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Implementation and Validation of the Fiala Tire Model in Chrono

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Abstract

A Fiala Tire model was recently added to CHRONO::Engine. To validate the Fiala tire implementation in CHRONO::Engine, a tire test rig model was created to compare simulated tire force and moments against MSC ADAMS simulation results. Both steady-state and transient results from CHRONO::Engine were in close agreement with those from MSC ADAMS.

Keywords: Validation, Fiala, Tire, CHRONO::Engine, ADAMS

Contents

1 Introduction

A variety of tire models exist for multi-body simulation. Of these, the Fiala model is one of the simplest, requiring only nine parameters for the steady-steady state implementation or eleven parameters for MSC ADAMS transient implementation. The limited number of parameters makes it easy to model a tire, but this is balanced by the lower fidelity of the tire model.

The Fiala tire model implemented in CHRONO::Engine was based on the transient Fiala model presented in the MSC ADAMS/Tire documentation with minor changes [1]. As such, this report closely mirrors the ADAMS/Tire documentation. To test the implementation of the Fiala model within CHRONO::Engine, a tire test rig model was created. Both steady-state and transient slip angle simulations were conducted and compared between ADAMS/tire and CHRONO. Overall, close agreement was seen between the results of the two multi-body simulation packages.

2 CHRONO Fiala Tire Model

2.1 Model Parameters

In addition to user defined functions for the normal force of the tire, $f_{stiffness}(depth)$ and $f_{damping}(depth, velocity)$, nine additional tire parameters are required for the Fiala model implemented in Chrono.

Parameter	Dimension	Description
Unloaded Radius	Length	This parameter is used to calculate the current penetration depth of the tire
RollingResistance	Length	This parameter is used to determine the rolling resistance of the tire, M_y
WIDTH	Length	In the model's current state, this parameter is used to help calculate the aligning moment of the tire and does not necessarily to correspond to the physical width of the tire
CSLIP	Force	The longitudinal slip stiffness, which is calculated as the partial derivative of the longitudinal force, F_x, with respect to the longitudinal slip ratio at zero slip
CALPHA	Force/radian	The lateral slip stiffness, which is calculated as the partial derivative of the lateral force, F_y, with respect to the slip angle, α, at zero slip angle
U_{max}	None	Coefficient of friction at no slip
U_{min}	None	Coefficient of friction at full slip
XRelaxationLength	Length	The ratio of the Longitudinal Slip Stiffness, $CSLIP$, to the longitudinal carcass stiffness
YRelaxationLength	Length/radian	The ratio of the Lateral Slip Stiffness, $CALPHA$, to the lateral carcass stiffness

2.2   Coordinate System

All calculations are performed in the ISO-W coordinate system until the final coordinate system transformation. The origin of this system is the contact patch point in the road plane. The x-axis points along the forward direction of travel along the wheel plane to ground plane intersection line. The z-axis points upwards normal to the ground plane and the y-axis is formed by the cross product of the z-axis and x-axis (right-hand rule).

2.3   Vertical Force

The normal force generated by the tire, F_z, is specified by two user defined call backs. The normal stiffness callback provides the user with the penetration depth. For a linear stiffness, the return value can simply be the penetration depth times the normal stiffness. If some other function is desired, such as a lookup table, it can be executed within the same framework. The normal damping force callback is very similar to the normal stiffness callback with the exception that is passes the penetration velocity in addition to the penetration depth.

$$F_z = f_{stiffness}(depth) + f_{damping}(depth, velocity), \text{ limited to } F_z \geq 0 \tag{1}$$
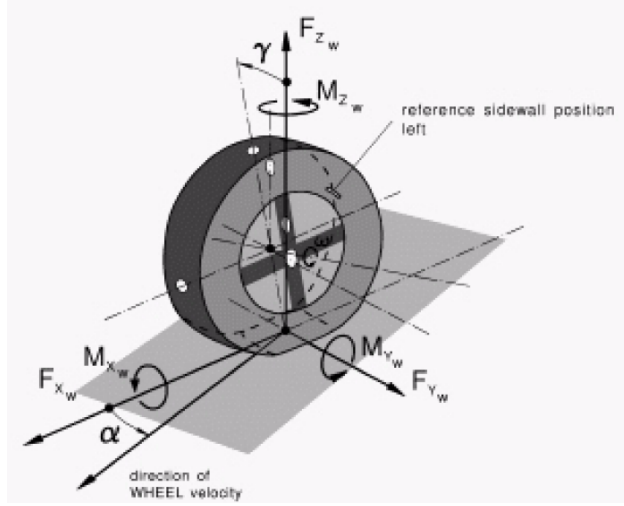
Figure 1: ISO-W Coordinate System - From ADAMS/Tire Documentation [1]

2.4 Contact Patch States

With the transient implementation of the Fiala tire model, two first order contact patch state variables are used to replace the steady-state longitudinal and lateral slip calculations. These states add increased fidelity into the model and they allow the model to handle zero velocity cases since division by the forward velocity is not performed.

2.4.1 Longitudinal Slip State Derivation

The derivation of longitudinal slip state, κ', which is substituted for the longitudinal slip, S_s, in the sections below begins with an ODE for the contact patch longitudinal displacement, u, in terms of the longitudinal slip velocity of the wheel, V_{sx}, and of the contact patch, V'_{sx}:

$$\frac{du}{dt} = -(V_{sx} - V'_{sx}) \tag{2}$$

$$V_{sx} = V_x - \Omega R_e \tag{3}$$

where V_x is the velocity of the wheel center in the x direction, Ω is the rotational velocity of the wheel about its spin axis, and R_e is unloaded radius of the tire minus the penetration depth.

The longitudinal force can written as

$$F_x = CSLIP \times \kappa' \tag{4}$$

or

$$F_x = C_{Fx} u \tag{5}$$

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where C_{Fx} is the longitudinal carcass stiffness. Equating the longitudinal force calculations gives u in terms of κ'

$$u = \frac{CSLIP}{C_{Fx}}\kappa' = (XRelationLength)(\kappa') \tag{6}$$

where $XRelationLength$ is defined as $\frac{CSLIP}{C_{Fx}}$. Since κ is defined as,

$$\kappa = -\frac{V_{sx}}{|V_x|} \tag{7}$$

, κ' is defined similarly as

$$\kappa' = -\frac{V'_{sx}}{|V_x|} \tag{8}$$

which can be rearranged in terms of V'_{sx}

$$V'_{sx} = -|V_x|\,\kappa' \tag{9}$$

When equation 6 and equation 9 are substituted into the starting ODE, equation 2, the final form of the longitudinal slip state is formed.

$$\frac{d((XRelationLength)(\kappa'))}{dt} = -\left(V_{sx} - (-|V_x|\,\kappa')\right) \tag{10a}$$

$$\frac{d\kappa'}{dt} = -\frac{1}{XRelationLength}\left(|V_x|\,\kappa' + V_{sx}\right) \tag{10b}$$

With this definition, κ' is negative for braking and positive during acceleration.

2.4.2 Lateral Slip State Derivation

The derivation of the lateral slip state is very similar to the longitudinal slip state. The derivation begins with an ODE for the contact patch lateral displacement, v, in terms of the lateral slip velocity of the wheel, V_{sy}, and of the contact patch, V'_{sy}:

$$\frac{dv}{dt} = -(V_{sy} - V'_{sy}) \tag{11}$$

$$V_{sy} = V_y \tag{12}$$

where V_y is the velocity of the wheel center in the y direction. The lateral force can be written as

$$F_y = -CALPHA \times \alpha' \tag{13}$$

or

$$F_y = C_{Fy}v \tag{14}$$

where C_{Fy} is the lateral carcass stiffness. Equating the lateral force calculations gives v in terms of α'

$$v = -\frac{CALPHA}{C_{Fy}}\alpha' = -(YRelationLength)(\alpha') \tag{15}$$

where *YRelationLength* is defined as $\frac{CALPHA}{C_{Fy}}$. Since α is defined as,

$$\tan(\alpha) = \frac{V_{sy}}{|V_x|} \tag{16}$$

, α' is defined similarly as

$$\tan(\alpha') = \frac{V'_{sy}}{|V_x|} \tag{17}$$

which can be rearranged in terms of V'_{sy}

$$V'_{sy} = |V_x| \tan(\alpha') \tag{18}$$

When equation 15 and equation 18 are substituted into the starting ODE, equation 11, the final form of the lateral slip state is formed.

$$\frac{d(-(YRelationLength)(\alpha'))}{dt} = -(V_{sy} - (|V_x| \tan(\alpha'))) \tag{19a}$$

$$\frac{d\alpha'}{dt} = \frac{1}{YRelationLength} (V_{sy} - |V_x| \tan(\alpha')) \tag{19b}$$

Note that this equation is different than what is described in the MSC ADAMS/Tire documentation [1]. With the differential equation above, when $\frac{d\alpha'}{dt} = 0$, $\tan(\alpha') = \frac{V_{sy}}{|V_x|} = \tan(\alpha)$.

2.5 Intermediate Calculations

In order to determine the current coefficient of friction, U, which is used in subsequent calculations, the comprehensive slip ratio, $S_s\alpha$ needs to be calculated first.

$$S_s\alpha = \sqrt{S_s{}^2 + \tan^2(\alpha)}, \text{ limited to } S_s\alpha \le 1 \tag{20}$$

With that value in hand, the current coefficient of friction, U, can then be calculated.

$$U = U_{max} - (U_{max} - U_{min}) \times S_s\alpha \tag{21}$$

2.6 Longitudinal Force

The longitudinal force calculation is broken up into two potential states, an elastic deformation state and a complete sliding state. To determine which state the tire is in, a critical longitudinal slip ratio is first calculated.

$$S_{critical} = \left| \frac{U \times F_z}{2 \times CSLIP} \right| \tag{22}$$

If the absolute value of the longitudinal slip ratio, $|S_s|$ is less than or equal to the critical longitudinal slip ratio, $S_{critical}$, then the tire is in the elastic deformation state. Otherwise,

the tire is in the complete sliding state.

Elastic Deformation State: $|S_s| \leq S_{critical}$

$$F_x = CSLIP \times S_s \tag{23}$$

Complete Sliding: $|S_s| > S_{critical}$

$$F_x = sgn(S_s)(F_{x1} - F_{x2}), \text{ where} \tag{24a}$$

$$F_{x1} = U \times |F_z| \tag{24b}$$

$$F_{x2} = \left| \frac{(U \times F_z)^2}{4 \times S_s \times CSLIP} \right| \tag{24c}$$

Note that the sign of these terms is opposite to that of the ADAMS documentation so that a negative longitudinal slip ratio indicates braking.

2.7 Lateral Force and Aligning Moment

Just like the longitudinal force calculation, the lateral force and aligning moment calculations are broken up into the same two categories of states, an elastic deformation state and a complete sliding state. To determine which state the tire is in for these calculations, a critical slip angle needs to be calculated.

$$\alpha_{critical} = \arctan\left(\frac{3 \times U \times |F_z|}{CALPHA} \right) \tag{25}$$

If the absolute value of the slip angle is less than or equal to $\alpha_{critical}$, then the tire is in the elastic deformation state for the purpose of these calculations. Otherwise, it is in the complete sliding state.

Elastic Deformation State: $|\alpha| \leq \alpha_{critical}$

$$F_y = -U \times |F_z| \times \left(1 - H^3\right) \times sgn(\alpha), \tag{26a}$$

$$M_z = U \times |F_z| \times WIDTH \times (1 - H) \times H^3 \times sgn(\alpha), \text{ where} \tag{26b}$$

$$H = 1 - \frac{CALPHA \times |\tan(\alpha)|}{3 \times U \times |F_z|} \tag{26c}$$

Complete Sliding: $|\alpha| > \alpha_{critical}$

$$F_y = -U \times |F_z| \times sgn(\alpha) \tag{27a}$$

$$M_z = 0 \tag{27b}$$

2.8 Rolling Resistance

$$M_y = -RollingResistance \times |F_z| \times sgn(\omega), \text{ where} \tag{28}$$

ω is the angular velocity of the wheel about its spin axis.

2.9 Overturning Moment

Due to the assumptions in the Fiala tire model, the overturning moment is always assumed to be zero.

$$M_x = 0 \tag{29}$$

2.10 Final Coordinate System Transformation

Since the convention in Chrono is to apply the tire force and moments to the wheel center in the global coordinate system, a coordinate system transformation is applied to move from the ISO-W coordinate system into Global coordinates and orientation. The forces are then moved from the contact patch to the wheel center resulting in a change in the applied moments.

3 Results

Since the equations implemented in CHRONO::Engine differed slightly from the equations given in the ADAMS/Tire documentation, a series of comparison simulation were conducted to validate the CHRONO Fiala tire implementation against MSC ADAMS. In ADAMS, the tire rig rig feature in ADAMS/car was used to perform the simulations with the standard settings (GSTIFF,I3 with a maximum step size of 0.01 seconds). In CHRONO::Engine, a tire test rig model was created with similar mass properties as the tire test rig used in ADAMS. For this comparison, a step size of 1e-4 seconds was used with the "INT EULER IMPLICIT LINEARIZED" integrator. Both models were run at 3000 and 4500N of normal load and a forward global x velocity of 20m/s.

The following Fiala model parameters were used in both ADAMS and CHRONO:

Parameter	Value
Vertical Stiffness	310000
Vertical Damping	3100
Unloaded Radius	0.3099
RollingResistance	0.001
WIDTH	0.235
CSLIP	1000000
CALPHA	45836.6236
U_{max}	1.0
U_{min}	0.9
XRelaxationLength	0.05
YRelaxationLength	0.15

For the first test, a series of different constant slip angles were simulated and the forces and moments in the global frame were compared at the final time step. For the second test,

the slip angle was sweep between $+/-10$ degrees with a 0.1Hz sine wave and the results were compared against each other in time.
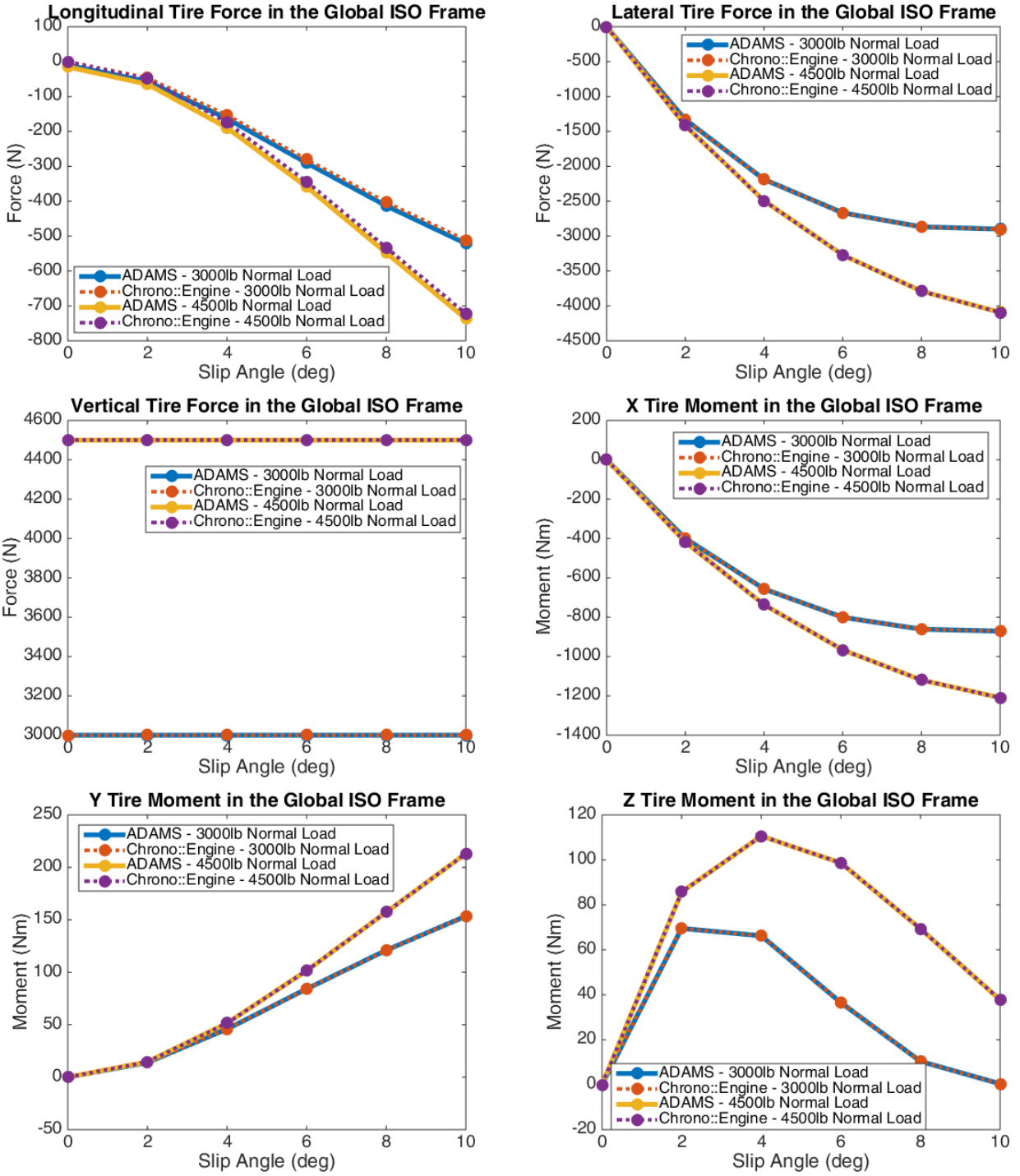
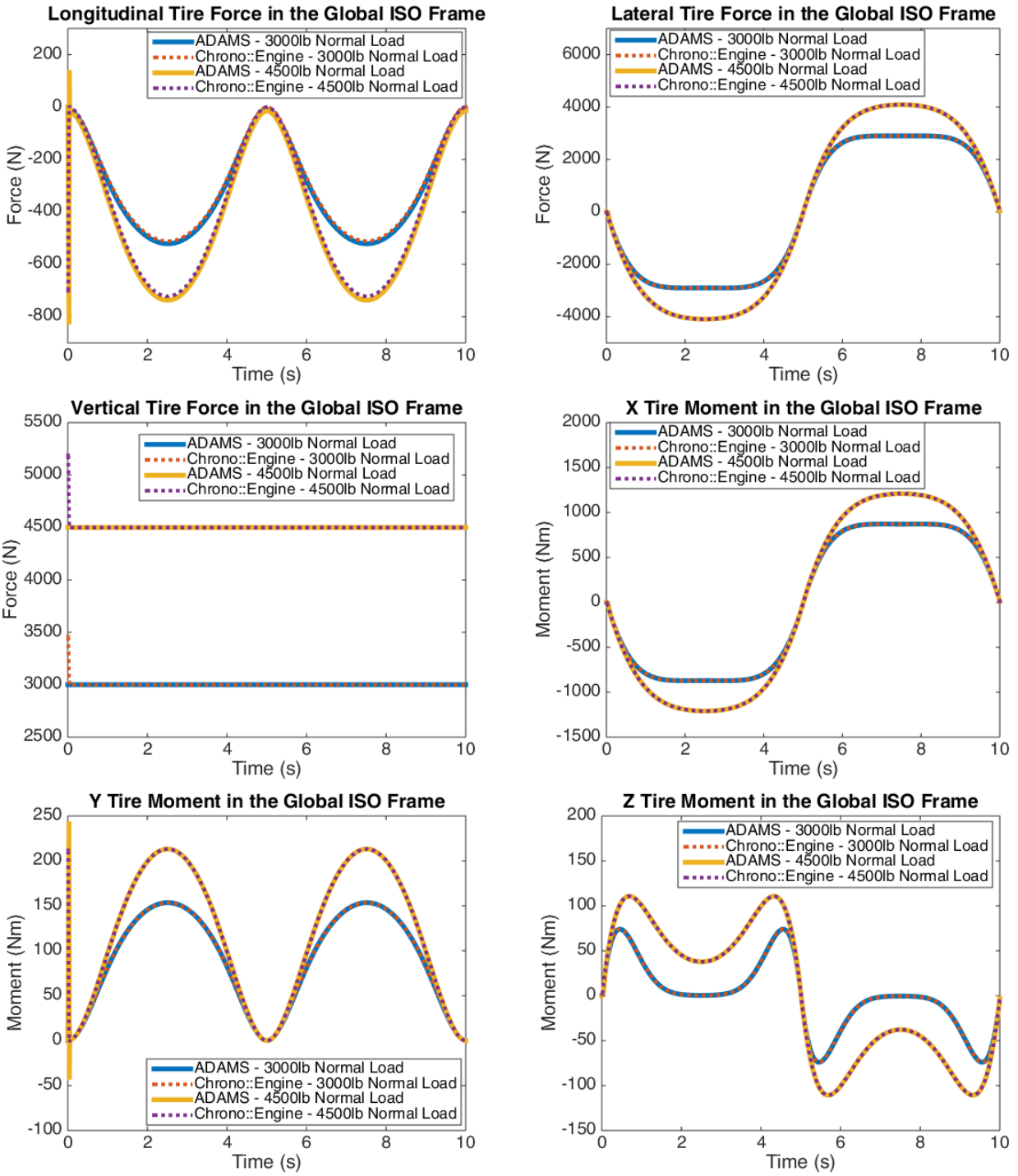Figure 2: Fiala Tire Steady-State Slip Angle Comparison between CHRONO::Engine and MSC ADAMS

Figure 3: Fiala Tire Transient Slip Angle Comparison between CHRONO::Engine and MSC ADAMS

4   Conclusion

Overall, close agreement can be seen between the simulation results of MSC ADAMS and CHRONO::Engine for the Fiala tire models. Although not shown, if the step size for the CHRONO::Engine simulations was decreased further, even closer alignment of the results would be seen.

5   Acknowledgement

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References

[1] MSC Software. Adams/tire help - adams 2015. `https://simcompanion.mscsoftware.com/infocenter/index?page=content&id=DOC10813&cat=2015_ADAMS_DOCS&actp=LIST/`, July 2015.