moment stiffness in Figure 9. Figures 10-11 show the lateral force and overturning moment inclination angle stiffnesses at all test speeds and vertical loads.

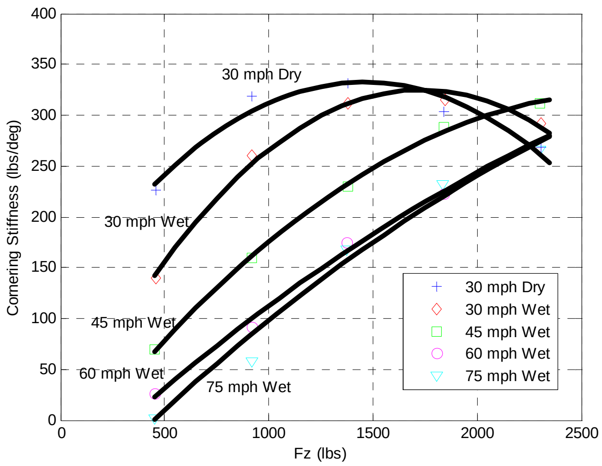

Figure 7. Effective Lateral Stiffness

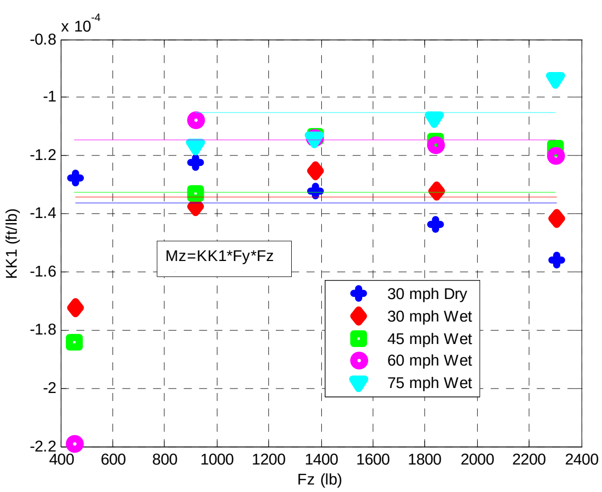

Figure 8. Effective Aligning Moment Stiffness

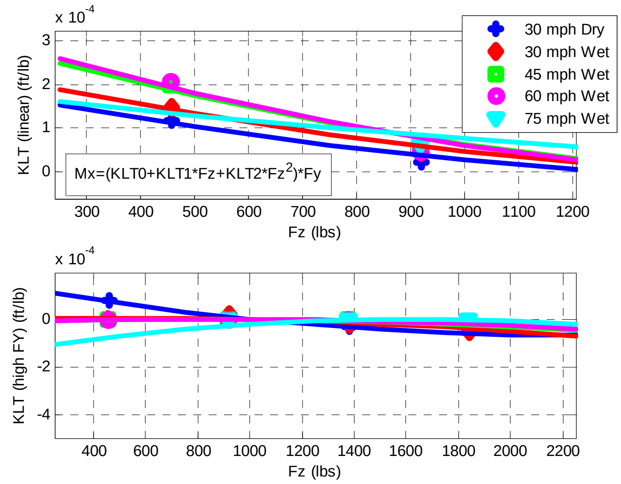

Figure 9. Effective Overturning Moment Stiffness

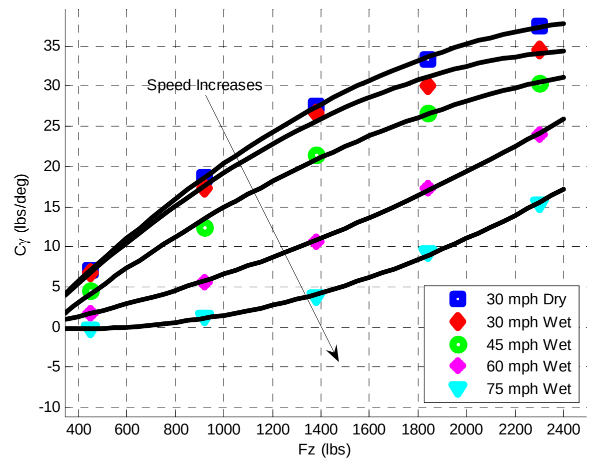

Figure 10. Lateral Force-Inclination Angle Stiffness

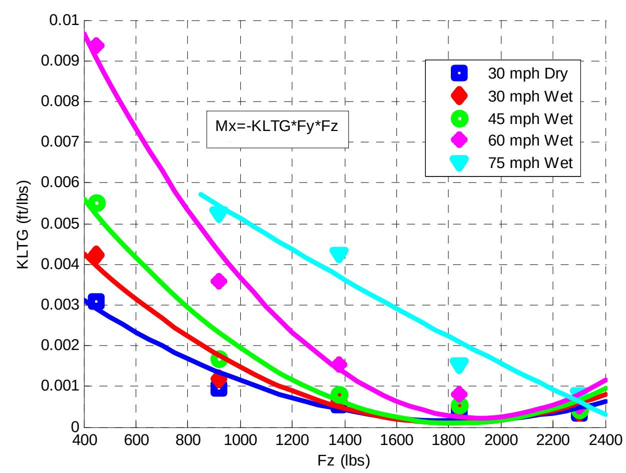

Figure 11. Overturning Moment-Inclination Angle Stiffness

The experimental tire data is fitted with the empirical STI saturation function given below, and the results for dry and wet conditions at 30 mph are shown in Figures 12 and 13.

$$f(\sigma) = \frac{\sqrt{\left(\frac{F_x}{\mu_x}\right)^2 + \left(\frac{F_y}{\mu_y}\right)^2}}{F_z}$$

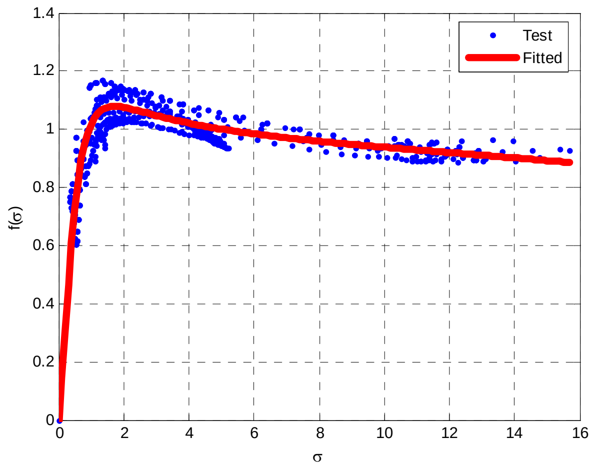

Figure 12. Saturation Function For Dry Tests (30 mph)

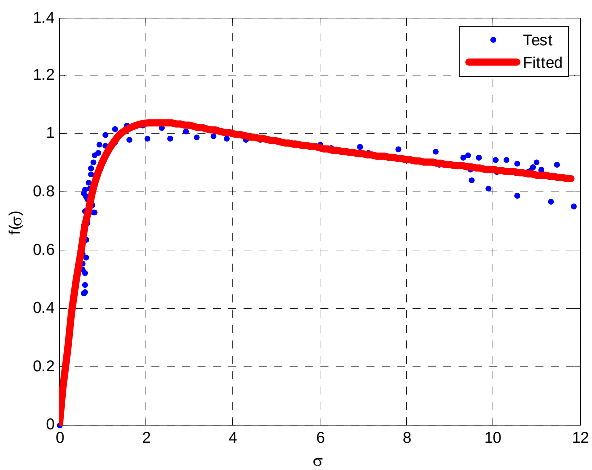

Figure 13. Saturation Function For Wet Tests (30 mph)

Wet peak and slide braking and cornering traction coefficients are reduced by increasing speed in an approximately linear manner as reported by Veith [6]. Our testing confirms this observation, and adds another dimension: that is; tire normal load variations. Polynomial fits were done for vertical load variations, and linear interpolation is used to account for speed variations.

Tire Model Verifications

Figures 14-18 show the measured and modeled lateral forces versus slip angle for the dry test (30 mph) and four wet tests done at different speeds (30, 45, 60, and 75 mph). (The 200% rated load data was not used for the 60 mph wet test.) Overall, the model does a good job of predicting the peak forces and linear range stiffnesses for all conditions, and a decent job of modeling the forces when the tires reach high slip angles.

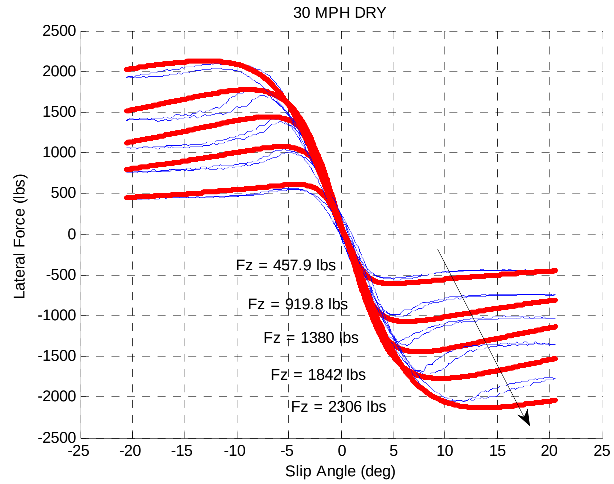

Figure 14. Lateral Forces at 30 mph Dry

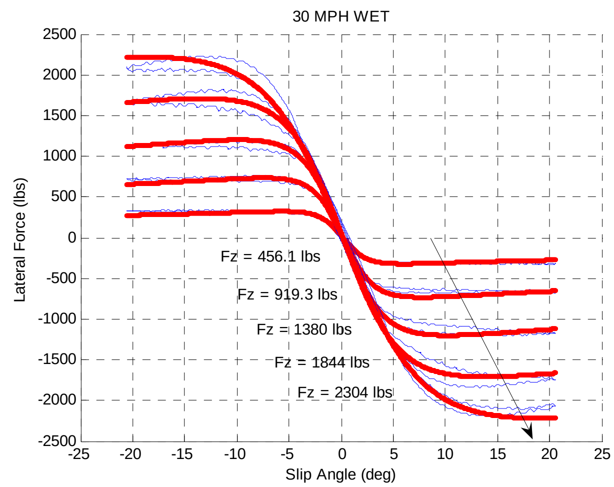

Figure 15. Lateral Forces at 30 mph Wet

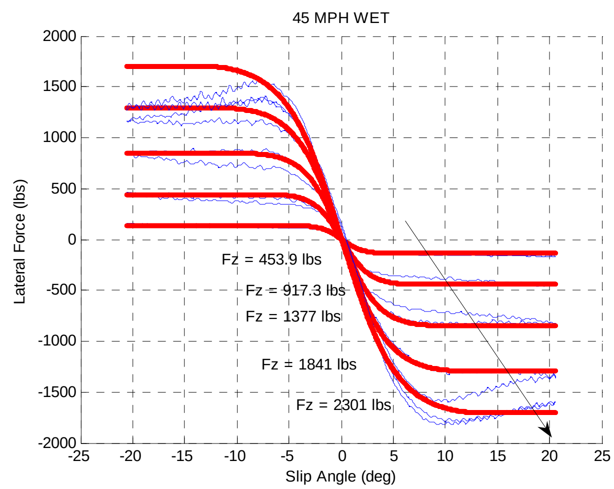

Figure 16. Lateral Forces at 45 mph Wet

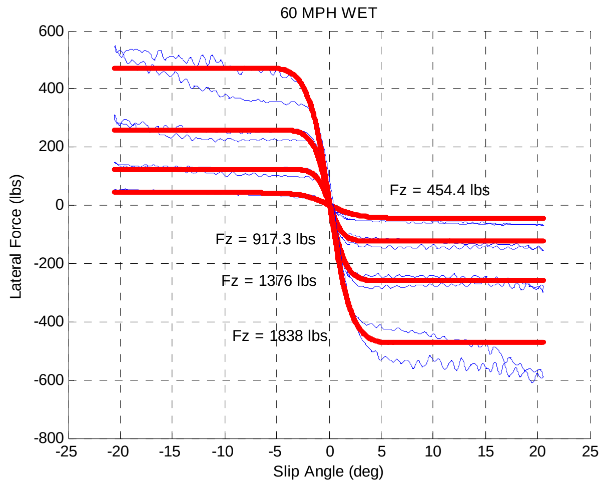

Figure 17. Lateral Forces at 60 mph Wet

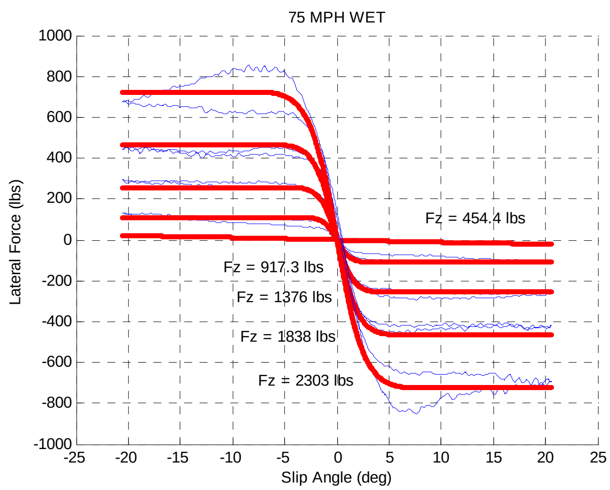

Figure 18. Lateral Forces at 75 mph Wet

Figure 19 shows measured and modeled results for longitudinal, lateral, and combined forces at 30 mph for both wet and dry conditions. The model does a good job of assimilating the measured results. At 30 mph the wet tire peak longitudinal and lateral forces are only slightly less than the dry peak forces.

At higher speeds, the measured results from the combined tests are not consistent due the previously mentioned lack of quality in the higher speed longitudinal data measurements. Nonetheless, the model predictions for higher speed combined conditions based on peak lateral and longitudinal forces are reasonable.

Conclusions

This paper presented the results from testing shaved passenger car tires on a low-coefficient test surface. Straight-line and cornering tests were performed, yielding data for both longitudinal and lateral forces and cornering moments. Five loading conditions were used, yielding a good fit in the lateral direction and a reasonable fit in the longitudinal direction (despite some difficulties with the test procedure in this mode). One of the goals for the testing program was to find the combination of tread depth and water depth which would yield a high coefficient of friction at low speeds and a low coefficient at high speeds. This goal was accomplished. It should be noted that shaving a tire does not produce the same effects that would come about by allowing a tire to wear down to 4/32 inches through normal use. The aging effects of rubber were ignored.

The tire forces and moments were then used to generate the tire parameters required by the STI tire model used by the NADS vehicle simulation dynamics. Some of these parameters include coefficients for equations describing the lateral and longitudinal peak coefficient of friction for varying loads at different speeds, effective lateral stiffness, effective aligning moment stiffness, several other stiffnesses, and the tire saturation function.

The STI model was then exercised with the generated coefficients. Overall, the model did a good job of predicting peak forces and linear range stiffnesses for all conditions, and a decent job of modeling the forces when the tires reach high slip angles.

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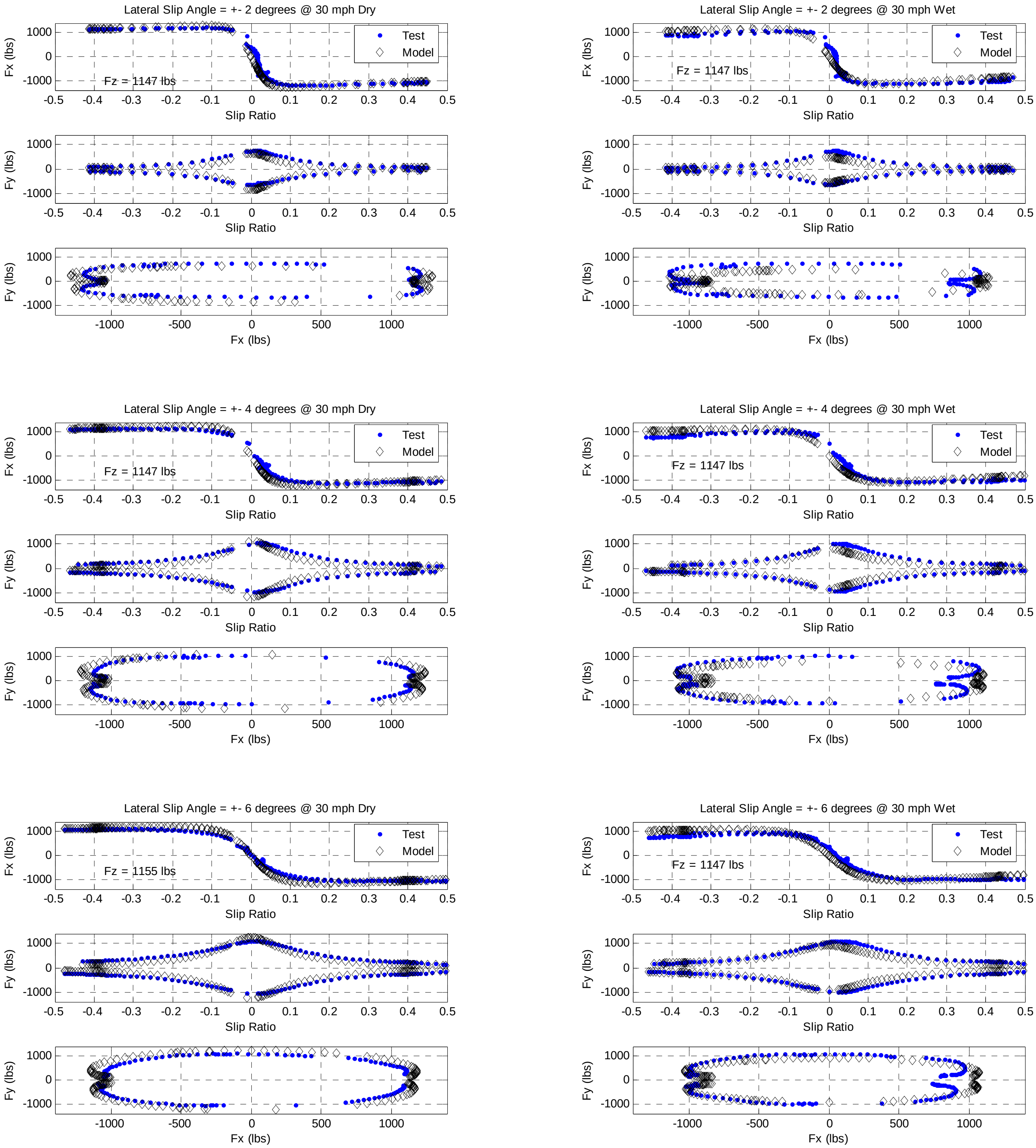

Figure 19. Combined Longitudinal and Lateral Forces at 30 mph – Dry and Wet