Stackpole Engineering Program Summary

Single Pressure, USE_MODE 2, MF5.2 Handling Tire Model Development and Validation Report

Manufacturer	Bridgestone
Brand Identity	Ecopia Ologic
Tire Size	95/80R16
Inflation Pressures	499.9 kPa
Customer	Bridgestone Americas
Contact	Cara Adams

Submission Date: July 19, 2019
Revision: 1.0

Contents

Tire Modeling Program Overview

The single pressure, USE_MODE 2, MF5.2 tire modeling program presented within this report has been conducted by Stackpole Engineering Services, Inc. for Bridgestone Americas. All physical testing for this program was conducted at Smithers Rapra. The tests performed were Velocity Ramp and Pure Cornering. All tire data processing and tire model fitting procedures have been conducted by Stackpole Engineering. All aspects of data processing for this project have been supervised by our expert team of engineers to ensure the delivery of a valid and viable model for this single pressure, USE_MODE 2, MF5.2 project.

Stackpole Engineering Services has completed the development of a single pressure, USE_MODE 2, MF5.2 tire model of a Bridgestone Ecopia Ologic 95/80R16 39M tire on a 16” x 3.0” wheel at 499.9 kPa inflation pressure. This report summarizes the results of the tire model provided to Bridgestone Americas.

Tire File Description (TIR)

The single pressure, USE_MODE 2, MF5.2 tire model was developed using the standard *.tir file format, which is the industry standard for the interchange of tire models. This tire model is compatible with TNO MF-Tyre & MF-Swift version 6.2.

1. Units and Coordinate System

The MF5.2 model utilizes standard SI units for all inputs and outputs. The test data from Smithers was converted to standard SI units prior to beginning the modeling process. This modeling project used the ISO W-axis system. For further reference on the ISO W-axis standard, please reference ISO Standard 8855 or the TYDEX Reference Manual, Release 1.3.

The general sign convention for this tire model is as follows:

- X-axis is positive *forward*.
- Y-axis is positive *left.*
- Z-axis is positive *upward.*

Forces are aligned with this axis system and moments follow the right hand rule. Other important properties for this coordinate system include:

- Slip Angle is positive for right hand turns. Positive Slip Angle results in a negative Lateral Force.
- Inclination Angle is positive when the top of the tire is tilted to the right. This is the same as the SAE coordinate system. Positive inclination is the same as *negative* camber on the *left* side of the vehicle and *positive* camber on the *right* side.

- Slip Ratio is expressed as a fraction (generally $-1 \leq SR \leq 1$). Zero Slip Ratio represents a free rolling tire, positive Slip Ratio generates a drive force, and negative Slip Ratio generates a braking force.

2. Model

The MF5.2 tire model developed for this program was completed as a single pressure USE_MODE 2, which indicates smooth road contact, steady state calculations for F_x, F_y, F_z, M_x, M_y, M_z combined forces and moments, and linear transient compatible. The valid ranges for this tire model (as specified in the tire file) are as follows:

- Slip Angle Range: +/- 0.261799 radians [+/- 15 degrees]
- Inclination Angle Range: +/- 0.069813 radians [+/- 4 degrees]
- Slip Ratio Range: +/- 0.0 [+/- 0%]
- Vertical Load Range: 100 to 1322 N

Notice About the Tire Model Validity Range:

The maximum and minimum ranges for Slip Angle, Inclination Angle, Slip Ratio and Vertical Load were set to be equivalent to the ranges specified for the physical tire test. If this tire model were to be used in a simulation that would exceed these limits, the simulation may fail to complete. Through our extensive tire testing and analysis history at Stackpole Engineering Services, a tire model validation method has been developed to test the validity of a tire model beyond its defined test/fitted limits. If the user chooses, they may adjust the specified limits for simulations if deemed necessary. SES recommends the limits not be extended any further than +/- 15° of Slip Angle, +/- 5° of Inclination Angle, and 1500 N Vertical Load.

3. Tire Conditions

This section provides the nominal and actual tire inflation pressures.

4. Tire Dimensions

The tire tested for this program was a Bridgestone Ecopia Ologic 95/80R16 39M, tested on a 16” x 3.0” wheel at 499.9 kPa inflation pressure. The following physical properties were either directly measured or calculated:

- Unloaded Radius = 0.2785 m [Calculated during the fitting process]
- Section Width = 0.095 m [Taken from Manufacturer literature]
- Aspect Ratio = 0.80 [Taken from Manufacturer literature]
- Wheel Radius = 0.2032 m [Specified by testing facility]
- Wheel Width = 0.0762 m [Specified by testing facility]

5. Vertical Specifications

The nominal specifications used for the tire were selected based on best practices and optimum fit performance. The resulting nominals are summarized below:

- Nominal Wheel Load (N):
    - The Nominal Load for this test program was selected to be 927 N. This value was selected during the fitting process.
- Average Vertical Stiffness (N/m):
    - The Nominal Vertical Stiffness was calculated to be 175000 N/m. This value was calculated as part of the fitting process and calculated at the Nominal Load.
- Average Vertical Damping (N*s/m):
    - No Vertical Damping testing was conducted for this tire. Therefore, this value was set as 50.000 N*s/m.
- B_{Reff}, C_{Reff}, D_{Reff}: These are the coefficients for the Effective Radius model. These are fit using the data from Velocity Ramp testing. Effective Radius is calculated using the Belt Speed and Wheel Angular Velocity from this test, assuming a free rolling tire (zero Slip Ratio).

Tire Model Fit Results

This section of the report summarizes the results of the tire model fitting process, and provides select comparison graphs for each of the relevant sections of the tire model. Sections are provided for Vertical Force (F_z), Effective Radius (R_e), Pure Slip Lateral Force (F_{y0}), Pure Slip Aligning Torque (M_{z0}), and Pure Slip Overturning Moment (M_x).

1. Vertical Force

The Vertical Force function fits the available data well, as shown in Figure 1 below. The reason for the plots consisting of a series of straight, horizontal lines is that Smithers controls the Velocity Ramp tests to a constant Vertical Load, which is replicated by the model.

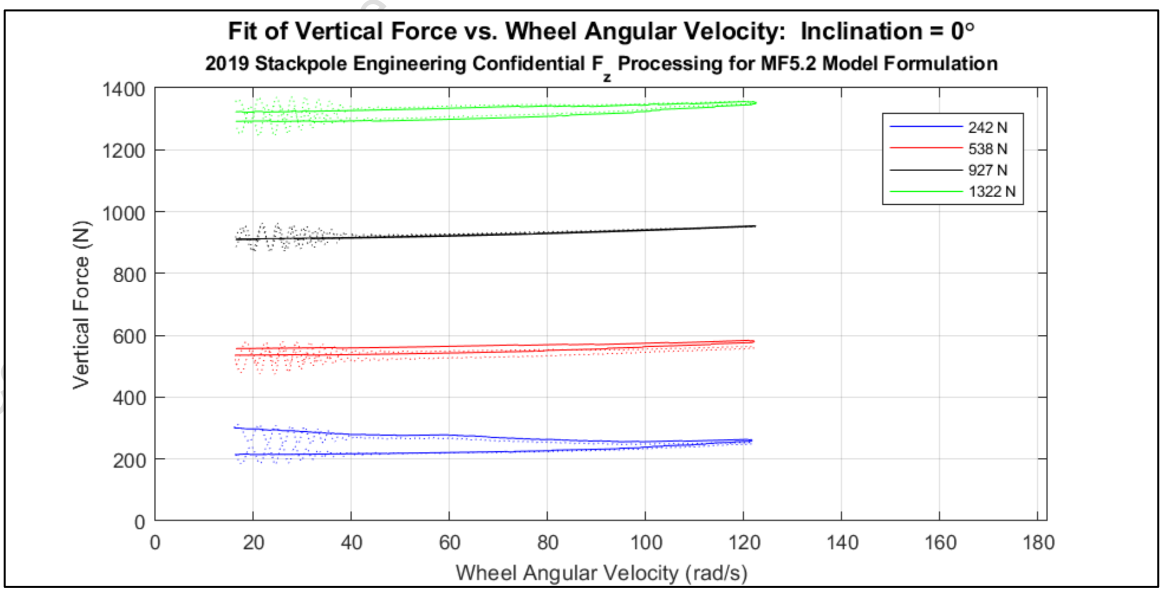

Figure 1: Plot of Vertical Force fit vs. raw data: Bridgestone Ecopia Ologic 95/80R16

2. *Effective Radius*

The coefficients that make up the Effective Radius function were also fit using data taken from Velocity Ramp testing. The Effective Radius was calculated from the velocity data using the Belt Speed and Wheel Angular Velocity, assuming zero Slip Ratio. The resulting fit is shown in Figure 2 below.

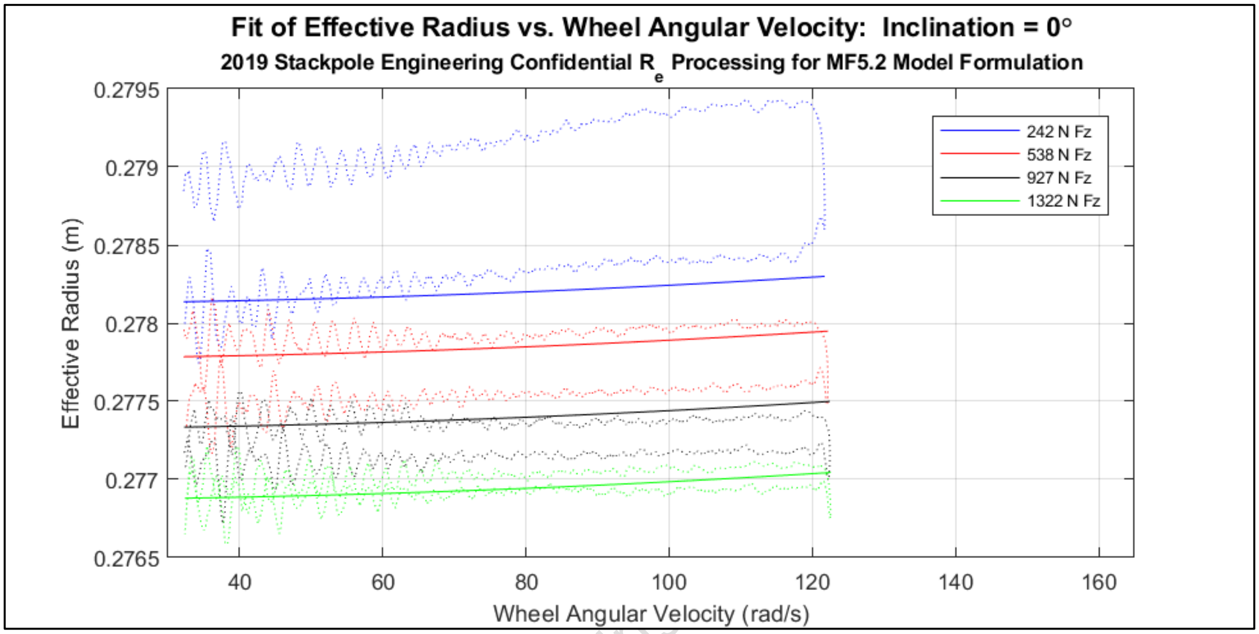

Figure 2: Plot of Effective Radius fit vs. raw test data: Bridgestone Ecopia Ologic 95/80R16

Figure 2 shows that the model generally fits the data well, with the model trends of Effective Radius versus Vertical Load and speed following the data trends well. The model shows reliable prediction of the Effective Radius through the Vertical Load Sweep and at the Velocities tested.

3. *Lateral Force, Pure Sideslip*

The coefficients for Pure Sideslip Lateral Force are fit using the Pure Cornering data. The model follows the raw data well, as shown in Figure 3 on the following page, and can be used to reliably predict Lateral Forces through both the sweep range and the load range tested.

The plot in Figure 3 shows the behavior of the Lateral Force versus Slip Angle on the interval ±15°, which is the certification range for this fit. Additional plots showing the remainder of the fit conditions are included in Appendix A.

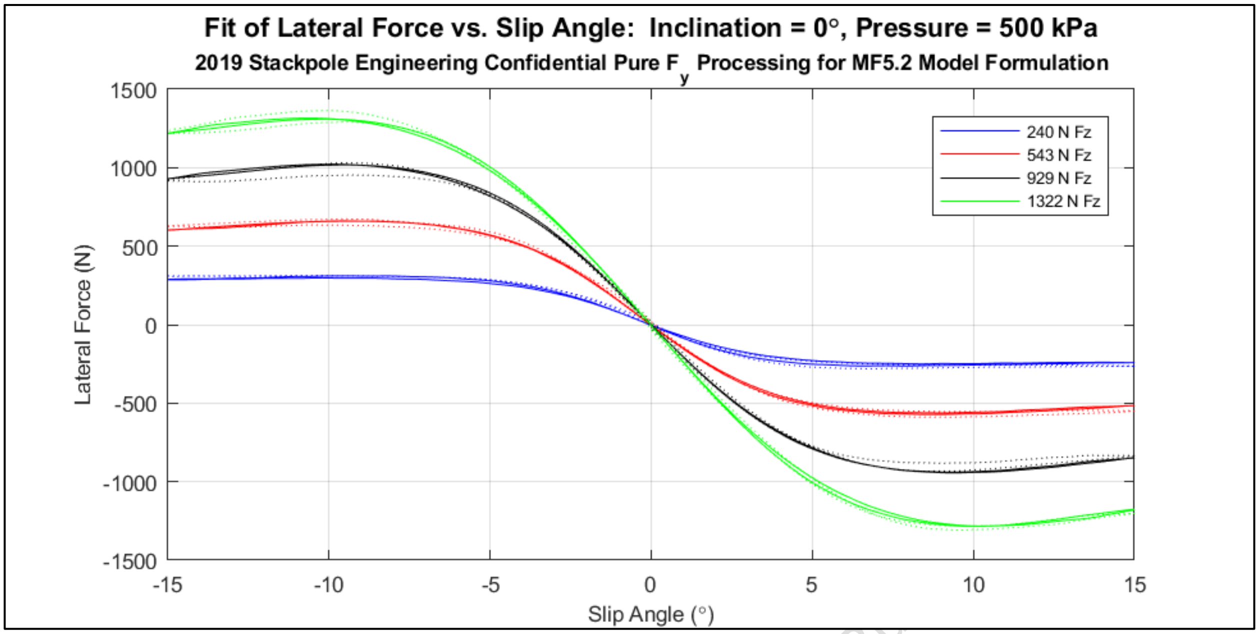

Figure 3: Plot of Lateral Force fit vs. raw data: Bridgestone Ecopia Ologic 95/80R16

4. Aligning Moment, Pure Sideslip

The Pure Sideslip Aligning Moment model is generated using the Pure Cornering data. This model fits the raw data well and was generated without issues. An example of the fit quality is shown in Figure 4 below.

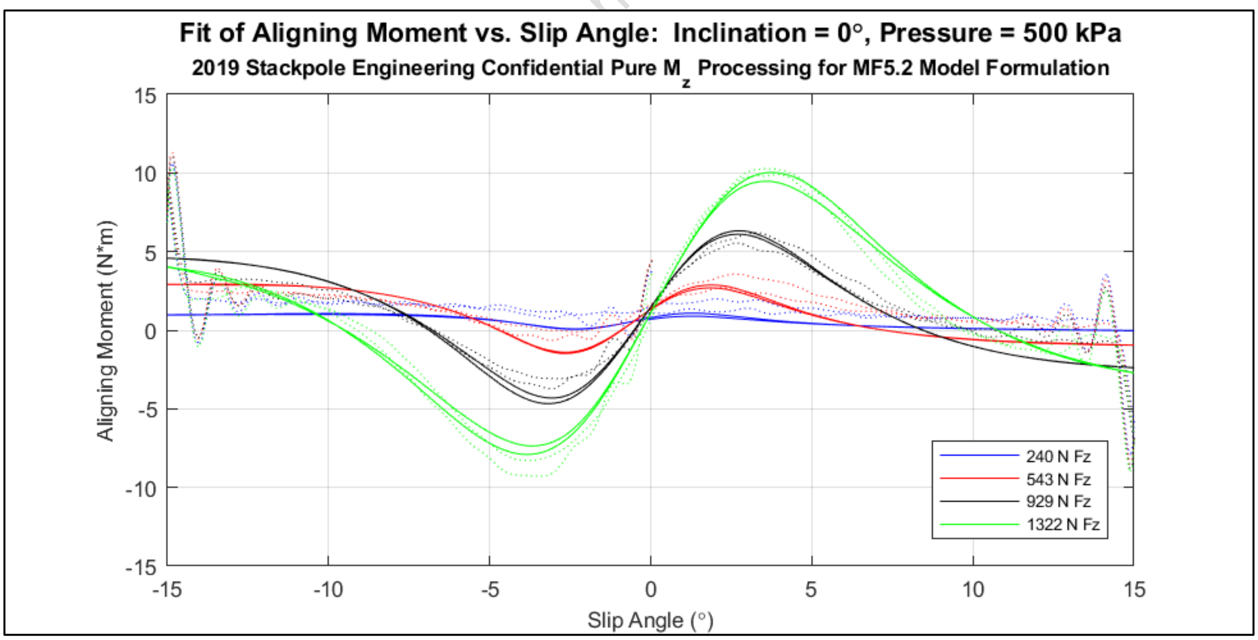

Figure 4: Plot of Aligning Moment fit vs. raw data: Bridgestone Ecopia Ologic 95/80R16

The Aligning Moment data in Figure 4 is plotted on the interval ±15°. This shows that the model operates well when compared to the raw test data. Additional plots showing the Aligning Moment fit versus raw data are contained in Appendix B.

5. Overturning Moment, Pure Sideslip

The Pure Sideslip Overturning Moment model was generated from the Pure Cornering raw data. An example of the modeled Overturning Moment is plotted against the raw data below in Figure 5.

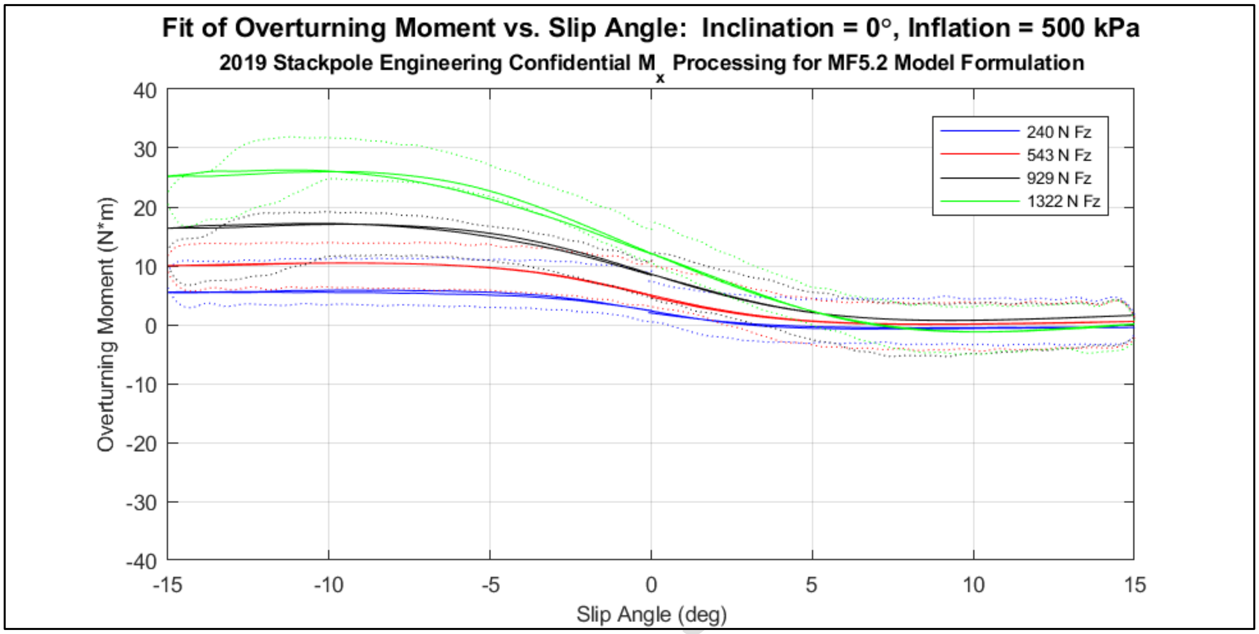

Figure 5: Plot of Overturning Moment fit vs. raw data: Bridgestone Ecopia Ologic 95/80R16

Figure 5 shows that the model follows the data trends well. Additional plots of the Overturning Moment model plotted against raw data are presented in Appendix C.

Conclusion

This report describes the details of the TNO 6.2 version of the USE_MODE 2 MF-Tyre 5.2 (MF5.2) Tire Model of the Bridgestone Ecopia Ologic 95/80R16 39M tire at 499.9 kPa Inflation pressure by Stackpole Engineering for Bridgestone Americas. All coefficients contained in the model were populated using a proprietary fitting process, and the resulting model has been shown to accurately represent the raw data.

If you have any questions regarding the tire model or this report, please feel free to contact Stackpole Engineering Services, Inc. using the information below.

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Appendix A

Plots of Lateral Force, Pure Sideslip Behavior vs. Raw Data

Bridgestone Ecopia Ologic 95/80R16 (16x3.0 wheel)

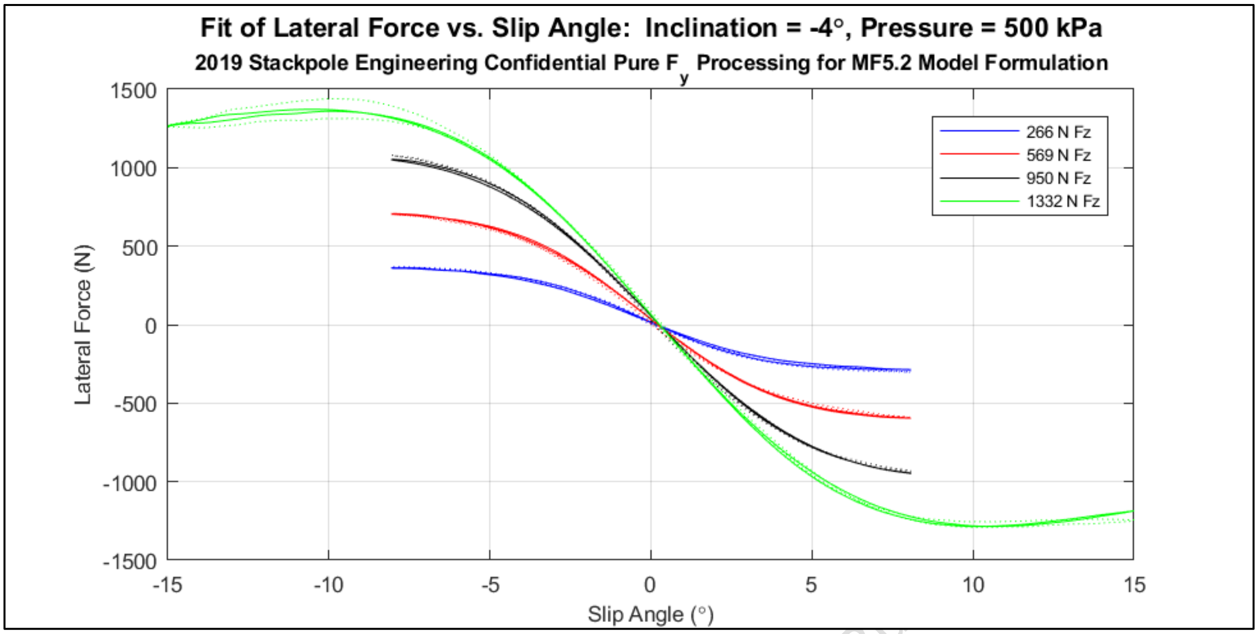

Figure A1: Comparison of F_{y0} fit to raw data, -4° Inclination

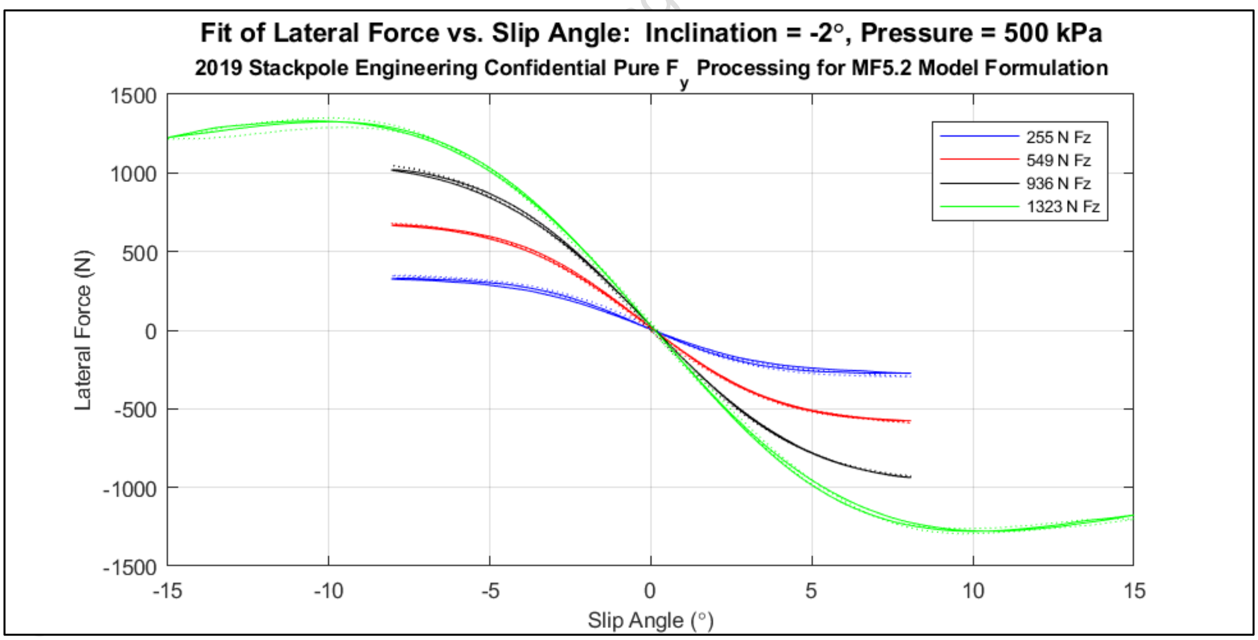

Figure A2: Comparison of F_{y0} fit to raw data, -2° Inclination

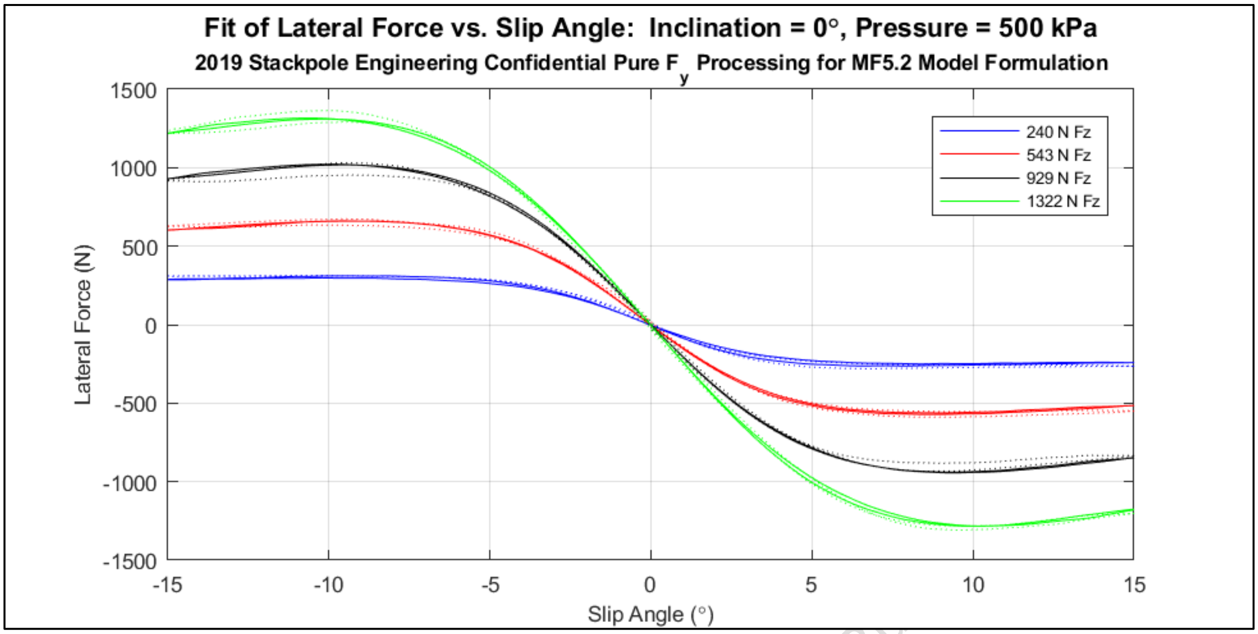

Figure A3: Comparison of F_{y0} fit to raw data, 0° Inclination

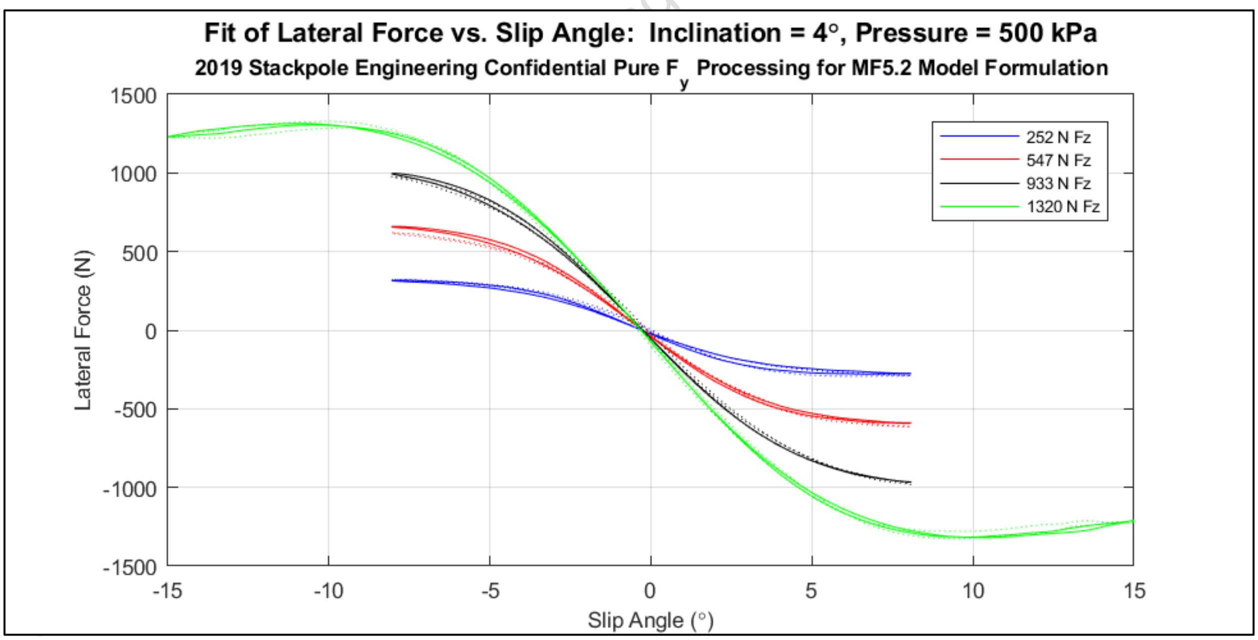

Figure A4: Comparison of F_{y0} fit to raw data, 4° Inclination

Appendix B

Plots of Aligning Moment, Pure Sideslip Behavior vs. Raw Data

Bridgestone Ecopia Ologic 95/80R16 (16x3.0 wheel)

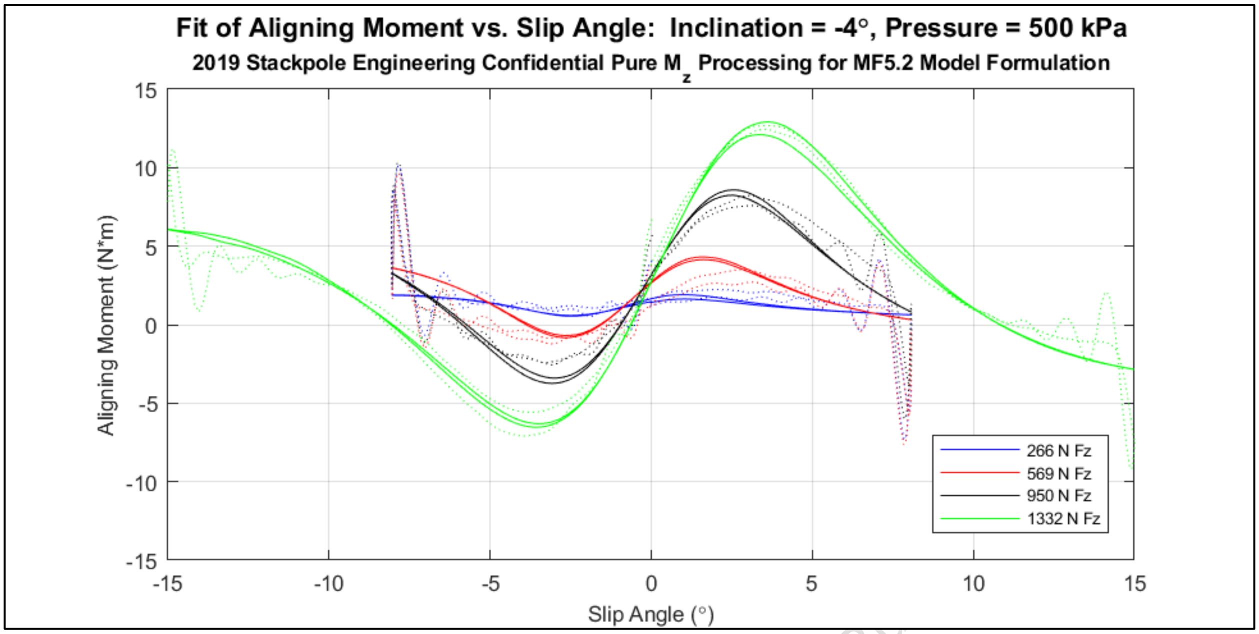

Figure B1: Comparison of M_{z0} fit to raw data, -4° Inclination

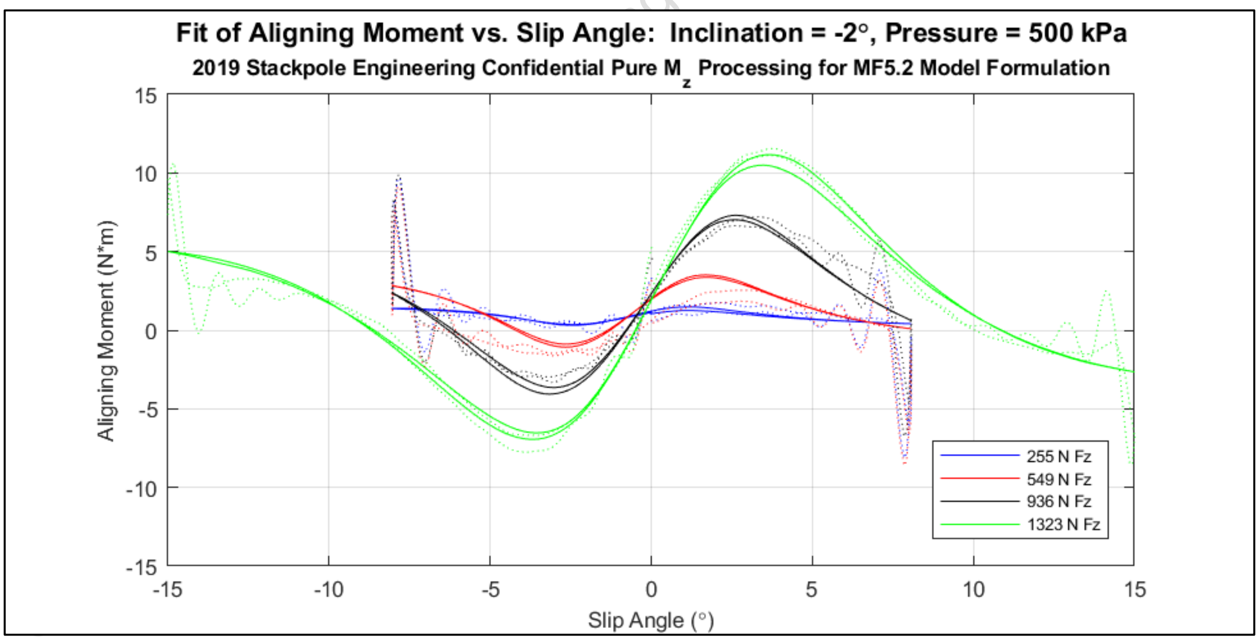

Figure B2: Comparison of M_{z0} fit to raw data, -2° Inclination

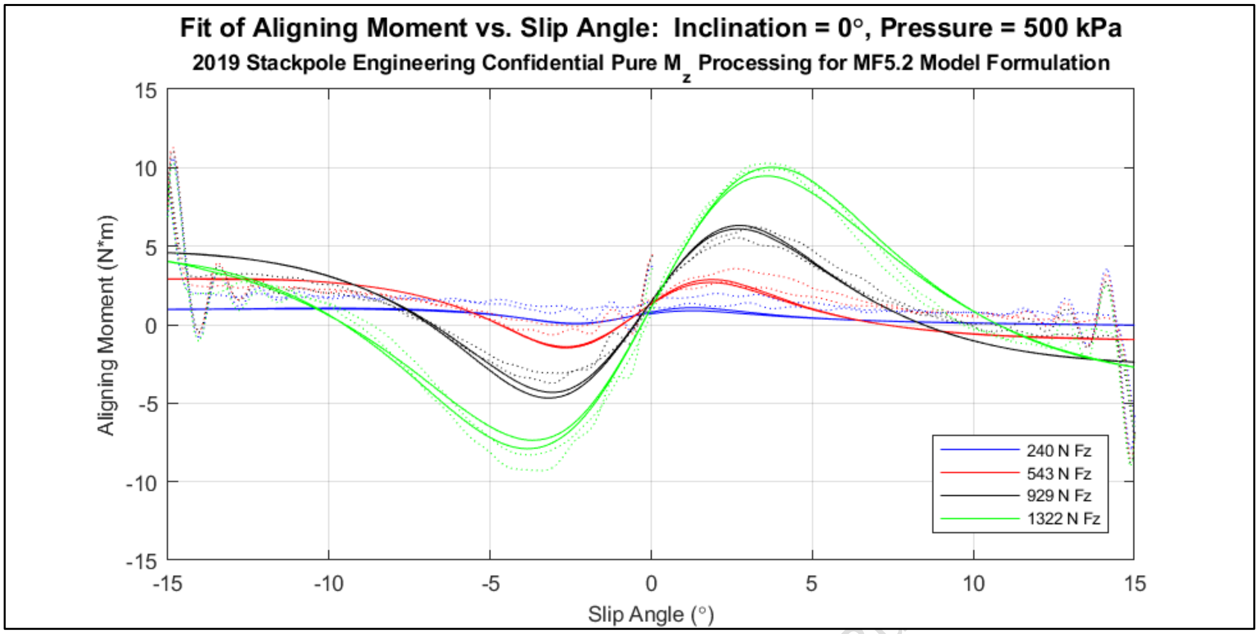

Figure B3: Comparison of M_{z0} fit to raw data, 0° Inclination

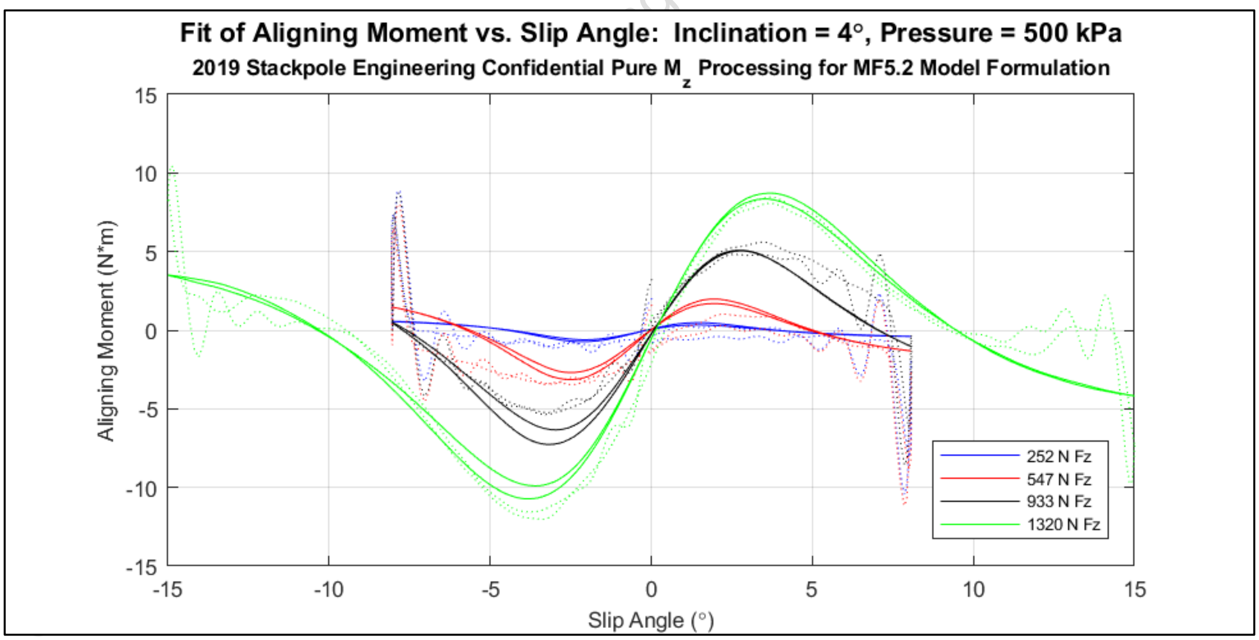

Figure B4: Comparison of M_{z0} fit to raw data, 4° Inclination

Appendix C

Plots of Overturning Moment, Pure Sideslip Behavior vs. Raw Data
Bridgestone Ecopia Ologic 95/80R16 (16x3.0 wheel)

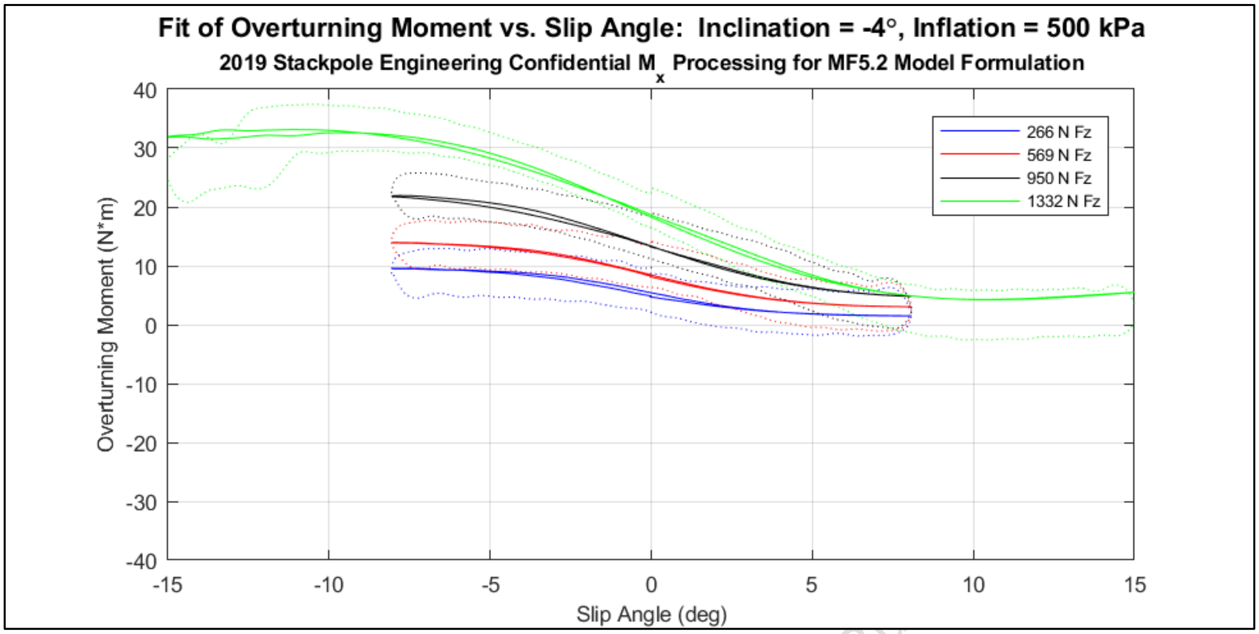

Figure C1: Comparison of M_{x0} fit to raw data, -4° Inclination

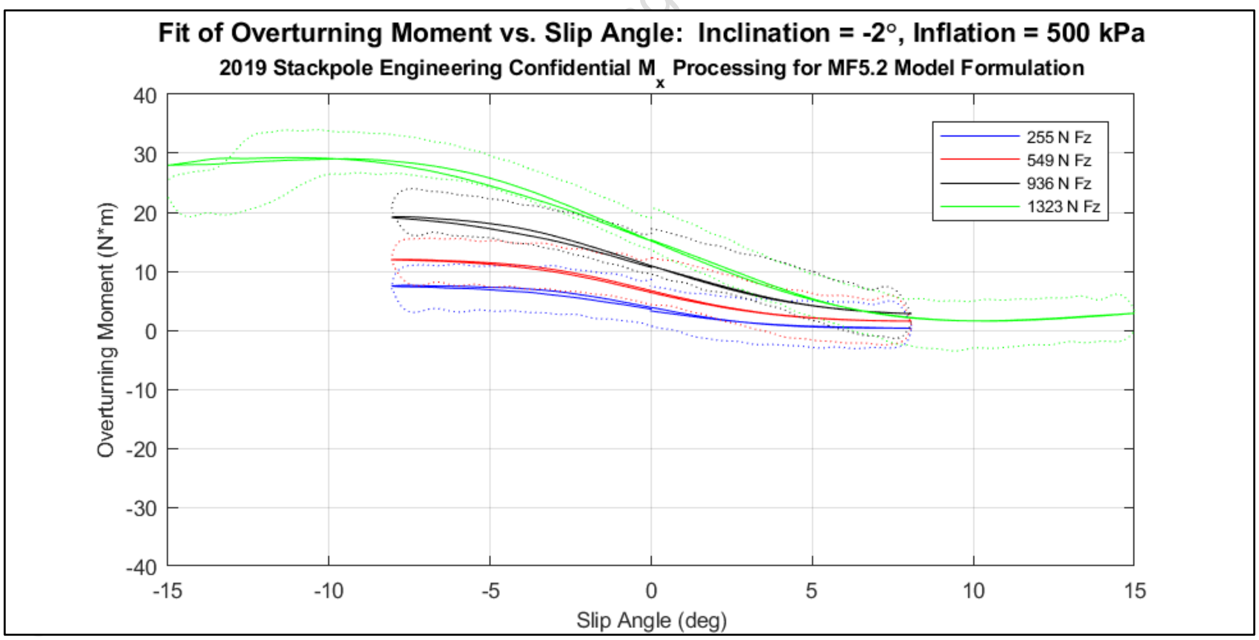

Figure C2: Comparison of M_{x0} fit to raw data, -2° Inclination

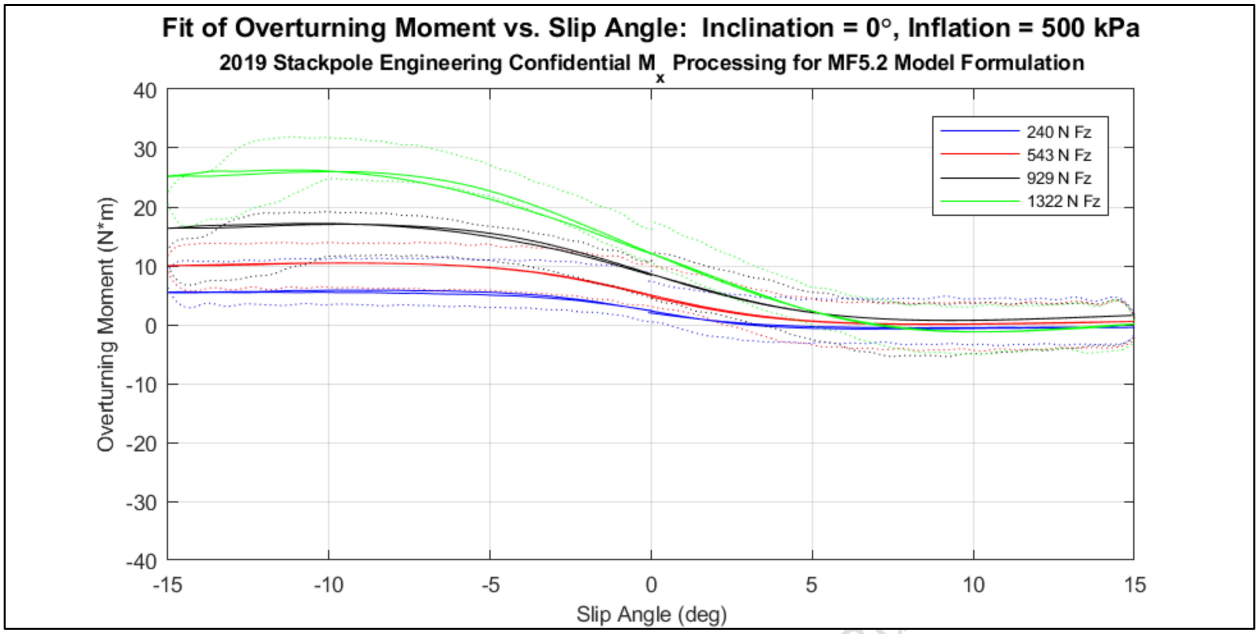

Figure C3: Comparison of M_{x0} fit to raw data, 0° Inclination

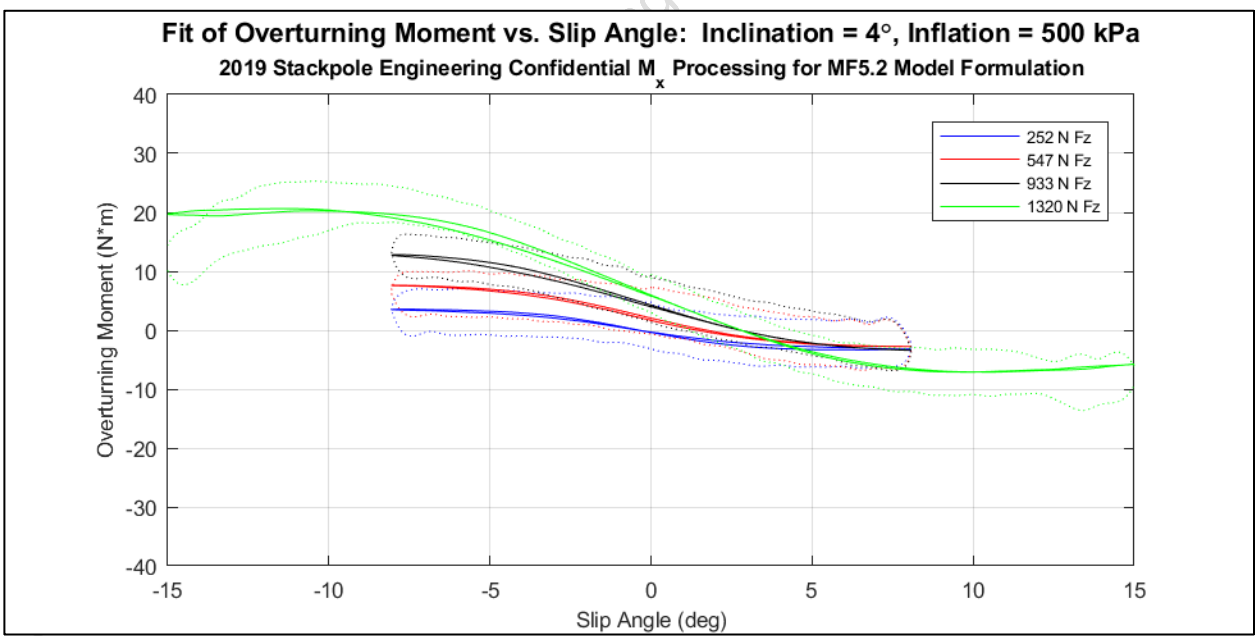

Figure C4: Comparison of M_{x0} fit to raw data, 4° Inclination