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ABSTRACT

A series of tire property tests have been performed at CALSPAN on the flat bed tire test machine. The tires used in the testing were inflated tires with the tread removed. Identical make/model/size tires in normal (tread not removed) condition were also tested. Three passenger car tires and one truck tire were tested. The purpose of this paper is to present comparative results of the testing and data analysis. The test results objectively demonstrate substantial differences in cornering properties. Grouping all tires together, the measured cornering stiffness of a modified tire was reduced on average to 36.1 percent of the normal tire measured properties (ranging from 24.1 to 49.4 percent; standard deviation was 7.7 percent). Overall the character of the modified tire cornering stiffness plots and other modified tire properties were demonstrated to be markedly changed.

INTRODUCTION

A tire forms a critical link between a motor vehicle and the road environment on which it is operated. A driver's "feel of the road" is transmitted through systems, which connect in series through the tires. Automotive texts derive mathematical relationships using front and rear tire cornering stiffnesses to describe first order effects to vehicle handling stability [1,2,3]. That such a critical link exists is demonstrated in the owners' manuals and placards of motor vehicles, wherein the size (including rim size), construction, load carrying capabilities, speed symbol, brand, and inflation pressure of front and rear tires are specified. A motor vehicle's owner's manual may admonish the operator as to the adverse consequences of using tires other than those specified.[1]

The study of tires in the cause of motor vehicle crashes is described in historic and contemporary scientific literature [4,5,6]. Police reports and in-depth crash investigations provide explicit coding of tire factors affecting motor vehicle crashes [7,8].

This paper conveys the results of tire properties testing performed at CALSPAN on the flat bed tire test machine. Testing of four different types, in pairs (8 total tires), one with and one without the tread removed, was performed. All tires were inflated during testing. Testing was conducted as part of the Engineering Dynamics Corporation "Tire Week 1999" in which 26 different tires were tested on the flat bed tire test machine at CALSPAN. Although brake testing was contemplated (and completed on normal tires), only cornering tests were completed on the modified tires and only comparative cornering results will be presented.

METHOD – TIRE PREPARATION

A pair of four different steel belted tires was selected for testing because the tire or similar tire had sustained a tread detachment preceding a crash resulting in injury to a motor vehicle occupant. Tires that were tested and certain test conditions are listed in Table 1. All tires were purchased new from a local tire dealer. All tires except type 4 were sent to the test facility new without pre-test conditioning. The type 4 tires were unique from the others in that both had been utilized in a prior handling test program.[2]

Tread detachment in this paper refers to an occurrence where the outer belt and/or tread of a tire detach and tire

1 For example, on page 145 of the 1987 Ford Aerostar's owner's guide, it states; "Warning – When replacing tires, use only the tires and wheels specified on the safety compliance certification label attached to the driver's door pillar . . .. Use of any other designation can adversely affect handling and/or safety of your vehicle. Further, make sure all four road tires are of the same size, construction, load carrying capability, speed symbol, and brand to assure predictable handling characteristics . . .. Failure to follow any of the above precautions can adversely affect the safety and handling of your vehicle."

2 The prior handling test program is described in SAE Paper 1999-01-0120, Vehicle Handling with Tire Tread Separation.[9]

pressure is (at least temporarily) maintained while the vehicle is in use. For each pair of tires there was a normal unmodified (control) and a tread detached tire (modified). Preparation of the tread detached condition for the tire types 1, 2, and 3 involved leaving both steel belts on the tire and removing all material outside of the outer steel belt. The tread removal process was performed by removing the tread utilizing a sharpened putty knife lubricated with soap and water. The tread was removed by first cutting the base of the tread shoulder laterally around the perimeter of both sides of the tire. A cut was then made across the tread down to the first steel belt. Using locking pliers, it was then possible to grab the loose end of the tread and peel the tread off the tire carcass by pulling and lightly cutting the interface between the tread and carcass. After removing the tread, a minimal residual thickness of rubber remained covering the outer steel belt.

The tires of type 4, due to their use in a prior test program, were unique in comparison to the other tire types. The normal tire type 4 had medium tire wear without excessive tire shoulder damage. The preparation of the modified tire type 4 involved removing the tread by a method identical to that described for tire types 1, 2, and 3. The outer steel belt was then removed by carefully cutting between the tread belts and pulling the outer belt wires out of the carcass. At the end of this process, the inner tread belt and carcass remained intact with most of the rubber between the inner and outer tread belt in place. Prior to the subject test, the tire was one of several utilized in handling testing, as described in SAE paper 1999-01-0120. While rubber outboard of the inner steel ply on the modified tire type 4 was worn away due to prior use, the inner steel ply was intact and judged in satisfactory condition to initiate the flat bed test.

Table 1.

Tire Type	Tire Make	Tire Description	Tire Size	Rim Width (in)	Tire Condition	100% Rated Load (lbs.)
1	Uniroyal	Tiger Paw XTM	P205 / 75 R15	5.5	New	1598
	Uniroyal	Tiger Paw XTM	P205 / 75 R15	5.5	Tread Removed	1598
2	Uniroyal	Laredo A/T M+S	31X10.5 R15	8.5	New	1775
	Uniroyal	Laredo A/T M+S	31X10.5 R15	8.5	Tread Removed	1775
3	Michelin	X - One; 96T M+S	P215 / 70 R14	6.5	New	1554
	Michelin	X - One; 96T M+S	P215 / 70 R14	6.5	Tread Removed	1554
4	Firestone	FR 480 M+S	P205 / 75 R15	5.5	Med Used	1598
	Firestone	FR 480 M+S	P205 / 75 R15	5.5	Tread Removed	1598

Table 2.

Test	Velocity (mph)	Inclination Angle (deg)	Percent Rated Load	Slip Angle (deg)
a	60	0	100%	0
b	60	0	100%	Sc
1	60	0	120%	S1
2	60	0	100%	S1
3	60	0	50%	S1
4	60	3	120%	S1
5	60	3	100%	S1
6	60	3	50%	S1
7	30	0	120%	S1
8	30	0	100%	S1
9	30	0	50%	S1
10	30	3	120%	S1
11	30	3	100%	S1
12	30	3	50%	S1

Sc: Goes from -3 to 10 to -10 to 2 deg.
S1: Goes from -3 to 15 to -15 to 2 deg.

Table 3.

Measured Quantities
Velocity
Slip Angle
Inclination Angle
Force (X)
Force (Y)
Force (Z)
Moment (X)
Moment (Y)
Pressure
Tread Temperature
Tire RPM
Loaded Rolling Radius
Effective Rolling Radius

METHOD – FLAT BED TESTING

A cornering and braking regime, each consisting of a variety of test conditions, was developed. The continuous cornering regime included testing 3 different normal loads (120 percent 100 percent and 50 percent of rated load), zero and three degrees inclination angle, 60 and 30 mph speeds, and –15 to +15 degrees of slip angle. The sequence of the cornering test regime is Table 2. Prior to each cornering test regime a 60 mph, 5 minute warm-up followed by a single conditioning sweep at 60 mph, 100 percent rated load, zero inclination angle was conducted. The conditioning sweep involved a –10 to +10 degree slip angle sweep.

Data was collected during the cornering regime at the rate of 10 samples per second (except during warm-up at one minute increments.) Data was digitally stored. The rate of slip angle sweep was two degrees per second. Tire pressure for all tires was maintained at a regulated 35 pounds per square foot (psi). Data collected or computed for each tire is listed in Table 3. A single video camera visually documents each test from an oblique angle. A description of the CALSPAN flat bed tire test machine is available [10]. SAE Information Report SAE J1107 describes various background and rational for tire testing [11].

RESULTS – GENERAL

On the new modified tires, tire types 1 through 3, the rubber remaining outboard of the outer steel belt was worn during the warm-up, conditioning test and the first phase of cornering testing. While rubber outboard of the outer steel belt was in place, tire-cornering properties were changed but remained similar to normal tire properties. As the rubber wore away, the steel belt came in contact with the test surface, and eventually sparks were observed emanating from the contact patch.

Cornering properties of the tires, while still inflated and after the initial wear of the new modified tire, are substantially different. The modified tire cornering stiffness is reduced, as shown in Figure 1. Percent cornering stiffness, as shown in Figure 1, is the relative rate of change of lateral force (Fy) versus slip angle at zero slip angle. Combining all of the modified tires, the cornering stiffness was reduced on average to 36.1 percent of the normal tire measured properties (ranging from 24.1 to 49.4 percent; standard deviation was 7.6 percent). For the tire type 2, the truck tire, the cornering stiffness was reduced on average to 38.4 percent of the normal tire measured properties (ranging from 31.5 to 48.9 percent; standard deviation was 5.9 percent). For the tire type 4, the cornering stiffness was reduced on average to 24.7 percent of the normal tire measured properties; standard deviation was 0.9 percent.

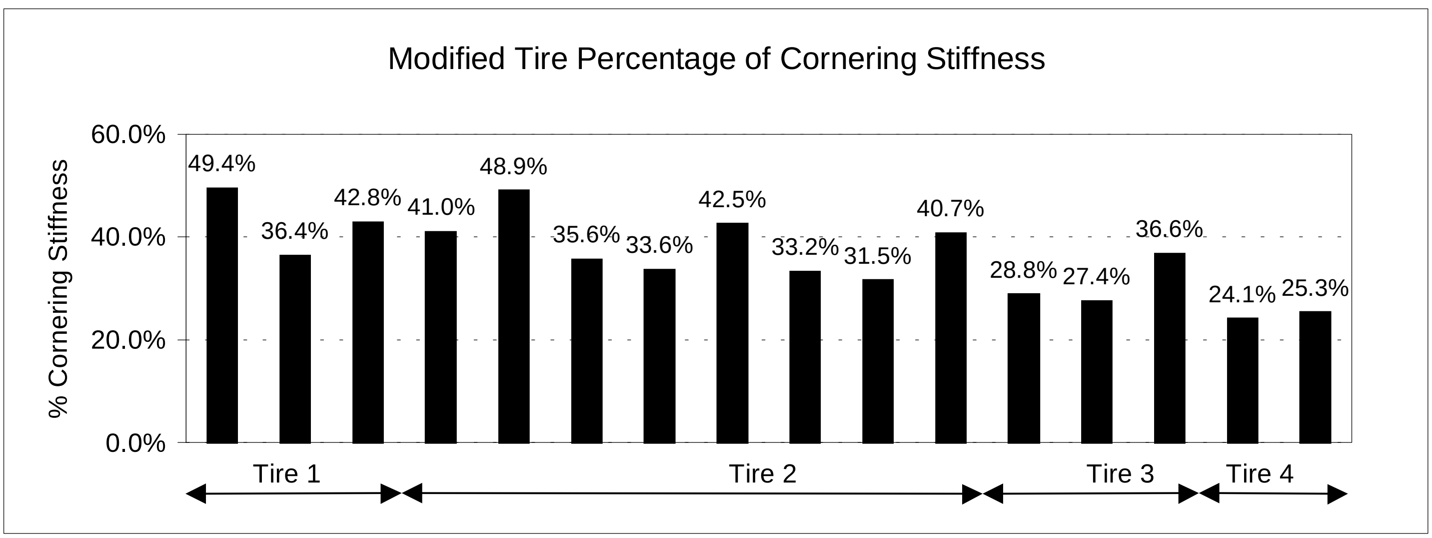

Figure 1.

The character of the tire cornering stiffness plot is different for the modified tire. For the modified tire, a linear lateral force response is observed over a wide slip angle range with altered or absent round off to a saturated response. The difference in tire cornering properties is demonstrated in the data presented in Appendix A and is illustrated in Figure 2 which plots lateral force (lbf.) versus slip angle (degree) and its derivative for several tire/load configurations.

In addition to the observed changes to the modified tire cornering properties, when the tire steel belt was in contact with the test belt, there are measured changes to the aligning torque. The aligning torque for modified tires shows a shift in its Y intercept magnitude as well as changes to the overall shape of plotted results. Figure 3 shows an example of measured differences in aligning torque.

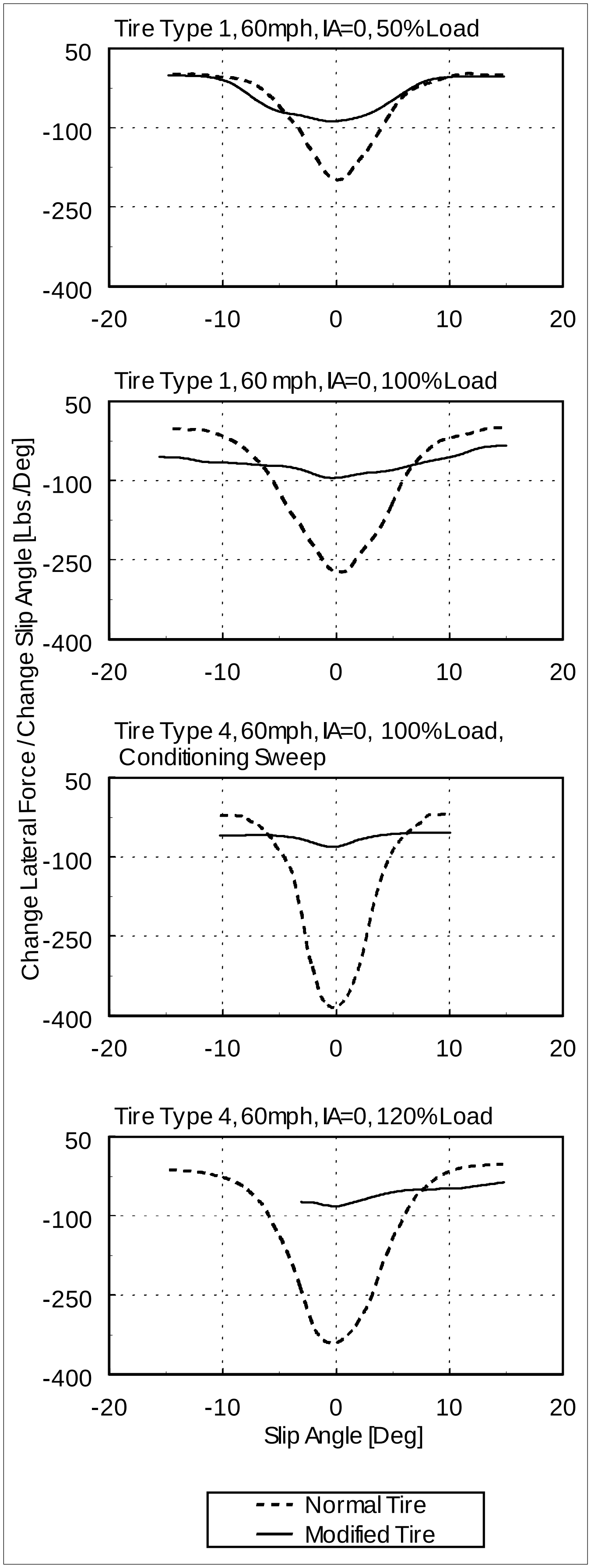

Figure 2.

The modified tires also demonstrate an increase in the loaded radius of operation in the range of 0.25 to 0.50 inches. Figure 4 shows comparison of modified and normal tires for three test loads. For the first test load, 120 percent rated load, shown as the data represented by the smallest loaded radius, the transition of the modified tire to the modified tire characteristic can be observed. In the first test, a smaller loaded radius is measured up to the period when a detachment event partially removing the outer steel ply occurs. After the detachment event a larger loaded radius is measured.

Finally, of note is the greater tread surface temperature for the modified tire. This effect is recorded both when rubber outboard of the steel belt remains and when tire steel belt is in contact with the test belt. Refer to Figure 5 for comparative results of tread surface temperature for the tire type 2.

Plotted comparative cornering test results are provided in Attachment A. Plots are only provided for those conditions where comparable data exists for normal and modified tire characteristics. The plots in Appendix A represent a curve fit of the raw data. All of the data from all eight tire tests is contained in Reference 12.

RESULTS – TIRE TYPE 1

The normal tire type 1 successfully completed the cornering test regime, while the modified tire type 1 completed the conditioning test and the first three tests. During the fourth test (60 mph, 50 percent rated load, 3-degree inclination angle) the tire lost pressure causing the test to conclude. Enough of the fourth test was conducted to calculate a cornering stiffness and warrant comparative analysis. The cornering stiffness for the tire type 1 was reduced to an average of 42.8 percent of the normal tire properties (ranging from 36.4 to 49.4 percent; standard deviation was 6.5 percent).

RESULTS – TIRE TYPE 2

Both the normal and modified tire type 2 completed all of the cornering test regime. The modified tire type 2 was not brake tested due to its post-cornering test regime condition. Although the outer tread was removed on the modified tire type 2, sufficient rubber remained such that contact between the outer steel belt and the test belt did not occur until the end of the 60 mph cornering tests. Test results of the modified tire show a pattern similar to the response of other modified tires when contact between the tire steel belt and test belt begins. Figure 6 shows how the calculated cornering stiffness of the tire changed as the cornering test regime for the type 2 progressed. Figure 5 shows the peak temperature progression for the same test series. Initially the cornering stiffness increased on the modified tire, and then as the tire steel belt is exposed the cornering stiffness degrades. For the tire type 2, the truck tire, the cornering stiffness was reduced on average to 38.4 percent of the normal tire properties (ranging from 31.5 to 48.9 percent; standard deviation was 5.9 percent).

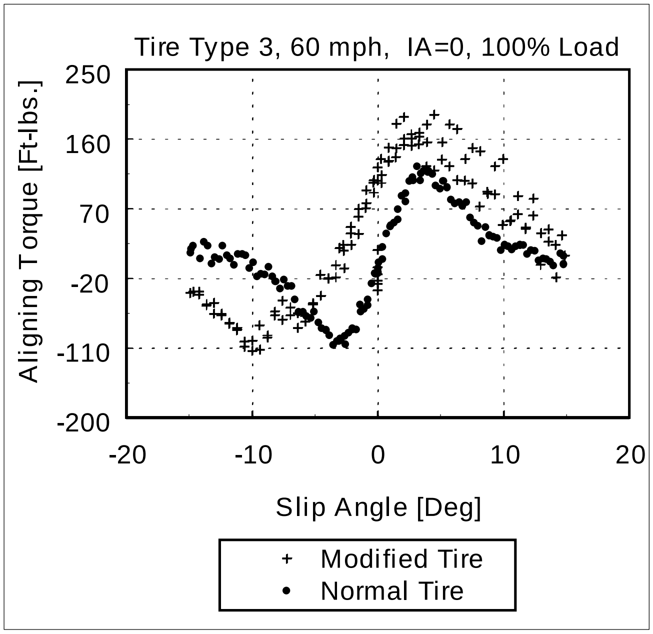

Figure 3.

RESULTS – TIRE TYPE 3

The modified tire type 3 completed the conditioning sweep and the first three cornering tests. The test regime for the modified type 3 tire was halted after the third test sweep due to imminent tire failure. The recorded cornering characteristics of modified tire type 3 are similar to the measured cornering characteristics of the other modified tires.

During the first test after conditioning (60 mph, 120 percent rated load, zero inclination angle), a large portion of the tire outer belt detaches. The detachment event occurs over approximately 10 seconds. The detachment event is proceeded by small pieces of tire detaching, and concluded by a large piece of tire outer belt detaching. The detachment event is obvious in the video record and occurs near the –15 degree sideslip angle. The section of recorded data over which the detachment event occurred was examined and some of the data is provided as Figure 7.

Of interest during the detachment event is the recorded 0.75 inch increase in loaded radius before regulated tire pressure is restored. Figure 7 shows the obvious change recorded for the loaded radius. There is also an observed decrease in the tire pressure and oscillations in the force response.

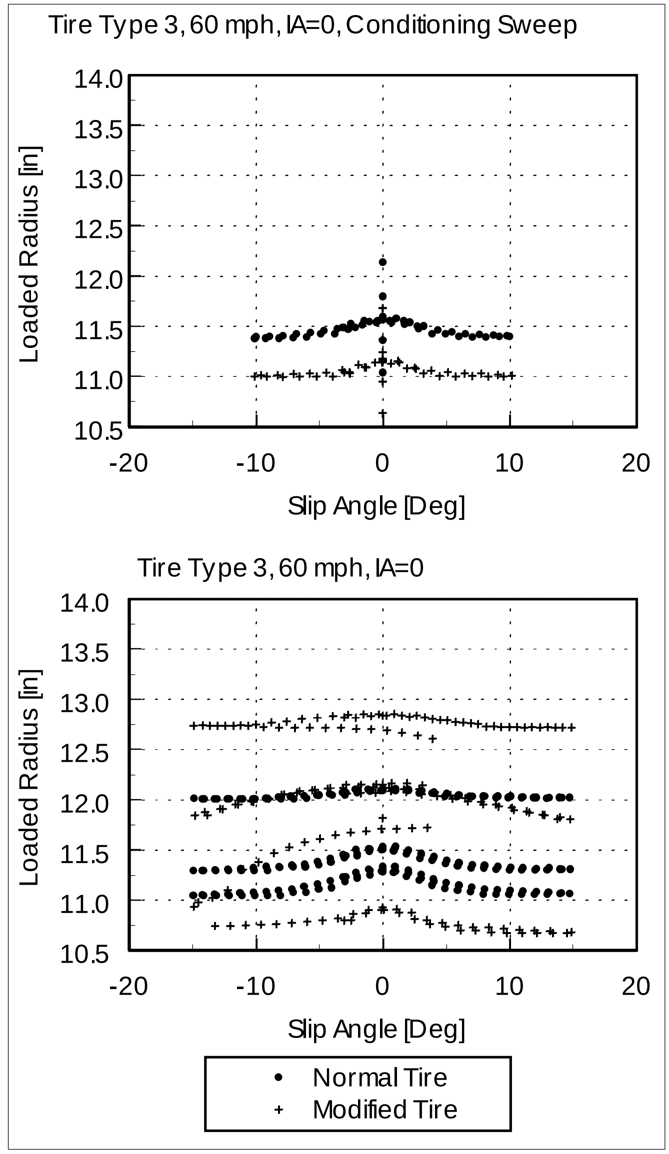

Figure 4.

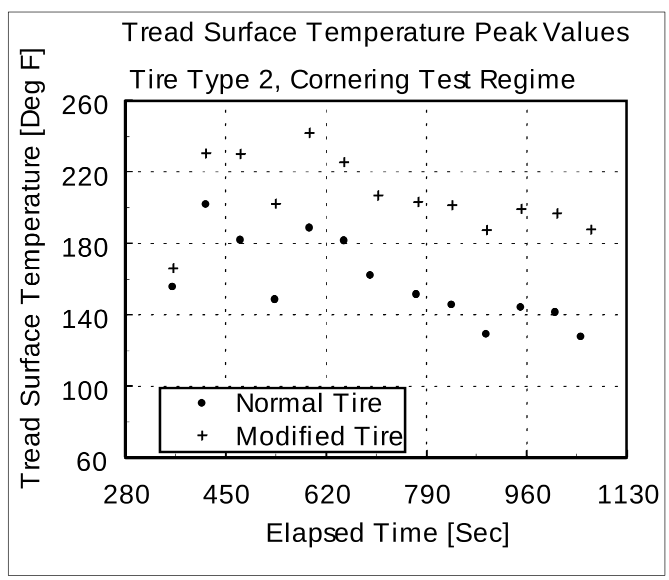

Figure 5.

During the modified tire type 3 cornering test regime, the visual character of the tire circumference changed from initially black, (representing the rubber outboard of the outer ply) to steel (representing the outer steel belt) to black again (after the detachment event representing the rubber between the steel belts) and finally to steel (representing the inner steel ply). Once the outer rubber is worn, during the changing visual appearance of the tire circumference, and after the detachment event the substantial changes in tire cornering properties remain constant and consistent with the measured cornering properties response of the other modified tires. The average cornering stiffness for the tire type 3 was reduced to 30.9 percent of the normal tire properties (ranging from 27.4 to 36.6 percent; standard deviation was 5.0 percent).

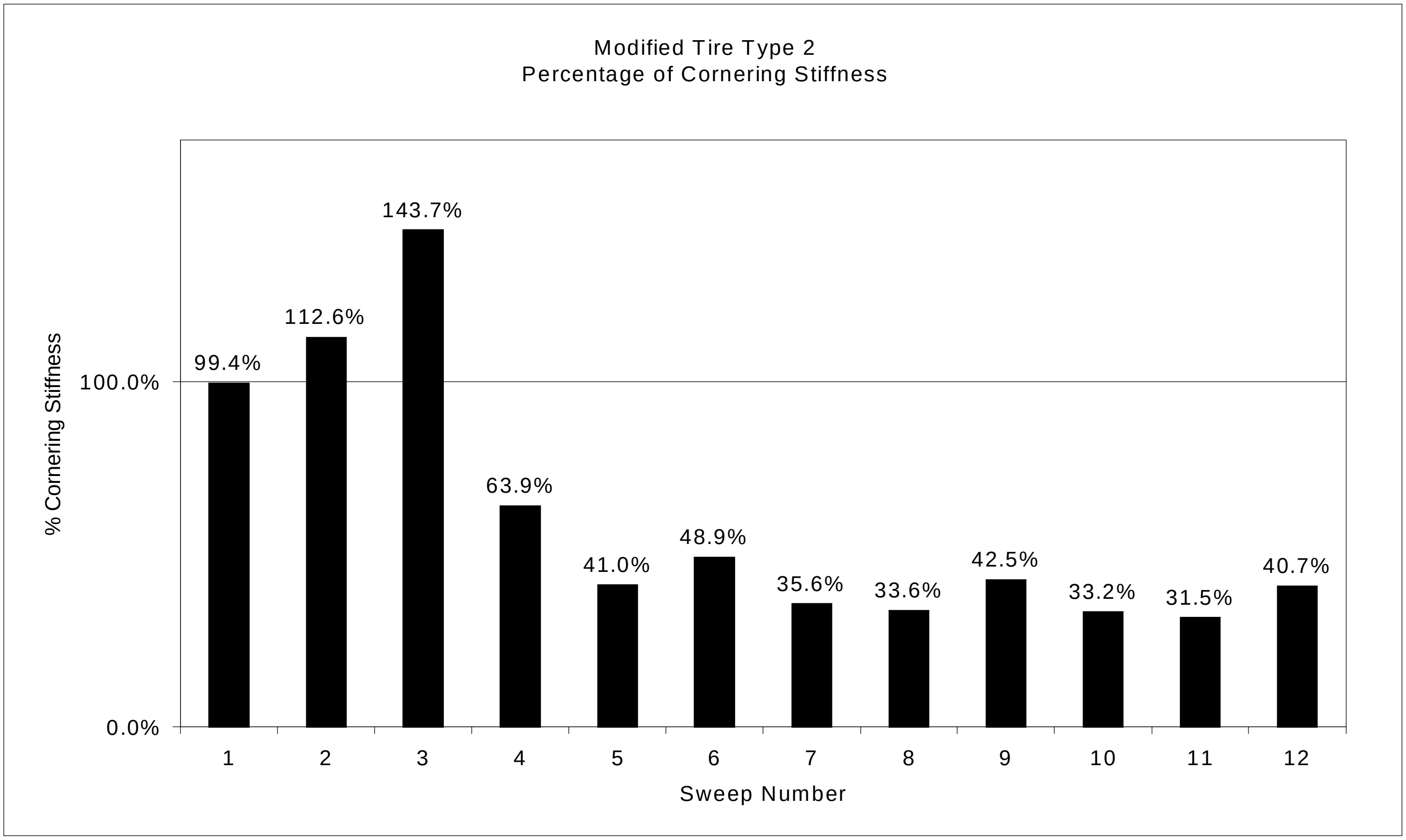

Figure 6.

RESULTS – TIRE TYPE 4

The modified tire type 4, completed the conditioning sweep and lost pressure during the second test (60 mph, 100 percent rated load, zero inclination angle). The modified tire type 4 was left over from a previous test program and did not have significant rubber outboard of the inner steel belt. The results for this modified tire are different from the other tires in this test program in that, from the start, the tire steel belt is in contact with the test belt. Results of this modified tire test are consistent with the reduced and changed capacity of a modified tire running on the steel belt.

For the tire type 4 the cornering stiffness was reduced on average to 24.7 percent of the normal tire properties; standard deviation was 0.9 percent. The percent cornering stiffness for the modified tire type 4 is significantly lower than the percent cornering stiffness for modified tires types 1, 2, and 3. The percent cornering stiffness for the modified tire types 1, 2, and 3 is on average 151.4 percent greater than the percent cornering stiffness observed for the modified tire type 4 (standard deviation was 24.4 percent).

DISCUSSION

In the testing of the modified tire types 1 and 3, a cornering characteristic associated with the steel belt being in contact with the test surface manifested after a conditioning sweep, and for the type 2 tire after numerous test sweeps at 60 mph. The modified tire types 1, 2, and 3 had rubber outboard of the outer steel ply that was probably thicker than actually occurs in tires involved in crashes with tread detachment tire disablement. Furthermore, for the modified tire types 1, 2 and 3, all of the steel plies were initially in place. For modified tire type 4, only the inner steel ply remained and at the initiation of the testing the steel ply was in contact with the tread surface.

The method of preparing the modified tire type 1, 2 and 3 in the subject test program left the outer steel tread plies in place. This test condition increases tire integrity and the tire resistance to deformation compared to conditions where the outer steel plies may be removed. It was observed that as tread was removed and as the outer steel plies were removed, the shape of the tire cross section changed from that of a flat tread to that of a ballooning, or rounded tire (more toroidal). Changes in the shape of the tire changes the tire contact patch and other tire deformation characteristics.

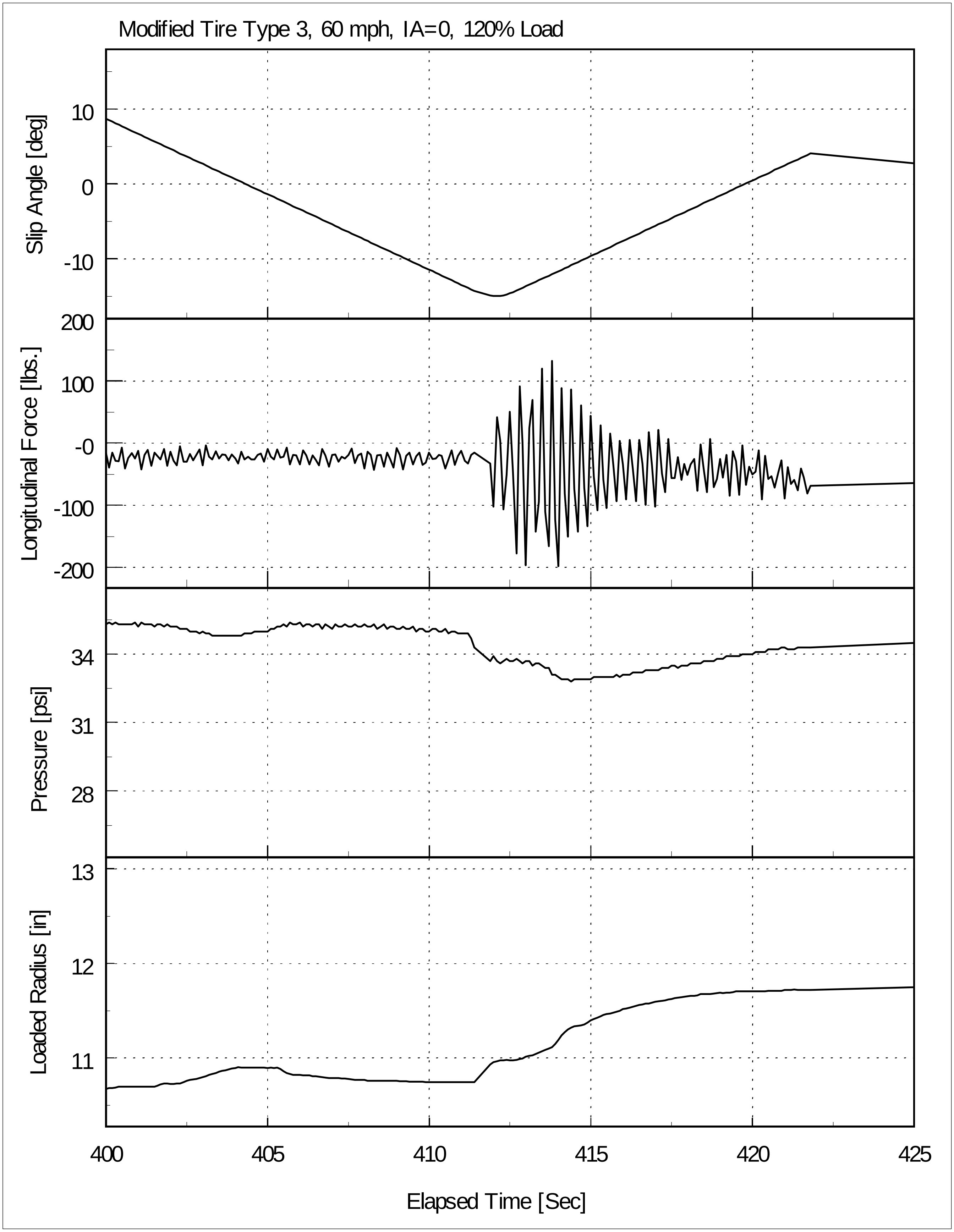

Figure 7.

For all of the modified tires in this test program, except the modified tire type 4, there was a delay in the onset of reduced cornering properties. This observation of delayed onset is caused by the modified tire preparation. The preparation of the modified tire left rubber outboard of the outer steel belt. The thickness of the remaining rubber on the modified tires was not measured. All of the modified tires, except modified tire type 2, demonstrated reduced cornering stiffness initially and during transition to outer steel belt contact with the test surface. The reduced cornering stiffness of a worn tire, as shown for tire types 1 and 3 is consistent with previously publish literature documenting the same results [13].

The modified tire type 2, during the transition to contact of the outer steel belt onto the test surface, demonstrated increased cornering stiffness. The initial cornering stiffness (as measure in sweep 1, figure 2) of the modified tire type 2 was slightly lower than the normal tire. While beyond the scope of this paper, causes of the differing transition characteristics may be due to the higher tread surface temperatures, truck tire construction, and increased rubber outboard of the outer steel belt.

Tire shape (more toroidal versus normal) and the absence of steel belt appears to play a role in the degree of cornering stiffness reduction. On average, the modified tire type 1 maintains the greatest degree of cornering stiffness, while the modified tire type 4 demonstrates the largest reduction in cornering stiffness.

CONCLUSION

1. For the tires which maintain pressure, but undergo a detachment of tread an average cornering stiffness reduction to 36.1 percent of the normal tire properties is demonstrated (ranging from 24.1 to 49.4 percent; standard deviation was 7.7 percent).
2. The modified truck tire showed an average cornering stiffness reduction to 38.4 percent of the normal tire properties (ranging from 31.5 to 48.9 percent; standard deviation was 5.9 percent).
3. The tire with the complete detachment of the outer steel ply and tread, tire type 4, results in the largest change in cornering stiffness. An average reduction to 24.7 percent of the normal tire properties was observed (standard deviation was 0.9 percent). The reduction in cornering stiffness for the tire type 4 was significantly lower than results for tires types 1, 2, and 3. The percent cornering stiffness for the modified tire types 1, 2, and 3 is, on average, 151.4 percent greater than the percent cornering stiffness observed for the tire type 4 (standard deviation was 24.4 percent).
4. Changes to the cornering stiffness properties of the modified tires were observed across the range of tested tire slip angle. The tire cornering stiffness plotted versus slip angle showed, in addition to the gross reductions, a more linear response and a changed or absent roll off to a saturated condition.
5. Other measured changes in tire properties were observed on the modified tires. Changes include a measured larger rolling radius and modified tire shape. Tire tread temperature was observed to increase on modified tires and aligning torque was shown to be different.
6. Data recorded during a steel ply detachment event showed relatively large oscillation in the longitudinal force generated by the tire and changes in the tire pressure and rolling radius. Once the detachment event was over the recorded tire data returned to its previously quiescent state.
7. The modified tires demonstrated a transition from relatively normal cornering stiffness to relatively low cornering stiffness.

ACKNOWLEDGMENTS

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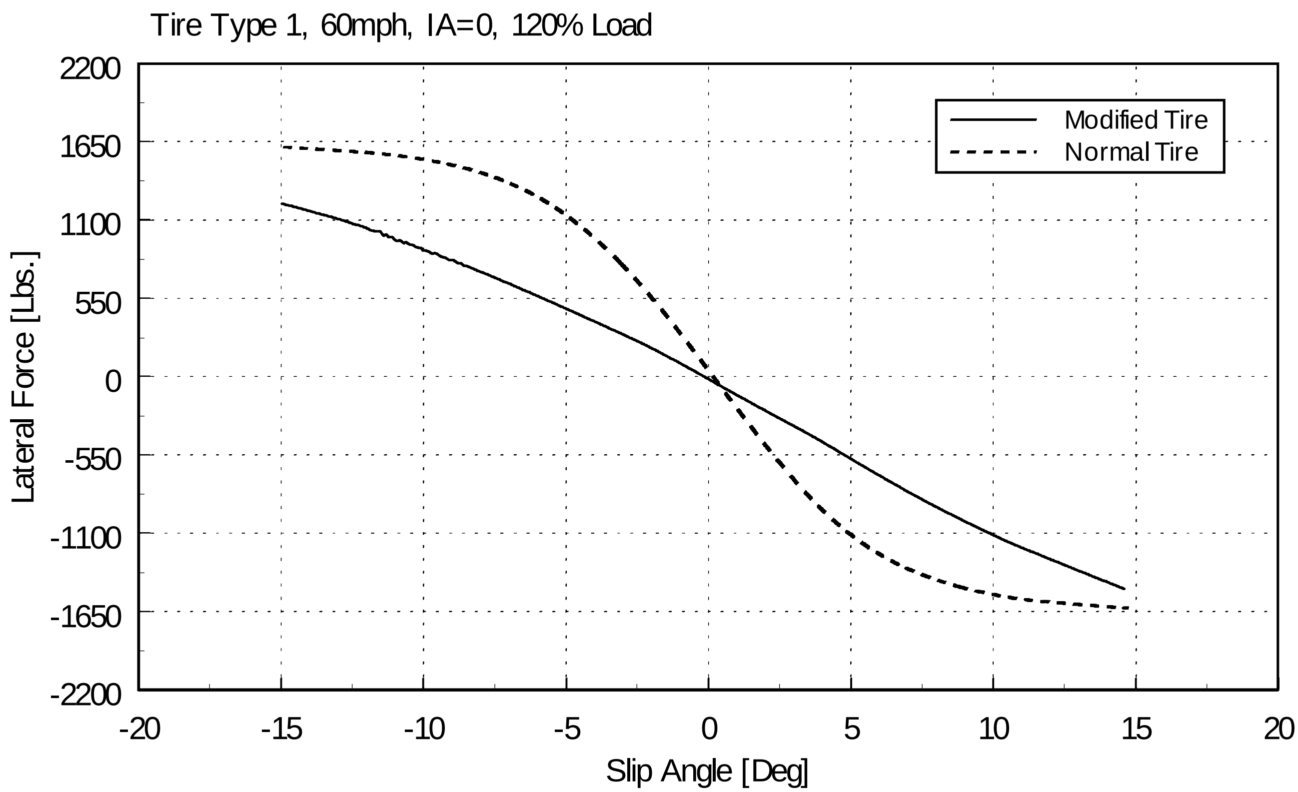
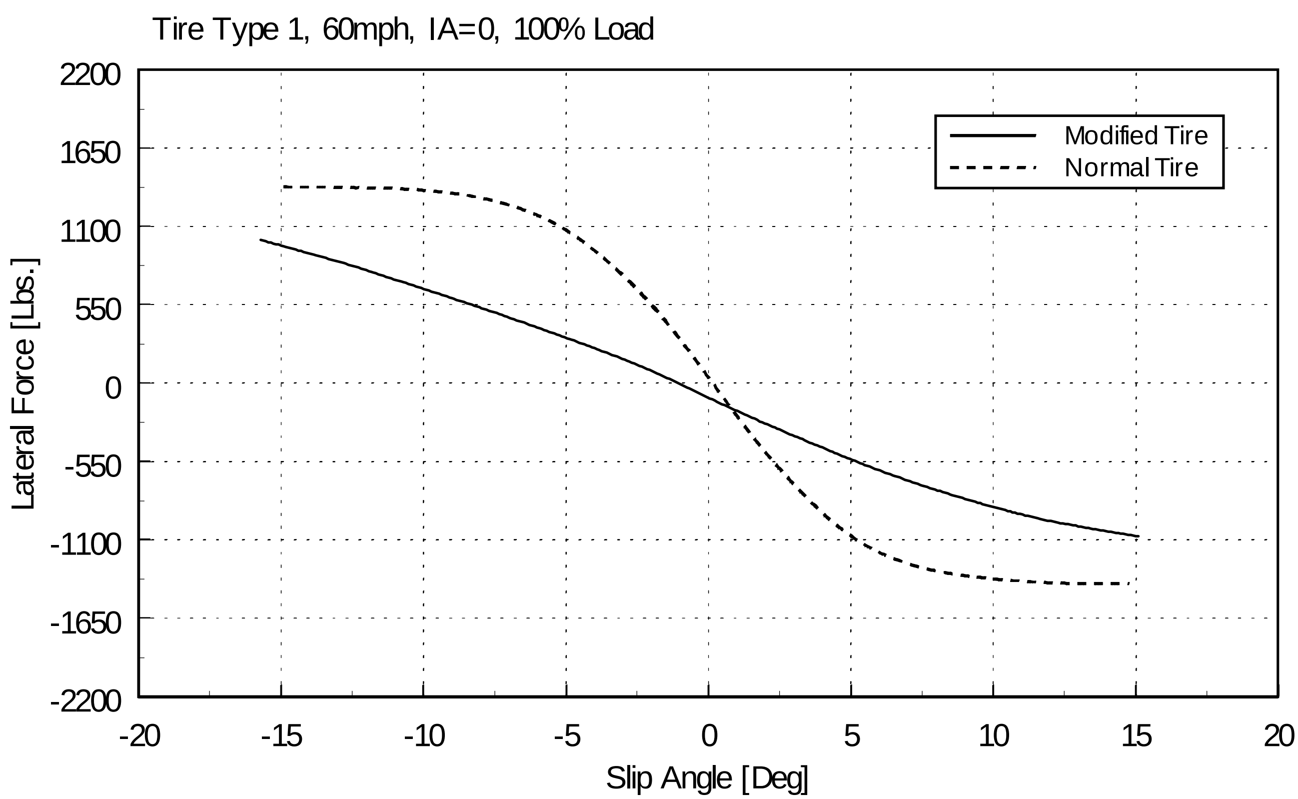
APPENDIX


Tire Type 1, 60mph, IA=0, 120% Load
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]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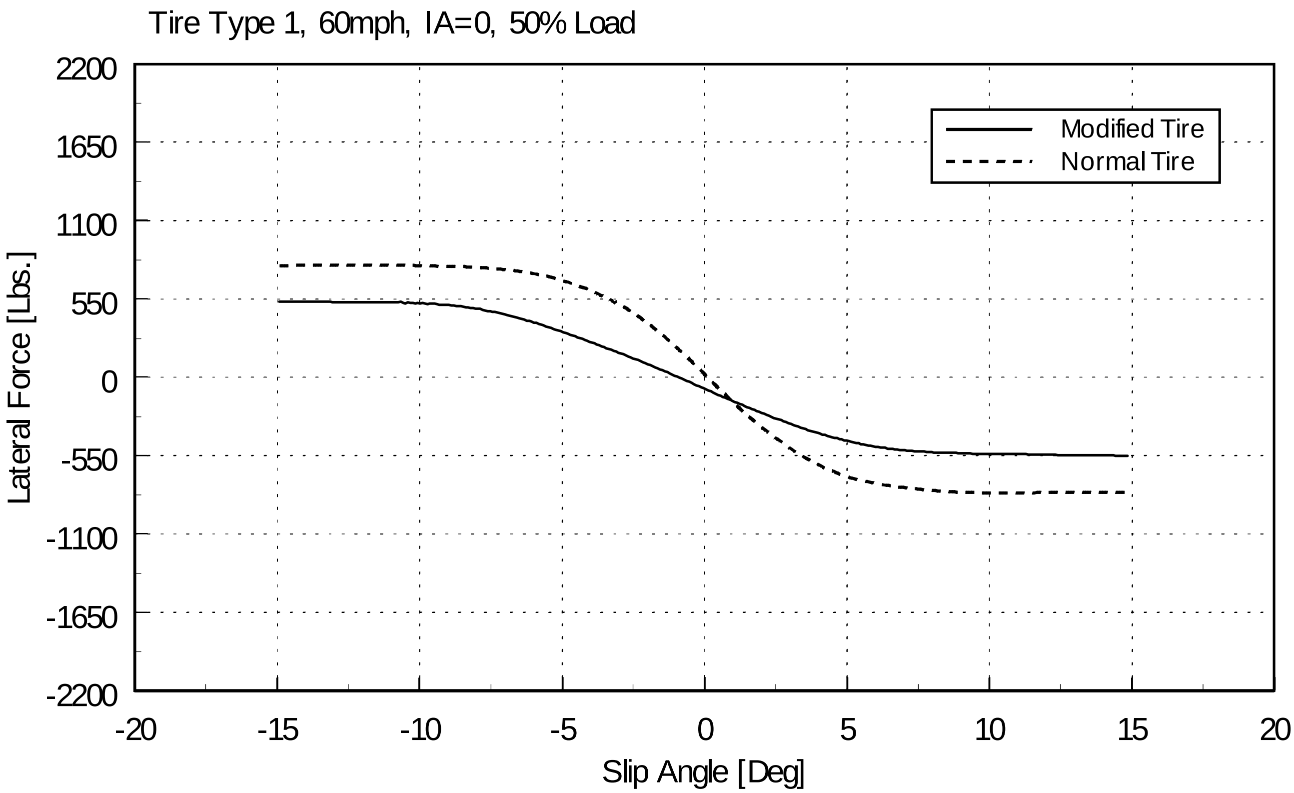
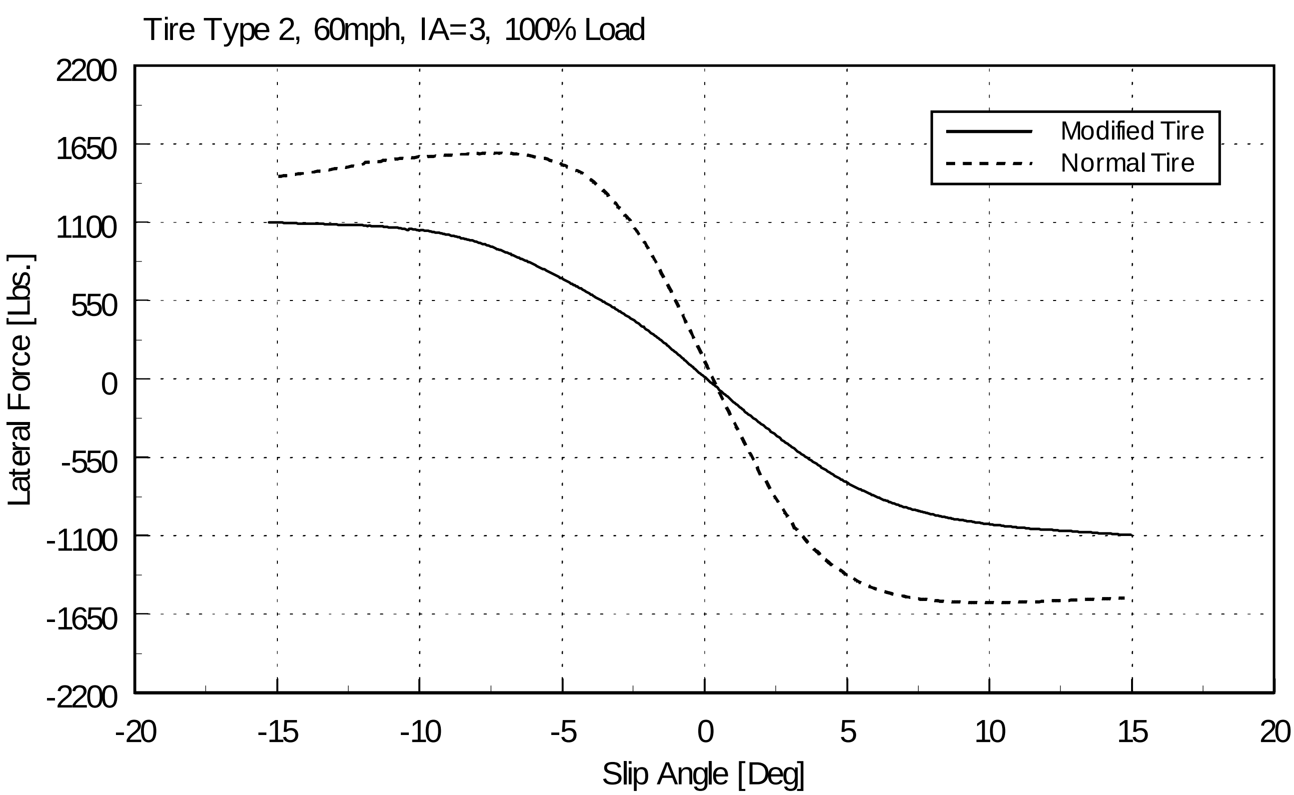
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]


Tire Type 1, 60mph, IA=0, 50% Load
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]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Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
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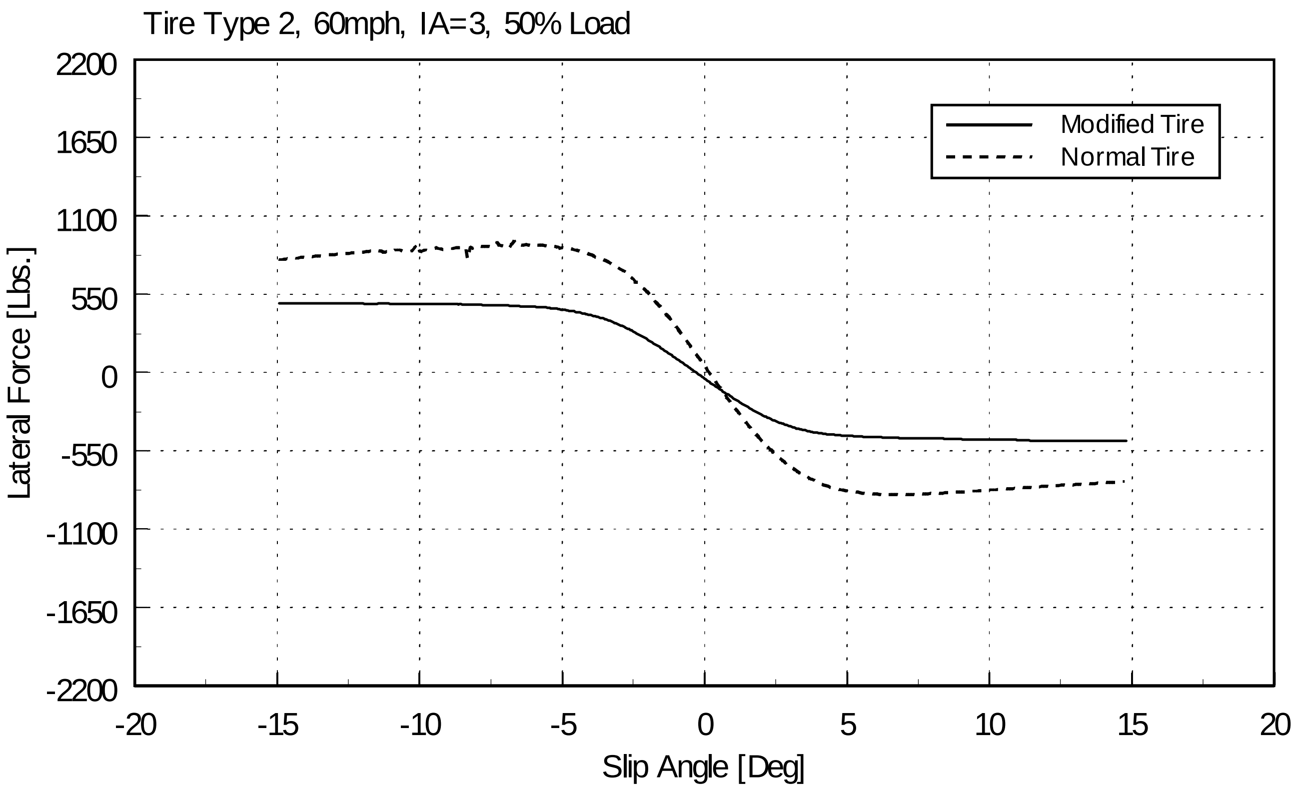
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]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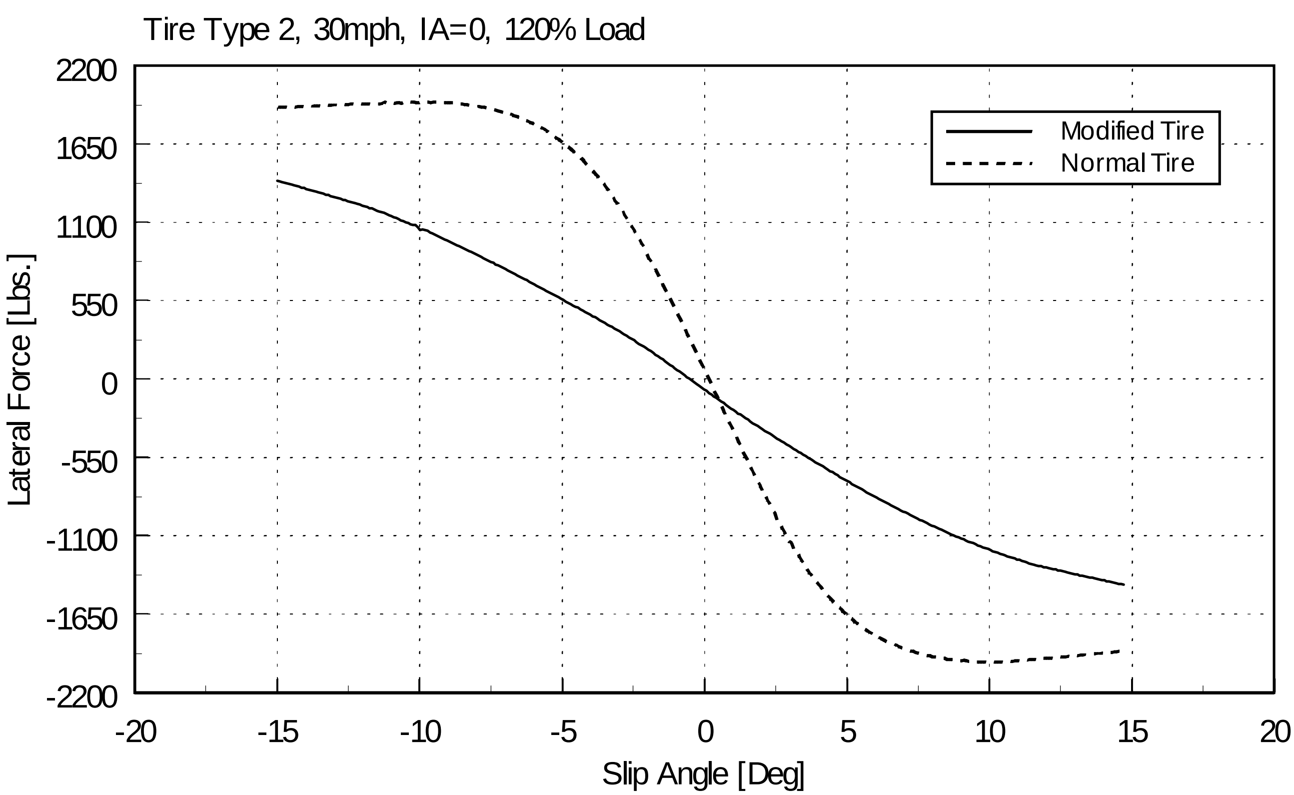
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]


Tire Type 2, 30mph, IA=0, 120% Load
Modified Tire
Normal Tire
Lateral Force [Lbs.]
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1650
1100
550
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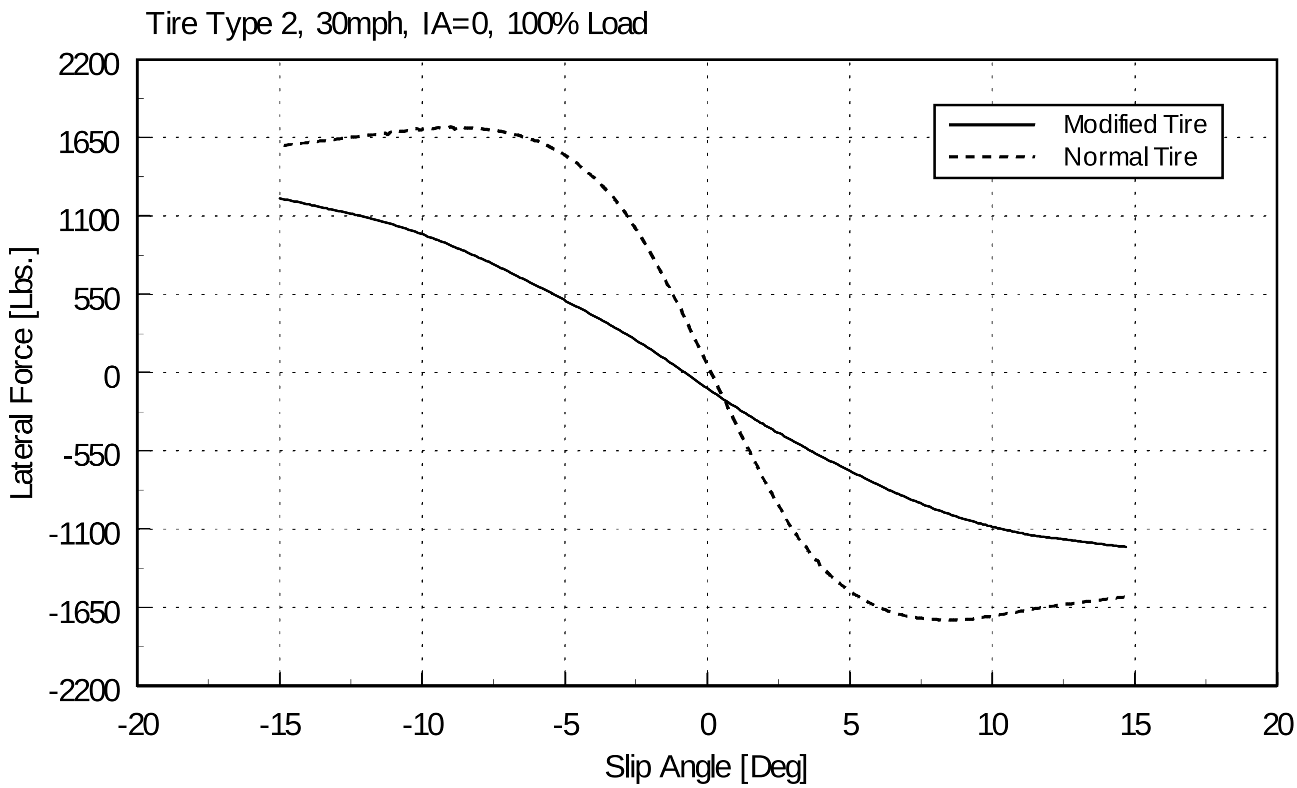
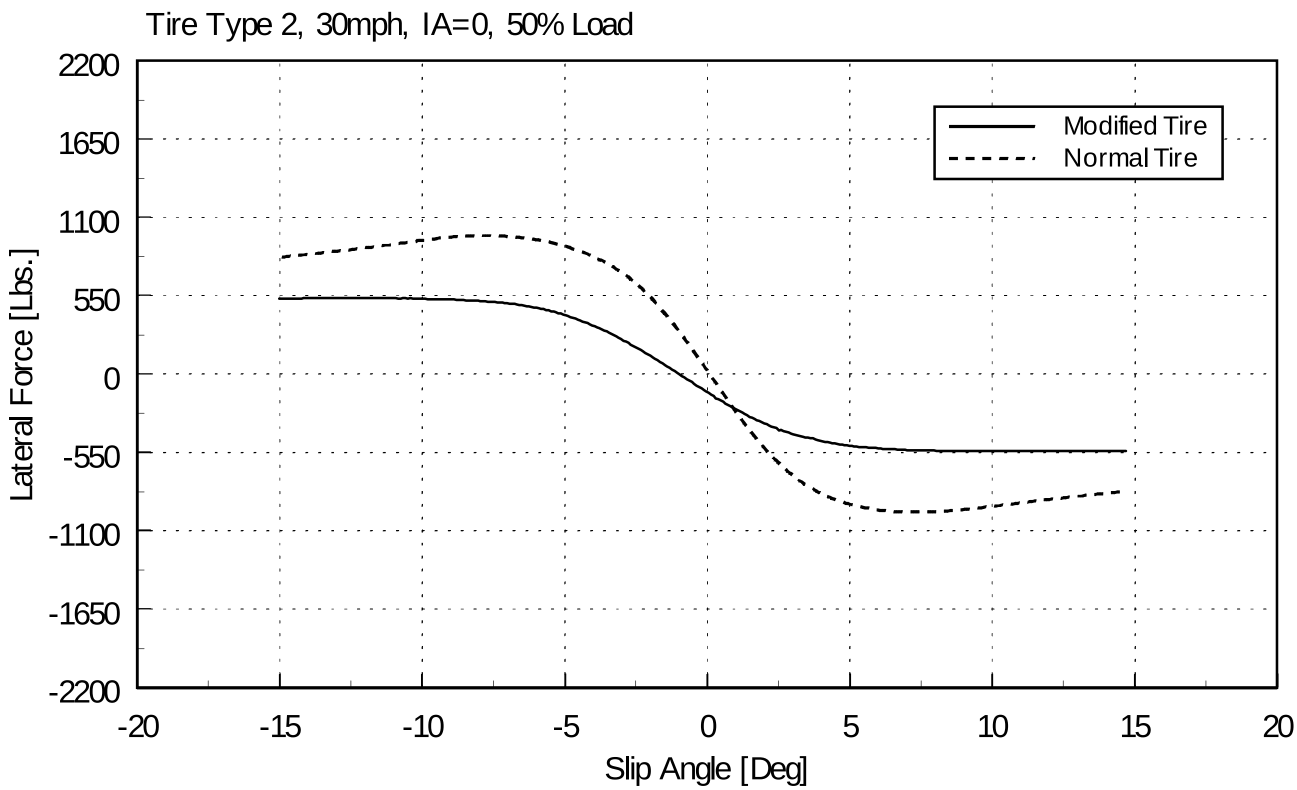
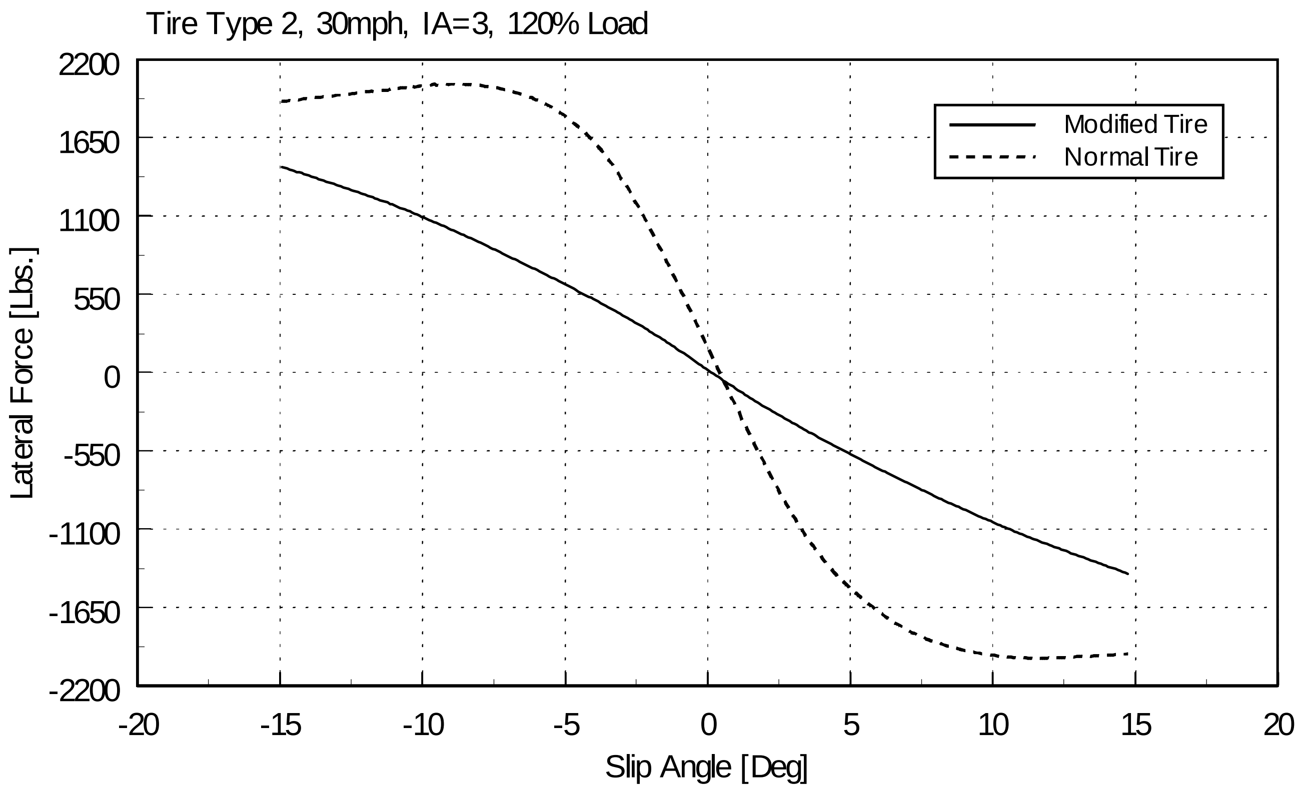
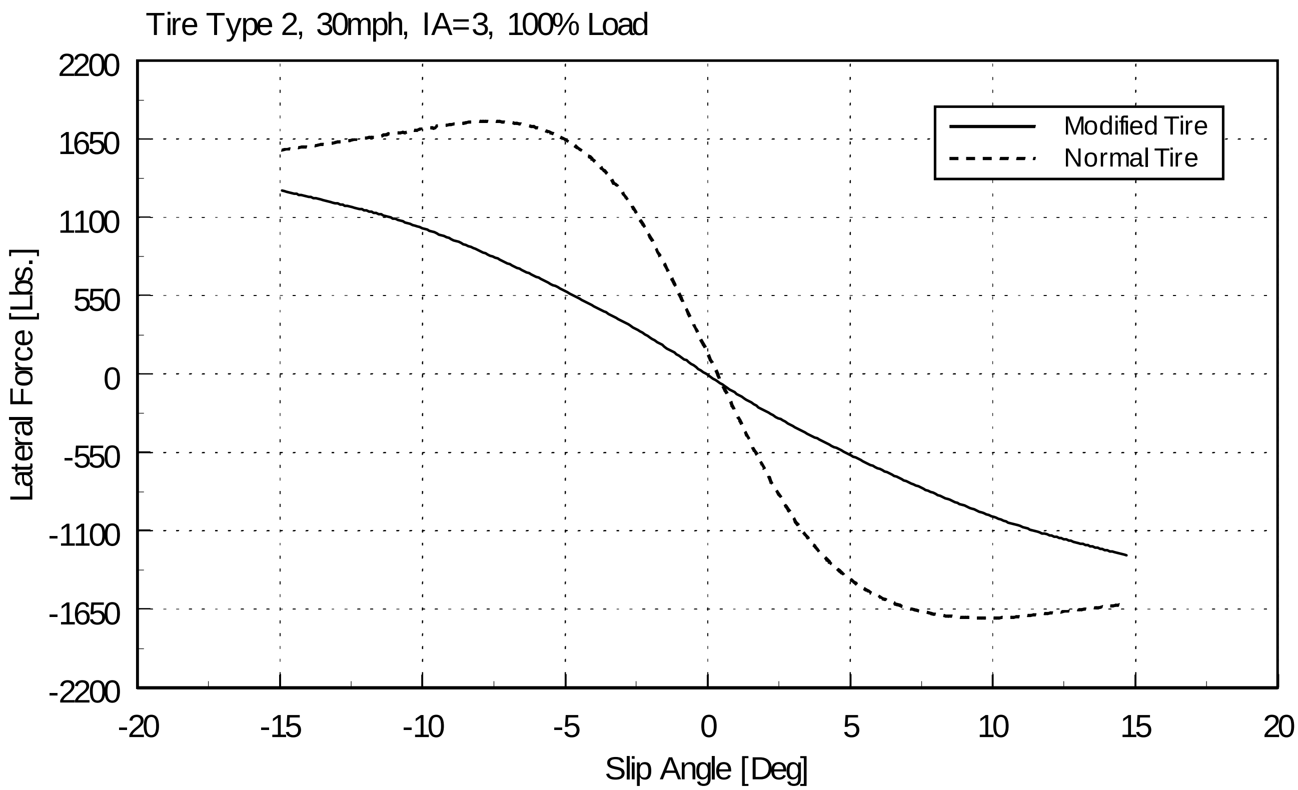
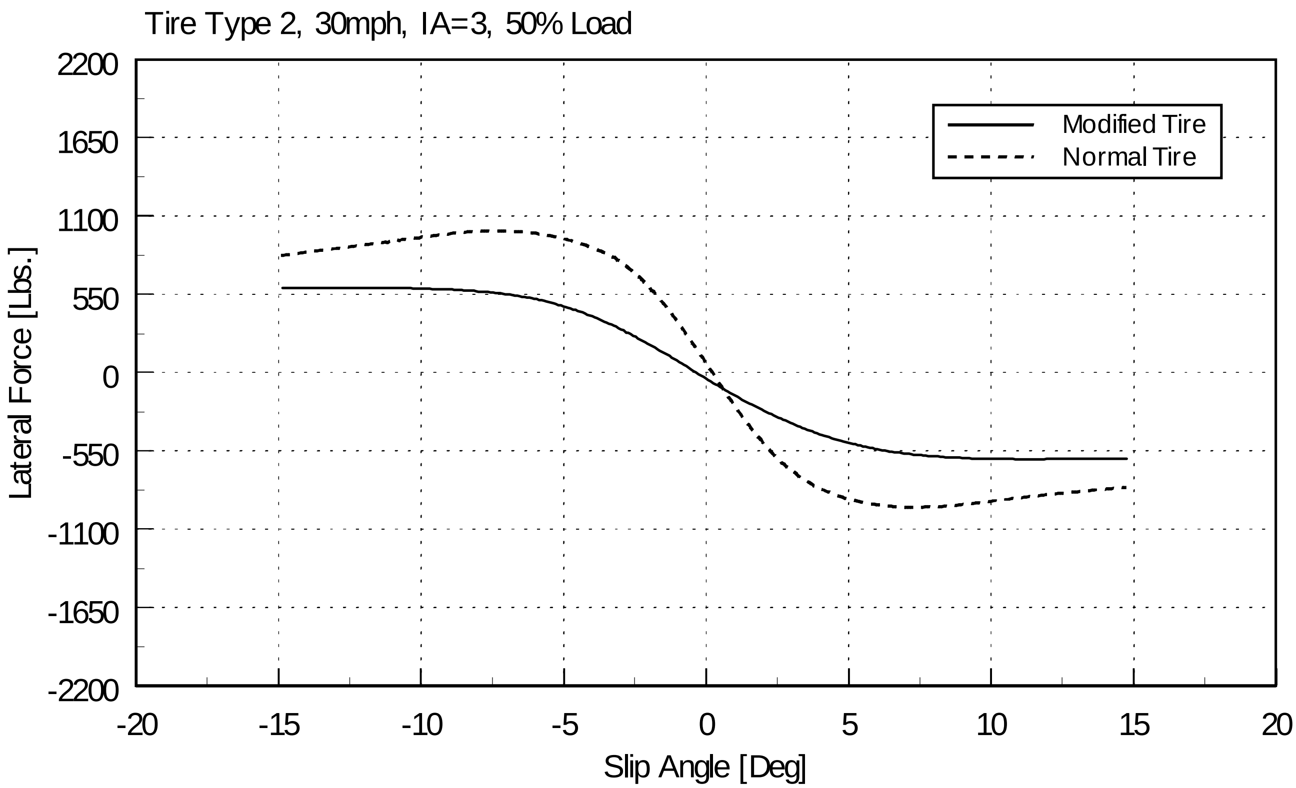
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]

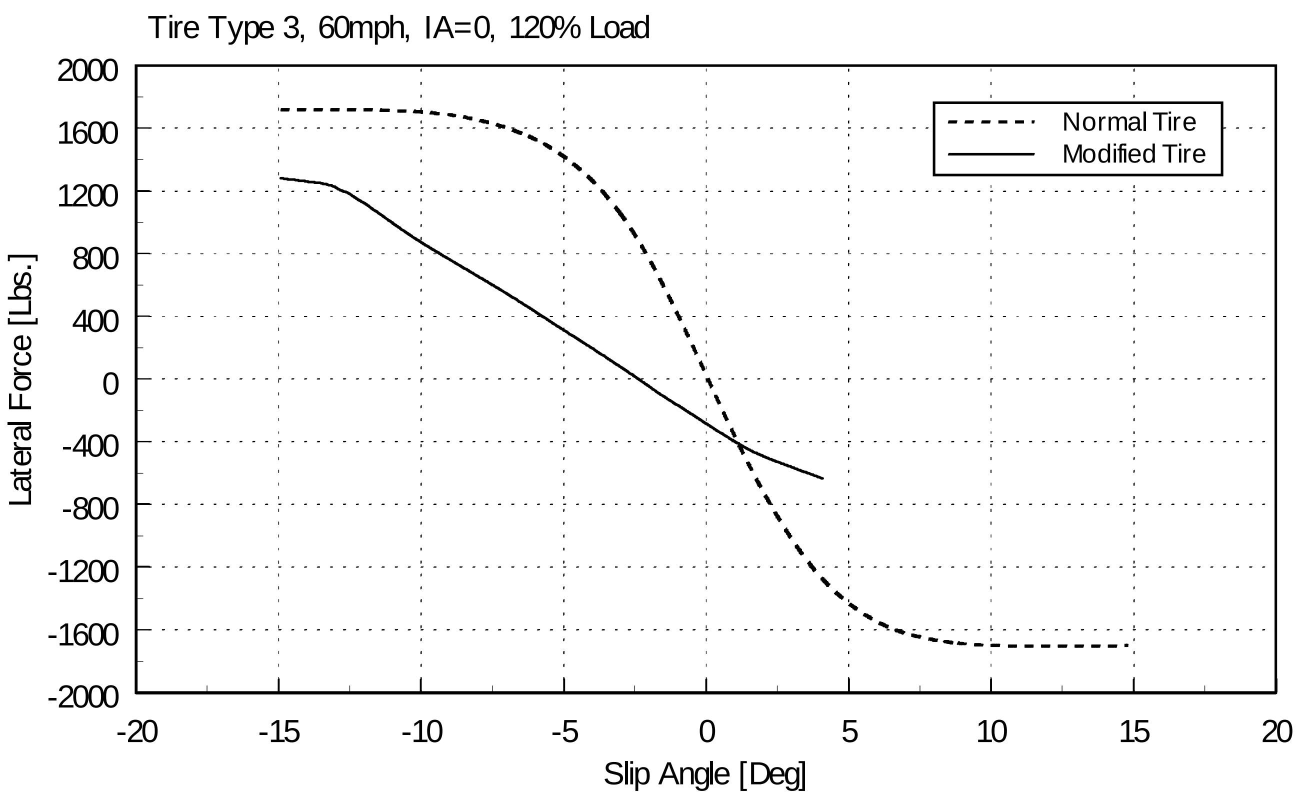

Tire Type 2, 30mph, IA=0, 100% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Modified Tire
Normal Tire

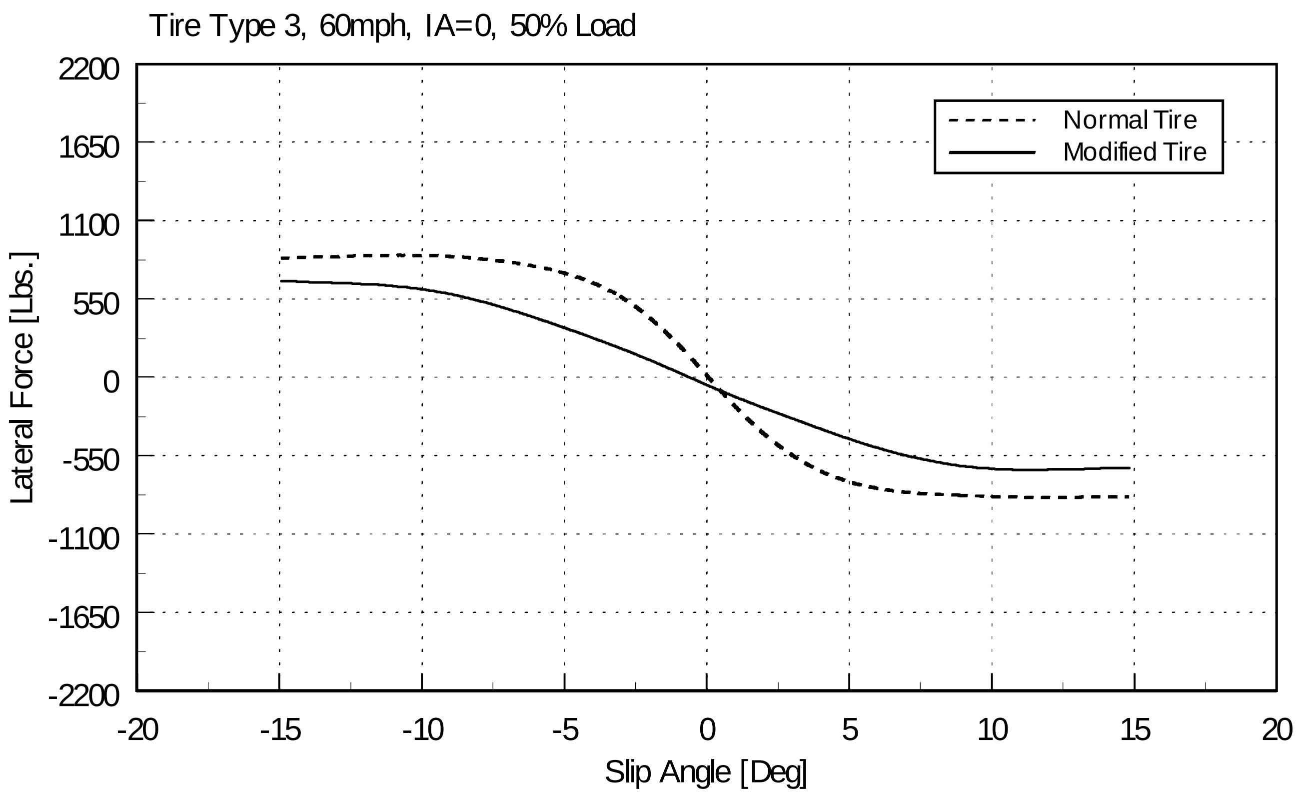

Tire Type 2, 30mph, IA=0, 50% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Modified Tire
Normal Tire

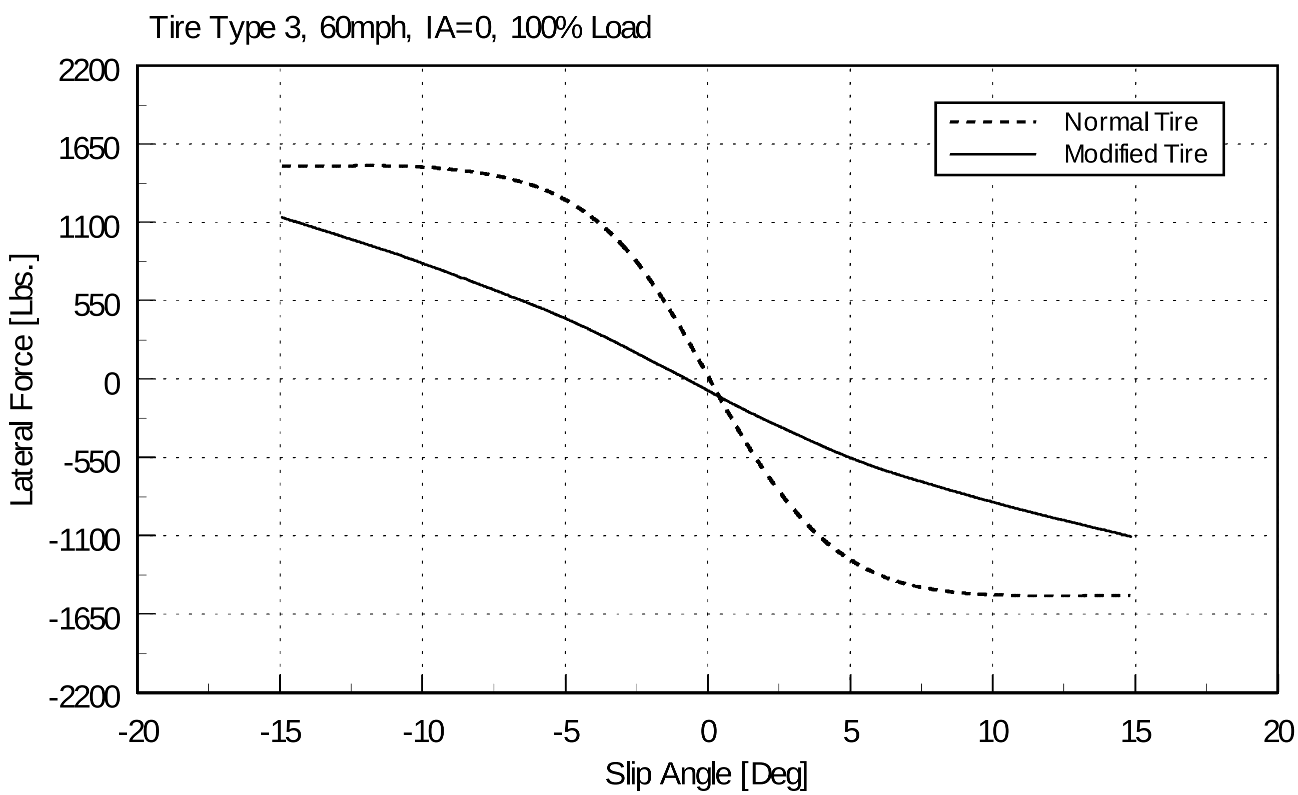

Tire Type 2, 30mph, IA=3, 120% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Modified Tire
Normal Tire

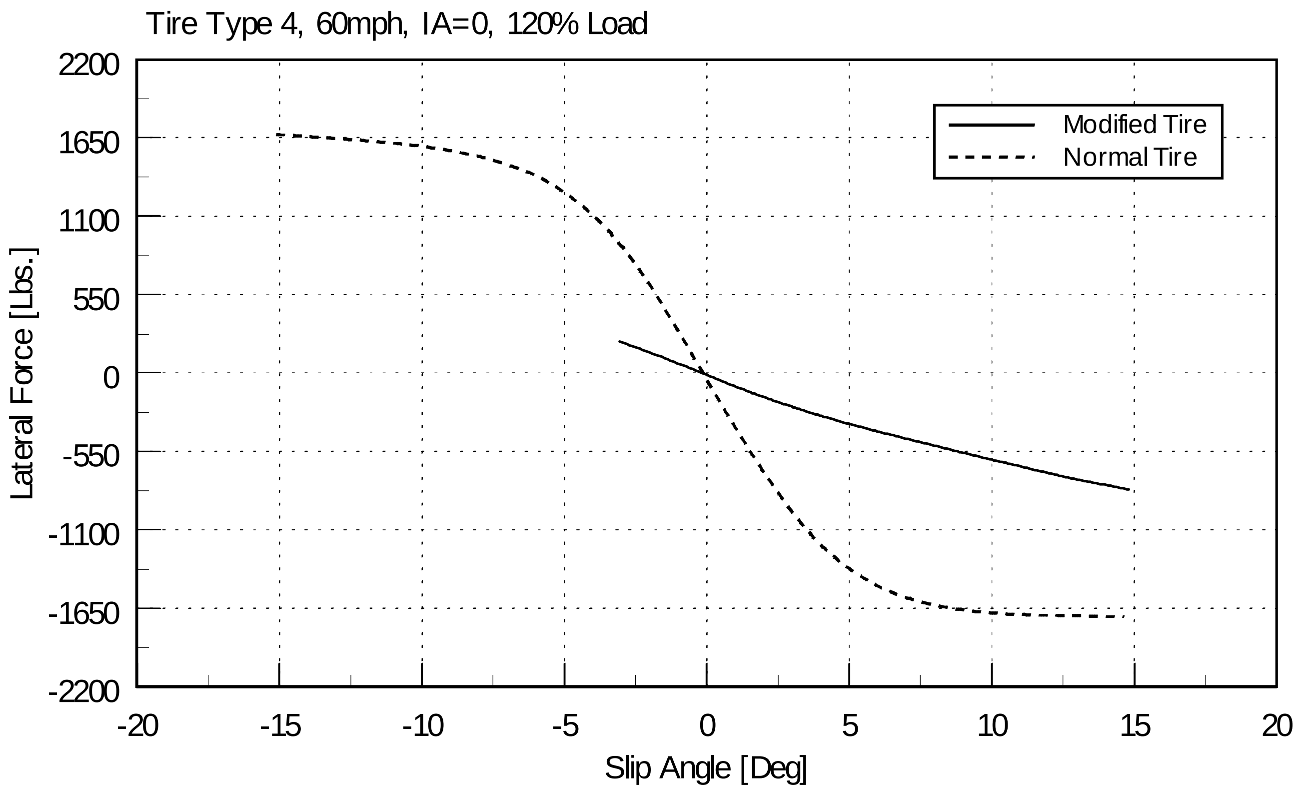

Tire Type 2, 30mph, IA=3, 100% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Modified Tire
Normal Tire

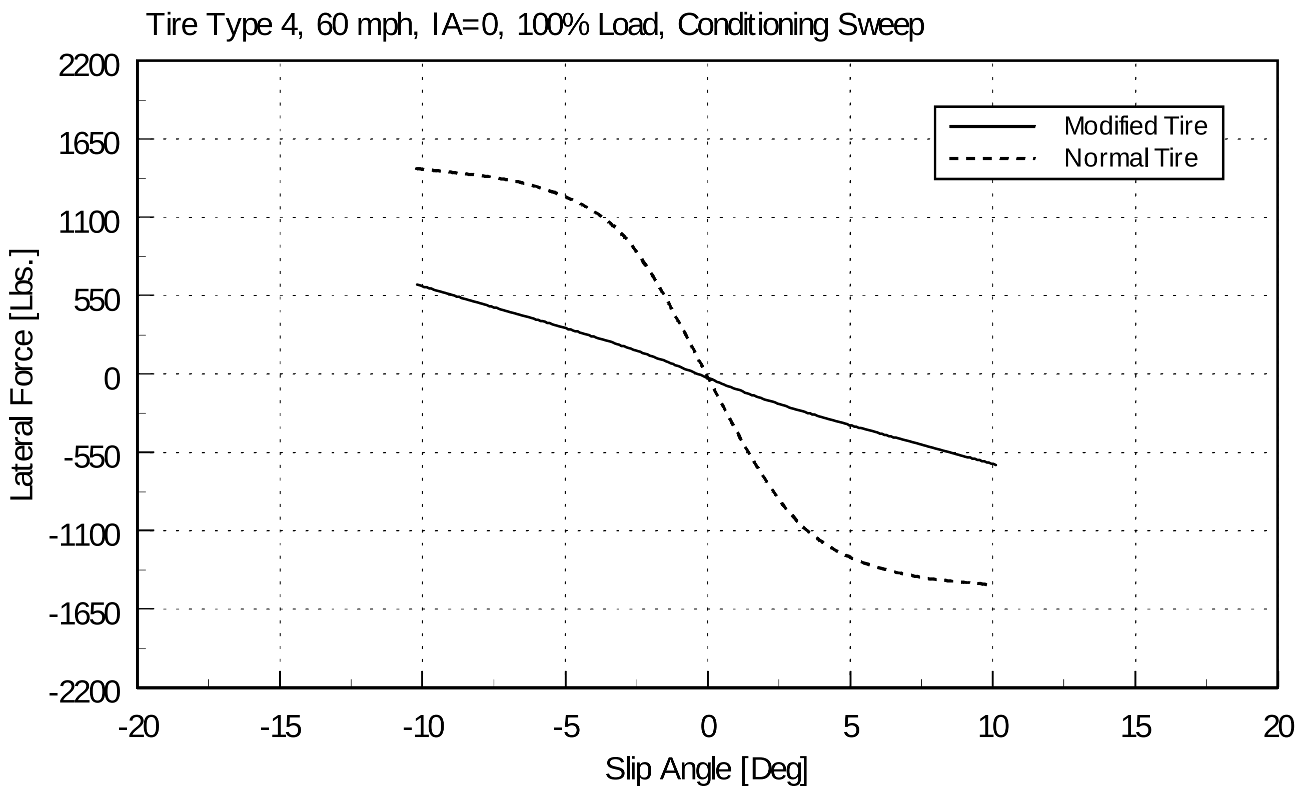

Tire Type 2, 30mph, IA=3, 50% Load
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]


Tire Type 3, 60mph, IA=0, 120% Load
Normal Tire
Modified Tire
Lateral Force [Lbs.]
2000
1600
1200
800
400
0
-400
-800
-1200
-1600
-2000
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]


Tire Type 3, 60mph, IA=0, 50% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Normal Tire
Modified Tire


Tire Type 3, 60mph, IA=0, 100% Load
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]
Lateral Force [Lbs.]
Normal Tire
Modified Tire


Tire Type 4, 60mph, IA=0, 120% Load
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]


Tire Type 4, 60 mph, IA=0, 100% Load, Conditioning Sweep
Modified Tire
Normal Tire
Lateral Force [Lbs.]
2200
1650
1100
550
0
-550
-1100
-1650
-2200
-20
-15
-10
-5
0
5
10
15
20
Slip Angle [Deg]