

An Analysis of Recreational Off Road Vehicle Tire Performance Characteristics

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ABSTRACT

Recreational Off Road Vehicles (ROVs) which are sometimes referred to as side-by-sides, have increased in popularity over the last decade. These vehicles are available in many different sizes and performance characteristics from a host of different manufacturers and also have a variety of different missions, just as there are many types of off road terrain. The United States Federal Government, through the Consumer Product Safety Commission (CPSC), has advocated and proposed vehicle handling and rollover resistance standards for the side-by-sides which have a top speed above 25 miles per hour (these are not defined as "low speed vehicles"). For the sake of repeatability, the proposed maneuvers are to be performed on a high friction hard surface (like asphalt) as opposed to the off road surfaces (i.e. grass, sand, dirt, mud, rocks, etc.) that these vehicles are designed to be operated on. Since ROV tires are designed for off road use only, their force and moment characteristics on an asphalt or concrete surface has not been studied in depth. This paper discusses a technical analysis of tire force and moment properties of two types of ROV tires, a bias ply and a radial ply both of the same size. The tests were conducted on an MTS Flat Trac III tire machine where slip angle sweep tests were performed at various vertical loads. Comparisons between the two ROV tire types, as well as comparisons to common passenger vehicle tires are made. Repeated step input of slip angle runs were also made to study how the ROV tire performance characteristics change as they wear during severe cornering in limit maneuvers.

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INTRODUCTION

ROVs have gained in popularity over the past decade. Purchasers of these vehicles use them for activities such as hunting (see [Figure 1](#)), recreational driving (see [Figure 2](#)), and other types of off road usage. The ROVs should not be confused with the low speed Utility Terrain Vehicles which have vastly different performance characteristics (see [Figure 3](#)). All these vehicles however are designed to be driven off road and, in fact, they cannot be licensed for use on public roadways. They are equipped with special off road tires which are designed to interact with off road surfaces such as dirt, grass, mud, rocks, etc.

Numerous studies have been conducted over the years to measure the force and moment properties of automobile tires. The vast majority of these tests were performed on tires for passenger cars, light trucks, heavy trucks, and race cars. The purpose of this study was to measure and analyze the on road performance characteristics of off road tires found on ROVs. There has been a study that measured the force and moment characteristics of ATV tires but these tests were performed on clay, grass, and sand surfaces [1].

In the study which is the subject of this paper, two different ROV tires were chosen to be tested for their force and moment properties on the Flat Trac III machine at Smithers RAPRA in Ravenna, Ohio.

The test tires represent a tire with bias ply construction and one with radial plies, both of the same dimensional size. All tires were new with full tread depth at the start of testing. The external factors varied in the testing consisted of normal load and slip angle, with belt speed, inclination angle, and internal tire pressure being kept constant.



Figure 1. Hunting with a recreational off road vehicle



Figure 2. Off road recreation with an ROV



Figure 3. Utility off road vehicle in a farm environment

Throughout the history of physical testing of vehicles to objectively characterize their performance at the handling limit, the question of the effect of tire wear caused by multiple limit runs on the same set of tires has been confronted. Early work by Fancher, et al. [2] essentially stumbled onto the magnitude of this effect as it pertained to the then prevalent bias-ply tires in use, which resulted in their recommendation that for their test purposes the “tires were initially worn in by repeated running at limit cornering levels such that a stabilized side force performance was attained”. Although this approach achieved the goal of improving repeatability, the fallout from this approach was that the adoption of this method assured that the vehicle performance would not be representative of what an in-field vehicle and tire would experience since normal customer use does not entail repeated limit handling events. Even the National Highway Traffic Safety Administration has adopted a rigorous tire changing protocol in its testing to help address the tire wear issues. Other studies have explored this phenomenon over various performance regimes [3, 4, and 5] and one paper performed a scientific study on a flat track machine with modern day tires [6]. The approach used in this last study was employed in this paper.

METHODOLOGY FOR MEASURING TIRE FORCES AND MOMENTS

The tire machines used in this project as well as the processes followed for the tire testing and data analysis procedures are described below.

Flat Trac III Machine

The Flat Trac III tire test machine is an indoor test facility capable of measuring tire performance data in a controlled environment.



Figure 4. ROV tire on Flat Trac III tire test machine at Smithers RAPRA.

Tire Positioning System

Figure 4 illustrates that the tire, wheel, the wheel force transducer, and hydraulic motor are mounted in the movable upper head of the Flat Trac III. The head controls the steering, inclination angle, and vertical motions to the tire. These motions (as well as vertical loading) are servo controlled and programmed in prior to the start of testing.

Roadway

The twenty eight inch wide roadway is made up of a stainless steel belt covered with an industrial sanding material that simulates the frictional properties of actual road surfaces. This surface is more aggressive than actual roadways. The belt is maintained flat to within one to two millimeters under the tire patch by an air-bearing pad which is beneath the belt in the tire patch region. The roadway belt is driven by a large electric motor connected to one of the two large diameter drums over which it runs. The road speed is servo controlled and can be programmed to be constant or varied.

The typical roadway surface materials used on the stainless steel belt of the Flat Trac II is the “3Mite” material obtained from the 3M Company. A grit size of 220 was employed to simulate a flat asphalt surface. No testing was performed on an off road environment such as sand, dirt, clay, mud, etc. as part of this study.

Tire-Wheel Drive

A drive system which is independent of the roadway is attached to the tire-wheel shaft. This separate drive allows full variation of tire slip both in the braking and driving modes. The tire slip ratio, referenced to road speed, is under servo control. All tests in this study were performed in the free rolling condition.

Balance System

A six-component strain gage balance surrounds the wheel drive shaft. Three orthogonal forces and the corresponding moments are measured through this system. The driving and braking torque is sensed by a torque link in the wheel drive shaft. Transfer to Force

and moments from the balance axis-system to the conventional SAE location at the tire-roadway interface is performed in the data reduction computer program.

Tire Forces and Moments

To understand tire forces and moments, an axis system must first be defined. Figure 5 shows the SAE tire axis system and the quantities used in reducing and presenting the tire force data.

The results of the testing produced a number of measured values. Every force and moment was measured and recorded. Normalized saturated lateral force, cornering stiffness, aligning stiffness, and saturated overturning moment were used in the analysis. Also seen in the test results are loaded radius and other force values that are examined [2].

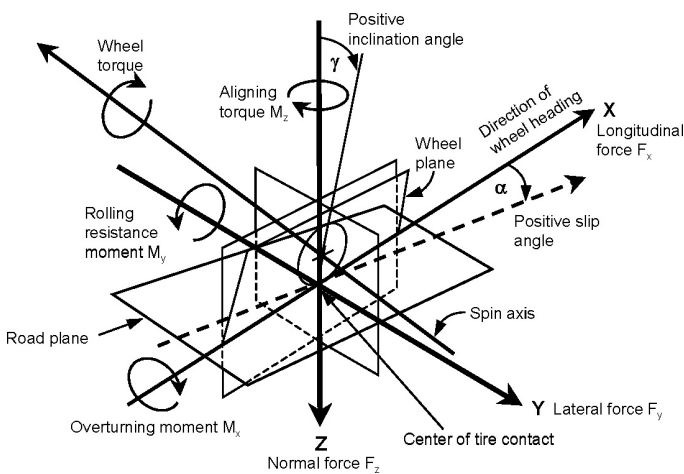


Figure 5. SAE Tire Axis System

Data Processing

The raw test data was processed using the MATLAB software. Some simple curve fitting techniques were used in the post processing of the data and are explained later.

DESCRIPTION OF TIRES TESTED

Two ROV tires were included in this study. One was a bias ply Maxxis Bighorn 2.0 25x10.00-12 and the other was a radial ply Maxxis Bighorn of the same basic dimensions, 25x10.00R12. Figure 6 is a photograph of an exemplar Maxxis Bighorn tire for reference. For comparison, tire data taken as part of another study was available which included an all season passenger car Goodyear Integrity 215/70R15 (see Figure 7) and an all-terrain light truck tire, a Uniroyal Liberator A/T LT235/75R15 (see Figure 8).

THE ON ROAD FORCE AND MOMENT PROPERTIES OF ROV TIRES

The first portion of this study was to perform standard sweep testing on the Flat Trac III in order to measure the on road force and moment characteristics on a bias and radial ROV tire and make comparisons between them and two other passenger vehicle tires. All tires were tested in a standard type sweep test where vertical load, belt speed,

and inclination angle are held constant and a sweep of slip angle is performed (see Table 1 for the test matrix). Then the tire is returned to free rolling and the load is increased to the next value in the test sequence. Another sweep test is performed. This continues until the tire has been tested at all vertical loads. All tire pressures were regulated to the table values. The inclination angle was set to zero for all tests and the maximum slip angle was 28 degrees.



Figure 6. Maxxis Bighorn 2.0 ROV tire



Figure 7. Goodyear Integrity 215/70R15 all season passenger car tire



Figure 8. Uniroyal Liberator LT235/75R15 all terrain light truck tire

Table 1. Test matrix for all tires tested

TIRE	Belt Speed (kph)	Pressure (psi)	Vertical Loads (kN)	Sweep Rate (deg/s)
Maxxis Bias ROV	48	16	1.1, 2.2, 3.3, 4.4	12.5
Maxxis Radial ROV	48	16	1.1, 2.2, 3.3, 4.4	12.5
215/70R15 all season	89	38.5	4.45, 8.9	12.5
LT235/75R15 all terrain	89	38.5	6.7, 11.1	12.5

The responses of interest in the study are cornering force, aligning torque, and overturning moment. These quantities are typically filtered then plotted versus slip angle. This data was then fit with the Loess non-parametric regression method in MATLAB in order to create a Loess Curve from which metrics could easily be calculated and smooth curves could be plotted.

Sweep Test Results for the Bias Ply Maxxis Bighorn 2.0 25x10.00-12 Tire

Figure A1 in the [Appendix](#) shows the filtered sweep test data for lateral force versus slip angle and Figure A2 in the [Appendix](#) shows the data for aligning torque for the bias ply tire. The overturning moment filtered data is plotted in Figure A3. Figure A4 in the [Appendix](#) shows the curve fit lateral force versus slip angle and Figure A5 shows the aligning torque fit data. Figure A6 shows the overturning moment versus slip angle graph. Note the asymmetric performance of overturning moment not found in the automobile tires. Figure A7 in the [Appendix](#) shows the lateral force coefficient which is calculated by dividing the lateral force by the vertical load. It represents an effective lateral friction. Note that these off road tires generate high friction levels in saturation when used on a hard, high friction surface.

Sweep Test Results for the Radial Ply Maxxis Bighorn AT25x10.00R12 Tire

Figure A8 in the [Appendix](#) shows the filtered sweep test data for lateral force versus slip angle and Figure A9 in the [Appendix](#) shows the data for aligning torque for the radial ply tire. Figure A10 contains the overturning moment filtered data. Figure A11 in the [Appendix](#) shows the curve fit lateral force versus slip angle and Figure A12 in the [Appendix](#) shows the aligning torque fit data. Figure A13 shows the fit overturning moment versus slip angle curves, which reveals again the same asymmetry noted in the bias tire. Figure A14 in the [Appendix](#) shows the lateral force coefficient versus slip angle curves. Once again, high effective friction levels were generated using these tires on a hard high friction surface.

Sweep Test Results for the Common Automobile Tires

As stated above, tire data from another project was used to compare the force and moment generation capacities of the ROV tires to that of an all season 215/70R15 passenger car tire and an all terrain LT235/75R15 light truck tire. For brevity, only the fit curves will be presented in this paper. Figure A15 in the [Appendix](#) shows the curve fit lateral force versus slip angle data and Figure A16 in the [Appendix](#) shows the aligning torque fit data for the Goodyear 215/70R15. Figure A17 contains the overturning moment versus slip angle chart and Figure A18 shows the lateral force coefficient versus slip angle curves for the all season tire. The same data for the Uniroyal Liberator A/T LT235/75R15 tire can be found in Figures A19 through A22 in the [Appendix](#).

Tire Performance Comparisons

Lateral Force Characteristics

In comparing Figures A4 and A11 in the [Appendix](#), it is clear that the bias ply and radial ply ROV tires do not have the same characteristics, even though they are of the same dimensional size and pressure. Note that the radial tire develops similar forces at low vertical loads to the bias ply tire but develops lower forces at the higher loads.

Another interesting comparison is the slip angle where the lateral force generated by the tire saturates. Saturation is the slip angle above which the lateral tire forces are insensitive to slip angle or the lateral force versus slip angle curve “flattens out.” Note that the radial ply tire saturates at a higher slip angle than the bias ply tire for each load condition tested.

In order to analyze the differences between the radial and the bias ply ROV tires in terms of their saturated lateral force capacities, a saturated lateral force value for each vertical load was calculated. Figure A23 shows the calculated saturated lateral force for both ROV tires in both left and right steer directions. The data is plotted versus vertical test load. Note that the bias ply tire has a higher force capacity at the limit.

Another interesting parameter is cornering stiffness which is basically the slope of the lateral force versus slip angle graph at zero slip angle. Figure A24 in the [Appendix](#) compares the cornering stiffness calculated at the selected vertical loads for the radial and bias ply ROV tires. The data shows that the bias ply tire has a much higher cornering stiffness than the radial tire. The value for the bias ply tire is nearly 20 percent higher than the radial at the low vertical loads then deviates by nearly 50 percent at the top load of 4,448 Newtons.

Aligning Torque Characteristics

The aligning torque performance characteristics shown in Figures A5 and A12 in the [Appendix](#) for the two ROV tires compare similarly, aside from the bias ply tire peaking at a slightly lower slip angle.

Overturning Moment Characteristics

A tire generates overturning moment when it deflects laterally when subjected to slip angles. Typically, the overturning moment versus slip angle chart follows the lateral force versus slip angle graph (see [Figures A17 and A21](#) in the [Appendix](#) for the overturning moment graphs for the all season and all terrain automobile tires). The two ROV tires tested as part of this study behaved asymmetrically with much higher overturning moments generated when steered in one direction as opposed to the other. This result is interesting and is likely due to a carcass stiffness difference in the tires, an analysis of which is beyond the subject of this study. Since overturning moment plays little role in vehicle steering and handling, the effect on vehicle performance is very small and would not be measurable in an off road environment.

Lateral Force Coefficient

As stated in the Introduction, there have been studies performed where force and moment properties of ATV tires were measured outdoors on various off road surfaces [1]. Even though these older ATV tires are not the same design or construction as modern day ROV tires, comparing the performance of the two can still provide some good insight. Figure 25 from [1] is reproduced in this paper as [Figure 9](#). Note that all the ATV tires tested as part of [1] have lateral force coefficients that fall well below 0.8 when tested on hard clay whereas the bias ply ROV tire (see [Figure A7](#) in the [Appendix](#)) exceeded 1.0 when tested on the Flat Trac III.

LATERAL FORCE COEFFICIENTS vs SLIP ANGLE
Exponential least squares fit, clay, 250 lb

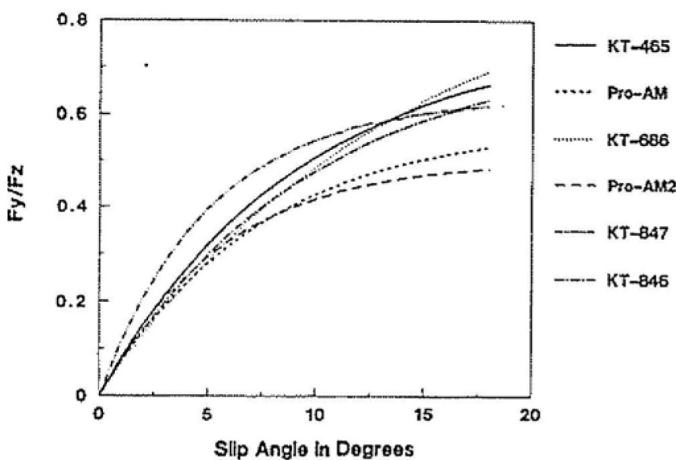


Figure 9. Figure 25 from [1] reproduced here - Summary of lateral force coefficients of ATV tires vs slip angle on hard clay.

EFFECT OF SEVERE CORNERING WEAR ON ROV TIRE PERFORMANCE

The second portion of this study was to measure how repeated test runs of an ROV on an asphalt test track affects how the tires generate force and quantify what that change is.

Method for Evaluating the Effect of Severe Cornering Induced Tire Wear

In order to isolate just the effect of severe cornering wear, controlled experiments were run where the ROV tires were subjected on the Flat Trac III to repeated step steer inputs of slip angle. These inputs were intended to simulate the duty cycle typically experienced by a tire in repeated limit handling events. The vertical load was kept at 4448 Newtons and the inclination angle was fixed at zero degrees. The metric chosen to objectively evaluate the change in tire performance was peak lateral force during each sweep. In the first phase of this part of the study, the ROV tires were subjected to repeated step steer runs in only one direction. The Flat Trac III machine input a 28 degree step input at 12.5 degrees per second and held that steer for five seconds before the tire was returned to straight ahead free rolling for one minute. This input was intended to simulate a limit test where the tire is saturated in a limit event such as a J-turn maneuver.

[Figure A25](#) in the [Appendix](#) shows the change in peak lateral force of the bias ply ROV tire with respect to repeated runs in one direction. [Figure A26](#) in the [Appendix](#) shows this same data for the radial ROV tire. As in the case with passenger car and light truck tires documented in [6], note how the lateral forces generated by both ROV tires climb quickly with repeated runs. The lateral force capacity of both tires increases in the range of 700 Newtons. [Figures A27 and A28](#) in the [Appendix](#) shows the lateral force coefficient data versus run number for the bias ply and radial tires respectively and show a change of around 0.16 from the first to the peak run. The ROV tires are able to generate effective friction values above 1.0. The data shows that the repeated runs wear the high spots off of the tread blocks and make the tire more efficient at developing force.

In the second phase of the cornering wear study, the ROV tires were exercised with same input parameters but steps were made to the left then right then left, etc. This profile was intended to simulate a condition where a vehicle is tested in alternative turn directions. The metric chosen to evaluate the change in tire performance was once again the peak lateral force at any time in the test run.

The data confirms that running tests in alternating directions will not “normalize” out the effect of cornering wear on tire performance. [Figure A29](#) shows the change in peak lateral force of the bias ply ROV tire with respect to repeated runs in alternating directions. [Figure A30](#) in the [Appendix](#) contains the processed data for the radial ROV tire. Once again, the lateral forces climb steadily with repeated runs as observed in the case with steers only in one direction. [Figures A31 and A32](#) in the [Appendix](#) shows the lateral force coefficient versus run number for the bias ply and radial ROV tires.

Discussion on Effect of Wear

Several conclusions can be drawn from this experiment. First, the force and moment properties of these ROV tires change with repeated test runs. In fact, the magnitude of change is significant and will have large effects on limit event outcomes (i.e. lateral accelerations or whether a vehicle will rollover or not). It is apparent from the data that the bulk of the changes in tire properties occur after a relatively small number of runs.

The test protocols used in this experiment produced wear patterns that were very similar to that seen in on-track vehicle testing. Since visual inspection is often used to decide when tires should be changed in the course of testing, combining the visual results with the corresponding objective results can be helpful in establishing a new standard for judging when to change tires.

The first and most important conclusion of this specific study is that if the goal of an experiment involving a vehicle in limit handling maneuvers is to characterize how that vehicle would respond in a customer's hands, only a limited set of runs can be made on a given set of ROV tires if the testing is performed on pavement. This is due to the significant increase in capacity after just several runs. This validates the NHTSA's procedure [5] to 'confirm' a reported tip up in a limit handling characterization test by replacing any worn tires with new tires and repeating the test that resulted in a tip up. All testing by all entities that endeavor to characterize the limit handling performance of vehicles should adhere to the NHTSA protocol regarding tire wear.

SUMMARY/CONCLUSIONS

1. Measuring tire forces and moments of an ROV tire using sweep testing is not only possible, but repeatable on the Flat Trac III tire machine. In doing so, the performance characteristics of an ROV tire can be quantified and analyzed. However, this testing does not provide data on how the tires perform in their true off road environment.
2. The bias ply ROV tire had higher cornering stiffness and lateral force capacity throughout the entire slip angle range of interest than the radial ROV tire of the same size. The aligning torque and overturning moment characteristics were similar between the two tires. Both tires exhibited an asymmetric performance in the overturning moment which is not seen in typical automobile tires.
3. Both the radial and bias ply ROV tires, which are designed for off road use, generated higher lateral force coefficients than the automobile tires. Values in excess of 1.0 were recorded which were also well above previous off road testing with ATV tires.
4. The test data confirmed that the peak lateral force that the ROV tires generate increases significantly in repeated step input runs.

The tire is wearing and changing and therefore will not perform the same as it did prior to the wearing of the tread blocks due to severe cornering. This is true if the steer input is only applied in one direction or if it is input in alternating directions. On track testing where runs are made in alternating directions will not "average out" this effect.

5. The first and most important conclusion of the tire wear study is that limit handling testing on pavement changes the performance characteristics of ROV tires quickly and with significant magnitude. If the goal of an experiment is to characterize how that vehicle would respond in a customer's hands, only a limited set of runs can be made on a given set of ROV tires. This is due to the significant increase in capacity after just several runs.

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APPENDIX

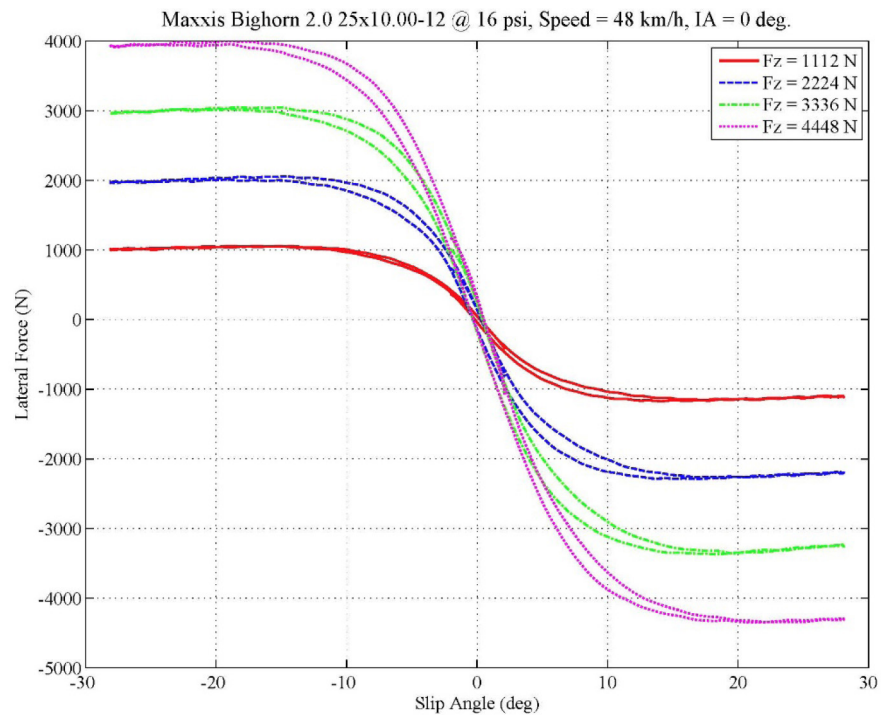


Figure A1. Filtered lateral force data versus slip angle for the Maxxis Bighorn 2.0 25x10.00-12 bias tire

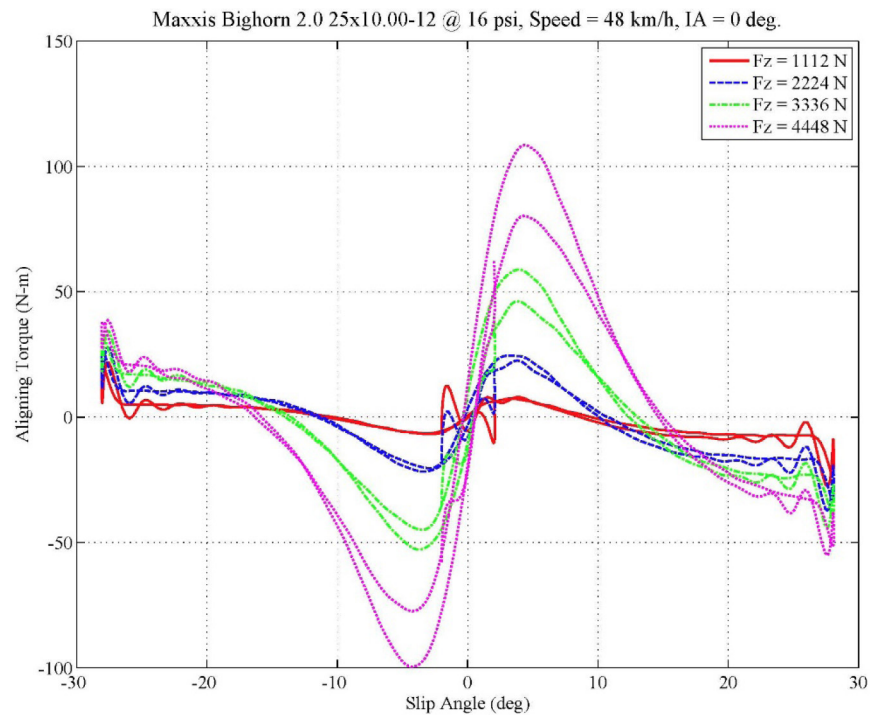


Figure A2. Filtered aligning torque data versus slip angle for the Maxxis Bighorn 2.0 25x10.00-12 bias tire