A MULTIBODY DYNAMICS APPROACH TO THE MODELING OF FRICTION WEDGE ELEMENTS FOR FRIEGHT TRAIN SUSPENSIONS

by

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Abstract

This thesis presents a theoretical application of multibody dynamics with unilateral contact to model the interaction of the damping element in a freight train suspension, the friction wedge, with the bolster and the side frame. The objective of the proposed approach is to produce a stand-alone model that can better characterize the interaction between the bolster, the friction wedge, and the side frame subsystems. The new model allows the wedge four degrees of freedom: vertical displacement, longitudinal (between the bolster and the side frame) displacement, pitch (rotation about the lateral axis), and yaw (rotation about the vertical axis). The new model also allows for toe variation. The stand-alone model shows the capability of capturing dynamics of the wedge which were not possible to simulate using previous models. The inclusion of unilateral contact conditions is integral in quantifying the behavior during lift-off and the stick-slip phenomena. The resulting friction wedge model is a 3D, dynamic, stand-alone model of a bolster-friction wedge-side frame assembly.

The new stand-alone model was validated through simulation using simple inputs. The dedicated train modeling software NUCARS® has been used to run simulations with similar inputs and to compare – when possible – the results with those obtained from the new stand-alone MATLAB friction wedge model. The stand-alone model shows improvement in capturing the transient dynamics of the wedge better. Also, it can predict not only normal forces going into the side frame and bolster, but also the associated moments. Significant simulation results are presented and the main differences between the current NUCARS® models and the new stand-alone MATLAB models are highlighted.

Acknowledgments

I would first like to thank Brendan Chan and Brent Ballew for their long days and nights in the lab assisting me with this project, without their help none of this would have been possible. I would also like to thank Nick Wilson and Curt Urban, of TTCi, for their endless support through out this project. I would also like to thank my advisor, Dr. Corina Sandu, who was always available to help me. I would like to thank my committee members, Dr. Mehdi Ahmadian and Dr. Steve Southward, for their support with this project as well.

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1 INTRODUCTION

The first section of this chapter discusses the motivation behind this project. The second section discusses objectives for this project. Following this section is a short background detailing the relevant aspects of freight train technology. A review of literature providing a summary of the technical papers reviewed to aid in this project is discussed in the fourth section. The final section is an overview of this thesis.

1.1 Motivation

The design of freight train suspension systems has seen relatively small changes in the past hundred years. As a consequence, until recently, there has been little interest in developing accurate computer simulations of the three piece bogie system, commonly used for freight cars. Moreover, the key damping element in such a suspension, the friction wedge, has almost negligible mass compared to the other components. For this reason the friction wedge has not usually been treated as a body, but as a simplistic force element. The inertial properties of the wedge could then be ignored with the motion of the friction wedge still being represented through a system of equations.

Traditionally, the damping for freight train truck suspensions comes from the dry friction between the bolster, the friction wedge, and the side frame. The friction in this system introduces a damping force that dampens the motion of the secondary suspension in bogies. Hydraulic damping, as seen in passenger cars and trucks, is uncommon in freight train suspensions. This is primarily because of the large freight loads placed on the secondary suspensions and freight line track irregularities as well as cost and reliability issues of the hydraulic damping devices.

Because of the wedge's non-linear frictional characteristics and load sensitive behavior, accurately capturing its dynamics in a computational model proves difficult. The limitations of the friction wedge model currently used in train modeling software cause the train models to act inaccurately at times. The existing wedge models must be improved to capture the loading moments and the longitudinal forces acting on the wedge and also the toe in/out variation throughout the stroke.

1.2 Problem Statement and Research Approach

The damping of the motion of the secondary suspension comes from the dry friction occurring due to the friction wedge-side frame and friction wedge-bolster interfaces. The effects of dry friction are difficult to model due to its non-linearities. Also due to the small size and mass of the friction wedge with respect to the other larger bodies associated with the rail vehicle, the numerical integration required to define the system is complicated. This study intends to use analytical and computational methods to increase the accuracy of the current friction wedge model.

The first phase of this project required evaluating the current model used in the railroad industry. Due to Virginia Tech being one of the universities affiliated with the Association of American Railroads (AAR), the train simulation software NUCARS® developed by the Transportation Technology Center, Inc. (TTCI) was made available for use in this project. The friction wedge models used in this software, which are called types 6.8 and 6.9, were evaluated. The capabilities of the current model were determined by running several simulations with different inputs and train models. The next phase of the project was to explore the state of the art in friction wedge modeling techniques. This was completed by performing an extensive review of literature, which is included in this paper.

In order to further analyze the capabilities and limitations of the current friction wedge model, a stand-alone numerical model of the friction wedge was designed using the MATLAB and the graphic visualization was made available through Mambo [5], a freeware educational multibody dynamics program used at Virginia Tech. The MATLAB model was designed to be compared to a modified single freight truck, with a half-loaded, 100 ton hopper car modeled in NUCARS® [14]. Since a stand-alone model is more difficult to accurately test in NUCARS®, the simplified truck was used. Each model was assembled so that the external forces acting on the wedge due to other factors (e.g., wheel – rail interaction) are ignored. This study was expanded to also include a variably-damped and a constantly-damped stand-alone wedge models in MATLAB, which are compared later in this paper to the simplified truck modeled in NUCARS®. The goal of developing a stand-alone model in MATLAB was to help understand the physical phenomena at the bolster-wedge-side frame interface, and to develop a more accurate friction wedge model which can eventually easily be implemented in train simulation software.

1.3 Background

1.3.1 Freight Train Technology

The three-piece bogie acts as a support for the car bodies so that they can run on both straight and curved track as well as absorbing vibrational energy generated by the track. The bogie's are made up of three main parts, two side frames and a bolster. Figure

1-1 shows a detailed view of a traditional three-piece bogie. The side frames run parallel to the rails and are connected to each other by the bolster, which runs perpendicular to the rail. The side frames are connected to the axles, which are directly connected to the wheels that run on the track through the primary suspension. The primary suspension includes the bearing adapter and pedestal roof.

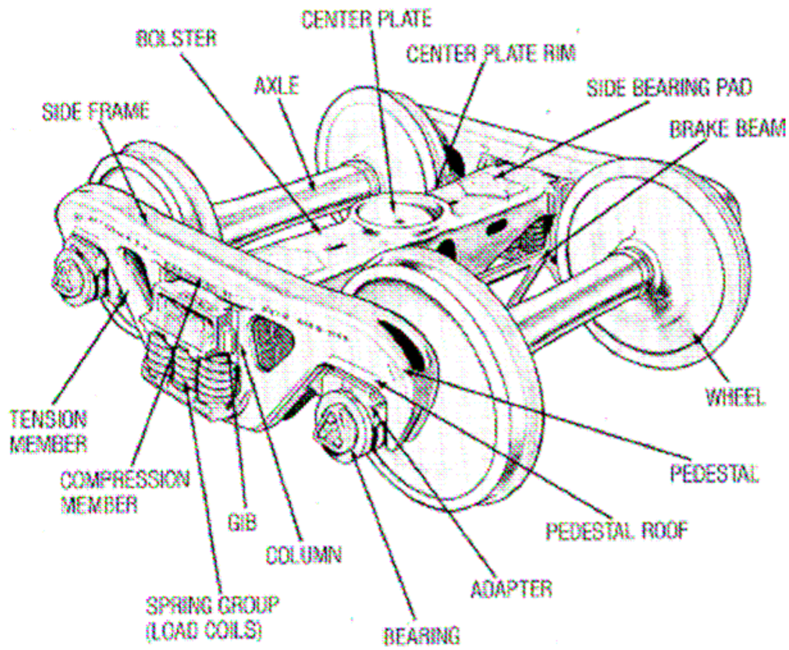


Figure 1-1. Diagram of a three piece bogie commonly used in freight trains.

The secondary suspension, which includes the friction wedge and load coils, connects and provides damping on each end of the bolster at its intersection with the side frame. The gib provides a bump-stop to the bolster-side frame connection so that both bodies can move vertically, but the lateral motion of the bolster is constrained. The friction wedge is an essential element of the secondary suspension used in three-piece bogies. It serves two main purposes: first to provide suspension damping and second to aid in warp resistance of the bogie. The damping is caused by the friction created by the wedge interaction with both the bolster and side frame, labeled “column” in Figure 1-1.

Toe In and Toe Out are often referred to in the bolster-friction wedge-side frame system, which introduce the friction damping into the secondary suspension. Figure 1-2 illustrates Toe In and Toe Out between a friction wedge and side frame. During Toe In, the distance from the bottom of the side frame to the bottom of the wedge is less than the distance from the top of the side frame to the top of the wedge. During Toe Out, the distance from the bottom of the side frame to the wedge is greater than the distance from the bottom of the side frame to the bottom of the wedge.

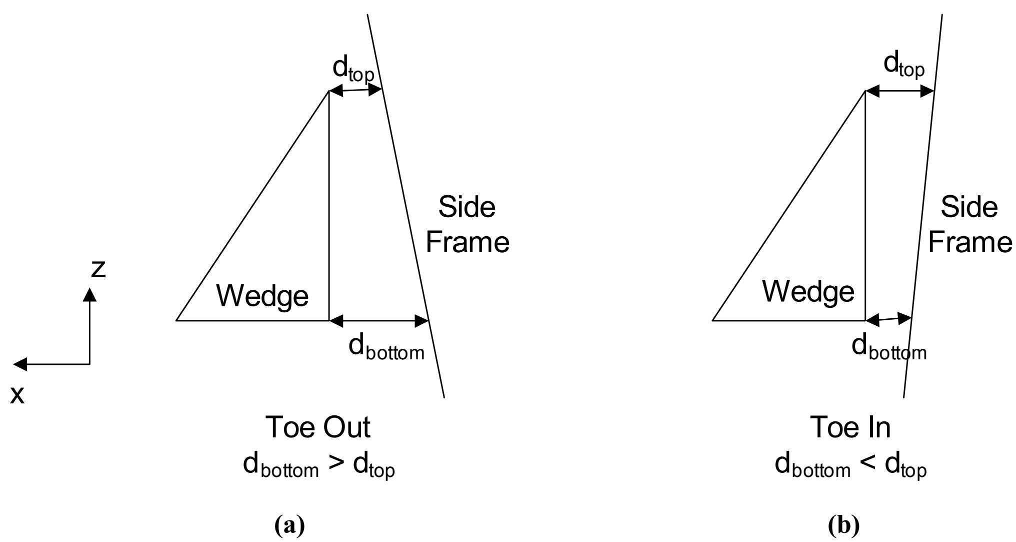


Figure 1-2. (a)Schematic of friction wedge and side frame in Toe Out. (b) Schematic of a friction wedge and side frame in Toe In.

Warp is a phenomenon which happens very often in freight train bogie motion. Since the axles and wheels are rigidly connected, curving track causes the bogie to form a parallelogram, or warp. Problems begin to arise with higher lateral forces when the bogie warp increases because the lateral forces acting on the axles and wheels also increase. The friction wedge provides warp resistance through its width by constraining the angle that the bolster can rotate. Figure 1-3 illustrates the warp phenomenon.

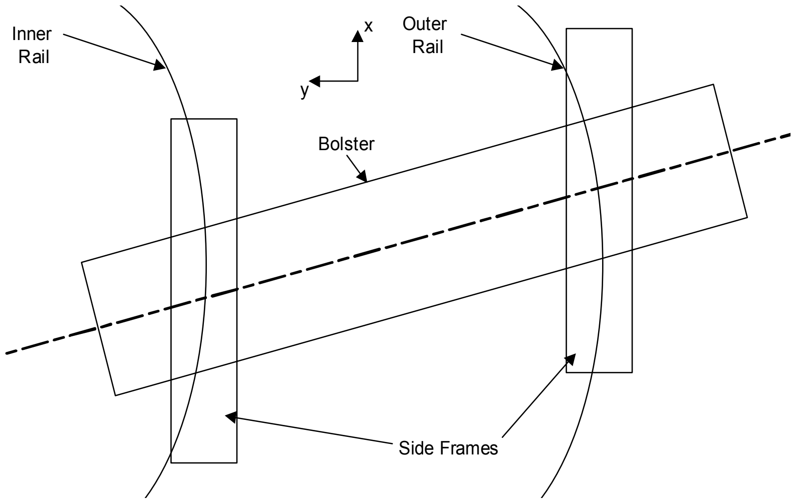


Figure 1-3. Schematic of a three-piece bogie traveling through curved track causing warp

1.3.2 Variably-Damped vs. Constantly-Damped Trucks

The main difference between a constantly-damped truck and a variably-damped truck is that the coil spring is separated from the spring nest (load coils) in a constantly-damped truck. Figure 1-4 highlights the difference between the two types of truck damping styles. In a constantly-damped truck, the wedge pocket fully encloses the wedge and its control coil, which compresses the control coil to a constant displacement. This design allows for the force applied to the wedge due to the control coil to be relatively constant. The wedge will move slightly in the bolster pocket, but not as much compared to the variably-damped wedge model. In the variably-damped model, the force applied by the control coil varies as the wedge and bolster traverse the side frame.

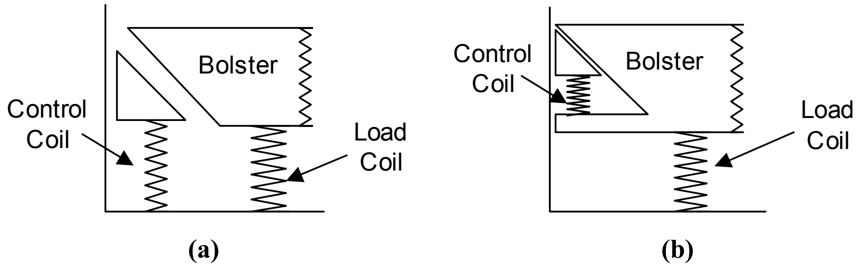


Figure 1-4. (a) Schematic of a variably-damped side frame-friction wedge-bolster system. (b) Schematic of a constantly-damped side frame-friction wedge-bolster system.

1.4 Review of Literature

Many documents were reviewed during the process of determining both how the friction wedge works and the limitations of the current friction wedge model. The documents reviewed include detailed descriptions of the uses, models, and set ups of a friction wedge and the bogie in which it is contained. The goal of this literature review is to have a vast understanding of the types, models, and uses of a friction wedge in order to develop a more up-to-date, all-inclusive model for a friction wedge.

1.4.1 How Bogies Work by Isao Okamoto

In this paper, Okamoto [13] defined the role of a railroad bogie in detail and discussed possible different configurations. Bogies are classified into types first by the number of axles in their configuration and the design of the suspension. The two axle bogie is the most common type found in rail vehicles and in the three-piece bogie. The suspension of the bogie is classified as either articulated or non-articulated. An articulated suspension is one that is located between two car bodies, holding the backside of one and the front side of the following car. A non-articulated suspension requires two separate trucks to support each end of one rail car. A Swing Hanger Bogie and a Small Lateral Stiffness Bolster Spring Bogie are two types of suspension designs which absorb rolling motion of the rail vehicle.

Bolster and bolster-less bogies are another way to differentiate the suspension. The bolster bogie has a solid bolster which is the third piece in a three-piece bogie and connects the side frames. The bolster-less bogie has a center plate and 2 separate suspensions on the side frames to support the rail vehicle. This paper also discusses the key elements of a bogie, which include the suspension gear, the bogie frame, the axle box suspension, wheels, axles, bearings, transmission and brakes. Some recent improvements include a tilting bogie, which tilts the rail vehicle toward the center of the circle when turning. Another improvement is the steering bogie which allows each of the axles on a bogie to steer along a rail separately from the other.

1.4.2 Modeling Friction Wedges, Part I: The State-of-the-Art by Peter E. Klauser

This paper discussed how the friction wedge is currently being modeled in train simulation software. Klauser [9] discusses the two dimensional friction wedge model used in both NUCARS® and VAMPIRE®. The current friction wedge model allows for translation in the vertical and lateral directions, which allows for the friction damping forces to exist in both directions. The "state-of-the-art" model also allows the user the option of having two different friction coefficients on each face of the wedge, the slope and column faces. Klauser also discusses how the model used in VAMPIRE® compares to the model used in NUCARS®. The results of this paper was a list of the shortcomings of both VAMPIRE® and NUCARS® and a list of the proposed features to improve the wedge model.

1.4.3 Modeling Friction Wedges, Part II: The State-of-the-Art by Peter E. Klauser

Klauser's [10] second document on the subject of modeling the friction wedge is an extension of the first which introduces "An Improved Model." This paper discusses the implementation of a new, more complex wedge model in the VAMPIRE® vehicle dynamics package as both a standalone model and incorporated into the entire car model.

The improved model included a mass for the wedge, rows and columns of elements across both faces to represent pressure distribution along the length and width of the faces, and a wedge width which affects the warp resistance of the bogie. The paper documented the benefits of using an improved friction wedge model as well as listed ways of further improving the model.

1.4.4 Dynamic Models of Friction Wedge Dampers by J.P. Cusumano and J.F. Gardner

In this paper, John Gardner and Joseph Cusumano [4] rederived the equations of motion of the friction wedges. The main difference in this paper from others is that it included the mass of the friction wedge; whereas the other papers and the model used in the train modeling software programs ignore the mass of the wedge.

1.4.5 Dynamic Modeling and Simulation of Three-Piece North American Freight Vehicle Suspensions with Non-linear Frictional Behavior Using ADAMS/Rail by Robert F. Harder

In this paper, Harder [8] discussed the method in which they derived equations for and modeled a constant damping friction wedge. The author introduced a "toggle" to the program to combat the problem of loading and unloading on the wedge. Loading is when the bolster is moving downward, while unloading is when the bolster is moving upward. The author found that the complex non-linear modeling of the friction wedge lead to modeling challenges due to its complexity.

1.4.6 Track Settlement Prediction using Computer Simulation Tools by S.D. Iwnicki, S. Grassie and W. Kik

In this paper, Iwnicki, Grassie and Kik [6] discussed the effects of different vehicles on track deterioration. The authors used MEDYNA, a simulation software, to determine the equations of motion of the track settlement, and then used ADAMS/Rail for the visualizations. The authors explained the three most common types of suspensions used on the tracks and determined how each affect the settlement. The track models they defined using the software represented the ballast in the vertical and lateral directions as parallel spring-damper systems which connect the track to the ground. The results of the paper were the higher the speed of the vehicles on the track, the greater the deterioration of the track.

1.4.7 Multibody Simulation of a Freight Bogie with Friction Dampers by N. Bosso, A. Gugliotta and A. Somà

In this paper, Bosso, Gugliotta and Somà [2] discussed the method in which they modeled the friction elements in a Y25 freight bogie, most commonly used in Europe. The main difference in this type of bogie with those commonly used in the United States is that the friction wedge is replaced by friction surfaces between the bogie and axle-box directly. The weight of the car is transferred to the friction surfaces by a mechanical link called a “Lenoir Link”. This link transfers the vertical load of the car to a normal force acting on the friction surfaces. The authors model this link and the subsequent friction damping forces in MATLAB as a transfer function between the axle-box and the bogie.

The authors replaced the discontinuities associated with friction force behavior with a non-linear vector of equations. The friction force vector is dependent on the vertical, lateral and longitudinal displacements and the spring forces. The model was compared to the ADAMS/Rail model through simple tests with vertical and lateral inputs. The numerical stability of the model was then tested using various tests commonly used in the rail industry. These tests included slant tests, ride stability tests and curving.

1.4.8 Consequences of Nonlinear Characteristics of a Secondary Suspension in a Three-Piece Freight Car Bogie by A. Berghuvud and A. Stensson

In this paper, Berghuvud and Stensson [1] discuss the effects of weather and wear and different conditions on the behavior of the secondary suspension in three-piece bogies. The authors developed two different constantly-damped suspension models, which only included one half of the bogie. The first model was a single degree of freedom model which included the mass of the car and bolster, coil springs with some damping, friction damping and a massless side frame which actuated the system. This model ignored the pitch moment of the wedge and the friction between the bolster and the wedge. Also the characteristics of each wedge were assumed identical. The second model was a planar model which allowed all bodies except the bolster to have vertical, longitudinal and pitch motion. The bolster could only move vertically and about the lateral axis. This model was also actuated through the side frame at the axle locations to represent the wheel/rail interaction.

Two different simulations were studied in this paper. The first was excitation in response to a sinusoidal track input which represents track irregularities. The second was different friction configurations. Four configurations were studied. These configurations were two with friction between the bolster and wedge, once with the same friction coefficients between the side frame and wedge and one with different coefficients, and two without friction between the bolster and wedge with the same friction coefficients as mentioned above. The results of the excitation were that the suspension locked up at frequencies below the natural frequencies for each model. Also for the different friction configurations, the resultant forces on each wedge were different which means that the wedges and side frames would wear at different rates.

1.4.9 Possibility of Jamming and Wedging in the Three-Piece Trucks of a Moving Freight Car by A.D McKisic, V. Ushkalov and M. Zhechev

In this paper, McKisic, Ushkalov and Zhechev [12] present a mathematical and numerical analysis of the secondary suspension in freight train motion. The main goals of this paper were to determine how wedging and jamming occur and how to decrease the frequency at which they occur. Wedging occurs when there is no relative motion between the wedge and side frame and wedge and bolster. Jamming depends on the direction of the sliding velocities of each force. The friction between the surfaces is assumed to be Coulomb Friction. The authors used multi-body dynamics to define the bolster-wedge-side frame system and to obtain the equations of motion. The equations of motion were then used to determine equations for when wedging and jamming would occur. The authors discovered that wedging is not possible for a friction damping system. They were also able to determine equations for when jamming would occur. Using numerical analysis of the equations of motion, jamming was found to occur due to track irregularities. The equations also allow for the determination of how and why jamming occurs and which suspension parameters effect it and how they effect it.

1.4.10 Active Yaw Damper for the Improvement of Railway Vehicle Stability and Curving Performances: Simulations and Experimental Results by F. Braghin, S. Bruni and F. Resta

In this paper, Braghin, Bruni and Resta [3] discussed the development of an active suspension, which includes an electro-mechanical actuator, to improve the behavior of the secondary suspension in bogies. This actuator would be used on “Tilting Trains,” which are used mostly in Europe because of their high speed capabilities. The problem with tilting trains is their suspensions are optimized for either steering or stability, not both, so an active suspension would be best suited for this type of truck. The parameters of the suspension would be changed slightly depending on the conditions that the railway vehicle is encountering. The active suspension designed in this paper plans for the parameters to change for straight rail and curved rail. The conditions would be determined in real time through a series of sensors and accelerometers placed on the car body and bolster. During straight track the actuator would provide a longitudinal force on the car body to prevent too much movement during hunting at high speeds. The application of this system on actual train operations produced positive results by increasing the vehicle stability. During curved track, the actuator would provide force to balance the loads on each axle. This system did reduce the difference between the axle loads during the authors’ analysis.

1.5 Summary of Thesis

Chapter 2 provides an explanation of the NUCARS models used as a comparison for the Stand-Alone MATLAB model. First a summary of how the built-in freight train model was simplified was discussed. The differences between the constantly- damped and variably-damped models were then highlighted. Chapter 3 discusses the means in which the Stand-Alone MATLAB model was derived. First the thought process behind the model was discussed. The kinematic and dynamic modeling techniques are then explained. The scenarios for which the simulations were run, which are a vertical displacement input and a vertical displacement with yaw input, are explained in Chapter 4. The results of the simulations are shown and discussed in chapters 5 and 6. Chapter 5 provides the results for the variably-damped models, while chapter 6 provides the results for the constantly-damped models. Finally the conclusions of this project and the proposed future work are presented in Chapter 7.

2 NUCARS® MODEL

This chapter will provide details about the model used as a comparison for the Stand-Alone MATLAB model. In order to accurately compare the NUCARS® model to the Stand-Alone MATLAB model, the NUCARS® model had to be simplified. The details and reasons for these simplifications are presented here as well. The main differences between the constantly-damped and variably-damped models are also discussed in this chapter.

2.1 Simplification of Half Truck Model

The NUCARS® model was created using the built-in loaded hopper car system file included in NUCARS®, known as Lhopr-06.sys, in the 2006.2.1.1 version which was last updated on August 8th, 2006. The simplified truck model's system file is called "bolst_wedge_sf_69_const.sys" and is included in Appendix *A*. Figure 2-1 is a schematic diagram of the simplified truck model used in NUCARS®. The truck was simplified as much as possible in order to eliminate external forces that may effect the movement of the wedge. Three piece trucks, when modeled in NUCARS®, have multiple dry friction connections between the car body and the bolster. These connections include the side bearing and center plate connections. In the simplified single truck model, the car body was combined with the bolster to create one large mass acting as the bolster. This eliminated the frictional connections between the car body and bolster, which affect the entire motion of the bolster.

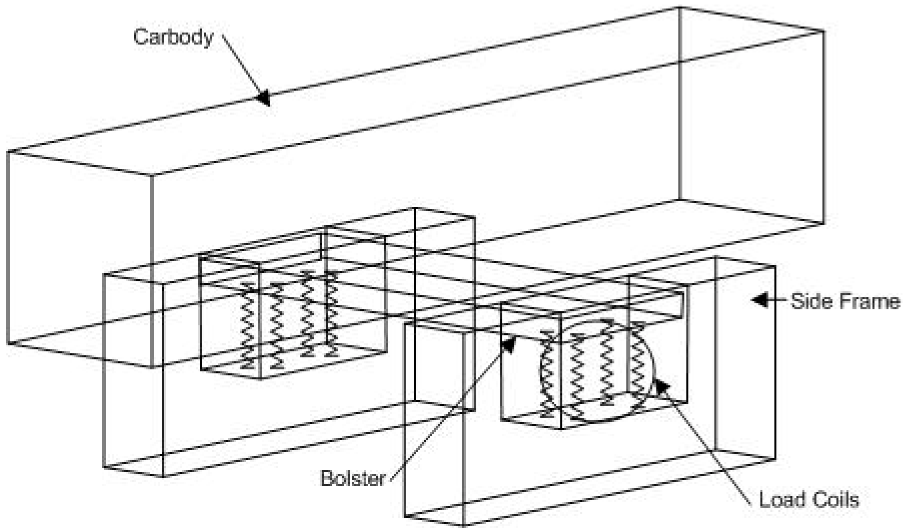


Figure 2-1. Simplified single truck model of loaded 50 ton hopper car in NUCARS®

The next simplification was eliminating the wheel – rail connections, and connecting the side frames directly to the ground. This project does not deal with the wheel – rail dynamics so they are not relevant at this phase of the project. Also since the Stand-Alone MATLAB model is a stand alone wedge model, the wheel - rail interactions are ignored in that model. The MATLAB model was now comparable to two NUCARS® models: a two-dimensional wedge connection with stick-slip capabilities (Type 6.8) and a three-dimensional wedge connection (Type 6.9). The type of wedge model used, 6.8 or 6.9, was specified in the “Connection Data” section of the system file. The Connection numbers for the friction wedge elements are 127, 128, 129 and 130 for both types, circled in blue (2) in Figure 2-2. Another change to the three piece bogie commonly used in NUCARS® is that the secondary suspension characteristics were changed. The load coil stiffness was changed for both the constantly- and variably-damped wedge models. The connection numbers for these elements are 119 – 126, circled in red (1) in Figure 2-2.

```
Body #  ' 15 Char Name  '              C.G. Posn in X, Y, & Z
             No. & DoF List            Mass, Roll, Pitch, & Yaw Inertia
------------------------------------------------------------------------------
\BODY DATA
  3
    1   ' Half Car+Bolst'            -35.0        0.0       83.0
       6   1  2  3  4  5  6     319.175    0.92276E06    0.8350204E07    0.835276E07
    3   'Lead Lft Sframe'            -35.0       39.5       18.0
       6   1  2  3  4  5  6     2.98    9.0E2      1.37E03    1.37E03
    4   'Lead Rgt Sframe'            -35.0      -39.5       18.0
       6   1  2  3  4  5  6     2.98    9.0E2      1.37E03    1.37E03

\INPUT BODY DATA
 3
    7  'Lft Input disp '  -35.0   39.5   18.0   5   1 2 3 4 5    1 2 3 4 5    .F.
    8  'Cntr Input disp'  -35.0   0.0    18.0   6   1 2 3 4 5 6  1 2 3 4 5 6  .F.
    9  'Rgt Input disp '  -35.0  -39.5   18.0   5   1 2 3 4 5    1 2 3 4 5    .F.

\CONNECTION DATA
 50
! No centerplate or contact bearings btwn carbody & bolster reqd
! Long.,Pitch, and Yaw bolster to side frame connections
 117    'Ld L Bol-SF LPY'   1.1    1  3 -35.0  39.5 18.0  3  1 5 6  8 9 10
 118    'Ld R Bol-SF LPY'   1.1    1  4 -35.0 -39.5 18.0  3  1 5 6  8 9 10
! Vertical bolster to side frame connections split into 4 seperate springs
! at each nest, dropped down 5"
 119    'Ld L Bol-SF V 1'   1.3    1  3 -31.25  35.75 13.0  3  2 3 4  11 12 13
 120    'Ld R Bol-SF V 1'   1.3    1  4 -31.25 -35.75 13.0  3  2 3 4  11 12 13
 121    'Ld L Bol-SF V 2'   1.3    1  3 -31.25  43.25 13.0  3  2 3 4  11 12 13
 122    'Ld R Bol-SF V 2'   1.3    1  4 -31.25 -43.25 13.0  3  2 3 4  11 12 13
 123    'Ld L Bol-SF V 3'   1.3    1  3 -38.75  35.75 13.0  3  2 3 4  11 12 13
 124    'Ld R Bol-SF V 3'   1.3    1  4 -38.75 -35.75 13.0  3  2 3 4  11 12 13
 125    'Ld L Bol-SF V 4'   1.3    1  3 -38.75  43.25 13.0  3  2 3 4  11 12 13
 126    'Ld R Bol-SF V 4'   1.3    1  4 -38.75 -43.25 13.0  3  2 3 4  11 12 13
! 3D Stick-Slip Friction wedge connection between bolster and side frame
 127    'Ld Bol-SF LL Wg'   6.9    1   3    -26.5     39.5     18.0    3 1 2  14
 128    'Ld Bol-SF LR Wg'   6.9    1   4    -26.5    -39.5     18.0    3 1 2  14
 129    'Ld Bol-SF TL Wg'   6.9    1   3    -43.5     39.5     18.0    3 1 2  114
 130    'Ld Bol-SF TR Wg'   6.9    1   4    -43.5    -39.5     18.0    3 1 2  114
! Vertical surface friction element for side frame to axle
```

1

2

Figure 2-2. View of the system file used to define the simplified truck model in NUCARS®, where the red (1) encircles the load coil connections and blue (2) encircles the wedge connections.

The NUCARS® models use the friction wedge model formulation[]. In this formulation the inertial properties of the wedge are ignored, and the wedge is considered to be a point contact between the bolster and side frame. The type 6.8 model is two dimensional and includes the lateral and vertical translation of the wedge, while the type 6.9 model also includes longitudinal translation of the wedge. The friction wedge in these models is considered to be in "quasi-static equilibrium," which means that since the mass is ignored, the net forces acting on the wedge are zero allowing the friction forces on the column face to be calculated in terms of those on the slope face. The friction forces are then assumed to be the viscous damping that acts on the system.

The model also includes a command to allow the user to input whether the wedge is toed in or toed out. This command is located in the "Characteristic Data" section of the system file. For the type 6.8 model, the characteristic data number is 14. For the type 6.9

model, the characteristic data numbers are 14 and 114, depending on the direction of the column face of the wedge. The newest friction wedge model used in NUCARS® is a three-dimensional model that allows for variation of the toe based on the shape of the column face. The variation of the toe is included by introducing a piecewise linear function that defines the face of the column. For example a hollowed section of the column face is estimated using a piece-wise linear function. As the wedge traverses the column face, it will follow the line of the hollowed section. The equations for both the type 6.8 and 6.9 wedge elements are calculated so that there is a slight toe out in the zero toe case. For this project the toe angles being compared were very small, 0.2°, so comparing type 6.8 and 6.9 (though 6.8 does not include an actual toe angle) was still accurate. The three dimensional model also introduces forces and displacement in the longitudinal direction, which were previously ignored.

2.2 Variably-Damped and Constantly-Damped Half Truck Models

The secondary suspension characteristics in the variably-damped model varied from those used in the constantly-damped model. The first major change was that the load coil stiffness had to be changed for the constantly-damped truck model. In the variably-damped model, the control coils help support some of the weight of the bolster and car body. In the constantly-damped model, the control coils do not support any of the weight of the bolster and car body. Therefore, the load coils for the constantly-damped truck model had to be stiff enough to account for the loss of the control coils. The piecewise linear function, which is used to define the spring stiffness, changes for the constantly-damped model. The function used was built-in to the Lhopr-06 system file for a constantly-damped truck model. The piecewise linear function was calculated so that they could support a static load of 15,404 lb, which would provide enough support for any given input. A stiffness of 6500 lb/in was used in order to support the large loads the secondary suspension would see. The piece-wise linear function used for the variably-damped model created a single line with a slope of 3000 lb/in, which was the stiffness used. The piecewise linear function used for the variably-damped model is shown in figure 2-3.

```
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
   17      3       -15.0E3   0.0   15.0E3
                   -5.0      0.0    5.0
!******************** Bearing Adapter Side Frame to Axle **********************
```

Figure 2-3. Piecewise linear function for the control coil stiffness used in NUCARS® for the variably-damped model

The next major change was the stiffness of the control coils for each model. In the variably-damped model, 3000 lb/in was enough to aid in supporting the bolster and car body weight. For the constantly-damped model, the preload force that would be applied to the wedge due to the spring had to be determined. The actual control coils used in freight train suspensions are sets of non-linear springs, which have two different lengths and diameters so one fits inside of another. This design allows for the spring stiffness to solidify at a maximum displacement. The net control coil stiffness is 1979 lb/in so this value was used as the linear spring stiffness for the constantly-damped model. The preload force was calculated using an undeformed spring length of 7.25 inches. The deformation of the spring at the start of the simulations was 5.38 inches so the preload force was 3702.2 lb. This value was input into the "Characteristic Data" for the type 6.8 wedge model. For the type 6.9 wedge model, a piecewise linear function, shown in figure 2-4, was calculated so that the force at 0 inches displacement was 3702.2 lb. Due to the small displacement that the wedge would be allowed to move, a maximum force was determined to be -5681.2 lb for a 1 inch compression of the control coil. Also lift-off was taken into account, by assuming that after the wedge moves 1.87064 inches, the force due to the control coil would be 0 lb.

```
!   23     2      -9204.7      -7473.25
!                  0.0          0.875
   23      5      -5681.2    -3702.2    -1723.2    0.0         0.0
                   -1.0        0.0        1.0     1.87064     10.0
! Column wear face - Hypothetical hollow, 0.1 inch deep centered on -0.75
```

Figure 02-4. Piecewise linear function for the control coil stiffness used in NUCARS® for the constantly-damped model

3 STAND-ALONE MATLAB MODEL

This chapter discusses the methods that were employed to develop the Stand-Alone MATLAB model. The first section describes the multibody dynamics used in both models. The second section discusses the kinematic approach used to define the friction wedge, for the variably- and constantly-damped models. The final section discusses the dynamic approach used to define the bolster – wedge – side frame system in MATLAB, for the variably- and constantly-damped models.

3.1 Multi-body Dynamics Definition of Model

The Stand-Alone model in MATLAB includes a mass and inertia for the friction wedge, which are ignored in the wedge model [#]. Figure 3-1 illustrates how the bolster - friction wedge - side frame system is modeled in MATLAB for both the variably and constantly-damped models. The wedge is broken up into two surfaces, A and B, with four contact points located at each corner. The points labeled B and W in the variably-damped model represent the vector length from the side frame, point W, to the bottom of the wedge, point B. The points labeled B and Q in the constantly-damped model represent the vector from the bolster, point Q, to the bottom of the wedge, point B.

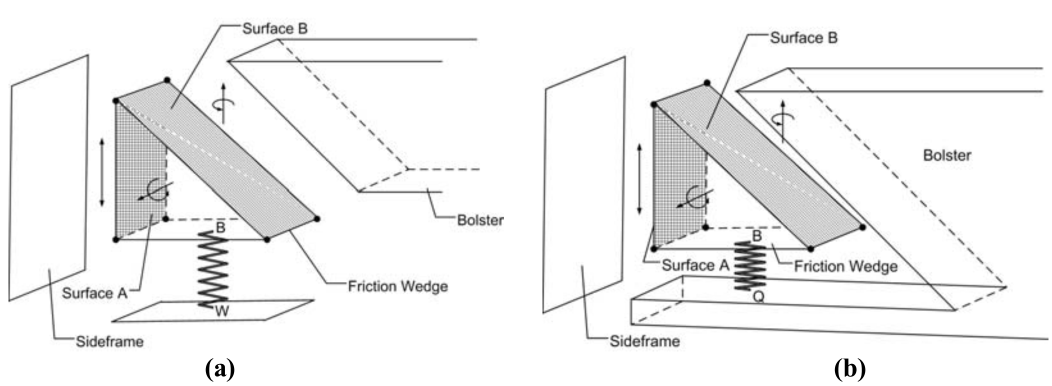


Figure 3-1. (a) Exploded view of the Side Frame-Friction Wedge-Bolster System for the Variably-damped wedge model. (b) Exploded view for the Constantly-damped wedge model.

Instead of assuming that there is one force acting on each face of the wedge, the wedge was assumed to have reaction forces that appear upon contact between surface A and the side frame and surface B and the bolster, as illustrated in Figure 3-2. The friction damping behavior is modeled as tangential Coulomb forces that depend explicitly on the coefficient of friction μ and the normal force. The moments generated as a result of the friction couple will, in turn, excite the allowable rotational degrees of freedom of the wedge.

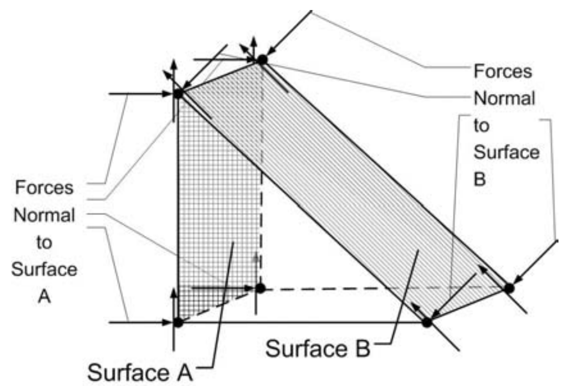


Figure 3-2. Forces acting on Friction Wedge due to the Side Frame and Bolster

The main idea behind the Stand-Alone model was to come up with a more accurate mathematical model that could be integrated easily into the framework of a train modeling software. For this reason, the model used was one which considered the friction wedge the main body of the system and the inputs of the system were the states of the bodies surrounding the wedge, which are the bolster, side frame and control coil. The output of this system consists of forces and moments which are the results of the motion of the wedge. One possible implementation of the model into the current train modeling software's frameworks for the bolster-friction wedge-side frame model is illustrated in Figure 3-3, where

$X_{bolster}(t(i))$ = Bolster Vertical Displacement at the ith time step

$V_{bolster}(t(i))$ = Bolster vertical velocity at the ith time step

$K(\delta(t(i)))$ = Stiffness of the control coils at the ith time step

$F_{vertical}(t(i))$ = Vertical forces at the ith time step

$F_{longitudinal}(t(i))$ = Longitudinal forces at the ith time step

$\delta(t(i))$ = Control coil deflection at the ith time step

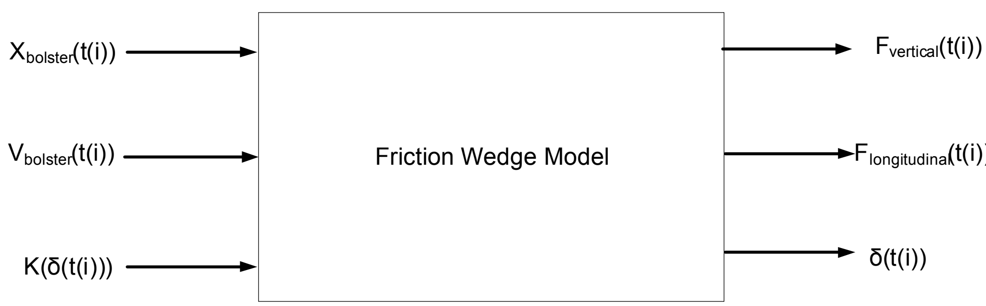


Figure 3-3. A possible implementation of the model into the current train modeling software's frameworks for the bolster-friction wedge-side frame model.

The four degrees of freedom of the friction wedge are shown in Figure 3-4 where the yaw and the pitch degrees of freedom are the only rotational degrees of freedom allowed for the wedge. Also, the wedge can only translate in the vertical and in the longitudinal direction for this model.

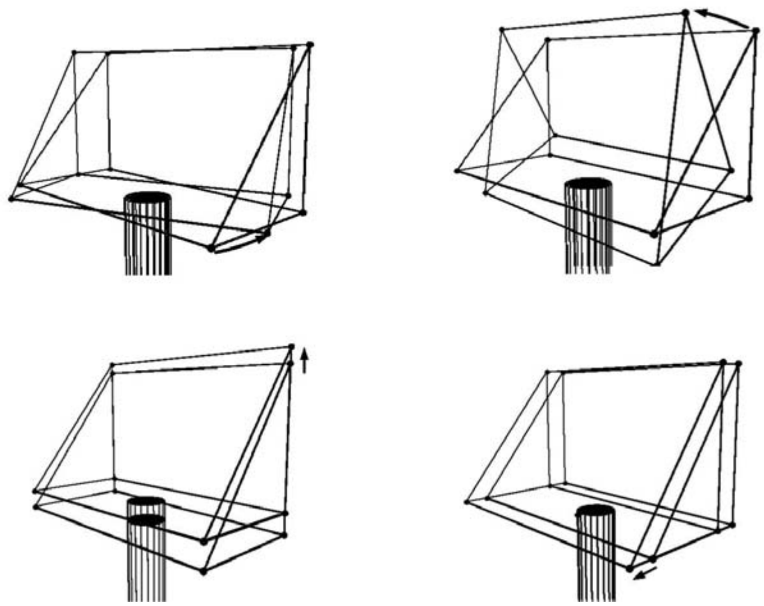


Figure 3-4. The degrees of freedom for the friction wedge: yaw (top left), pitch (top right), vertical translation (bottom left) and longitudinal translation (bottom right).

Many assumptions were made in the design of the Stand-Alone MATLAB model. The first was that the wedge may not be in contact with the bolster or with the side frame at all times. This assumption allows for lift-off, which is a phenomenon that occurs when the bolster is lifted completely off of the wedge. The next assumption was that the wedge faces and bolster and side frame faces interacting with the wedge were not rigid. This assumption allowed for stick-slip motion, which means there was a small shear displacement occurring at the interfaces between these surfaces before slip occurred. The geometry of the wedge was assumed to be represented by the points at the corners of the wedge. The next assumption was that the control coils were assumed to be linear springs, which is a reasonable hypothesis within the useful range of these springs. The final assumption made for this model was that the forces due to the bolster and side frame are reaction forces. The reaction forces are due to a unilateral spring which appears when there is contact between the wedge faces and the bolster and side frame.

3.2 Modeling Approach: Kinematics

3.2.1 Variably-Damped Friction Wedge Model

The state variables which define the translational and rotational motion of the friction wedge are q_1, q_2, q_3, and q_4. The translational motion of the wedge is defined by q_1 and q_2, which define the longitudinal and vertical motion of the wedge respectively. The rotational motion of the wedge is defined by q_3 and q_4, which define the pitch and yaw motion of the wedge respectively. The state variables are illustrated in Figure 3-5. The lateral translation and roll rotation are fixed in this version of the model since they are not relevant. The three-dimensional vector which defines the position of the wedge with respect to the point on the side frame just below the wedge is the vector from point W to point B which is:

$$\vec{r}^{\,WB} = \{q_1, 0, q_2\}^T \tag{3-1}$$

where point W is located on the side frame and point B is on the bottom face of the wedge, as shown in Figure 3-5. The position of the center of gravity from point B is then:

$$\vec{r}^{\,BCG} = \{p_1, p_2, p_3\}^T \tag{3-2}$$

where p_1, p_2, and p_3 define the location of the C.G. of the wedge in the x, y, and z directions. The rotation of the wedge is represented by a composite rotation matrix R^{WB},

$$R^{WB} = \begin{pmatrix} \cos(q_3) & 0 & -\sin(q_3) \\ 0 & 1 & 0 \\ \sin(q_3) & 0 & -\cos(q_3) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(q_4) & \sin(q_4) \\ 0 & -\sin(q_4) & \cos(q_4) \end{pmatrix} \tag{3-3}$$

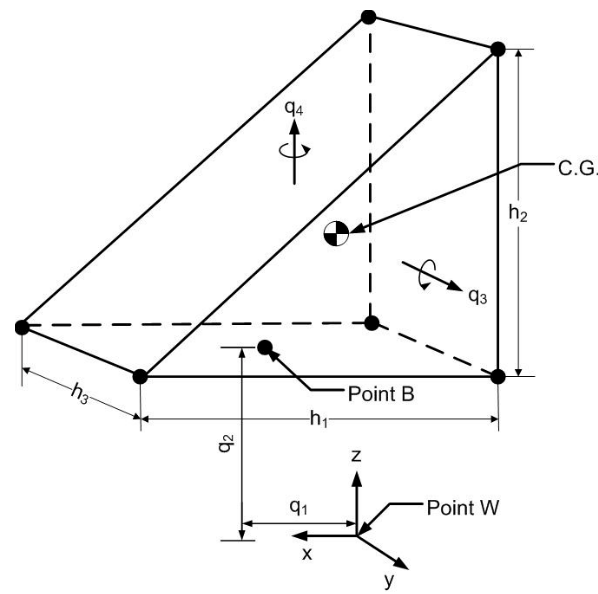


Figure 3-5. A diagram of the translational and rotational degrees of freedom of the wedge. Also included is origin of global coordinate system (W) relative to the origin of the body (B)

The dimensions of the wedge are also illustrated in Figure 3-5 and listed in Table 3-1. These dimensions were calculated based on the average weight of friction wedges and its material properties. The actual physical model of a variably-damping friction wedge is quite complicated and looks closer to a rectangular prism with a sloped face. The actual dimensions of a friction wedge were not relevant to the standalone model because the relevant surfaces, which are the sloped surface, the vertical surface, and the length h_3, were represented. The sloped and vertical surfaces of the wedge are responsible for the friction damping, while the length of the wedge provides warp resistance.

Table 3-1. Geometric parameters used in the variably-damped Stand-Alone models.

		Variably-Damped
Wedge angle, (°)	θ	32
Wedge dimensions, (in)	h_1	3.827
	h_2	6.125
	h_3	10.5
CG location relative to point B, (in)	p_1	-1.0734
	p_2	0
	p_3	2.0417

3.2.2 Constantly-Damped Friction Wedge Model

The translational and rotational motions of the friction wedge are defined by the state variables q_1, q_2, q_3, and q_4. The longitudinal and vertical translations of the wedge are defined by q_1 and q_2, respectively. The pitch and yaw rotations of the wedge are defined by q_3 and q_4, respectively. The four state variables are illustrated in Figure 3-6. As with the variably-damped wedge model, the lateral translation and roll rotation are fixed in this version of the model. The three-dimensional vector which defines the position of the wedge with respect to the point on the bolster just below the wedge is the vector from point Q to point B which is:

$$\vec{r}^{\,QB} = \{q_1, 0, q_2\}^T \tag{3-4}$$

where point Q is located at the point on the bolster directly below the wedge and point B is on the bottom face of the wedge, as shown in Figure 3-6. The position of the center of gravity with respect to point B is:

$$\vec{r}^{\,BCG} = \{p_1, p_2, p_3\}^T \tag{3-5}$$

where p_1, p_2, and p_3 defines the location of the C.G. of the wedge in the x, y, and z directions. The rotation of the friction wedge is represented by a composite rotation matrix R^{QB},

$$R^{QB} = \begin{pmatrix} \cos(q_3) & 0 & -\sin(q_3) \\ 0 & 1 & 0 \\ \sin(q_3) & 0 & -\cos(q_3) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(q_4) & \sin(q_4) \\ 0 & -\sin(q_4) & \cos(q_4) \end{pmatrix} \tag{3-6}$$

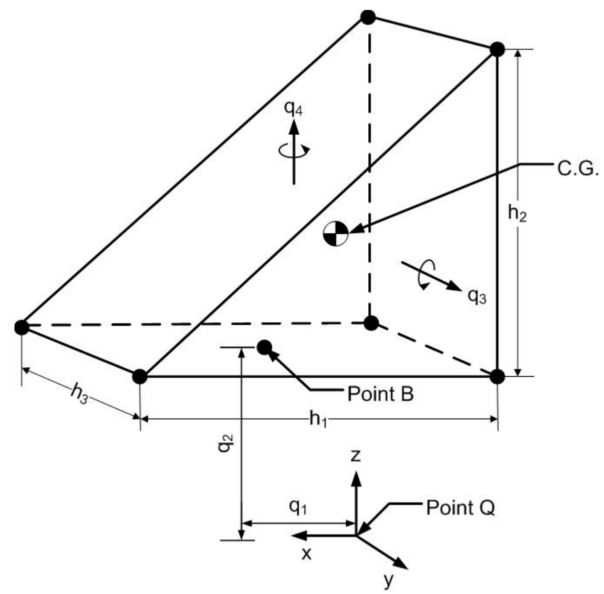


Figure 3-6. A diagram of the translational and rotational degrees of freedom of the friction wedge. Also included is the origin of the global coordinate system (Q) relative to the origin of the body (B)

The dimensions of the friction wedge model were determined based on its average weight, material properties, and values used in real-life situations. The actual physical model of a constantly-damping friction wedge is hollow, which allows for the control coil to be placed inside the wedge and the entire apparatus to be compressed inside the bolster pocket. The actual dimensions of a friction wedge were not relevant to the Stand-Alone model because the important surfaces are the sloped and vertical surfaces, which calculate the friction damping, and the length h_3, which provides warp resistance. The dimensions of the wedge used in the Stand-Alone model are included in Figure 3-6 and listed in Table 3-2.

Table 3-2. Geometric parameters used in the Constantly-Damped models.

		Constantly-Damped
Wedge angle, (°)	θ	37.5
Wedge dimensions, (in)	h_1	3.827
	h_2	6.125
	h_3	10.5
CG location relative to point B, (in)	p_1	-1.0734
	p_2	0
	p_3	2.0417

3.3 Modeling Approach: Dynamics

3.3.1 Variably-Damped Friction Wedge Model

For the variably-damped Stand-Alone model, the mass and the rotational inertia of the wedge are included to account for the inertial effects. The contact forces act on the points at the corners of the wedge that are in contact with the bolster and side frame. The current model uses six points to detect the penetration of the wedge into the contacting surfaces. The mapping of the points relative to point B is shown in Figure 3-7. Surface A is the surface that contacts the side frame, while surface B is the surface that contacts the bolster. Points A_1 and A_3 are the contact points on surface A, while points B_2 and B_3 are the contact points on surface B. The points A_2 and A_4 are the common points between the two surfaces A and B.

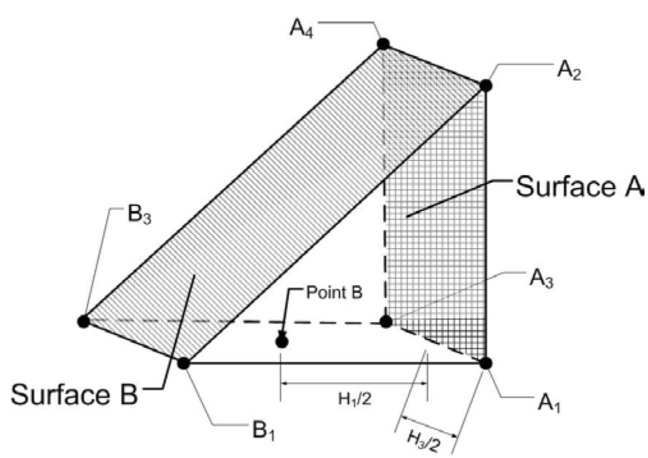


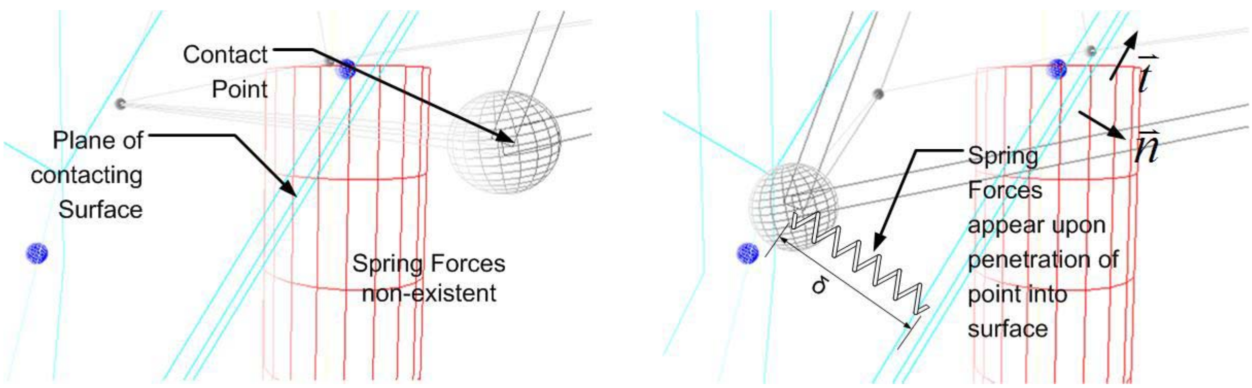
Figure 3-7. Diagram of the points and surfaces associated with the friction wedge.

The forces that occur on each surface are unilateral contact forces. Figure 3-8 aids in understanding the modeling of the unilateral contact forces. In order to illustrate how the contact forces are defined between the wedge and the contacting surfaces, the interaction of a single point is discussed. The contact forces are the result of contact between the wedge and side frame and bolster faces. A unilateral spring, shown in

Figure 3-8 (b), appears when there is contact between the surfaces. The penetration of the bolster or side frame face into the wedge causes the spring to compress resulting in a reaction force to occur. This reaction force is a normal spring force which is denoted as F_{normal},

$$F_{normal} = k \cdot \delta \cdot \vec{n} \tag{3-7}$$

where k is the approximate stiffness of the spring between the contacting surfaces, δ is the normal distance of penetration of the point into the contact surface along, and $\vec{n}$ is the vector normal to the contact surface. When there is no contact between the wedge and surfaces, there is no spring and therefore no reaction forces, as shown in Figure 3-8(a).



(a) (b)

Figure 3-8. (a) Before contact between the surfaces, represented by the grey sphere, the spring forces are non-existent. (b) Contact causes penetration of the contact point into the surface, causing spring forces to resist the penetration of the wedge into the surface.

The tangential friction forces are a function of the velocity tangential to the surface, which as shown in Figure 3-9. The tangential velocity, $V_{tangential}$, is meant to resist the motion of the wedge. The tangential forces can then be defined as:

$$F_{\text{tangential}} = \mu \cdot F_{normal} \cdot \tanh(V_{\text{tangential}} / 0.001) \cdot \vec{t} \tag{3-8}$$

where $\mu =$ coefficient of friction
$F_{normal} =$ normal forces from the contact surface
$V_{\text{tangential}} =$ velocity tangential to the contact surface
$\vec{t} =$ vector tangential to the contact surface

The "0.001" factor is a factor selected to increase the sensitivity of the hyperbolic tangent in order to approximate the sign function used to model Coulomb friction.

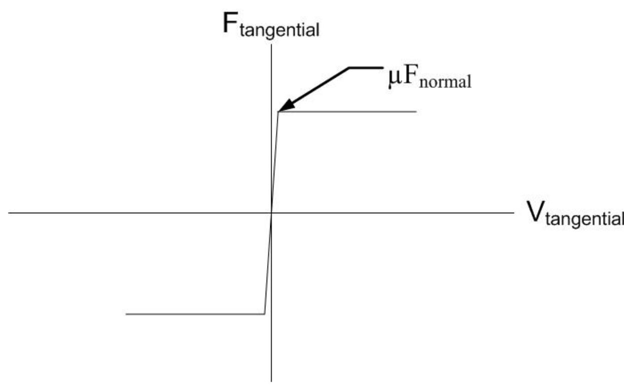


Figure 3-9. Graphical representation of the tangential force as a function of the tangential velocity.

The parameters used for the dynamic simulation for the variably-damped model are listed in Table 3-3. These values were used in calculating the forces acting on the wedge, including its weight and friction forces due to the bolster – wedge interaction and wedge – side frame interaction. These values were also used in calculating the moments acting on the wedge including its yaw and pitch moments.

Table 3-3. Dynamic modeling parameters for the variably-damped model.

Side frame coefficient of friction, μ_s		0.4
Bolster coefficient of friction, μ_b		0.4
Mass of the wedge, $m_{w,}$ (lb-f)		50
Moment of inertia	I_{11}	100
	I_{22}	100
	I_{33}	100
l_0, (in)		10.25
Force used to calculate static position, (lbf)		12500
$C_{damp,}$ (lbf-s/in)		1
K_s (lbf/in)		3000

Using Kane's Method and D'Alembert's Principle ([9],[6]), the differential equations which describe the system are derived as:

$$
\begin{aligned}
\dot{q}_1 &= u_1 \\
\dot{q}_2 &= u_2 \\
\dot{q}_3 &= u_3 \\
\dot{q}_4 &= u_4 \\
\dot{u}_1 &= -(\cos(q_3)\sin(q_4)F_x + \cos(q_3)\sin(q_4)F_y - F_z\sin(q_3))/m_w \\
\dot{u}_2 &= (\sin(q_3)\sin(q_4)F_x + \sin(q_3)\sin(q_4)F_y + F_z\cos(q_3))/m_w \\
\dot{u}_3 &= \frac{\cos(q_4)(2u_4I_{11}u_3\sin(q_4) - 2I_{22}u_3\sin(q_4)u_4 - T_x - T_y)}{(-I_{22}\cos(q_4)^2 - I_{11} + I_{11}\cos(q_4)^2)} \\
\dot{u}_4 &= -(\cos(q_4)p_2\sin(q_4)F_x + \cos(q_4)p_2\sin(q_4)F_y - p_1F_x\cos(q_4)^2 \\
&\quad - p_1F_y\cos(q_4)^2 + u_3^2\sin(q_4)I_{22}\cos(q_4) \\
&\quad - u_3^2\cos(q_4)I_{11}\sin(q_4) - T_z)/I_{33}
\end{aligned}
\tag{3-9}
$$

where

$\vec{F} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}$ is the force vector in the principal directions of the wedge-frame

and

$\vec{T} = \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix}$ is the torque vector in the principal directions of the wedge-frame

The force vector is calculated by summing the forces detected at each contact point on each surface. The magnitudes of the summed forces are then applied to the surfaces along the vectors illustrated in Figure 3-10.

$$\begin{aligned}\vec{F} = -m_w g \cdot \vec{z} &- \left(F^{A_1}_{normalSF} + F^{A_2}_{normalSF} + F^{A_3}_{normalSF} + F^{A_4}_{normalSF}\right) \cdot \vec{n}_{sideframe} \\ &+ \left(F^{A_1}_{\tan gentialSF} + F^{A_2}_{\tan gentialSF} + F^{A_3}_{\tan gentialSF} + F^{A_4}_{\tan gentialSF}\right) \cdot \vec{t}_{sideframe} \\ &- \left(F^{B_1}_{normalB} + F^{B_2}_{normalB} + F^{B_3}_{normalB} + F^{B_4}_{normalB}\right) \cdot \vec{n}_{bolster} \\ &- \left(F^{B_1}_{\tan gentialB} + F^{B_2}_{\tan gentialB} + F^{B_3}_{\tan gentialB} + F^{B_4}_{\tan gentialB}\right) \cdot \vec{t}_{bolster} + F_s + F_d\end{aligned} \tag{3-10}$$

where F_s is the force due to the control coil and F_d is the force due to the material damping of the spring. The control coil force for the wedge model is:

$$F_s = K_s \left(l_0 - \left\|\vec{r}^{\,WB}\right\|\right) \frac{\vec{r}^{\,WB}}{\left\|\vec{r}^{\,WB}\right\|} \tag{3-11}$$

The damping force for the wedge model is:

$$F_d = -C_{damp} \frac{\partial \vec{r}^{\,WB}}{\partial t} \tag{3-12}$$

The torque vector is calculated by summing the torques at each surface contact point.

$$\begin{aligned}\vec{T} = &-\begin{pmatrix}\vec{r}^{\,CGA_1} \times \left(F^{A_1}_{normalSF} \cdot \vec{n}_{sideframe}\right) + \vec{r}^{\,CGA_2} \times \left(F^{A_2}_{normalSF} \cdot \vec{n}_{sideframe}\right) + \vec{r}^{\,CGA_3} \times \left(F^{A_3}_{normalSF} \cdot \vec{n}_{sideframe}\right) \\ + \vec{r}^{\,CGA_4} \times \left(F^{A_4}_{normalSF} \cdot \vec{n}_{sideframe}\right)\end{pmatrix} \\ &+\begin{pmatrix}\vec{r}^{\,CGA_1} \times \left(F^{A_1}_{\tan gentialSF} \cdot \vec{t}_{sideframe}\right) + \vec{r}^{\,CGA_2} \times \left(F^{A_2}_{\tan gentialSF} \cdot \vec{t}_{sideframe}\right) + \vec{r}^{\,CGA_3} \times \left(F^{A_3}_{\tan gentialSF} \cdot \vec{t}_{sideframe}\right) \\ + \vec{r}^{\,CGA_4} \times \left(F^{A_4}_{\tan gentialSF} \cdot \vec{t}_{sideframe}\right)\end{pmatrix} \\ &-\left(\vec{r}^{\,CGB_1} \times \left(F^{B_1}_{normalB} \cdot \vec{n}_{bolster}\right) + \vec{r}^{\,CGB_2} \times \left(F^{B_2}_{normalB} \cdot \vec{n}_{bolster}\right) + \vec{r}^{\,CGB_3} \times \left(F^{B_3}_{normalB} \cdot \vec{n}_{bolster}\right) + \vec{r}^{\,CGB_4} \times \left(F^{B_4}_{normalB} \cdot \vec{n}_{bolster}\right)\right) \\ &-\begin{pmatrix}\vec{r}^{\,CGB_1} \times \left(F^{B_1}_{\tan gentialB} \cdot \vec{t}_{bolster}\right) + \vec{r}^{\,CGB_2} \times \left(F^{B_2}_{\tan gentialB} \cdot \vec{t}_{bolster}\right) + \vec{r}^{\,CGB_3} \times \left(F^{B_3}_{\tan gentialB} \cdot \vec{t}_{bolster}\right) \\ + \vec{r}^{\,CGB_4} \times \left(F^{B_4}_{\tan gentialB} \cdot \vec{t}_{bolster}\right)\end{pmatrix} \\ &- C_{damp} u_3 \cdot \vec{y} - C_{damp} u_4 \cdot \vec{z}\end{aligned} \tag{3-13}$$

where

$\dfrac{\vec{r}^{\,WB}}{\left\|\vec{r}^{\,WB}\right\|}$ = unit vector along the length of the spring for the variably - damped model

$(\cdot)$ = dot product operator

$(\times)$ = cross product operator

$\vec{r}^{\,CGA_i}$ = vector from the CG to the ith A point

$\vec{r}^{\,CGB_i}$ = vector from the CG to the ith B point

$F^{A_i}_{normalSF}$ = force acting normal to surface A on point A_i

$F^{A_i}_{normalB}$ = force acting normal to surface B on point A_i

$F^{B_i}_{normalB}$ = force acting normal to surface B on point B_i

$F^{A_i}_{\tan gentialSF}$ = force acting tangential to surface A on point A_i

$F^{A_i}_{\tan gentialB}$ = force acting tangential to surface B on point A_i

$F^{B_i}_{\tan gentialB}$ = force acting tangential to surface B on point B_i

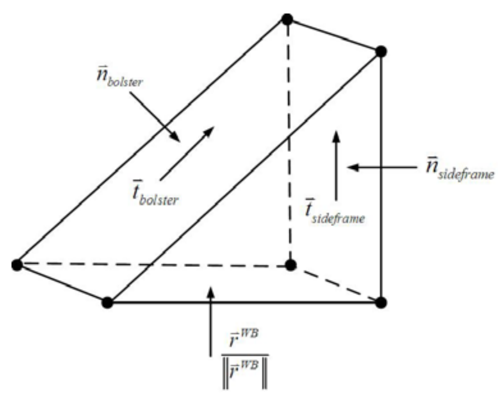


Figure 3-10. Force directions relative to the wedge for the variably-damped model.

3.3.2 Constantly-Damped Friction Wedge Model

For the constantly-damped Stand-Alone model, the mass and the rotational inertia of the wedge are included to account for the inertial effects. The contact forces act on the same points at the corners of the wedge as in the variably-damped model. These points were shown in Figure 3-7 in the previous section. The forces occurring at these points are modeled as unilateral forces, which were discussed in detail in the previous section.

The normal and tangential forces acting at each point during the simulations are defined by equations 3-7 and 3-8, respectively.

The parameters used for the dynamic simulation for the constantly-damped models are listed in Table 3-4. These values were used in calculating the forces acting on the wedge, including its weight and friction forces due to the bolster – wedge interaction and wedge – side frame interaction. These values were also used in calculating the moments acting on the wedge including its yaw and pitch moments.

Table 3-4. Dynamic modeling parameters for the constantly-damped model

<table>
<tr><td colspan="2">Side frame coefficient of friction, μ_s</td><td>0.4</td></tr>
<tr><td colspan="2">Bolster coefficient of friction, μ_b</td><td>0.4</td></tr>
<tr><td colspan="2">Mass of the wedge, $m_{w,}$ (lb-f)</td><td>50</td></tr>
<tr><td rowspan="3">Moment of inertia</td><td>I_{11}</td><td>100</td></tr>
<tr><td>I_{22}</td><td>100</td></tr>
<tr><td>I_{33}</td><td>100</td></tr>
<tr><td colspan="2">l_0, (in)</td><td>7.25</td></tr>
<tr><td colspan="2">Force used to calculate static position, (lbf)</td><td>12500</td></tr>
<tr><td colspan="2">$C_{damp,}$ (lbf-s/in)</td><td>1</td></tr>
<tr><td colspan="2">K_s (lbf/in)</td><td>1979</td></tr>
</table>

The differential equations which describe the system are the same as those derived in the previous section, which are in equation 3-9. The force and torque vectors are calculated in the same method as well. The force vector is calculated by summing the forces detected at each contact point on each surface. The magnitudes of the summed forces are then applied to the surfaces along the vectors illustrated in Figure 3-11.

$$
\begin{aligned}
\vec{F} = &-m_w g \cdot \vec{z} - \left(F^{A_1}_{normalSF} + F^{A_2}_{normalSF} + F^{A_3}_{normalSF} + F^{A_4}_{normalSF}\right) \cdot \vec{n}_{sideframe} \\
&+ \left(F^{A_1}_{\tan gentialSF} + F^{A_2}_{\tan gentialSF} + F^{A_3}_{\tan gentialSF} + F^{A_4}_{\tan gentialSF}\right) \cdot \vec{t}_{sideframe} \\
&- \left(F^{B_1}_{normalB} + F^{B_2}_{normalB} + F^{B_3}_{normalB} + F^{B_4}_{normalB}\right) \cdot \vec{n}_{bolster} \\
&- \left(F^{B_1}_{\tan gentialB} + F^{B_2}_{\tan gentialB} + F^{B_3}_{\tan gentialB} + F^{B_4}_{\tan gentialB}\right) \cdot \vec{t}_{bolster} + F_s + F_d
\end{aligned}
\tag{3-15}
$$

where F_s is the force due to the control coil and F_d is the force due to the material damping of the spring. The control coil force for this model is:

$$
F_s = K_s \left(l_0 - \left\|\vec{r}^{\,QB}\right\|\right) \frac{\vec{r}^{\,QB}}{\left\|\vec{r}^{\,QB}\right\|} \tag{3-16}
$$

The damping force for this model is:

$$
F_d = -C_{damp} \frac{\partial \vec{r}^{\,QB}}{\partial t} \tag{3-17}
$$

The Torque vector is calculated by summing the torques at each surface contact point.

$$
\begin{aligned}
\vec{T} = &-\left(\vec{r}^{\,CGA_1} \times (F^{A_1}_{normalSF} \cdot \vec{n}_{sideframe}) + \vec{r}^{\,CGA_2} \times (F^{A_2}_{normalSF} \cdot \vec{n}_{sideframe}) + \vec{r}^{\,CGA_3} \times (F^{A_3}_{normalSF} \cdot \vec{n}_{sideframe}) + \vec{r}^{\,CGA_4} \times (F^{A_4}_{normalSF} \cdot \vec{n}_{sideframe})\right) \\
&+\left(\vec{r}^{\,CGA_1} \times (F^{A_1}_{\mathrm{tangential}SF} \cdot \vec{t}_{sideframe}) + \vec{r}^{\,CGA_2} \times (F^{A_2}_{\mathrm{tangential}SF} \cdot \vec{t}_{sideframe}) + \vec{r}^{\,CGA_3} \times (F^{A_3}_{\mathrm{tangential}SF} \cdot \vec{t}_{sideframe}) + \vec{r}^{\,CGA_4} \times (F^{A_4}_{\mathrm{tangential}SF} \cdot \vec{t}_{sideframe})\right) \\
&-\left(\vec{r}^{\,CGB_1} \times (F^{B_1}_{normalB} \cdot \vec{n}_{bolster}) + \vec{r}^{\,CGA_2} \times (F^{A_2}_{normalB} \cdot \vec{n}_{bolster}) + \vec{r}^{\,CGB_3} \times (F^{B_3}_{normalB} \cdot \vec{n}_{bolster}) + \vec{r}^{\,CGA_4} \times (F^{A_4}_{normalB} \cdot \vec{n}_{bolster})\right) \\
&-\left(\vec{r}^{\,CGB_1} \times (F^{B_1}_{\mathrm{tangential}B} \cdot \vec{t}_{bolster}) + \vec{r}^{\,CGA_2} \times (F^{A_2}_{\mathrm{tangential}B} \cdot \vec{t}_{bolster}) + (F^{B_3}_{\mathrm{tangential}B} \cdot \vec{t}_{bolster}) + \vec{r}^{\,CGA_4} \times (F^{A_4}_{\mathrm{tangential}B} \cdot \vec{t}_{bolster})\right) \\
&-C_{damp} u_3 \cdot \vec{y} - C_{damp} u_4 \cdot \vec{z}
\end{aligned}
\tag{3-18}
$$

where

$\dfrac{\vec{r}^{\,QB}}{\left\|\vec{r}^{\,QB}\right\|}$ = unit vector along the length of the spring for the constantly - damped model

$(\cdot)$ = dot product operator

$(\times)$ = cross product operator

$\vec{r}^{\,CGA_i}$ = vector from the CG to the ith A point

$\vec{r}^{\,CGB_i}$ = vector from the CG to the ith B point

$F^{A_i}_{normalSF}$ = force acting normal to surface A on point A_i

$F^{A_i}_{normalB}$ = force acting normal to surface B on point A_i

$F^{B_i}_{normalB}$ = force acting normal to surface B on point B_i

$F^{A_i}_{\tan gentialSF}$ = force acting tangential to surface A on point A_i

$F^{A_i}_{\tan gentialB}$ = force acting tangential to surface B on point A_i

$F^{B_i}_{\tan gentialB}$ = force acting tangential to surface B on point B_i

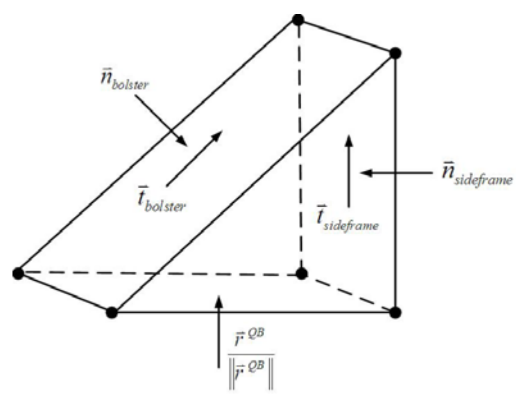


Figure 3-11. Force directions relative to the wedge for the constantly-damped model.

4 SIMULATION SCENARIO

In order to accurately compare the NUCARS® model with the MATLAB stand alone model, displacement inputs were used on the bolster, resulting in the motion of the wedge. In using the displacement of the bolster, we could be sure that the input to both models is the same. A pure vertical displacement and a vertical input while the bolster was rotated and held at a fixed angle were input into the system. The pure vertical input was a sinusoidal vertical displacement of the bolster with a peak-to-peak amplitude of 2 inches and a frequency of 2 radians/second, illustrated in Figure 4-1. The vertical input with the fixed rotation used the same vertical input as before with the bolster rotated 0.012 radians to one side, illustrated as 'psi' in Figure 4-2. The inputs for each case are summarized in Table 4-1.

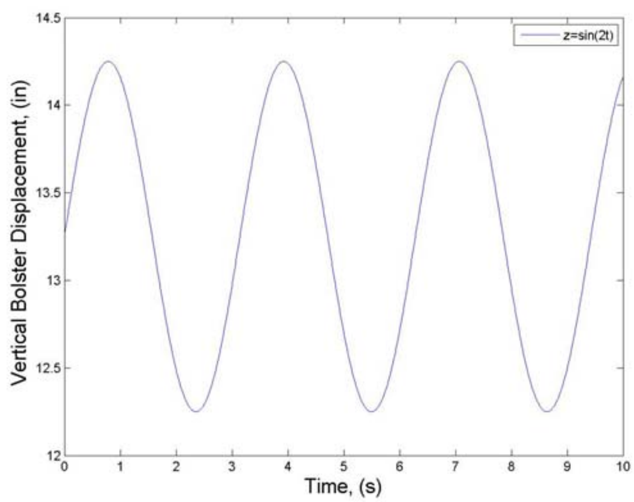


Figure 4 -1. The bolster input motion for all cases of the simulations.

Table 4-1. Simulation cases for the Stand-Alone MATLAB and NUCARS® models.

Case Number	Toe Angle, (°)	Yaw Angle, (rad)
1	+0.2	0
2	0	0
3	-0.2	0
4	+0.2	0.012
5	0	0.012
6	-0.2	0.012

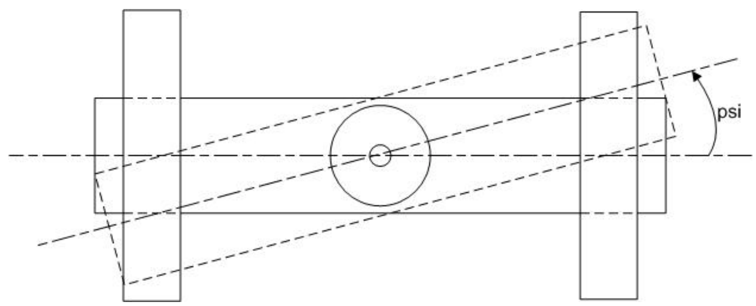


Figure 4-2. Fixed rotation of the bolster in the three piece truck. The bolster was rotated from the center of the centerplate.

The vertical inputs were applied to the NUCARS® model using type 1 connections acting in the center of the spring nests located on either end of the bolster and acting between the bolster and side frame. The rotation was applied using a type 1 connection at the center of the bolster. For both the NUCARS® and standalone models, toe out, meaning the bottom of the wedges are further towards the side frame than the upper part, and toe in were tested. For the Type 6.9 NUCARS® connection and the Stand-Alone model, the toe angles used were +0.2° for toe in and -0.2° for toe out.

5 VARIABLY-DAMPED FRICTION WEDGE MODEL RESULTS

In this chapter, the variably-damped Stand-Alone MATLAB friction wedge model was compared to the type 6.8 and 6.9 variably-damped models created using NUCARS®. Comparisons were made between the three toe cases of the Stand-Alone model and between the Stand-Alone model and the two NUCARS® models all in toe out. The first section shows the results of the vertical bolster displacement input to the three models. The second section shows the results of the vertical bolster displacement with a yaw input to the three models.

5.1 Vertical Bolster Displacement Input

In order to compare the NUCARS® model to the Stand-Alone MATLAB model, the vertical damping forces for each model were calculated. The damping force in NUCARS® is the friction force between the wedge and side frame calculated by

$$F_{sfz} = F_s \frac{\cos\theta + \mu\sin\phi}{(\cos\phi - \mu\sin\phi)(\sin\theta - \mu\cos\theta) + (\mu\cos\phi + \sin\phi)(\cos\theta + \mu\sin\theta)} \tag{5-1}$$

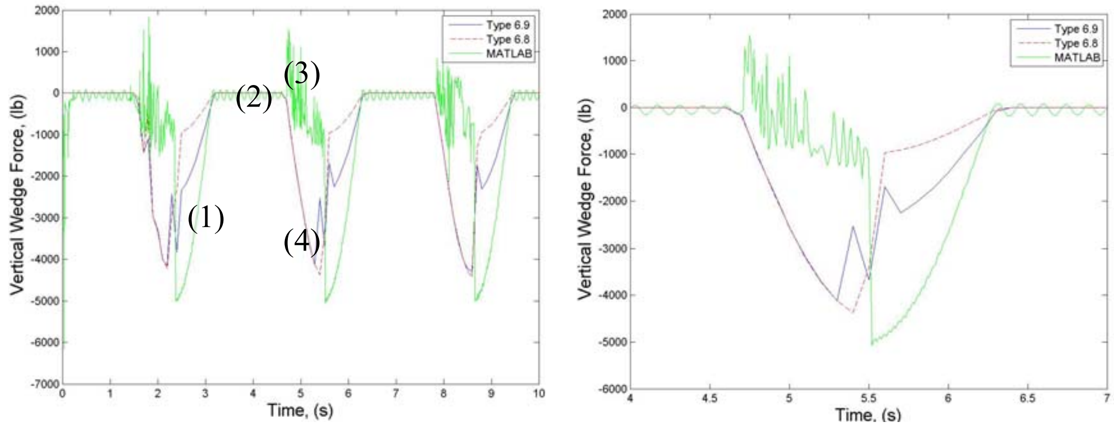
where F_s is the spring force from the control coil, θ is the wedge angle, μ is the friction coefficient on the wedge faces, and ϕ is the toe angle. The toe angle is positive for toe out and negative for toe in. Because the friction wedge is considered a point of connection between the bolster and side frame in NUCARS®, the vertical damping force calculated is equivalent to the vertical component of the side frame friction. The forces in the MATLAB model include all of the forces acting along the unit vectors normal and tangential to the wedge faces, as shown in Figure 3-10.

$$F_x = -\left(F^{A_1}_{normalSF} + F^{A_2}_{normalSF} + F^{A_3}_{normalSF} + F^{A_4}_{normalSF}\right) \tag{5-2}$$

$$F_z = F_s + \left(F^{A_1}_{\tan gentialSF} + F^{A_2}_{\tan gentialSF} + F^{A_3}_{\tan gentialSF} + F^{A_4}_{\tan gentialSF}\right) \tag{5-3}$$

where $F_s = K_s(l_0 - \|\vec{r}^{\,WB}\|)\dfrac{\vec{r}^{\,WB}}{\|\vec{r}^{\,WB}\|}$. l_0 is the undeformed control coil length and $\vec{r}^{\,WB}$ is the vector from the bottom of the control coil, which is located on the side frame, to the bottom of the wedge.

Figure 5-1 compares the vertical wedge forces of the two NUCARS® models with the MATLAB model. The magnitudes of the vertical forces for all of the models are similar. However, the Stand-Alone model seemed to have significantly better capabilities in capturing the stick-slip behavior as well as lift-off. Due to the large control coil stiffness and small wedge mass in the Stand-Alone model, the force oscillates close to 0 lb when the bolster is lifted off of the wedge. When the bolster first pushes down on the wedge, t=1.5 s to t=2.4 s, the MATLAB model shows how the wedge sticks and slips while traversing the side frame face. As the bolster is lifted off of the wedge, t=2.4 s to t=3.2 s, the wedge slides upwards more smoothly.



(a) **(b)**

Figure 5-1. (a) Comparison of the Vertical wedge force for the each type of connection in NUCARS® and the Stand-Alone Model in Toe Out. (b) Vertical forces for all models from t=4 s to t=7 s.

The sections labeled in Figure 5-1 coincide with the sections labeled in Figure 5-2. Figure 5-2 illustrates the movement of the wedge by comparing the vertical wedge force to the wedge's vertical displacement for one period of the input. The wedge and bolster are both moving up in Section (1) in Figure 5-2. In Section (2) the bolster is lifted off of the wedge completely. Section (3) represents the force due to the bolster moving down, pressing against the wedge and forcing it to slip down the face of the side frame. Section (4) occurs in the same phase of the input as (3), but is the result of the wedge sticking against the side frame.

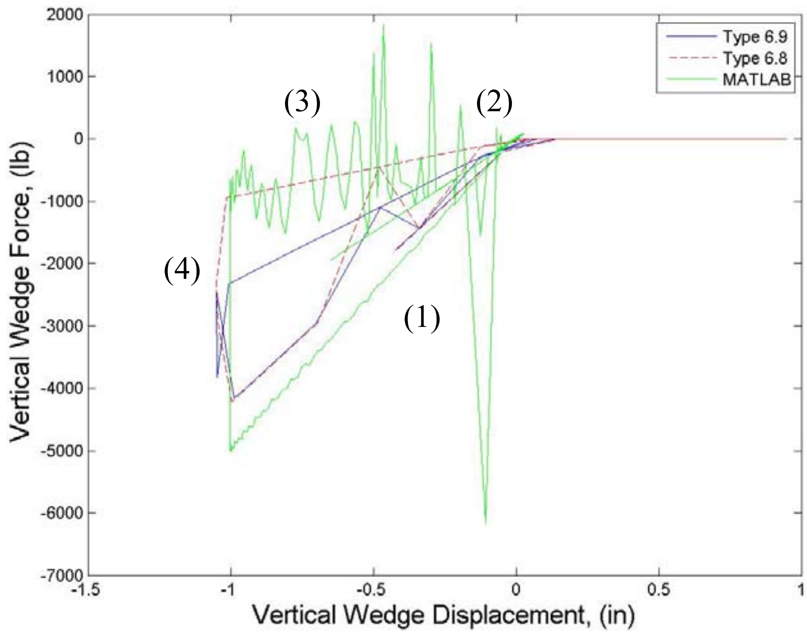


Figure 5-2. Comparison of the Vertical wedge force hysteresis loops for each type of connection in NUCARS® and the Stand-Alone Model in Toe Out.

Figure 5-3 compares the toe in, toe out and zero toe versions of the Stand-Alone model. Since the toe angles used are very small, the differences between the magnitudes of the vertical force plots for all toe cases should be very small. The small differences in magnitudes in Figure 5-3 show how the Stand-Alone MATLAB model captures the actual motion of the wedge accurately.

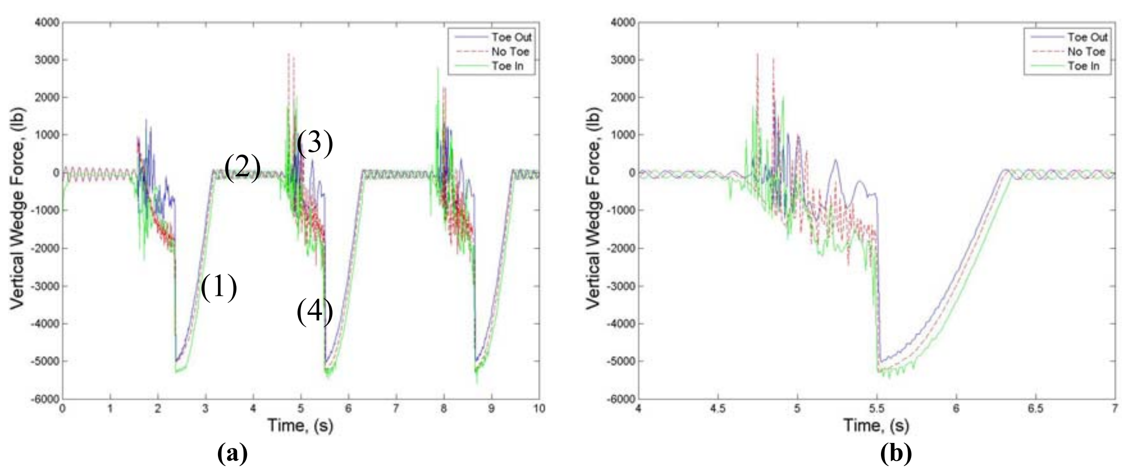


Figure 5-3. (a) Comparison of the Vertical wedge force for the Stand-Alone Model with Toe In, No Toe, and Toe Out. (b) Vertical forces for all toe cases from t=4 s to t=7 s.

From Figures 5-3 and 5-4, it can be observed that the toed-out forces are lower because the contact between the wedge and side frame is smoother, and the toed-in forces are the highest because of the more forced contact between the wedge and side frame. During lift-off, which happens slightly after 3 seconds of simulation, the wedge oscillates around 0 lb because of the interaction of the mass and the spring. The sections labeled in Figure 5-3 coincide with the sections labeled in Figure 5-4. Figure 5-4 illustrates the small differences in all of the toe cases by comparing the vertical wedge force directly to the wedge vertical displacement.

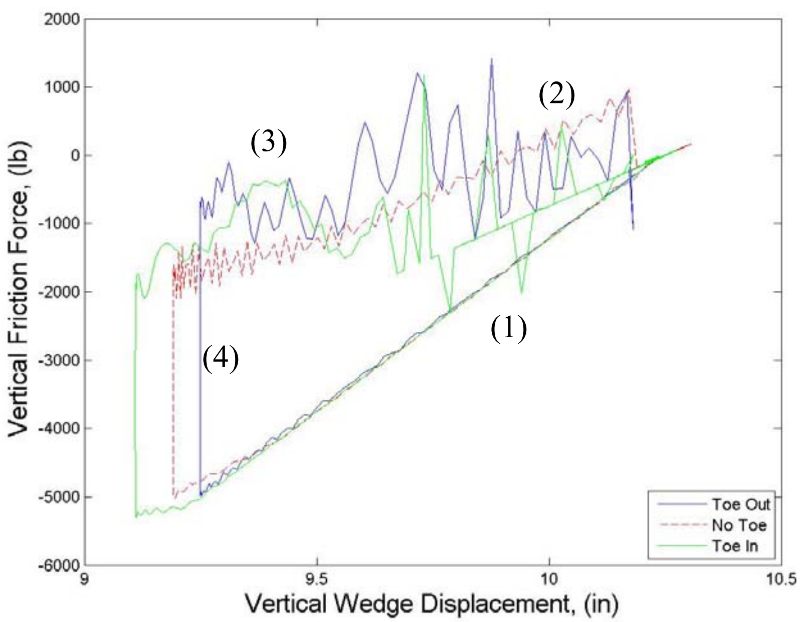
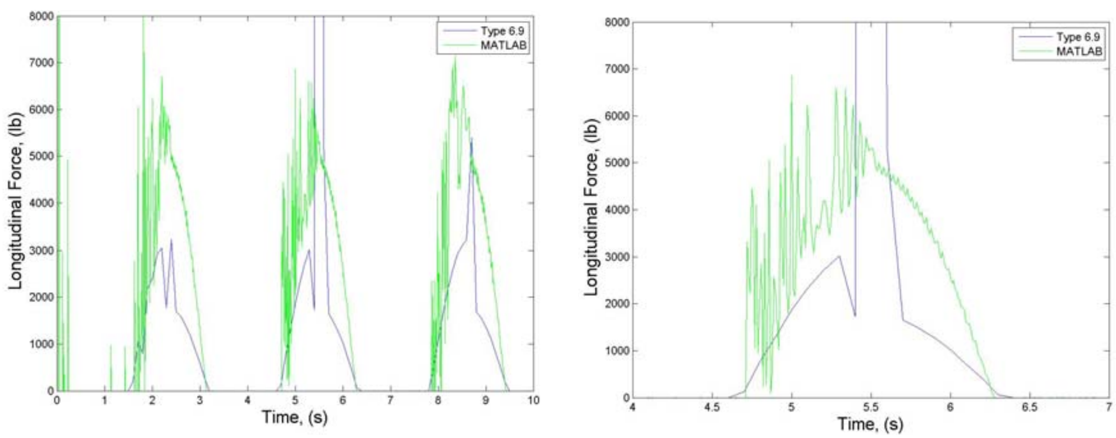


Figure 5-4. Vertical Friction Force Hysteresis loops for all toe cases.

Section (1) in Figure 5-4 represents the force acting on the wedge when the bolster is moving upwards, the wedge is moving upwards as well. Section (2) represents the sequence when the bolster is lifted off the wedge. The vertical forces oscillate close to 0 lb. Section (3) represents the friction force when the bolster is moving downwards and pushing the wedge downwards with it. The wedge is slipping down the side frame face during this section. In Section (4) the wedge is in the same phase of the input as (3), but the wedge is now sticking to the side frame causing a large force with no motion.

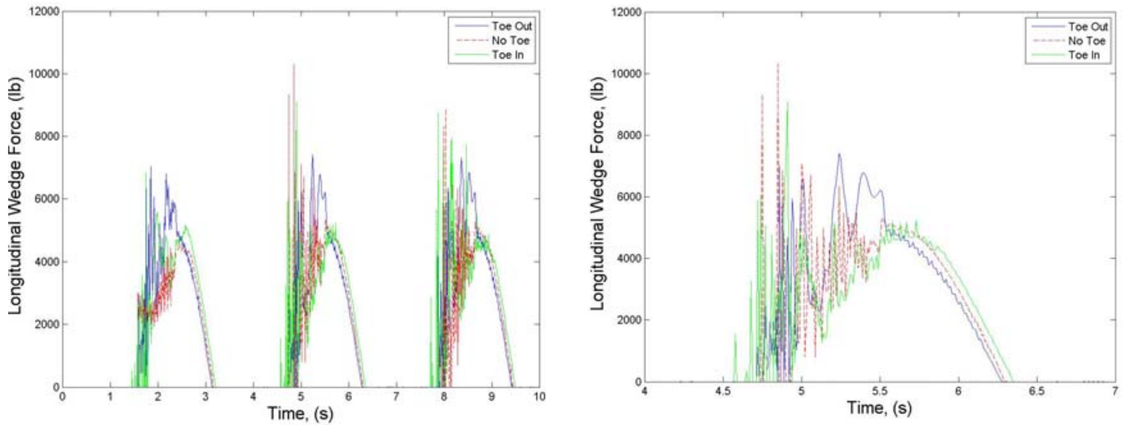
Figure 5-5 illustrates that the Stand-Alone model's ability to calculate the wedge's longitudinal forces is on par with NUCARS® type 6.9 wedge model. The NUCARS® type 6.8 wedge model is a two-dimensional model so it does not have the capabilities to calculate longitudinal forces. The longitudinal forces represent the wedge ringing between the bolster and side frame. The forces remain relatively periodic which is expected given the periodic input.



(a) **(b)**

Figure 5-5. (a) Comparison of the longitudinal forces of the Type 6.9 NUCARS® friction wedge model and the Stand-Alone Model for Toe Out. (b) Longitudinal forces from t=4 s to t=7 s.

Figure 5-6 compares the longitudinal forces for all toe cases for the Stand-Alone model. The toe in and toe out cases have less peaks than the zero toe version due to the geometry of the bolster-wedge-side frame system. While in toe in and in toe out, the bolster and the side frame provide physical constraints on the movement of the wedge.



(a) **(b)**

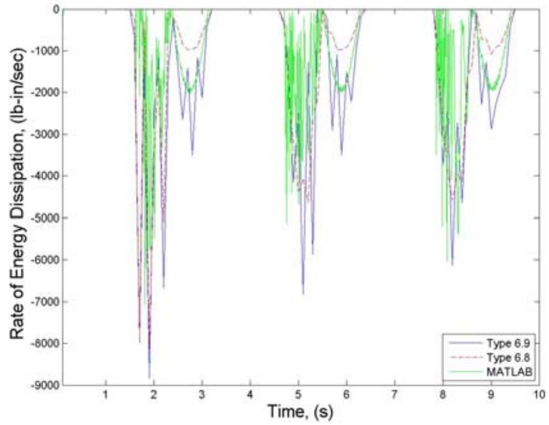
Figure 5-6. (a) Comparison of the longitudinal forces for the Stand-Alone Model with Toe In, No Toe, and Toe Out. (b) Longitudinal forces for all toe cases from t=4 s to t=7 s.

The rate of energy dissipated is calculated by taking the dot product of the force between the contacting points and their relative velocities to the surface in contact.

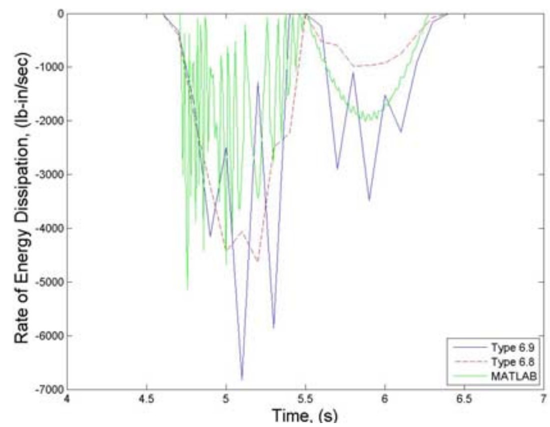
$$\frac{\partial E_{sideframeT}}{\partial t} = \left(v_{A_1} \cdot F^{A_1}_{\tan gentialSF} + v_{A_2} \cdot F^{A_2}_{\tan gentialSF} + v_{A_3} \cdot F^{A_3}_{\tan gentialSF} + v_{A_4} \cdot F^{A_4}_{\tan gentialSF} \right) \quad (5\text{-}4)$$

$$\frac{\partial E_{bolsterT}}{\partial t} = \left(v_{B_1} \cdot F^{B_1}_{\tan gentialB} + v_{B_2} \cdot F^{B_2}_{\tan gentialB} + v_{B_3} \cdot F^{B_3}_{\tan gentialB} + v_{B_4} \cdot F^{B_4}_{\tan gentialB} \right) \quad (5\text{-}5)$$

Figure 5-7 compares the rate of the energy dissipated between the friction wedge and side frame for each of the two NUCARS® models with the MATLAB model. The energy dissipated between the side frame and wedge from the friction is calculated for the Toe out scenario in both the NUCARS® models and the standalone friction wedge model. As seen in the figure, there is no energy dissipation during lift-off because the spring-mass system conserves energy during its oscillations.



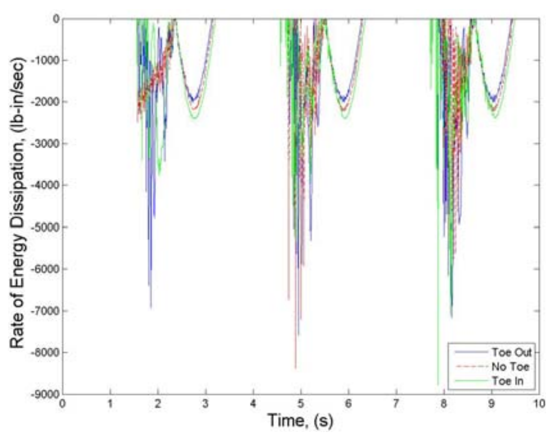
(a)



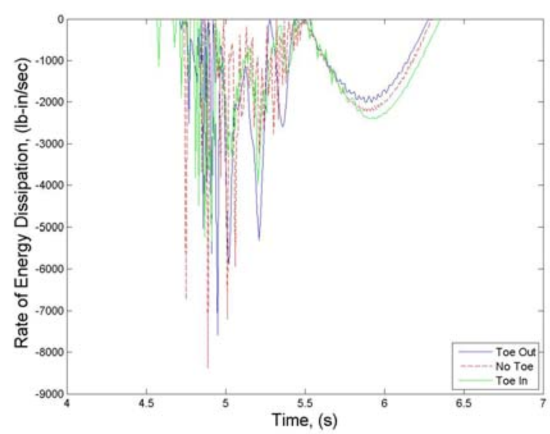
(b)

Figure 5-7. (a) Comparison of the rate of energy dissipation between the side frame and wedge for the NUCARS® friction wedge model and the Stand-Alone Model in Toe Out. (b) Energy dissipation for all models from t=4 s to t=7 s.

Figure 5-8 is a comparison of the rate of energy dissipated for toe in, toe out and zero toe cases for a vertical bolster displacement input. Note that the energy dissipated is less for the toed out case because of the reduced contact surface and the reduced forces that act on the wedge. For the toe in case, the rate of energy dissipated is the largest because of the increase in forces that act on the wedge as well as a greater contact surface. As expected, the zero toe case falls between the toe in and toe out cases.



(a)



(b)

Figure 5-8. (a) The energy dissipated between the side frame and wedge from the Stand-Alone MATLAB model for all toe cases. (b) Energy dissipation for all toe cases from t=4 s to t=7 s.

The major advantage of the MATLAB model, besides its inclusion of inertial properties, is its ability to calculate the moments acting on the friction wedge. Due to the simplicity of the input, which was a vertical displacement of the bolster, the moments calculated were small. For more complicated inputs, the MATLAB model would be able to calculate the moments that would act on the bolster and side frames due to the wedge. Some of the more complicated inputs include twist and roll, yaw and sway.

5.2 Vertical Bolster Displacement with Yaw Input

The vertical damping forces for each of the models, NUCARS® and the Stand-Alone, were calculated in the same manner as the vertical displacement section, using equations 5-1, 5-2 and 5-3. The main difference is the constant yaw angle that was input to the system through the bolster. The bolster was yawed 0.012 radians, shown previously in Figure 4-2, and held constant there while the same vertical displacement was input. Figure 5-9 shows a comparison of the vertical wedge force between the two NUCARS® models and the Stand-Alone model all in toe out.

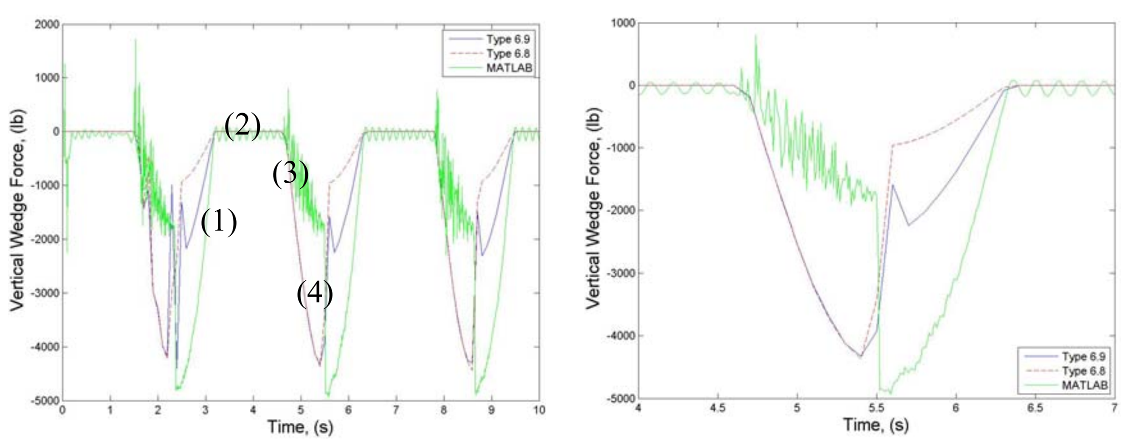


Figure 5-9. (a) Comparison of the Vertical wedge force for each type of connection in NUCARS® and the Stand-Alone Model in Toe Out with a Yaw Input. (b) Vertical forces for all models from t=4 s to t=7 s.

The sections labeled in Figure 5-9 coincide with the sections labeled in Figure 5-10. Figure 5-10 is a comparison of the vertical wedge forces to the vertical wedge displacement for both of the NUCARS® models and the Stand-Alone model due to a yaw input. The first section of the plot represents the wedge moving upwards with the bolster until it is lifted off of the wedge. The yaw input on the system caused noise in section 1. The second section represents the bolster lifting off of the wedge completely. The wedge then oscillates around 0 lbf due to the large control coil stiffness and small mass of the wedge. The third section represents the wedge slipping down the face of the side frame due to the bolster moving downwards. The fourth section represents the static friction occurring on the wedge just before it begins moving upwards with bolster.

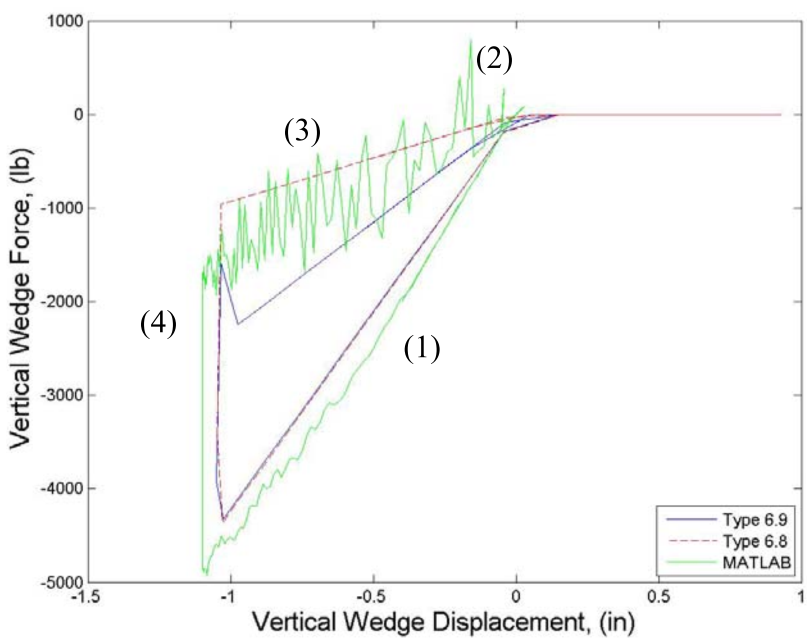
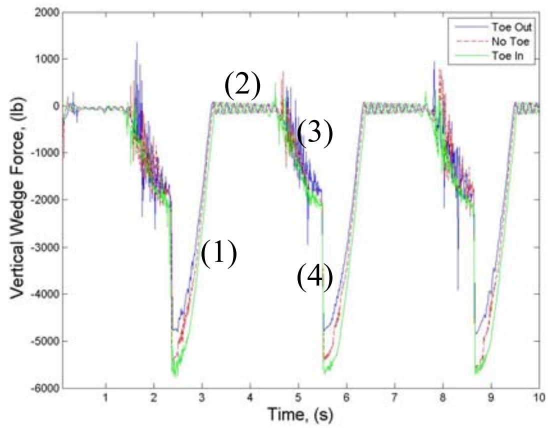
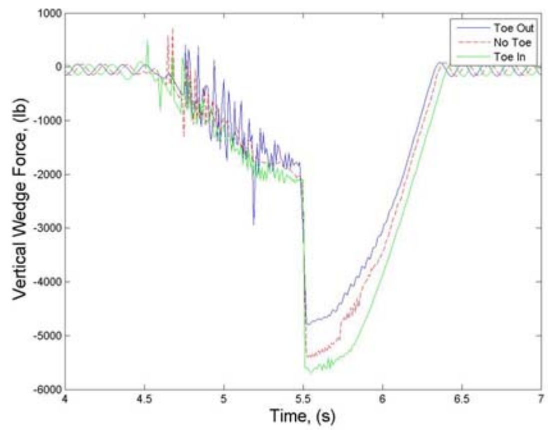


Figure 5-10. Comparison of the Vertical wedge force hysteresis loops for the each type of connection in NUCARS® and the Stand-Alone Model in Toe Out with a Yaw Input.

Figure 5-11 compares the Toe In, Toe Out and Zero Toe versions of the Stand-Alone model for a vertical displacement with a yaw rotation as the input. The differences between the Toe Out, Toe In and Zero Toe versions are large because the geometry of the bolster – wedge –side frame system changes with toe.



(a)



(b)

Figure 5-11. (a) Comparison of the Vertical wedge force for the Stand-Alone Model with Toe In, No Toe and Toe Out with a Yaw Input. (b) Vertical forces for all toe cases from t=4 s to t=7 s.

The sections labeled in Figure 5-11 coincide with the sections labeled in Figure 5-12. Figure 5-12 is a comparison of the vertical wedge forces to the vertical wedge displacement for the toe in, toe out and zero toe cases of the Stand-Alone model due to a yaw input. The first section of the plot represents the wedge moving upwards with the bolster until it reaches lift-off, with the yaw input on the system causing noise. The second section represents the bolster lifting off of the wedge completely causing the wedge to oscillate around zero pounds. The third section represents the wedge slipping against the side frame as the bolster and wedge move downwards. The fourth section of the plot represents the wedge sticking against the side frame causing a large force without any displacement. The wedge then moves upwards with bolster, which is shown in section (1).

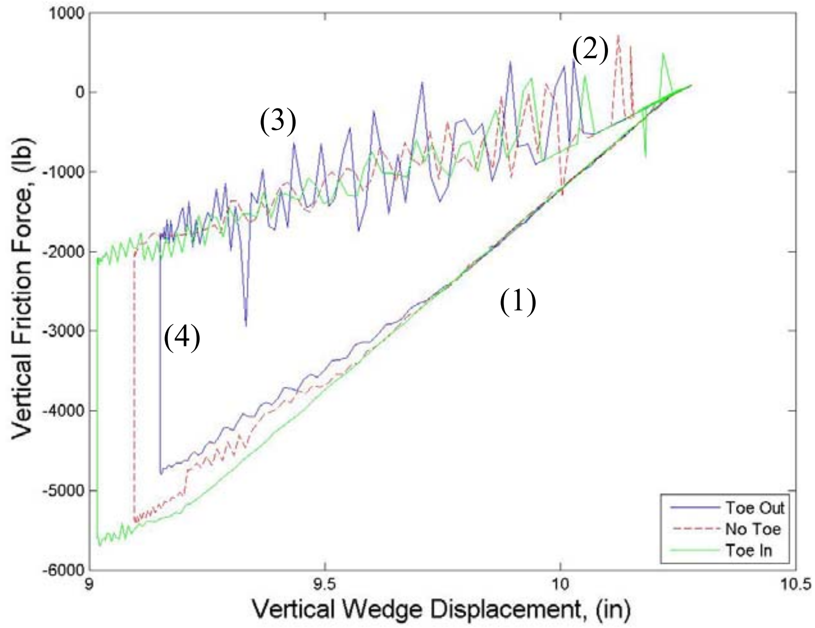
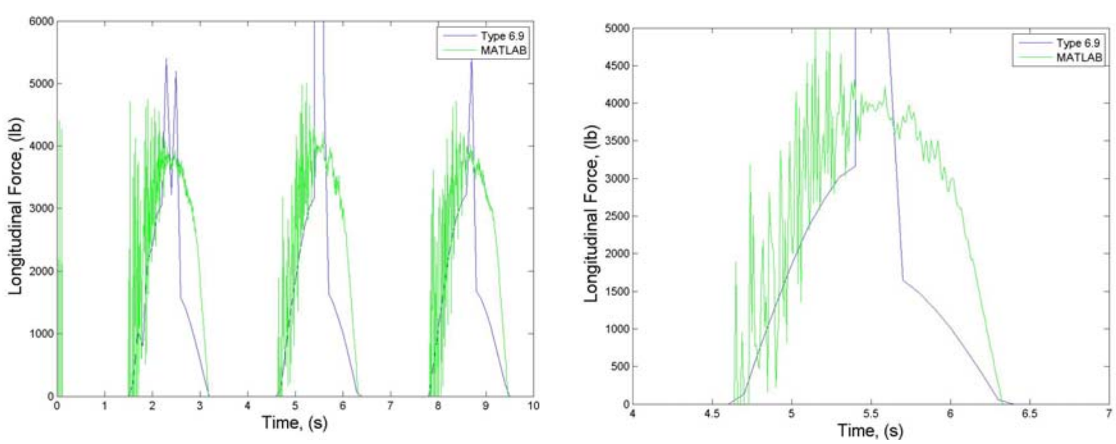


Figure 5-12. Vertical Friction Force Hysteresis loops for all toe cases with a Yaw Input.

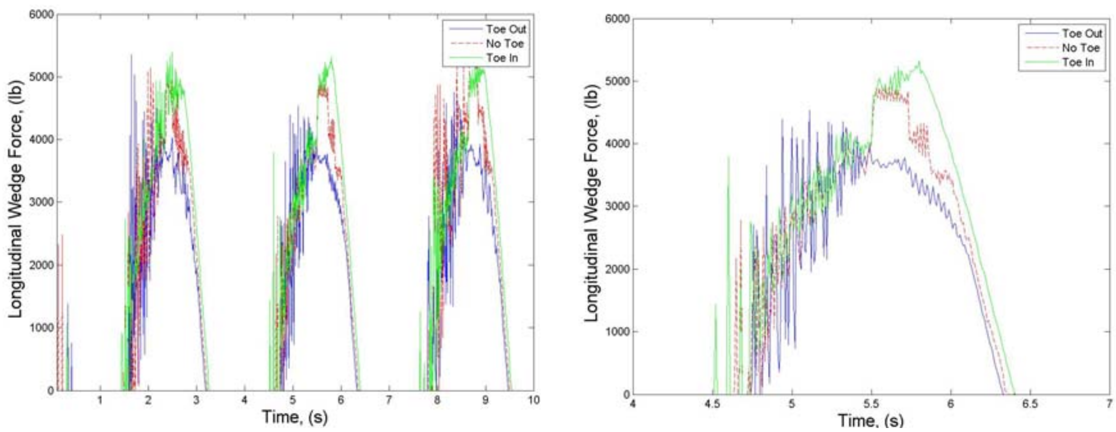
The longitudinal forces on the friction wedge are due to the wedge moving horizontally between the bolster and side frame. Figure 5-13 illustrates these forces and compares the Stand-Alone MATLAB model's to the NUCARS® model with the type 6.9 connection. The forces are lower with the yaw input compared to with the pure vertical displacement because the yaw input prevents the wedge from moving as much between the bolster and side frame.



(a) **(b)**

Figure 5-13. (a) Longitudinal force comparison of the NUCARS® friction wedge model and the Stand-Alone Model for Toe Out with Yaw input. (b) Longitudinal forces from t=4 s to t=7 s.

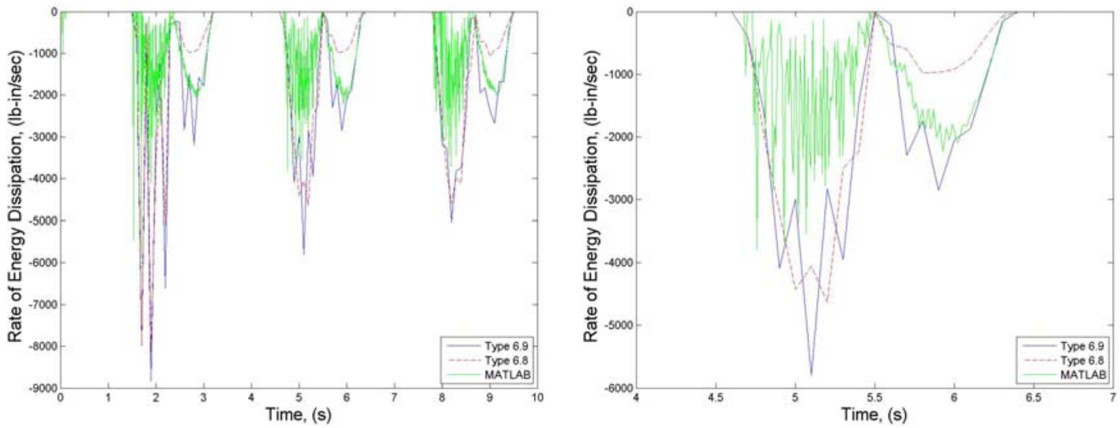
Figure 5-14 compares the longitudinal forces for all toe cases for the Stand-Alone model. The toe in case begins with lower forces than the toe out and zero toe cases because the geometry of the wedge-side frame interface, while in toe in, provides a larger physical constraint on the movement of the wedge while the bolster is lifted-off of the wedge. As with the vertical force, toe in also has the largest longitudinal force while the wedge and bolster are moving downwards.



(a) (b)

Figure 5-14. (a) Comparison of the longitudinal forces of the Stand-Alone Model for Toe In, No Toe and Toe Out with Yaw rotation. (b) Longitudinal forces for all toe cases from t=4 s to t=7 s.

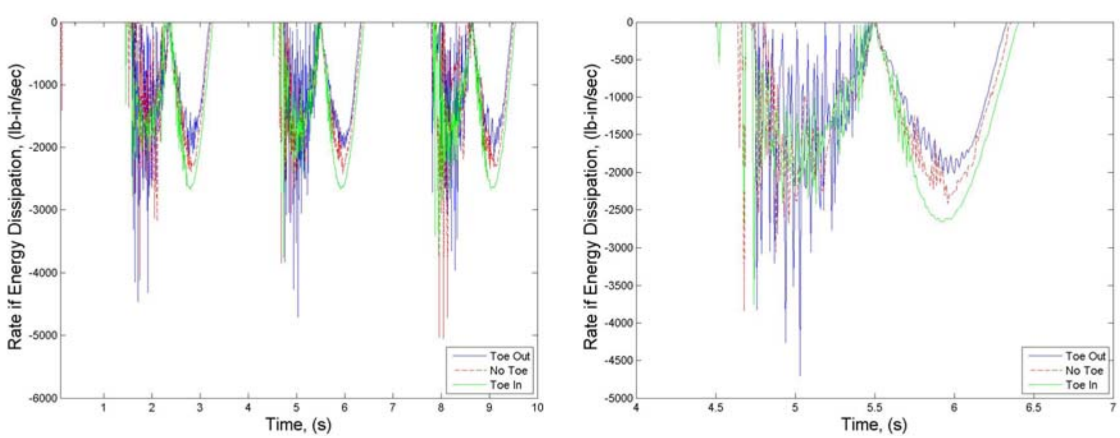
The rate of energy dissipated was calculated in the same way as discussed in the Vertical Displacement section, which used equations 5-4 and 5-5. Equation 5-4 was used to calculate the rate of energy dissipated between the friction wedge and the side frame. Figure 5-15 is a comparison of the rate of energy dissipated for the Stand-Alone MATLAB and NUCARS® models. The Stand-Alone model correlates closely especially to the type 6.9 NUCARS® model and is comparable to the type 6.8 model.



(a) (b)

Figure 5-15. (a) Comparison of the rate of energy dissipation between the side frame and wedge for the NUCARS® friction wedge models and the Stand-Alone Model for Toe Out. (b) Rate of energy dissipated between the side frame and wedge due to friction from t=4 s to t=7 s.

Figure 5-16 is a comparison of the rate of energy dissipated for Toe In, Toe Out and Zero Toe cases for a vertical bolster displacement with yaw input. The rate of energy dissipated for the yaw input is very close in magnitude to that calculated in the previous section because the vertical wedge forces for each were very close in magnitude. The section of the plot from about 1.5 s to 2.5 s, which is after lift-off, represents the MATLAB models ability to capture the stick-slip motion of the wedge as it traverses down the side frame face.



(a) (b)

Figure 5-16. (a) Rate of energy dissipated between the side frame and wedge for the Stand-Alone MATLAB model for all toe cases. (b) Rate of energy dissipation from t=4 s to t=7 s.

The major advantage of the Stand-Alone MATLAB model is its ability to calculate the moments acting on the wedge as well as the forces. The input for this section is also simple so the pitch and yaw moments are small in magnitude. Figures 5-17 illustrates the pitch moment for the toe in, toe out and zero toe cases of the Stand-Alone MATLAB model with a yaw input. Figure 5-18 illustrates the yaw moment for all toe cases of the Stand-Alone model. The pitch and yaw moments were caused by stick-slip motion of the wedge as it traverses the side frame. When the wedge sticks, the resulting forces cause moments to act on the wedge about the vertical and lateral axis. The largest moments are caused when the wedge is moving downwards and decrease as the wedge and bolster return upwards.

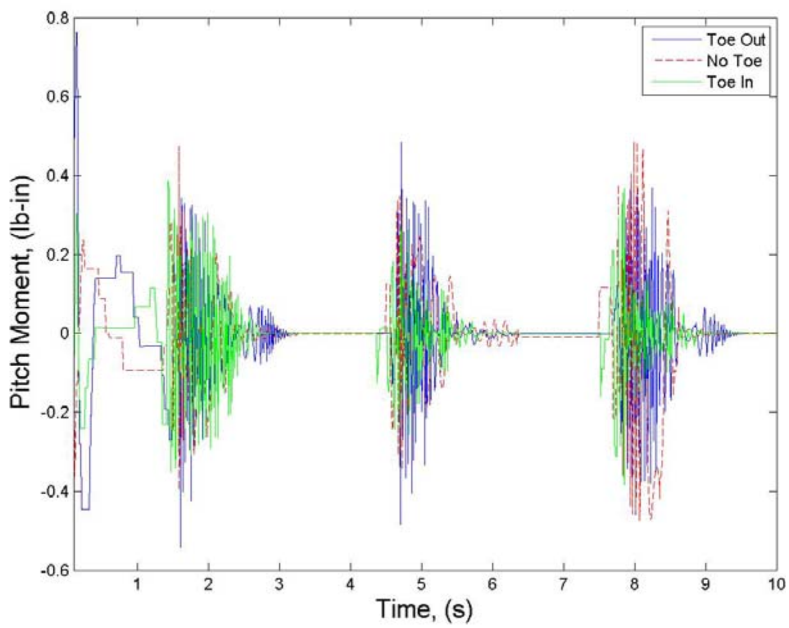


Figure 5-17. Pitch Moment for all toe cases for the Stand-Alone MATLAB Model

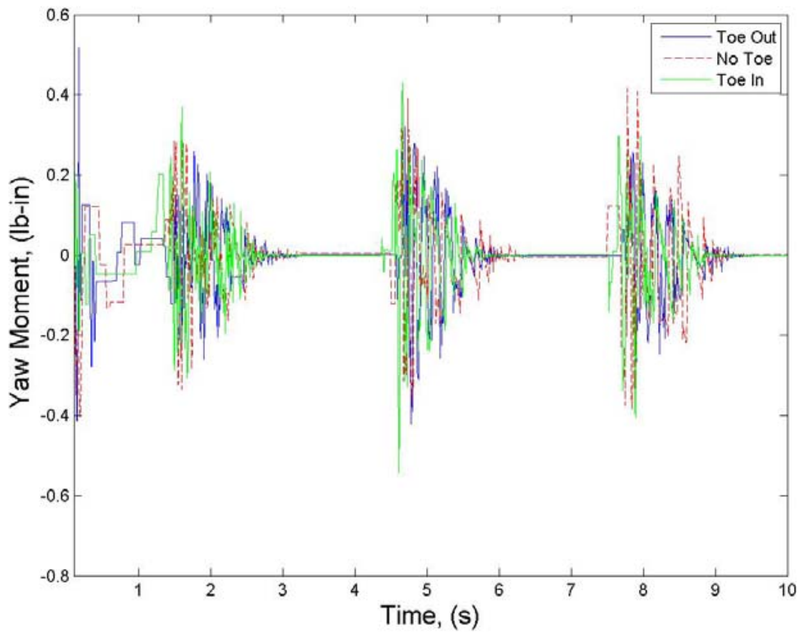


Figure 5-18. Yaw Moment for all toe cases for the Stand-Alone MATLAB Model

6 CONSTANTLY-DAMPED FRICTION WEDGE MODEL RESULTS

In this chapter, the constantly-damped Stand-Alone MATLAB friction wedge model was compared to the type 6.8 and 6.9 constantly-damped models created using NUCARS®. Comparisons were made between the three toe cases of the Stand-Alone model and between the Stand-Alone model and the two NUCARS® models all in toe out. The first section shows the results of the vertical bolster displacement input to the three models. The second section shows the results of the vertical bolster displacement with a yaw input to the three models.

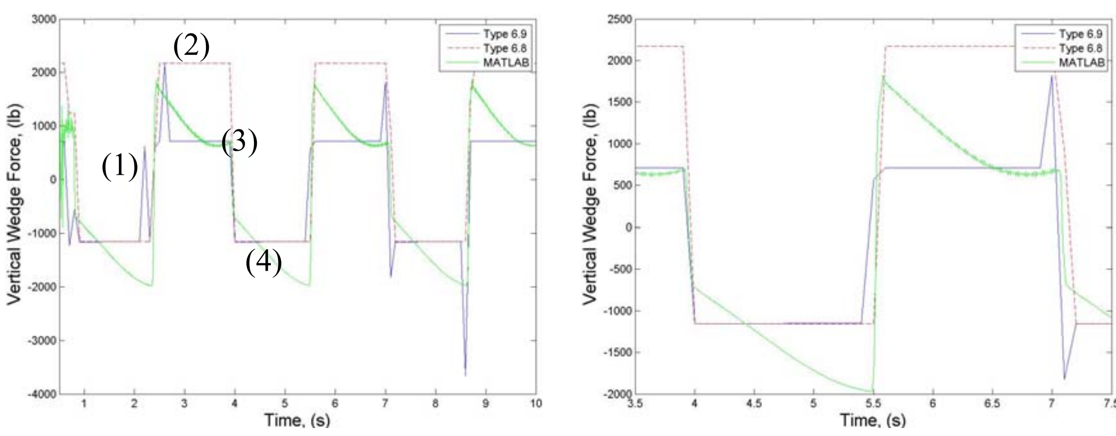
6.1 Vertical Bolster Displacement Input

In order to evaluate the constantly-damped version of the Stand-Alone MATLAB model, the vertical damping forces were compared in the same manner as in the previous section. The damping force in NUCARS® was again calculated using equation 5-1. The main difference is that F_s, the spring force from the control coil, is considered constant. Although the control coil does displace slightly throughout the simulation, the resultant change in force is very small. The wedge angle, θ, also changes as noted in Chapter 2. Because the friction wedge is considered a point of connection between the bolster and the side frame in NUCARS®, the vertical damping force calculated is equivalent to the vertical component of the side frame friction. The MATLAB model has the ability to calculate the forces acting along the unit vectors normal and tangential to the wedge faces, as shown in Figure 3-10. Equation 5-2 was used to calculate the longitudinal forces acting normal to surface A. Equation 5-3 was used to calculate the vertical forces acting tangential to surface A. The main difference in equation 5-3 compared with the variably-damped case is the force due to the control coil, which becomes

$$F_s = K_s(l_0 - \left\| \vec{r}^{\,QB} \right\|)\frac{\vec{r}^{\,QB}}{\left\| \vec{r}^{\,QB} \right\|} \tag{6-1}$$

where l_0 is the undeformed control coil length and $\vec{r}^{\,QB}$ is the vector from the bottom of the control coil, which is located on the bolster, to the bottom of the wedge.

Figure 6-1 compares the vertical wedge force of the two NUCARS® models with the Stand-Alone MATLAB model. The magnitude of the vertical forces for both the NUCARS® models and the Stand-Alone MATLAB model are similar. However, the Stand-Alone friction wedge model seemed to have significantly better capabilities to capture the stick-slip oscillation behavior. When the bolster displaces downwards, labeled sections (3) and (4) in Figure 6-1, the MATLAB model shows how the wedge sticks against the side frame face until it reaches a break out point where it slips and traverses the side frame face. This same motion applies for the case when the bolster is displacing upward, labeled sections (1) and (2) in the figure.



(a) **(b)**

Figure 6-1. (a) Comparison of the Vertical wedge force for each type of connection in NUCARS® and the Stand-Alone Model in Toe Out. (b) Vertical forces for all models from t=4 s to t=7 s.

Figure 6-2 illustrates the movement of the wedge throughout one period of the input by comparing the vertical wedge force to the wedge's vertical displacement. The sections labeled in Figure 6-2 coincide with the sections labeled in Figure 6-1. The wedge and bolster have reached the minimum point in their displacement and begin their motion upward in section (1). The start of this motion causes a large force to occur without any motion due to the static friction between the wedge and side frame, which is also called stick. In section (2) the bolster and wedge displace upward because the break out force has been exceeded so the wedge slips against the side frame allowing for motion. Section (3) is the static friction force due to the bolster beginning its downward movement. Section (4) shows the wedge displacing after the break out force has been reached and the wedge begins slipping.

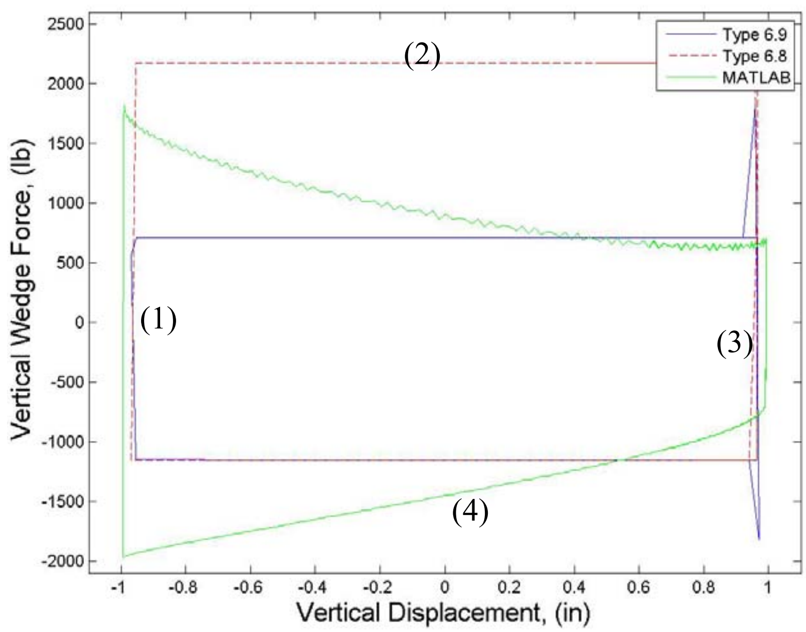
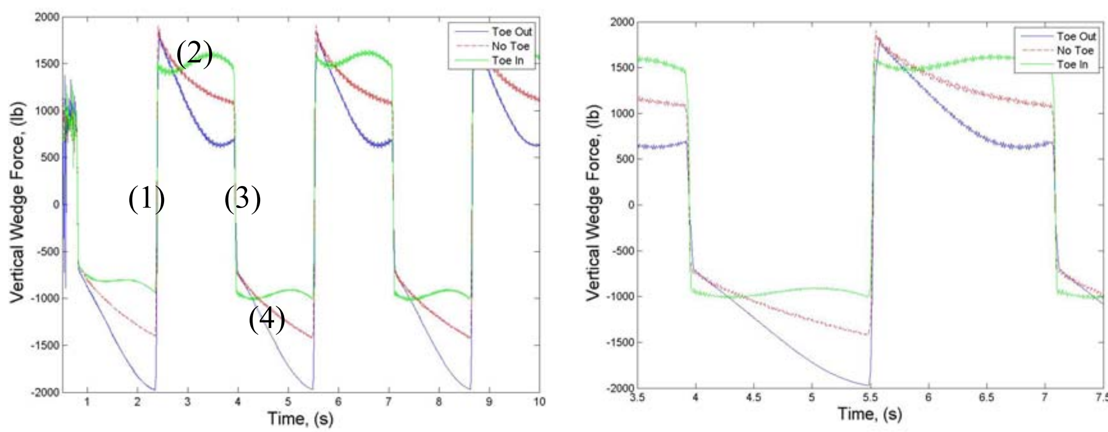


Figure 6-2. Comparison of the Vertical wedge force hysteresis loops for types 6.8 and 6.9 in NUCARS® and the Stand-Alone Model in Toe Out.

Figure 6-3 compares the Toe In, Toe Out and Zero Toe versions of the Stand-Alone model. Since the toe angles used are very small, the differences between the magnitudes of the vertical force at the start of the upward motion of the bolster and wedge, which is the connection point between sections (1) and (2), for all toe cases is small with the toe out case having larger forces then the toe in case. Refering back to Figure 1-2, the geometry of the friction wedge - side frame system changes with the toe input, which causes the difference in forces. For the downward motion of the wedge and bolster, which is represented in sections (3) and (4), the Toe In forces are the largest. The differences in magnitudes given the different toe cases show how the Stand-Alone MATLAB model captures the motion of the friction wedge.



(a) **(b)**

Figure 6-3. (a) Comparison of the Vertical wedge force for three versions of the Stand-Alone Model with Toe In, No Toe, and Toe Out. (b) Vertical forces for all toe cases from t=4 s to t=7 s.

The sections labeled (1) and (2) in Figures 6-3 and 6-4 represent the upward movement of the bolster and wedge beginning from the minimum bolster displacement. As illustrated in Figure 6-4, the forces for the toe in case during the upward movement of the bolster are the least, but this case allows for the most wedge displacement. The forces are the greatest for the toe out case while the least wedge vertical displacement is allowed. This is due to the interaction of the wedge and side frame in toe out. During the downward movement of the bolster and wedge, the forces for the toe in case are largest while the vertical displacement of the wedge is the least because of the resistance caused by the geometry of the side frame and wedge. The opposite is true for the toe out case.

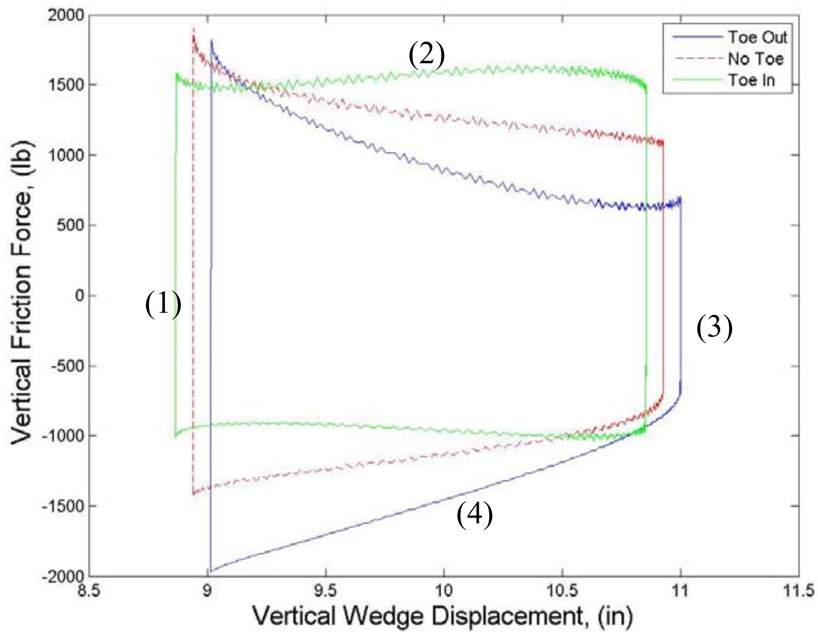


Figure 6-4. Vertical Friction Force Hysteresis loops for all toe cases.

Figure 6-5 illustrates the constantly-damped Stand-Alone MATLAB model's ability to calculate the longitudinal forces acting on the wedge. The magnitudes of the forces for the Stand-Alone model are similar to those forces calculated with the NUCARS® type 6.9 wedge model. As mentioned in Chapter 5, the NUCARS® type 6.8 wedge model does not have the capabilities to calculate longitudinal forces. The longitudinal forces represent the wedge ringing between the bolster and side frame. The forces remain relatively periodic which is expected given the periodic input.

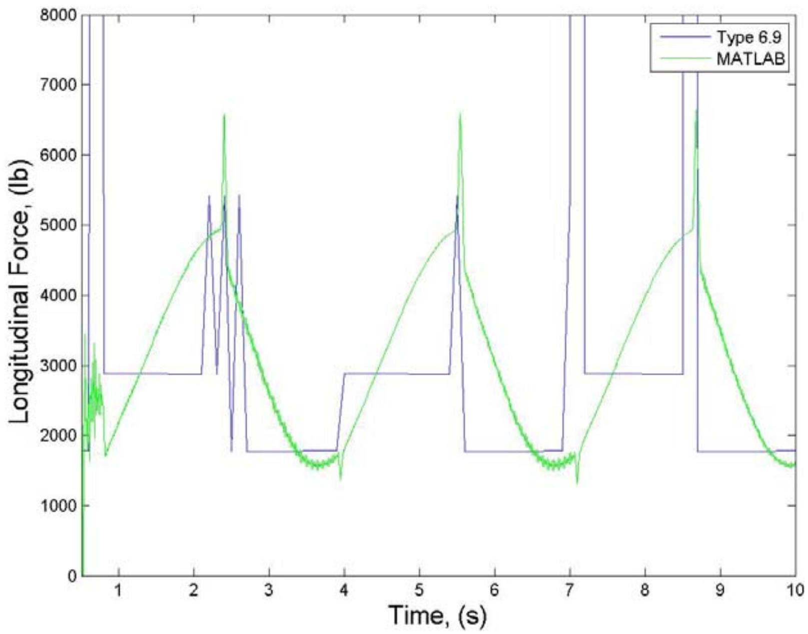
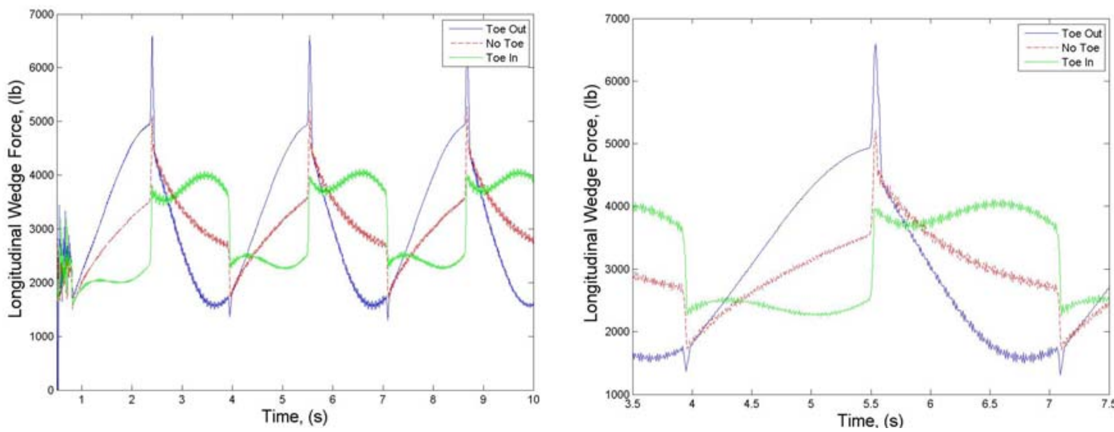


Figure 6-5. Comparison of the longitudinal forces of the Type 6.9 NUCARS® friction wedge model and the Stand-Alone Model for Toe Out.

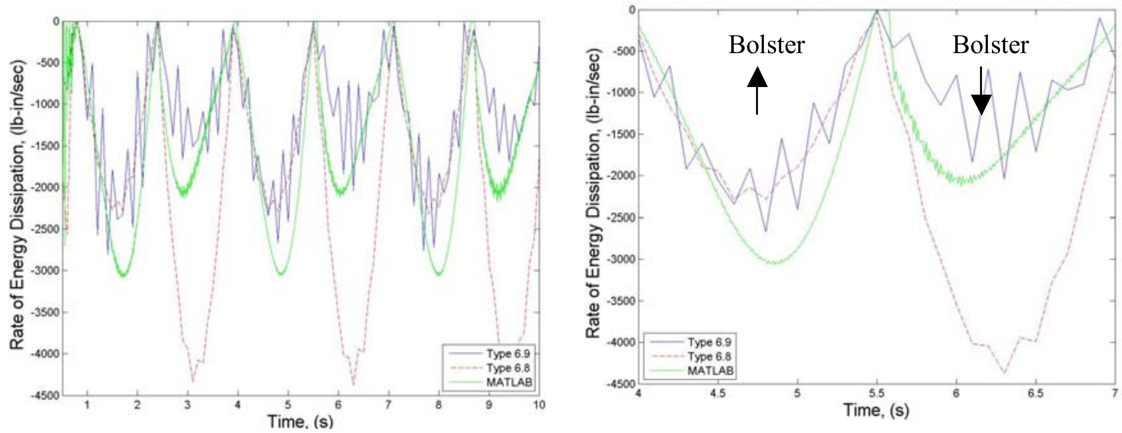
Figure 6-6 compares the longitudinal forces for all toe cases for the constantly-damped Stand-Alone model. The toe out case has its maximum forces when the bolster reaches its minimum vertical displacement. The toe out case has the largest peaks because the distance from the wedge to the bottom of the side frame is greatest at this point in the motion so the wedge has a longer distance to move before colliding with the side frame, which causes the forces. The largest forces for the toe in case occur during the upward motion of the bolster because the distance between the top of the side frame and the wedge is greatest at that point in the motion. The longitudinal forces for the zero toe case fall in between the toe in and toe out cases which is to be expected.



(a) **(b)**

Figure 6-6. (a) Comparison of the longitudinal forces for the Stand-Alone Model for Toe In, No Toe, and Toe Out. (b) Longitudinal forces for all toe cases from t=4 s to t=7 s.

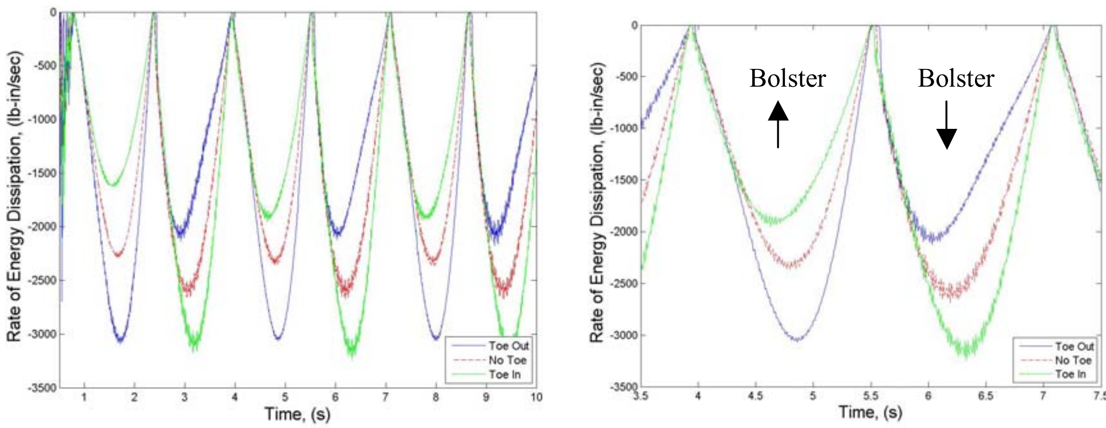
The rate of energy dissipated is calculated by taking the dot product of the force between the contacting points and their relative velocities to the contacting surface. Equation 5-4 was used to calculate the rate of energy dissipated between the friction wedge and side frame. Figure 6-7 compares the rate of energy dissipated between the friction wedge and side frame for the type 6.8 and 6.9 NUCARS® models with the MATLAB model. The energy dissipated between the side frame and wedge from the friction is calculated for the toe out scenario for all of the models. For the constantly-damped friction wedge models, the rate of energy dissipated is only zero when the wedge is sticking because there is never lift-off using this wedge model.



(a) **(b)**

Figure 6-7. (a) Comparison of the rate of energy dissipation between the side frame and wedge for the NUCARS® friction wedge model and the Stand-Alone Model for Toe Out. (b) Energy dissipation for all models from t=4 s to t=7 s.

Figure 6-8 is a comparison of the rate of energy dissipated for toe in, toe out and zero toe cases for a vertical bolster displacement input. During the upward movement of the bolster, the rate of energy dissipated is greatest for the toed-out case because of the increase in forces that acts on the wedge due to the side frame at this stage in the motion. The toe in case has the least dissipation because the forces acting on the wedge are smallest. The motion of the wedge is conserved, which causes the rate of energy dissipation to be zero at the peaks of the input. During the downward movement of the bolster, the largest forces are acting on the wedge in the toe in case so its rate of dissipation is largest. As expected, the zero toe case falls between the toe in and toe out cases.



(a) **(b)**

Figure 6-8. (a) The energy dissipated between the side frame and wedge for the Stand-Alone MATLAB model for all toe cases. (b) Energy dissipation for all toe cases from t=4 s to t=7 s.

The major advantage of the MATLAB model is its ability to calculate the moments acting on the friction wedge. Due to the simplicity of the input, which was a vertical displacement of the bolster, the yaw moment calculated was negligible. For more complicated inputs, the MATLAB model would be able to calculate yaw moments that would act on the bolster and side frames due to the wedge. The pitch moment calculated is larger because of the stick-slip motion of the wedge while moving up and down the face of the side frame. The stick-slip motion of the wedge causes an uneven distribution of forces on the wedge column face from the side frame, which causes the wedge to pitch. Figure 6-9 illustrates the pitch moment for the Stand-Alone model for toe in, toe out, and zero toe given a vertical bolster displacement input.

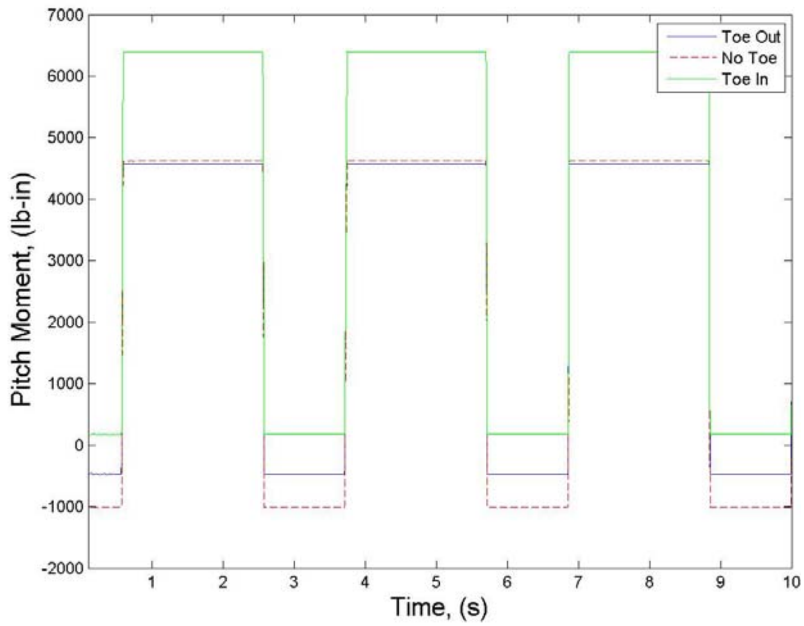
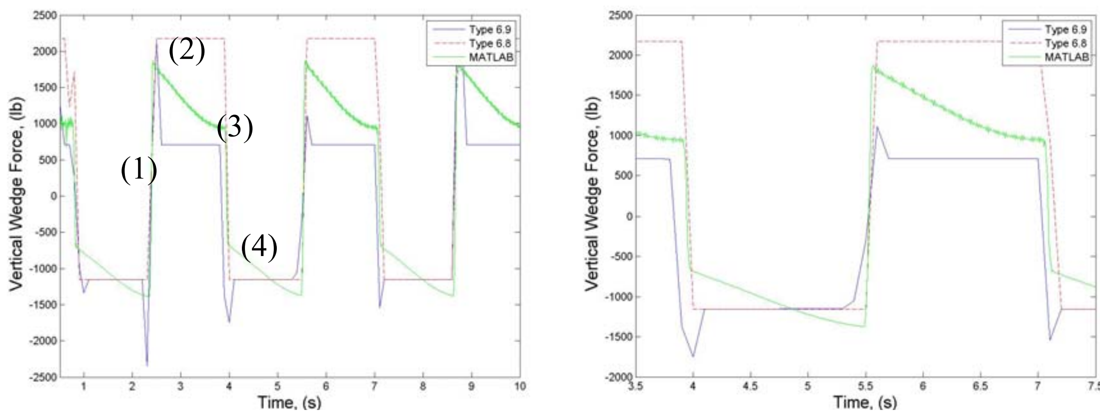


Figure 06-9. Pitch Moment for all toe cases for the constantly-damped Stand-Alone MATLAB Model for a vertical bolster displacement input

6.2 Vertical Bolster Displacement with Yaw Input

The vertical damping forces for the type 6.8 and 6.9 NUCARS® models and the Stand-Alone model were calculated in the same manner as in the vertical displacement section, using equations 5-1, 5-2 and 5-3. The results are different due to the constant yaw angle that was input to the system through the bolster. The bolster was yawed 0.012 radians, shown previously in Figure 4-2, and held constant there while the same vertical displacement was input.

Figure 6-10 compares the vertical wedge force of the two NUCARS® models with the Stand-Alone MATLAB model all in toe out. The magnitude of the vertical forces for both the NUCARS® models and the Stand-Alone MATLAB model are similar. However, as in the previous section, the constantly-damped Stand-Alone model seemed to have significantly better capabilities to capture the stick-slip oscillation behavior. When the bolster displaced downwards, labeled sections (3) and (4) in the figure, the MATLAB model shows how the wedge sticks against the side frame face until it reaches a break out point where it slips and traverses the side frame face. This same motion applies for when the bolster is displacing upward, labeled sections (1) and (2) in the figure.



(a) **(b)**

Figure 6-10. (a) Comparison of the Vertical wedge force for each type of connection in NUCARS® and the Stand-Alone Model in Toe Out. (b) Vertical forces for all models from t=4 s to t=7 s.

Figure 6-11 illustrates the movement of the wedge throughout one period of the input by comparing the vertical wedge force to the wedge's vertical displacement due to the yaw input. The sections labeled in Figure 6-11 coincide with the sections labeled in Figure 6-10. In Section (1), the wedge and bolster have reached the minimum point in their displacement and begin their motion upward. The start of this motion causes a large force to occur without any movement of the wedge due to the static friction between the wedge and side frame, which is also called stick. In Section (2) the bolster and wedge displace upward because the break-out force has been exceeded so the wedge slips against the side frame allowing for motion of the wedge. Section (3) is the static friction force due to the bolster beginning its downward movement. Section (4) shows the wedge displacing after the break out force has been reached and the wedge begins slipping.

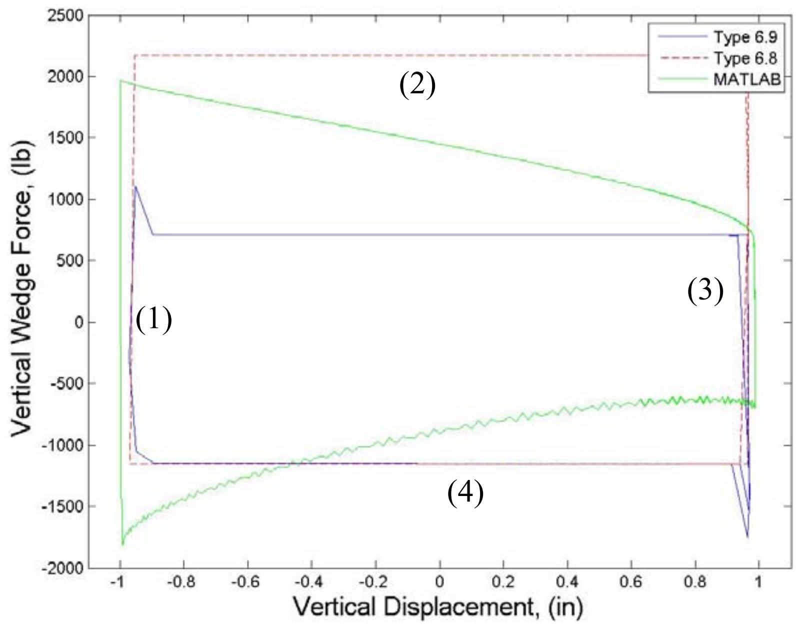
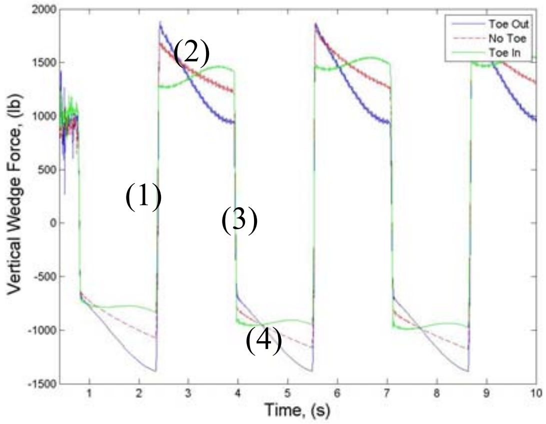
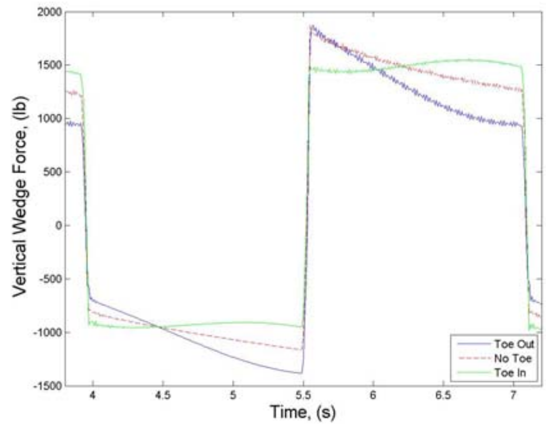


Figure 6-11. Comparison of the Vertical wedge force hysteresis loops for types 6.8 and 6.9 in NUCARS® and the Stand-Alone Model in Toe Out.

Figure 6-12 compares the toe in, toe out and zero toe versions of the Stand-Alone model. Since the toe angles used are very small, the differences between the magnitudes of the vertical force at the start of the upward motion of the bolster and wedge, which is shown in the figure as the connection point between sections (1) and (2), for all toe cases is small. The toe out case has larger break-out forces than the toe in case for this part of the motion because of the resistance caused by the geometry of the side frame in toe out. The toe in case has the largest break-out force for the downward motion of the wedge and bolster because of the physical constraint caused by the toed in side frame. The differences in magnitudes given the different toe cases show how the Stand-Alone MATLAB model captures the actual motion of the wedge accurately.



(a)



(b)

Figure 6-12. (a) Comparison of the Vertical wedge force for each type of connection in NUCARS® and the Stand-Alone Model in Toe Out. (b) Vertical forces for all models from t=4 s to t=7 s.

Figure 6-13 is a comparison of the vertical wedge forces to the vertical wedge displacement for the constantly-damped Stand-Alone model with a yaw input for all toe cases. The sections labeled in this figure coincide with those labeled in Figure 6-12. During the upward motion of the wedge and bolster, the forces for the toe in case are smallest, but allow for the largest wedge displacement. The forces are largest for the toe out case, which has the least wedge displacement because of the side frame geometry for a given toe. During the downward movement of the wedge, shown in sections (3) and (4), the toe in case has the largest forces with the smallest wedge displacement because of the resistance caused by the side frame while in toe in. The opposite is true for the toe out case. The zero toe case falls between toe in and toe out.

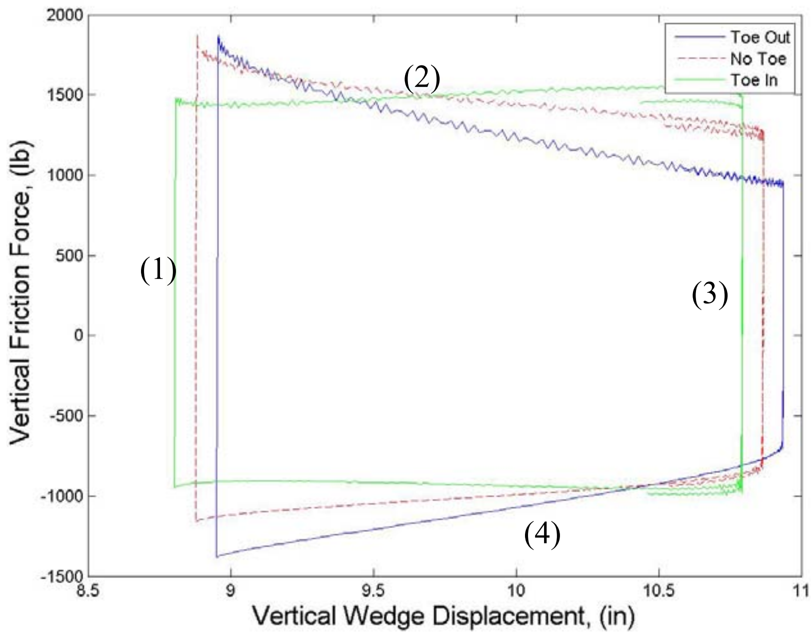


Figure 6-13. Comparison of the Vertical wedge force hysteresis loops for all toe cases of the Stand-Alone Model.

The longitudinal forces calculated for the Stand-Alone model were of the same magnitude as those calculated in the NUCARS® type 6.9 model for both simulation inputs. Figure 6-14 is a comparison of the Stand-Alone model's longitudinal forces for both the vertical displacement and the yaw inputs. The forces resulting from the yaw input were less than those resulting from the vertical displacement input for the bolster moving down because the yaw prevented some of the longitudinal motion that the wedge saw during the vertical input. When the bolster was moving upward, the longitudinal forces acting on the wedge were greater for the yaw input because the motion was more difficult. For the vertical displacement, this same motion was much easier so the forces were lower.

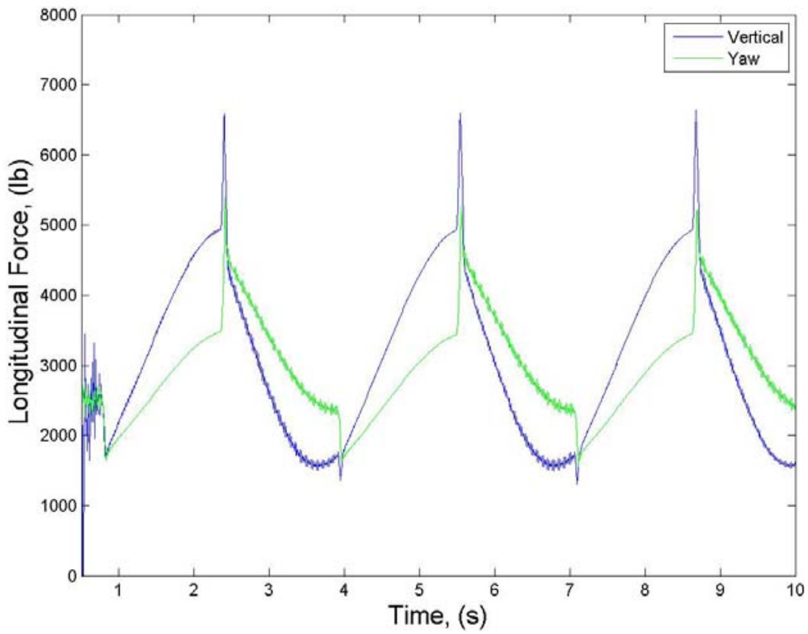
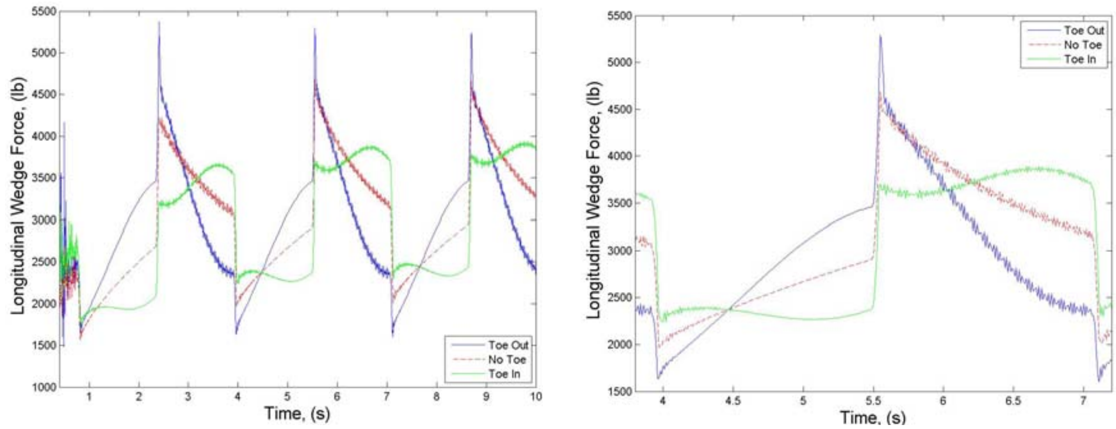


Figure 6-14. Longitudinal force comparison for both simulation inputs for the constantly-damped Stand-Alone Model in Toe Out.

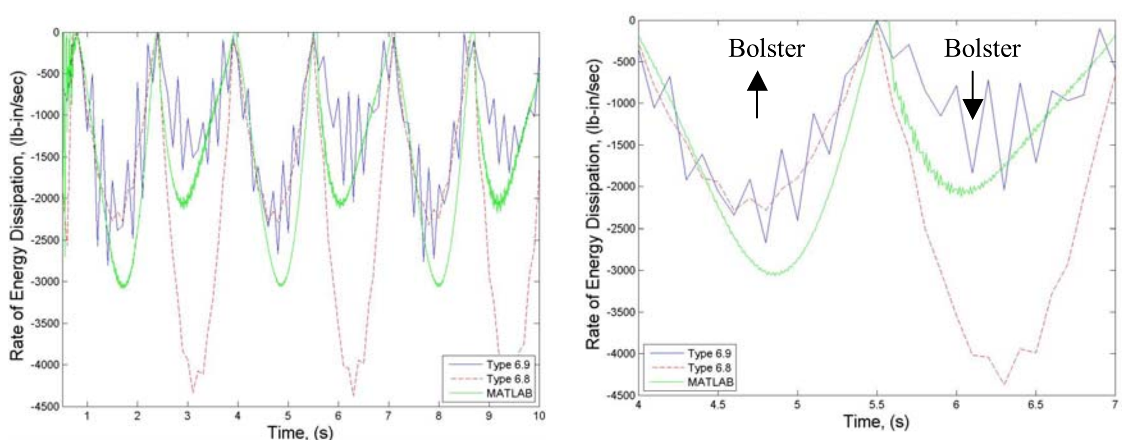
Figure 6-15 compares the longitudinal forces for all toe cases for the Stand-Alone model given a yaw input. The toe out case has the largest forces when the bolster reaches its minimum vertical displacement because the distance from the wedge to the bottom of the side frame is greatest at this point in the motion. This allows the wedge to move a longer distance before colliding with the side frame, which causes greater forces than the other cases. The largest forces for the toe in case occur during the upward motion of the bolster because the distance between the top of the side frame and the wedge is greatest. The longitudinal forces for the zero toe case fall in between the toe in and toe out cases which is to be expected.



(a) **(b)**

Figure 6-15. (a) Comparison of the longitudinal forces for the Stand-Alone Model for Toe In, No Toe, and Toe Out. (b) Longitudinal forces for all toe cases from t=4 s to t=7 s.

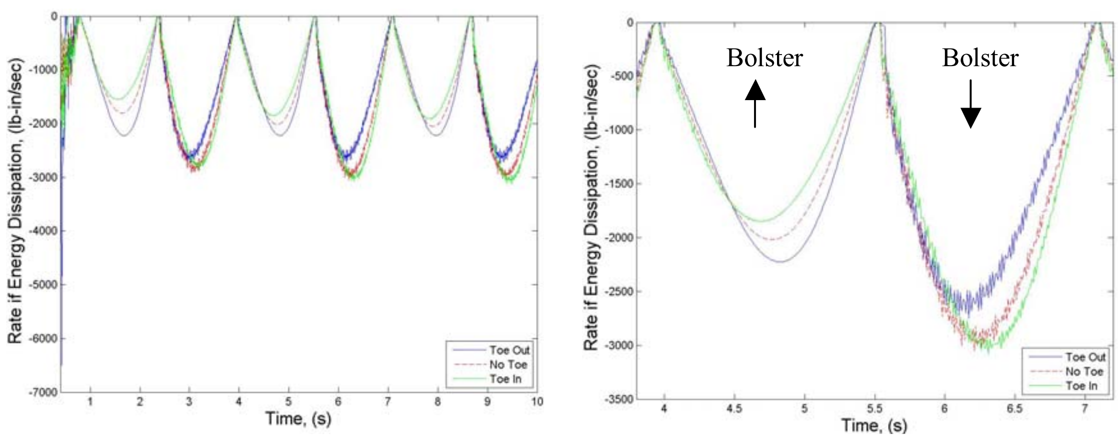
The rate of energy dissipated is calculated by taking the dot product of the force between the contacting points and their relative velocities to the surface in contact. Equations 5-4 from the previous chapter was used to calculate the rate of energy dissipated between the friction wedge and side frame. Figure 6-16 compares the rate of energy dissipated for both of the NUCARS® models with the MATLAB model for the toe out scenario. For the constantly-damped friction wedge models, the rate of energy dissipated is only zero when the wedge is sticking.



(a) **(b)**

Figure 6-16. (a) Comparison of the rate of energy dissipation between the side frame and wedge for the NUCARS® friction wedge model and the Stand-Alone Model for Toe Out. (b) Energy dissipation for all models from t=4 s to t=7 s.

Figure 6-17 is a comparison of the rate of energy dissipated for the toe in, toe out and zero toe cases for a vertical bolster displacement with yaw input. The rate of energy dissipated is more for the toed-out case while the motion of the wedge is upwards because of the larger contact surface and the increased forces that act on the wedge. For the toe in case, the rate of energy dissipated is the smallest then because of the reduced forces that act on the wedge. The opposite is true when the wedge is moving downwards because the toed in case has the larger forces than the toed out case. As expected, the zero toe case falls between the toe in and toe out cases.



(a) **(b)**

Figure 6-17. (a) The energy dissipated between the side frame and wedge for the Stand-Alone MATLAB model for all toe cases. (b) Energy dissipation for all toe cases from t=4 s to t=7 s.

The Stand-Alone MATLAB model has the ability to calculate the moments acting on the friction wedge as well as the forces. The input for this system was simple, but the moments resulting from the motion were significant. Figure 6-18 illustrates the pitch moment for the toe in, toe out, and zero toe cases for the constantly-damped Stand-Alone MATLAB model. Figure 6-19 illustrates the yaw moment for the toe in, toe out, and zero toe cases for the MATLAB model. The moments were the result of the wedge sticking during its movement. The stick-slip motion of the wedge caused uneven distribution of the forces acting on the wedge, which caused the moments.

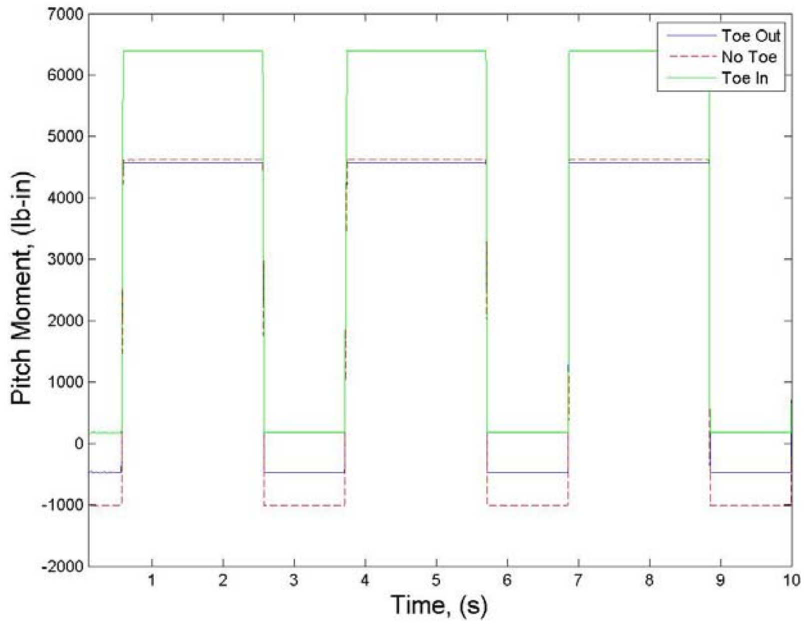


Figure 6-18. Pitch Moment for all toe cases for the Stand-Alone MATLAB Model.

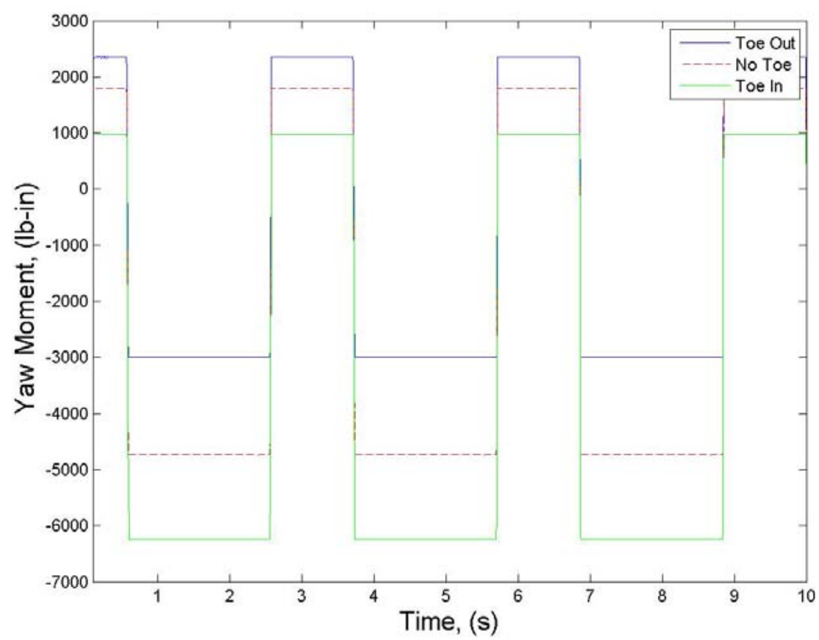


Figure 6-19. Yaw Moment for all toe cases for the Stand-Alone MATLAB Model.

7 CONCLUSIONS AND FUTURE WORK

This chapter will discuss the conclusions drawn from the simulations run using both the variably-damped and constantly-damped Stand-Alone MATLAB friction wedge models. The future work planned for this project is also discussed.

7.1 Conclusions

This study developed a Stand-Alone bolster-friction wedge-side frame interaction model, formulated within the multibody dynamics framework. The development of this model provides the opportunity to improve the overall bogie behavior, especially when dealing with critical situations such as wedge lock-up and train derailments caused by the resultant wheel lift-off. Figure 7-1 shows a screen shot of the Stand-Alone model during a simulation.

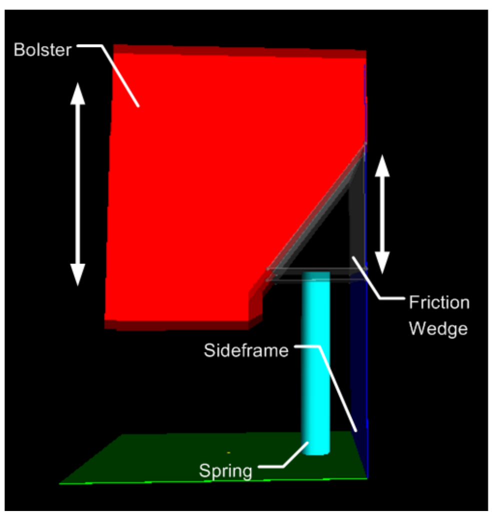


Figure 7-1. A snapshot of the Stand-Alone MATLAB model during simulation.

The Stand-Alone model presented in this paper includes the two directions of translational motion, vertical and longitudinal, as well as the pitch and yaw moments. The model also includes the inertial properties of the wedge, which were ignored in previous models. Specific angles of toe in and toe out are also able to input into the system. The inclusion of the inertial and geometric parameters allows for the design of future wedges to be modeled and tested using simulation software instead of creating and testing a physical model.

For lack of actual experimental data, the Stand-Alone MATLAB model was evaluated against the proven models used in NUCARS®. Two types of friction wedge models were evaluated against the NUCARS® software: a constantly-damped model and a variably-damped model. The results of these comparisons show that the longitudinal and vertical wedge forces correlate closely. Following the comparisons made with the NUCARS® models for this project, the type 6.9 NUCARS® wedge model was updated. In a general comparison, the updated model produced results that were very similar to the Stand-Alone model especially with the longitudinal forces. The lateral forces for the inputs being analyzed are zero for all of the models. The yaw and pitch moments cannot be validated as of yet, but they are able to be calculated which is a large improvement over previous models.

The rate of energy dissipation due to the friction was similar in magnitude and shape in both the Stand-Alone model and the NUCARS® models. Toe in, toe out and a zero toe model were compared for both the variably and constantly-damped Stand-Alone models. The results help to prove that the variably-damped Stand-Alone MATLAB model is accurate because during lift-off, which is when the bolster lifts–off from the wedge, the rate of energy dissipated is zero and therefore conserved. Also, the rate of energy dissipated during the toe in model is greater than the toe out model. This is the result of a larger surface area being in contact during the toe in model. In the constantly-damped model, the energy is conserved as well.

The force and rate of energy dissipation plots demonstrate that the Stand-Alone MATLAB model has the ability to capture the stick-slip dynamics of the friction wedge. The friction between the friction wedge and the side frame and the bolster and the friction wedge cause the wedge to "stick" to either body, causing large forces without motion, and "slip", in which the wedge slides against either body. The stick-slip motion was seen best in the hysteresis plots, where the largest forces were the result of the wedge sticking to the side frame.

7.2 Future Work

In the future, the friction wedge model will continue to be improved upon to better capture the bolster-wedge-side frame dynamic interaction. The current Stand-Alone model does not have the curved sloped wedge surface, which actual friction wedges have. This would not affect the motion for simple inputs, but in the future, for more complicated inputs, the sloped surface would help the model be more accurate. In addition, validating the friction wedge behavior in the presented model against experimental data is very important. A more in depth analysis of the energy dissipated by the friction wedge should also be performed. Finally, the dynamics of the friction wedge should be analyzed under extreme loading conditions.

The Stand-Alone model will also be expanded in order to create a full truck model. The full truck model will have all four friction wedges, two side frames and a bolster. The full truck model will allow for more complicated inputs to be applied to the system. These inputs can include track irregularities, track curvature, and any other track input. This model will also help in validating the current friction wedge model because tests to obtain validation data for an entire truck are easier to perform.

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APPENDIX A: VARIABLY-DAMPED NUCARS® FILES

This section includes the NUCARS® files required to run the simulations for the variably-damped comparison model. The system file houses the body and connection information, as well as the characteristics of those connections. The input files were used to input the vertical bolster displacement and yaw inputs. The data files tell which variables would be output for each simulation. The run files collect the files to be used in the simulation and read them using the Integration Engine in NUCARS®.

A.1 Type 6.8 Friction Wedge Model

A.1.1. System Files

Type 6.8 system file entitled 'Bolst_wedge_sf_68_variable.sys':

```
System file (.SYS) for NUCARS Version 2004
=========================================

\SYSTEM TITLE
Bolster & Half Loaded 100T Hopper Carbody combo-Wedge-Side Frame-Ground Connections


Details of Model:
1 - Single Truck being modeled so only half car body req
2 - Constrain Car body to lateral trans, vert transl & roll
3 - Side Frames connected to rail (Ground)
4 - Displacement input at Bolster
5 - Type 6.8 wedge connection

Give the number of bodies, then for each, list the number, name, up to 15
characters in single quotes, and c.g. position, relative to a chosen datum,
followed by the number and list of degrees of freedom required (from 1=x,
2=y, 3=z, 4=phi, 5=theta, 6=psi, 7=epsx, 8=epsy, 9=epsz), and the mass and
inertias in roll, pitch, and yaw.  The degrees of freedom required for each
axle are 2, 3, 4, and 6.  A longitudinal degree of freedom, 1, is optional.

 Body #  ' 15 Char Name  '         C.G. Posn in X, Y, & Z
              No. & DoF List          Mass, Roll, Pitch, & Yaw Inertia
-----------------------------------------------------------------------
\BODY DATA
  3
! Half of the car weight is used, also centered on Bolster
    1   ' Half Car+Bolst'        -35.0      0.0      83.0
          6   1  2  3  4  5  6    319.175    0.92276E06   0.8350204E07   0.835276E07
```

```
    3  ' Lft Sframe    '          -35.0     39.5     18.0
      6  1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03
    4  ' Rgt Sframe    '          -35.0     -39.5     18.0
      6  1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03

Body #  ' 15 Char Name  '   Posn in X, Y, & Z   No.   DoF List      Input      Lag
---------------------------------------------------------------------------------
\INPUT BODY DATA
  3
    7  'Lft Input disp '  -35.0   39.5   18.0   5   1 2 3 4 5     1 2 3 4 5    .F.
    8  'Cntr Input disp'  -35.0   0.0    18.0   6   1 2 3 4 5 6   1 2 3 4 5 6  .F.
    9  'Rgt Input disp '  -35.0  -39.5   18.0   5   1 2 3 4 5     1 2 3 4 5    .F.

\CONNECTION DATA
 50
! Long.,Pitch, and Yaw bolster to side frame connections
  117   'Ld L Bol-SF LPY'   1.1   1  3 -35.0  39.5 18.0  3  1 5 6  8 9 10
  118   'Ld R Bol-SF LPY'   1.1   1  4 -35.0 -39.5 18.0  3  1 5 6  8 9 10
! Vertical bolster to side frame connections
! split into 4 seperate springs at each nest, dropped down 5"
  119   'Ld L Bol-SF V 1'   1.3   1  3 -31.25  35.75 13.0  3  2 3 4  11 12 13
  120   'Ld R Bol-SF V 1'   1.3   1  4 -31.25 -35.75 13.0  3  2 3 4  11 12 13
  121   'Ld L Bol-SF V 2'   1.3   1  3 -31.25  43.25 13.0  3  2 3 4  11 12 13
  122   'Ld R Bol-SF V 2'   1.3   1  4 -31.25 -43.25 13.0  3  2 3 4  11 12 13
  123   'Ld L Bol-SF V 3'   1.3   1  3 -38.75  35.75 13.0  3  2 3 4  11 12 13
  124   'Ld R Bol-SF V 3'   1.3   1  4 -38.75 -35.75 13.0  3  2 3 4  11 12 13
  125   'Ld L Bol-SF V 4'   1.3   1  3 -38.75  43.25 13.0  3  2 3 4  11 12 13
  126   'Ld R Bol-SF V 4'   1.3   1  4 -38.75 -43.25 13.0  3  2 3 4  11 12 13
! 2D Stick-Slip Friction wedge connection between bolster and side frame
  127   'Ld Bol-SF LL Wg'   6.8   1   3   -26.5    39.5    18.0   3 2  14
  128   'Ld Bol-SF LR Wg'   6.8   1   4   -26.5   -39.5    18.0   3 2  14
  129   'Ld Bol-SF TL Wg'   6.8   1   3   -43.5    39.5    18.0   3 2  14
  130   'Ld Bol-SF TR Wg'   6.8   1   4   -43.5   -39.5    18.0   3 2  14
! Vertical surface friction element for side frame to ground
! connections elements are placed +/- 3.0 inches apart to react roll, and
! pitch of the side frame
  131   'SdFm-Grd 1 LVL '   6.5   3   0     0.0    42.5    22.5   3 1 2  15
  132   'SdFm-Grd 1 LVR '   6.5   3   0     0.0    36.5    22.5   3 1 2  15
  133   'SdFm-Grd 1 RVR '   6.5   4   0     0.0   -42.5    22.5   3 1 2  15
  134   'SdFm-Grd 1 RVL '   6.5   4   0     0.0   -36.5    22.5   3 1 2  15
  135   'SdFm-Grd 2 LVL '   6.5   3   0   -70.0    42.5    22.5   3 1 2  15
  136   'SdFm-Grd 2 LVR '   6.5   3   0   -70.0    36.5    22.5   3 1 2  15
  137   'SdFm-Grd 2 RVR '   6.5   4   0   -70.0   -42.5    22.5   3 1 2  15
  138   'SdFm-Grd 2 RVL '   6.5   4   0   -70.0   -36.5    22.5   3 1 2  15
! Vertical dampers for surface friction elements
  139   'SdFm-Grd 1 LVL '   1.2   3   0     0.0    42.5    22.5   3  16
  140   'SdFm-Grd 1 LVR '   1.2   3   0     0.0    36.5    22.5   3  16
  141   'SdFm-Grd 1 RVR '   1.2   4   0     0.0   -42.5    22.5   3  16
  142   'SdFm-Grd 1 RVL '   1.2   4   0     0.0   -36.5    22.5   3  16
  143   'SdFm-Grd 2 LVL '   1.2   3   0   -70.0    42.5    22.5   3  16
  144   'SdFm-Grd 2 LVR '   1.2   3   0   -70.0    36.5    22.5   3  16
  145   'SdFm-Grd 2 RVR '   1.2   4   0   -70.0   -42.5    22.5   3  16
  146   'SdFm-Grd 2 RVL '   1.2   4   0   -70.0   -36.5    22.5   3  16
! Side frame to ground lateral and yaw Stops
  147  'SdFm-Grd 1 LVL '   1.1   3   0    0.0   39.5 22.5  2  2 6  18 19
  148  'SdFm-Grd 1 RVR '   1.1   4   0    0.0  -39.5 22.5  2  2 6  18 19
```

```
  149  'SdFm-Grd 2 LVL '   1.1   3   0  -70.0   39.5 22.5  2  2 6  18 19
  150  'SdFm-Grd 2 RVR '   1.1   4   0  -70.0  -39.5 22.5  2  2 6  18 19
! NEW Bolster Input Connections used to displace bolster using Input Body Data
  201  'Lft Long Disp  '    1    1  7    -35.0   39.50    18.0   1   21
  202  'Lft Latl Disp  '    1    1  7    -35.0   39.50    18.0   2   21
  203  'Lft Vert Disp  '    1    1  7    -35.0   39.50    18.0   3   21
  204  'Lft Roll Disp  '    1    1  7    -35.0   39.50    18.0   4   21
  205  'Lft Pitch Disp '    1    1  7    -35.0   39.50    18.0   5   21
!  206  'Lft Yaw Disp   '    1    1  7    -35.0   39.50    18.0   6   21
  211  'Cntr Long Disp '    1    1  8    -35.0   0.0      18.0   1   21
  212  'Cntr Latl Disp '    1    1  8    -35.0   0.0      18.0   2   21
  213  'Cntr Vert Disp '    1    1  8    -35.0   0.0      18.0   3   21
  214  'Cntr Roll Disp '    1    1  8    -35.0   0.0      18.0   4   21
  215  'Cntr Pitch Disp'    1    1  8    -35.0   0.0      18.0   5   21
  216  'Cntr Yaw Disp  '    1    1  8    -35.0   0.0      18.0   6   21
  221  'Rgt Long Disp  '    1    1  9    -35.0  -39.50    18.0   1   21
  222  'Rgt Latl Disp  '    1    1  9    -35.0  -39.50    18.0   2   21
  223  'Rgt Vert Disp  '    1    1  9    -35.0  -39.50    18.0   3   21
  224  'Rgt Roll Disp  '    1    1  9    -35.0  -39.50    18.0   4   21
  225  'Rgt Pitch Disp '    1    1  9    -35.0  -39.50    18.0   5   21
!  226  'Rgt Yaw  Disp  '    1    1  9    -35.0  -39.50    18.0   6   21

For each connection characteristic, list its number, identification numbers
for the piecewise linear stiffness and damping characteristics, respectively,
zero if absent, and the force, moment, or stroke limits in extn and compn,
(if no limit exists, set the values outside the expected range).

 Pair #  Stiffness & Damping  F/S-extn.  F/S-comp.    K/D-parameters
--------------------------------------------------------------------------
\CHARACTERISTIC DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
   8   11         12       1.0E09     -1.0E09
! Pitch stiffness and stops
   9   13          0       1.0E09     -1.0E09
! Warp/torsion
  10   14          0       1.0E09     -1.0E09
! Lateral stiffness and stops
  11   15          0       1.0E09     -1.0E09
! Vertical Springs
  12   16          0       0.0        -1.0E09
! Dummy roll characteristic for type 1.3 connection
  13    0          0       0.0        -1.0E09
! # 4 is a 6.3 wedge element with pwl numbers, wedge angle, force, LVB,
! and friction, Constant damped truck is 1979 lb/in in the control coils
! at zero wedge rise the control coils are compressed 1.8393 inches
! 0.0 inch wedge rise
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       3.640E03  1.0E04  0.40
! 0.25 inch wedge rise (1.8393 - 0.25 = 1.5893 * 1979 = 3145)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       3.1450E03 1.0E04  0.40
! 0.375 inch wedge rise (1.8393 -.375=1.4643*1979=2898)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       2.898E03  1.0E04  0.40
! modified for new type 6.7, MU1 for slope Mu2 for Face, T=Toe out, F=Toe in
```

```
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force   LB     Mu1    Mu2    Toe
!    14      0       0       37.5   2.898E3  1.0E04  0.40   0.40   .T.
! 0.50 inch wedge rise (1.8393 - 0.50 = 1.3393 * 1979 = 2650)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force  LB      Mu
!   14      0       0       37.5      2.650E03 1.0E04  0.40
! 0.75 inch wedge rise (1.8393 - 0.75 = 1.0893 * 1979 = 2155)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force  LB      Mu
!   14      0       0       37.5      2.155E03 1.0E04  0.40
!
! Option for a VARIABLE DAMPED TRUCK design
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force   LB     Mu1    Mu2    Toe
!    14     17       0     32.0    0.0    1.0E04   0.40   0.40   .T.
!
!  NEW Type 6.8 Stick-Slip Wedge
!  Ka and Ca are force accumulator stiffness and damping - NO LVB!
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force   Ka     Ca     Mu1    Mu2    Toe  FWNMAX
    14     17       0      32     0.0     1.0E6  1.0E3   0.40   0.40   .T.   1.0D5
!
!******************* Bearing Adapter Side Frame to Axle ********************
! Vertical side frame to axle connections with friction, type 6.5
   15   18          0       1.0E06      1.0E03  0.5
! Vertical damping for bearing adapters with gap element
   16    0         19        1000.0     0.031382
! Lateral stiffness and stops
   18   21          0       1.0E09    -1.0E09
! Yaw stiffness and stops
   19   22          0       1.0E09    -1.0E09
! Dummy Center Plate Roll/Pitch/Yaw Connection
!   20   0          0       1.0E09    -1.0E09
! NEW Bolster Displacement Input Connections
   21    23         0       1.0E09    -1.0E09
```

For each piecewise linear function, list the identification number, the number of break points, and the ordinate, lb or in-lb, over abscissa, inches or rad, at each break point.

Note - extension is assumed to be positive for both ordinate and abscissa and 0.0 for the first break point indicates symmetry about the origin.

```
  PWL    IBP    Ordinates over Abscissae
-------------------------------------------------------------------------
\PWL DATA
! ********************* Bolster to Side Frame Connections ******************
! Longitudinal
   11     2      0.0      1.E6
                         0.0      1.0
   12     2      0.0      1.E3
                         0.0      1.0
! Pitch Stiffness and Stops Mid Tolerance is Approx +/- 2.4 Degrees=0.042mRad
   13      3      0.0      0.0    6.40E7
              0.0      0.042  1.042
!******************Warp resistance ***********************************
! worn truck
! Warp resistance for bolster to side frame
!   14      3      0.0      5.25E04   6.924E05
!                0.0      0.030     0.040
```

```
! New truck
! Warp resistance for bolster to side frame
  14     3     0.0     2.55E05   8.95E05
               0.0     0.030     0.040
! Stiff H-frame truck
! Warp resistance for bolster to side frame
!   14     3     0.0     1.275E06  1.915E06
!               0.0     0.030     0.040
! Lateral Stiffness of bolster to side frame connection divided by 4
!    15    3     0.0     2.225E3   1.09E5
!                       0.0     0.50     0.60
   15     3    0.0    1.808E3     1.018E5
              0.0    0.50       0.60
! Vertical Secondary Suspension
! 9-D5 outers and 5-D5 inners
!   16     5    -1.954E5 -9.5414E4  -3.50E2    0.0      0.0
!              -3.7875  -3.6875     0.0       0.0625   1.0
! stiffness divided by 4
!   16     5    -0.4885E5 -2.38535E4 -8.75E1    0.0      0.0
!              -3.7875  -3.6875     0.0       0.0625   1.0
! with initial offsets calculated for loaded static weight of -15403.78
!   16     6    -0.4885E5 -2.38535E4  -1.540378E4 -8.75E1   0.0      0.0
!              -1.39747  -1.29747     0.0        2.3900   2.4525   4.0
!
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
!   16     3    -3.0E03   0.0   3.0E3
!              -1.0      0.0    1.0
   16     3    -15E3     0.0   15E3
              -5.0      0.0   5.0
! Spring nest for the variable damped option (6 D5 Outers and 7 D5 Inners)
!  16     6     -4.48E+04 -1.98E+04   -1.22E+04   -1.23E+02 0.0      0.0
!              -1.5171   -1.4171      0.0        2.2704   2.3329   3.2079
!
!***********Optional control coils for a variably damped truck****************
!   17     6     -5.91E+04 -9.14E+03   -6.39E+03   -1.81E+02 0.0      0.0
!              -1.5171   -1.4171     0.0        3.2079   3.5204   4.5204
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
!   17     3    -3.0E03   0.0   3.0E3
!              -1.0      0.0    1.0
   17     3    -15E3     0.0   15E3
              -5.0      0.0   5.0
!******************* Bearing Adapter Side Frame to Axle ********************
! Vertical Bearing adapter connection with offset for static load
  18     3    -1.5691E4 0.0        0.0
               0.0     0.031382    1.0
! Vertical Bearing adapter damping
  19     2     0.0      1.E3
                        0.0      1.0
! Bearing adapter stops
! Lateral Stiffness with Stops
  21     3     0.0      1.0     1.E3
               0.0     0.250   0.251
! Yaw Stiffness with Stops
  22     3     0.0      0.0    6.4E5
               0.0     0.030  0.040
! NEW Displacement Input Stiffnesses
```

```
  23     2      0.0      1.0E6
              0.0      1.0
```

A.1.2. Input Files

Vertical input file entitled ‘bolst_displ_input3.inp’:

```
Input file (.INP) for NUCARS 2006
========================================
Vertical Displacement of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
-----------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-----------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1      0    2000.0        0.0          0.0     0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1      0    2000.0        0.0          0.0     0.0     0.0    0.0
! History 3 (Vertical) is defined as a swept sine with nat'l freq = 2rad/sec, with amp=1.0in
3  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1      4    2000.0        0.0          0.0  0.31831  0.31831  1.0
! History 4 (Roll) is Null for this input
4  1  1
   1      0    2000.0        0.0          0.0     0.0     0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
   1      0    2000.0        0.0          0.0     0.0     0.0    0.0
! History 6 (Yaw) is Null for this input
6  1  1
   1      0    2000.0        0.0          0.0     0.0     0.0    0.0
```

Yaw input file entitled ‘bolst_displ_input36.inp’:

```
Input file (.INP) for NUCARS 2006
```

```
========================================
Yaw Rotation of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
-------------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-------------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1     0    2000.0       0.0          0.0     0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1     0    2000.0       0.0          0.0     0.0     0.0    0.0
! History 3 (Vertical) is Null for this input
3  1  1
   1     4    2000.0       0.0          0.0     0.31831    0.31831    1.0
! History 4 (Roll) is Null for this input
4  1  1
   1     0    2000.0       0.0          0.0     0.0     0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
   1     0    2000.0       0.0          0.0     0.0     0.0    0.0
! History 6 (Yaw) is defined as sine with nat'l freq = 2 rad/sec., with amp=0.0031645rad
6  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1     2    2000.0       0.0         0.0    0.1     100.0   0.012
```

A.1.3. Data Files

Data file entitled ‘sngl_trk.dat’:

```
Data file (.DAT) for NUCARS Version 2.0
========================================

$\EQUILIBRIUM

SELECTION OF OUTPUT
==================
```

```
!\CURVATURE
!    1
!    8

!\SUPERELEVATION
!    1
!    8

  Body #    No. & List of DoF's
------------------------------------------------------------------------
$\DOF DISPLACEMENT
  16
    7   5   1 2 3 4 5
    8   6   1 2 3 4 5 6
    9   5   1 2 3 4 5

$\DOF VELOCITY
  18
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6

$\DOF ACCELERATION

$\DOF FORCE
  18
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6


\CONNECTION FORCE
16
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
 119.1 119.2 121.1 121.2 123.1 123.2 125.1 125.2


\CONNECTION FORCE SUM
    2
    'Ld Trk Lft Vert Sprg Nest'  1   4  119.2 121.2 123.2 125.2  1.0 1.0 1.0 1.0
    'Ld Trk Lft Latl Sprg Nest'  1   4  119.1 121.1 123.1 125.1  1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Vt For'  1   6  119.2 121.2 123.2 125.2 127.1 129.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Vt For'  1   6  120.2 122.2 124.2 126.2 128.1 130.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Lat Fr'  1   6  119.1 121.1 123.1 125.1 127.2 129.2  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Lat Fr'  1   6  120.1 122.1 124.1 126.1 128.2 130.2  1.0 1.0 1.0 1.0 1.0 1.0
!    'LEAD TRK SPG GRP ROLL MOM'  2   2  13  14  39.5  -39.5

\CONNECTION STROKE
 12
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
 119.2 121.2 123.2 125.2


\CONNECTION VELOCITY
  8
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
```

A.1.4. Run Files

Run file for the vertical bolster displacement input entitiled 'Bolst_wedge_sf_bolst-vert-displ_68_variable.run':

```
Run file (.RUN) for NUCARS Version 2.0
======================================
\RUN TITLE
Bolster-wedge-side frame lhopr w/type 6.8 wedge toeout, Vertical bolster displacement as input

\SYSTEM FILE
   'Bolst_wedge_sf_68_variable.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input3.INP'

!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0     .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

Run file for the vertical bolster displacement input entitiled 'Bolst_wedge_sf_bolst-vert-displ_68_variable.run':

```
Run file (.RUN) for NUCARS Version 2.0
======================================
\RUN TITLE
Bolster-wedge-side frame lhopr w/type 6.8 wedge toeout, Yaw as input

\SYSTEM FILE
   'Bolst_wedge_sf_68_variable.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input_36.INP'

!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0     .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

A.2 Type 6.9 Friction Wedge Model

A.2.1. System Files

Type 6.9 system file entitled 'bolst_wedge_sf_69_var.sys':

```
! System file (.SYS) for NUCARS Version 2006
==========================================

\SYSTEM TITLE
Bolster+Carbody combo - Wedge - Side Frame - Ground Connections, Tyoe 6.9 Wedge Connection
Details About Model
 - Half Carbody = Loaded 100T Hopper Car
 - Toe angle of 0.2degrees
 - Bolster + Carbody constrained to Lateral & Vertical Translation & Roll
 - No Longitudinal connections between side frame & ground

09/15/06  Type 6.9 3dof stick slip wedge - hollow column face wear, constant damped
        Values for longitudinal Gib clearance not confirmed,may require adjustment
        Includes empirical values for truck warp restraint from LHOPR-04

Give the number of bodies, then for each, list the number, name, up to 15
characters in single quotes, and c.g. position, relative to a chosen datum,
followed by the number and list of degrees of freedom required (from 1=x,
2=y, 3=z, 4=phi, 5=theta, 6=psi, 7=epsx, 8=epsy, 9=epsz), and the mass and
inertias in roll, pitch, and yaw.  The degrees of freedom required for each
axle are 2, 3, 4, and 6.  A longitudinal degree of freedom, 1, is optional.

 Body #  ' 15 Char Name  '        C.G. Posn in X, Y, & Z
           No. & DoF List          Mass, Roll, Pitch, & Yaw Inertia
-------------------------------------------------------------------------
\BODY DATA
   3
    1   ' Half Car+Bolst'        -35.0      0.0      83.0
          6   1  2  3  4  5  6  319.175    0.92276E06   0.8350204E07   0.835276E07
    3   'Lead Lft Sframe'         -35.0     39.5      18.0
      6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03
    4   'Lead Rgt Sframe'         -35.0    -39.5      18.0
      6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03

\INPUT BODY DATA
  3
    7  'Lft Input disp '  -35.0   39.5   18.0   5   1 2 3 4 5    1 2 3 4 5    .F.
    8  'Cntr Input disp'  -35.0   0.0    18.0   6   1 2 3 4 5 6  1 2 3 4 5 6  .F.
    9  'Rgt Input disp '  -35.0  -39.5   18.0   5   1 2 3 4 5    1 2 3 4 5    .F.

\CONNECTION DATA
  50
! No centerplate or contact bearings btwn carbody & bolster reqd
! Long.,Pitch, and Yaw bolster to side frame connections
  117   'Ld L Bol-SF LPY'   1.1    1  3 -35.0  39.5 18.0  3   1 5 6   8 9 10
  118   'Ld R Bol-SF LPY'   1.1    1  4 -35.0 -39.5 18.0  3   1 5 6   8 9 10
! Vertical bolster to side frame connections split into 4 seperate springs
! at each nest, dropped down 5"
```

```
  119   'Ld L Bol-SF V 1'   1.3   1  3 -31.25  35.75 13.0  3  2 3 4  11 12 13
  120   'Ld R Bol-SF V 1'   1.3   1  4 -31.25 -35.75 13.0  3  2 3 4  11 12 13
  121   'Ld L Bol-SF V 2'   1.3   1  3 -31.25  43.25 13.0  3  2 3 4  11 12 13
  122   'Ld R Bol-SF V 2'   1.3   1  4 -31.25 -43.25 13.0  3  2 3 4  11 12 13
  123   'Ld L Bol-SF V 3'   1.3   1  3 -38.75  35.75 13.0  3  2 3 4  11 12 13
  124   'Ld R Bol-SF V 3'   1.3   1  4 -38.75 -35.75 13.0  3  2 3 4  11 12 13
  125   'Ld L Bol-SF V 4'   1.3   1  3 -38.75  43.25 13.0  3  2 3 4  11 12 13
  126   'Ld R Bol-SF V 4'   1.3   1  4 -38.75 -43.25 13.0  3  2 3 4  11 12 13
! 3D Stick-Slip Friction wedge connection between bolster and side frame
  127   'Ld Bol-SF LL Wg'   6.9   1   3   -26.5    39.5    18.0   3 1 2  14
  128   'Ld Bol-SF LR Wg'   6.9   1   4   -26.5   -39.5    18.0   3 1 2  14
  129   'Ld Bol-SF TL Wg'   6.9   1   3   -43.5    39.5    18.0   3 1 2  114
  130   'Ld Bol-SF TR Wg'   6.9   1   4   -43.5   -39.5    18.0   3 1 2  114
! Vertical surface friction element for side frame to axle
! connections elements are placed +/- 3.0 inches apart to react roll, and
! pitch of the side frame
  131   'SdFm-Grd 1 LVL '   6.5   3   0     0.0    42.5    22.5   3 1 2  15
  132   'SdFm-Grd 1 LVR '   6.5   3   0     0.0    36.5    22.5   3 1 2  15
  133   'SdFm-Grd 1 RVR '   6.5   4   0     0.0   -42.5    22.5   3 1 2  15
  134   'SdFm-Grd 1 RVL '   6.5   4   0     0.0   -36.5    22.5   3 1 2  15
  135   'SdFm-Grd 2 LVL '   6.5   3   0   -70.0    42.5    22.5   3 1 2  15
  136   'SdFm-Grd 2 LVR '   6.5   3   0   -70.0    36.5    22.5   3 1 2  15
  137   'SdFm-Grd 2 RVR '   6.5   4   0   -70.0   -42.5    22.5   3 1 2  15
  138   'SdFm-Grd 2 RVL '   6.5   4   0   -70.0   -36.5    22.5   3 1 2  15
! Vertical dampers for surface friction elements
  139   'SdFm-Grd 1 LVL '   1.2   3   0     0.0    42.5    22.5   3  16
  140   'SdFm-Grd 1 LVR '   1.2   3   0     0.0    36.5    22.5   3  16
  141   'SdFm-Grd 1 RVR '   1.2   4   0     0.0   -42.5    22.5   3  16
  142   'SdFm-Grd 1 RVL '   1.2   4   0     0.0   -36.5    22.5   3  16
  143   'SdFm-Grd 2 LVL '   1.2   3   0   -70.0    42.5    22.5   3  16
  144   'SdFm-Grd 2 LVR '   1.2   3   0   -70.0    36.5    22.5   3  16
  145   'SdFm-Grd 2 RVR '   1.2   4   0   -70.0   -42.5    22.5   3  16
  146   'SdFm-Grd 2 RVL '   1.2   4   0   -70.0   -36.5    22.5   3  16
! Side frame to Ground lateral and yaw Stops
  147  'SdFm-Grd 1 LVL '   1.1   3   0    0.0   39.5 22.5  2  2 6  18 19
  148  'SdFm-Grd 1 RVR '   1.1   4   0    0.0  -39.5 22.5  2  2 6  18 19
  149  'SdFm-Grd 2 LVL '   1.1   3   0  -70.0   39.5 22.5  2  2 6  18 19
  150  'SdFm-Grd 2 RVR '   1.1   4   0  -70.0  -39.5 22.5  2  2 6  18 19
! NEW Bolster Input Connections used to displace bolster using Input Body Data
  201  'Lft Long Disp  '    1    1  7    -35.0   39.50    18.0   1   21
  202  'Lft Latl Disp  '    1    1  7    -35.0   39.50    18.0   2   21
  203  'Lft Vert Disp  '    1    1  7    -35.0   39.50    18.0   3   21
  204  'Lft Roll Disp  '    1    1  7    -35.0   39.50    18.0   4   21
  205  'Lft Pitch Disp '    1    1  7    -35.0   39.50    18.0   5   21
!  206  'Lft Yaw Disp   '    1    1  7    -35.0   39.50    18.0   6   21
  211  'Cntr Long Disp '    1    1  8    -35.0   0.0      18.0   1   21
  212  'Cntr Latl Disp '    1    1  8    -35.0   0.0      18.0   2   21
  213  'Cntr Vert Disp '    1    1  8    -35.0   0.0      18.0   3   21
  214  'Cntr Roll Disp '    1    1  8    -35.0   0.0      18.0   4   21
  215  'Cntr Pitch Disp'    1    1  8    -35.0   0.0      18.0   5   21
  216  'Cntr Yaw Disp  '    1    1  8    -35.0   0.0      18.0   6   21
  221  'Rgt Long Disp  '    1    1  9    -35.0  -39.50    18.0   1   21
  222  'Rgt Latl Disp  '    1    1  9    -35.0  -39.50    18.0   2   21
  223  'Rgt Vert Disp  '    1    1  9    -35.0  -39.50    18.0   3   21
  224  'Rgt Roll Disp  '    1    1  9    -35.0  -39.50    18.0   4   21
  225  'Rgt Pitch Disp '    1    1  9    -35.0  -39.50    18.0   5   21
```

```
! 226 'Rgt Yaw  Disp '   1    1 9    -35.0  -39.50    18.0   6   21
```

For each connection characteristic, list its number, identification numbers for the piecewise linear stiffness and damping characteristics, respectively, zero if absent, and the force, moment, or stroke limits in extn and compn, (if no limit exists, set the values outside the expected range).

```
 Pair #  Stiffness & Damping  F/S-extn.  F/S-comp.    K/D-parameters
-------------------------------------------------------------------------
\CHARACTERISTIC DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
   8  11          12       1.0E09    -1.0E09
! Pitch stiffness and stops
   9  13          0        1.0E09     -1.0E09
! Warp/torsion
  10   14         0       1.0E09    -1.0E09
! Lateral stiffness and stops
  11   15         0        1.0E09     -1.0E09
! Vertical Springs
  12   16         0       0.0       -1.0E09
! Dummy roll characteristic for type 1.3 connection
  13    0         0       0.0       -1.0E09
! # 4 is a 6.3 wedge element with pwl numbers, wedge angle, force, LVB,
! and friction, Constant damped truck is 1979 lb/in in the control coils
! at zero wedge rise the control coils are compressed 1.8393 inches
! 0.0 inch wedge rise
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       3.640E03  1.0E04  0.40
! 0.25 inch wedge rise (1.8393 - 0.25 = 1.5893 * 1979 = 3145)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       3.1450E03 1.0E04  0.40
! 0.375 inch wedge rise (1.8393 -.375=1.4643*1979=2898)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!    14      0        0       37.5       2.898E03  1.0E04  0.40
! modified for new type 6.7, MU1 for slope Mu2 for Face, T=Toe out, F=Toe in
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force    LB      Mu1    Mu2    Toe
!    14      0        0        37.5   2.898E3  1.0E04  0.40   0.40   .T.
! 0.50 inch wedge rise (1.8393 - 0.50 = 1.3393 * 1979 = 2650)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       2.650E03 1.0E04  0.40
! 0.75 inch wedge rise (1.8393 - 0.75 = 1.0893 * 1979 = 2155)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5       2.155E03 1.0E04  0.40
!
! Option for a VARIABLE DAMPED TRUCK design
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force    LB      Mu1    Mu2    Toe
!    14     17        0     32.0     0.0    1.0E04   0.40   0.40   .T.
!
!  NEW Type 6.9 3D Stick-Slip Wedge
!  Pwl-toe is for cloumn wear face
!  V/C = .F. for constant damped
!  Ka and Ca are force accumulator stiffness and damping
!  XDIR = 1.d0 for leading wedges, -1.d0 for trailing wedges
!  Column Face Normal Force limit FWNMAX = 1.0D5
!
```

```
!   Ch #  Pwl-Stf Pwl-Toe  Wedge Ang  V/C    Ka     Ca     Mu1  Mu2  XDIR  FWNMAX
   14      17     24       32.0     .T.   1.0E6  1.0E3   0.40  0.4  1.D0   1.0D5
  114      17     24       32.0     .T.   1.0E6  1.0E3   0.40  0.4 -1.D0   1.0D5
!
!******************* Bearing Adapter Side Frame to Axle ********************
! Vertical side frame to axle connections with friction, type 6.5
   15   18          0       1.0E06      1.0E03  0.5
! Vertical damping for bearing adapters with gap element
   16    0         19        1000.0     0.031382
! Longitudinal stiffness and stops
!   17  20          0        1.0E09    -1.0E09
! Lateral stiffness and stops
   18   21          0       1.0E09    -1.0E09
! Yaw stiffness and stops
   19   22          0       1.0E09    -1.0E09
! NEW Bolster Displacement Input Connections
   21    25         0       1.0E06    -1.0E06
```

For each piecewise linear function, list the identification number, the number of break points, and the ordinate, lb or in-lb, over abscissa, inches or rad, at each break point.

Note - extension is assumed to be positive for both ordinate and abscissa and
      0.0 for the first break point indicates symmetry about the origin.

```
   PWL    IBP    Ordinates over Abscissae
-------------------------------------------------------------------------
\PWL DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
! Includes shear stiffness of coils - same stiffness as lateral 17,800 lb/in
! Longitudinal clearances +/- 0.125 inches
! some damping for integration stability
!   11     3      0.0      1.225E3   1.02225E5
!             0.0      0.125     0.60
! variable Damped truck
   11     3      0.0      1.808E3   1.01808E5
                          0.0      0.125     0.60
   12     2      0.0      1.E3
                          0.0      1.0
! Pitch Stiffness and Stops Mid Tolerance is Approx +/- 2.4 Degrees=0.042mRad
   13     3      0.0      0.0    6.40E7
                0.0      0.042  1.042
! ****************** Warp resistance ****************************************
! these values are empirical to include the missing effects of wedging action
! worn truck
! Warp resistance for bolster to side frame
!   14     3      0.0      5.25E04   6.924E05
!               0.0      0.030     0.040
! New truck
! Warp resistance for bolster to side frame
  14     3      0.0      2.55E05   8.95E05
               0.0      0.030     0.040
! Stiff H-frame truck
! Warp resistance for bolster to side frame
!   14     3      0.0      1.275E06  1.915E06
```

```
!               0.0      0.030     0.040
! Lateral Stiffness of bolster to side frame connection divided by 4
! 17,800 lb/in
!   15    3     0.0      2.225E3   1.022E5
!                        0.0      0.50      0.60
! Lateral Stiffness of bolster to side frame connection divided by 4, Variable Damped truck
! 14,666 lb/in
   15    3      0.0      1.808E3   1.018E5
                         0.0      0.50      0.60
! Vertical Secondary Suspension
! 9-D5 outers and 5-D5 inners
!   16     5    -1.954E5 -9.5414E4  -3.50E2    0.0      0.0
!              -3.7875  -3.6875     0.0       0.0625   1.0
! stiffness divided by 4
!   16     5    -0.4885E5 -2.38535E4 -8.75E1    0.0      0.0
!              -3.7875  -3.6875      0.0       0.0625   1.0
! with initial offsets calculated for loaded static weight of -15403.78
!   16     6    -0.4885E5 -2.38535E4  -1.540378E4 -8.75E1   0.0      0.0
!              -1.39747  -1.29747     0.0        2.3900   2.4525   4.0
!
! Spring nest for the variable damped option (6 D5 Outers and 7 D5 Inners)
!  16      6     -4.48E+04 -1.98E+04   -1.22E+04   -1.23E+02 0.0      0.0
!             -1.5171   -1.4171      0.0        2.2704   2.3329   3.2079
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
  16      2      0.0   3.0E3
              0.0    1.0
!
!***********Optional control coils for a variably damped truck***************
! 2 B353 outers and 2 B354 inners, zero wedge rise - this is different than LHOPR-04
!  17      8    -5.903E+04 -9.0314E+03 -6.303E+03 -1.89E+02 -1.767E3 -72.25   0.0    0.0
!            -1.5085    -1.4085      0.0        2.279    2.3415   3.2165  3.3415 4.3415
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
  17      2      0.0   3.0E3
              0.0    1.0
!****************** Bearing Adapter Side Frame to Axle ********************
! Vertical Bearing adapter connection with offset for static load
  18      3     -1.5691E4 0.0         0.0
              0.0      0.031382    1.0
! Vertical Bearing adapter damping
  19      2      0.0      1.E3
                         0.0      1.0
! Bearing adapter stops
! Longitudinal Stiffness with Stops
!   20     3      0.0      1.0     1.E3
!                        0.0      0.0468  0.0478
! Lateral Stiffness with Stops
  21      3      0.0      1.0     1.E3
              0.0      0.250   0.26
! Yaw Stiffness with Stops
  22      3      0.0      0.0    6.4E5
              0.0      0.030  0.040
!****************** Type 6.9 Wedge PWLs ********************
! Control Coil Stiffness - 100 ton constant damped truck theoretical data
! 3640 lbs at 0.0 wedge rise.   1908.3 lbs at 0.875 rise, 1979.3 lbs/in
!   23      2     -3640.2  -1908.3
!               0.0      0.875
```

```
! Toe Out
  24     3    0.015708   0.0    -0.015708
               -4.5       0.0    4.5
! NEW Displacement Input Stiffnesses
   25     2      0.0      1.0E6
                 0.0      1.0
```

A.2.2. Input Files

Vertical input file entitled 'bolst_displ_input3.inp':

```
Input file (.INP) for NUCARS 2006
========================================
Vertical Displacement of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
---------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
---------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1      0    2000.0       0.0         0.0    0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1      0    2000.0       0.0         0.0    0.0     0.0    0.0
! History 3 (Vertical) is defined as a swept sine with nat'l freq = 2rad/sec, with amp=1.0in
3  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1      4    2000.0       0.0         0.0  0.31831  0.31831  1.0
! History 4 (Roll) is Null for this input
4  1  1
   1      0    2000.0       0.0         0.0    0.0     0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
```

```
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
! History 6 (Yaw) is Null for this input
6  1  1
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
```

Yaw input file entitled 'bolst_displ_input36.inp':

```
Input file (.INP) for NUCARS 2006
=========================================
Yaw Rotation of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
-----------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-----------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
! History 3 (Vertical) is Null for this input
3  1  1
   1      4   2000.0       0.0         0.0   0.31831    0.31831   1.0
! History 4 (Roll) is Null for this input
4  1  1
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
   1      0   2000.0       0.0         0.0    0.0     0.0    0.0
! History 6 (Yaw) is defined as sine with nat'l freq = 2 rad/sec., with amp=0.0031645rad
6  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1      2   2000.0       0.0        0.0    0.1     100.0   0.012
```

A.2.3. Data Files

Data file entitled 'sngl_trk.dat':

Data file (.DAT) for NUCARS Version 2.0

```
========================================

$\EQUILIBRIUM

SELECTION OF OUTPUT
===================

!\CURVATURE
!    1
!    8
!\SUPERELEVATION
!    1
!    8

  Body #    No. & List of DoF's
-------------------------------------------------------------------------
$\DOF DISPLACEMENT
  34
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6
    7   5   1 2 3 4 5
    8   6   1 2 3 4 5 6
    9   5   1 2 3 4 5

$\DOF VELOCITY
    52
    1       8      2 3 4 5 6 7.01 8.01 9.01
    2       4      2 3 4 6
    3       4      2 3 4 6
    4       5      1 2 3 5 6
    5       5      1 2 3 5 6
    6       5      1 2 3 5 6

$\DOF ACCELERATION

$\DOF FORCE
   18
     1   6   1 2 3 4 5 6
     3   6   1 2 3 4 5 6
     4   6   1 2 3 4 5 6

\CONNECTION FORCE
  20
  127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
  119.1 119.2 121.1 121.2 123.1 123.2 125.1 125.2

\CONNECTION FORCE SUM
    2
    'Ld Trk Lft Vert Sprg Nest'  1   4  119.2 121.2 123.2 125.2  1.0 1.0 1.0 1.0
    'Ld Trk Lft Lat Sprng Nest'  1   4  119.1 121.1 123.1 125.1  1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Vt For'  1   6  119.2 121.2 123.2 125.2 127.1 129.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Vt For'  1   6  120.2 122.2 124.2 126.2 128.1 130.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Lat Fr'  1   6  119.1 121.1 123.1 125.1 127.2 129.2  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Lat Fr'  1   6  120.1 122.1 124.1 126.1 128.2 130.2  1.0 1.0 1.0 1.0 1.0 1.0
```

```
!    'LEAD TRK SPG GRP ROLL MOM'  2   2  13  14  39.5  -39.5

\CONNECTION STROKE
  16
  127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
  119.2 121.2 123.2 125.2

\CONNECTION VELOCITY
12
 127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
```

A.2.4. Run Files

Run file for the vertical bolster displacement input entitiled ‘bolst_wedge_sf_bolst-vert-displ_69_var.run’:

```
Run file (.RUN) for NUCARS Version 2.0
========================================
\RUN TITLE
Single Truck with 1/2 car mass, type 6.9 wedge toeout w/vert displ of bolster as input
\SYSTEM FILE
   'bolst_wedge_sf_69_var.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input3.INP'


!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0    .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

Run file for the yaw input entitiled ‘bolst_wedge_sf_bolst-vrt-displ-w-yaw_69_var.run’:

```
Run file (.RUN) for NUCARS Version 2.0
========================================
\RUN TITLE
Single Truck with 1/2 car mass, type 6.9 wedge toeout w/yaw as input
\SYSTEM FILE
   'bolst_wedge_sf_69_var.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input_36.INP'
```

```
!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0    .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

APPENDIX B: CONSTANTLY-DAMPED NUCARS® FILES

This section includes the NUCARS® files required to run the simulations for the constantly-damped comparison model. The system file houses the body and connection information, as well as the characteristics of those connections. The input files were used to input the vertical bolster displacement and yaw inputs. The data files tell which variables would be output for each simulation. The run files collect the files to be used in the simulation and read them using the Integration Engine in NUCARS®.

B.1 Type 6.8 Friction Wedge Model

B.1.1. System Files

Type 6.8 system file entitled 'Bolst_wedge_sf_68_constant.sys':

```
System file (.SYS) for NUCARS Version 2004
=========================================

\SYSTEM TITLE
Bolster & Half Loaded 100T Hopper Carbody combo-Wedge-Side Frame-Ground Connections

Details of Model:
1 - Single Truck being modeled so only half car body req
2 - Constrain Car body to lateral trans, vert transl & roll
3 - Side Frames connected to rail (Ground)
4 - Displacement input at Bolster
5 - Type 6.8 wedge connection

Give the number of bodies, then for each, list the number, name, up to 15
characters in single quotes, and c.g. position, relative to a chosen datum,
followed by the number and list of degrees of freedom required (from 1=x,
2=y, 3=z, 4=phi, 5=theta, 6=psi, 7=epsx, 8=epsy, 9=epsz), and the mass and
inertias in roll, pitch, and yaw.  The degrees of freedom required for each
axle are 2, 3, 4, and 6.  A longitudinal degree of freedom, 1, is optional.

 Body #  ' 15 Char Name  '       C.G. Posn in X, Y, & Z
             No. & DoF List        Mass, Roll, Pitch, & Yaw Inertia
--------------------------------------------------------------------------
\BODY DATA
  3
! Half of the car weight is used, also centered on Bolster
    1   ' Half Car+Bolst'        -35.0      0.0      83.0
          6   1  2  3  4  5  6    319.175    0.92276E06   0.8350204E07   0.835276E07
    3   ' Lft Sframe    '        -35.0     39.5      18.0
```

```
     6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03
    4   ' Rgt Sframe    '          -35.0     -39.5      18.0
     6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03

Body #  ' 15 Char Name  '   Posn in X, Y, & Z   No.   DoF List     Input      Lag
----------------------------------------------------------------------------------
\INPUT BODY DATA
  3
    7  'Lft Input disp '  -35.0   39.5   18.0   5   1 2 3 4 5    1 2 3 4 5   .F.
    8  'Cntr Input disp'  -35.0   0.0    18.0   6   1 2 3 4 5 6  1 2 3 4 5 6  .F.
    9  'Rgt Input disp '  -35.0  -39.5   18.0   5   1 2 3 4 5    1 2 3 4 5   .F.

\CONNECTION DATA
 50
! Long.,Pitch, and Yaw bolster to side frame connections
  117   'Ld L Bol-SF LPY'   1.1    1  3 -35.0  39.5 18.0  3   1 5 6  8 9 10
  118   'Ld R Bol-SF LPY'   1.1    1  4 -35.0 -39.5 18.0  3   1 5 6  8 9 10
! Vertical bolster to side frame connections
! split into 4 seperate springs at each nest, dropped down 5"
  119   'Ld L Bol-SF V 1'   1.3    1  3 -31.25  35.75 13.0  3  2 3 4  11 12 13
  120   'Ld R Bol-SF V 1'   1.3    1  4 -31.25 -35.75 13.0  3  2 3 4  11 12 13
  121   'Ld L Bol-SF V 2'   1.3    1  3 -31.25  43.25 13.0  3  2 3 4  11 12 13
  122   'Ld R Bol-SF V 2'   1.3    1  4 -31.25 -43.25 13.0  3  2 3 4  11 12 13
  123   'Ld L Bol-SF V 3'   1.3    1  3 -38.75  35.75 13.0  3  2 3 4  11 12 13
  124   'Ld R Bol-SF V 3'   1.3    1  4 -38.75 -35.75 13.0  3  2 3 4  11 12 13
  125   'Ld L Bol-SF V 4'   1.3    1  3 -38.75  43.25 13.0  3  2 3 4  11 12 13
  126   'Ld R Bol-SF V 4'   1.3    1  4 -38.75 -43.25 13.0  3  2 3 4  11 12 13
! 2D Stick-Slip Friction wedge connection between bolster and side frame
  127   'Ld Bol-SF LL Wg'   6.8   1   3   -26.5    39.5    18.0   3 2  14
  128   'Ld Bol-SF LR Wg'   6.8   1   4   -26.5   -39.5    18.0   3 2  14
  129   'Ld Bol-SF TL Wg'   6.8   1   3   -43.5    39.5    18.0   3 2  14
  130   'Ld Bol-SF TR Wg'   6.8   1   4   -43.5   -39.5    18.0   3 2  14
! Vertical surface friction element for side frame to ground
! connections elements are placed +/- 3.0 inches apart to react roll, and
! pitch of the side frame
  131   'SdFm-Grd 1 LVL '   6.5   3   0     0.0    42.5    22.5   3 1 2  15
  132   'SdFm-Grd 1 LVR '   6.5   3   0     0.0    36.5    22.5   3 1 2  15
  133   'SdFm-Grd 1 RVR '   6.5   4   0     0.0   -42.5    22.5   3 1 2  15
  134   'SdFm-Grd 1 RVL '   6.5   4   0     0.0   -36.5    22.5   3 1 2  15
  135   'SdFm-Grd 2 LVL '   6.5   3   0   -70.0    42.5    22.5   3 1 2  15
  136   'SdFm-Grd 2 LVR '   6.5   3   0   -70.0    36.5    22.5   3 1 2  15
  137   'SdFm-Grd 2 RVR '   6.5   4   0   -70.0   -42.5    22.5   3 1 2  15
  138   'SdFm-Grd 2 RVL '   6.5   4   0   -70.0   -36.5    22.5   3 1 2  15
! Vertical dampers for surface friction elements
  139   'SdFm-Grd 1 LVL '   1.2   3   0     0.0    42.5    22.5   3  16
  140   'SdFm-Grd 1 LVR '   1.2   3   0     0.0    36.5    22.5   3  16
  141   'SdFm-Grd 1 RVR '   1.2   4   0     0.0   -42.5    22.5   3  16
  142   'SdFm-Grd 1 RVL '   1.2   4   0     0.0   -36.5    22.5   3  16
  143   'SdFm-Grd 2 LVL '   1.2   3   0   -70.0    42.5    22.5   3  16
  144   'SdFm-Grd 2 LVR '   1.2   3   0   -70.0    36.5    22.5   3  16
  145   'SdFm-Grd 2 RVR '   1.2   4   0   -70.0   -42.5    22.5   3  16
  146   'SdFm-Grd 2 RVL '   1.2   4   0   -70.0   -36.5    22.5   3  16
! Side frame to ground lateral and yaw Stops
  147  'SdFm-Grd 1 LVL '   1.1    3   0    0.0   39.5 22.5  2  2 6  18 19
  148  'SdFm-Grd 1 RVR '   1.1    4   0    0.0  -39.5 22.5  2  2 6  18 19
  149  'SdFm-Grd 2 LVL '   1.1    3   0  -70.0   39.5 22.5  2  2 6  18 19
```

```
  150  'SdFm-Grd 2 RVR '   1.1    4    0  -70.0  -39.5 22.5  2  2 6  18 19
! NEW Bolster Input Connections used to displace bolster using Input Body Data
  201  'Lft Long Disp  '    1    1  7    -35.0   39.50    18.0   1   21
  202  'Lft Latl Disp  '    1    1  7    -35.0   39.50    18.0   2   21
  203  'Lft Vert Disp  '    1    1  7    -35.0   39.50    18.0   3   21
  204  'Lft Roll Disp  '    1    1  7    -35.0   39.50    18.0   4   21
  205  'Lft Pitch Disp '    1    1  7    -35.0   39.50    18.0   5   21
!  206  'Lft Yaw Disp   '    1    1  7    -35.0   39.50    18.0   6   21
  211  'Cntr Long Disp '    1    1  8    -35.0   0.0      18.0   1   21
  212  'Cntr Latl Disp '    1    1  8    -35.0   0.0      18.0   2   21
  213  'Cntr Vert Disp '    1    1  8    -35.0   0.0      18.0   3   21
  214  'Cntr Roll Disp '    1    1  8    -35.0   0.0      18.0   4   21
  215  'Cntr Pitch Disp'    1    1  8    -35.0   0.0      18.0   5   21
  216  'Cntr Yaw Disp  '    1    1  8    -35.0   0.0      18.0   6   21
  221  'Rgt Long Disp  '    1    1  9    -35.0  -39.50    18.0   1   21
  222  'Rgt Latl Disp  '    1    1  9    -35.0  -39.50    18.0   2   21
  223  'Rgt Vert Disp  '    1    1  9    -35.0  -39.50    18.0   3   21
  224  'Rgt Roll Disp  '    1    1  9    -35.0  -39.50    18.0   4   21
  225  'Rgt Pitch Disp '    1    1  9    -35.0  -39.50    18.0   5   21
!  226  'Rgt Yaw  Disp  '    1    1  9    -35.0  -39.50    18.0   6   21

For each connection characteristic, list its number, identification numbers
for the piecewise linear stiffness and damping characteristics, respectively,
zero if absent, and the force, moment, or stroke limits in extn and compn,
(if no limit exists, set the values outside the expected range).

 Pair #  Stiffness & Damping  F/S-extn.  F/S-comp.    K/D-parameters
--------------------------------------------------------------------------
\CHARACTERISTIC DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
   8   11         12       1.0E09     -1.0E09
! Pitch stiffness and stops
   9   13          0       1.0E09     -1.0E09
! Warp/torsion
   10   14         0       1.0E09     -1.0E09
! Lateral stiffness and stops
   11   15         0       1.0E09     -1.0E09
! Vertical Springs
   12   16         0       0.0       -1.0E09
! Dummy roll characteristic for type 1.3 connection
   13    0         0       0.0       -1.0E09
! # 4 is a 6.3 wedge element with pwl numbers, wedge angle, force, LVB,
! and friction, Constant damped truck is 1979 lb/in in the control coils
! at zero wedge rise the control coils are compressed 1.8393 inches
! 0.0 inch wedge rise
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      3.640E03  1.0E04  0.40
! 0.25 inch wedge rise (1.8393 - 0.25 = 1.5893 * 1979 = 3145)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      3.1450E03 1.0E04  0.40
! 0.375 inch wedge rise (1.8393 -.375=1.4643*1979=2898)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!    14      0        0       37.5      2.898E03  1.0E04  0.40
! modified for new type 6.7, MU1 for slope Mu2 for Face, T=Toe out, F=Toe in
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force    LB      Mu1    Mu2    Toe
```

```
!   14      0        0       37.5   2.898E3  1.0E04  0.40   0.40   .T.
! 0.50 inch wedge rise (1.8393 - 0.50 = 1.3393 * 1979 = 2650)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force  LB      Mu
!   14      0        0       37.5       2.650E03 1.0E04  0.40
! 0.75 inch wedge rise (1.8393 - 0.75 = 1.0893 * 1979 = 2155)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force  LB      Mu
!   14      0        0       37.5       2.155E03 1.0E04  0.40
!
! Option for a VARIABLE DAMPED TRUCK design
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force   LB      Mu1    Mu2    Toe
!   14     17        0     32.0     0.0    1.0E04   0.40   0.40  .T.
!
!  NEW Type 6.8 Stick-Slip Wedge
!  Ka and Ca are force accumulator stiffness and damping - NO LVB!
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force   Ka     Ca     Mu1    Mu2    Toe  FWNMAX
   14      0        0      37.5   3.7022E3  1.0E6  1.0E3  0.40   0.40   .T.   1.0D5
!
!******************* Bearing Adapter Side Frame to Axle ********************
! Vertical side frame to axle connections with friction, type 6.5
   15   18          0        1.0E06      1.0E03  0.5
! Vertical damping for bearing adapters with gap element
   16    0          19        1000.0     0.031382
! Lateral stiffness and stops
   18   21          0        1.0E09     -1.0E09
! Yaw stiffness and stops
   19   22          0        1.0E09     -1.0E09
! Dummy Center Plate Roll/Pitch/Yaw Connection
!   20   0          0        1.0E09     -1.0E09
! NEW Bolster Displacement Input Connections
   21    23         0        1.0E09     -1.0E09
```

For each piecewise linear function, list the identification number, the number of break points, and the ordinate, lb or in-lb, over abscissa, inches or rad, at each break point.

Note - extension is assumed to be positive for both ordinate and abscissa and 0.0 for the first break point indicates symmetry about the origin.

```
   PWL    IBP    Ordinates over Abscissae
--------------------------------------------------------------------------
\PWL DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
   11     2      0.0      1.E6
                         0.0      1.0
   12     2      0.0      1.E3
                         0.0      1.0
! Pitch Stiffness and Stops Mid Tolerance is Approx +/- 2.4 Degrees=0.042mRad
   13     3      0.0      0.0    6.40E7
              0.0      0.042  1.042
! ****************** Warp resistance ***************************************
! worn truck
! Warp resistance for bolster to side frame
!   14     3      0.0      5.25E04   6.924E05
!              0.0      0.030     0.040
! New truck
```

```
! Warp resistance for bolster to side frame
  14     3     0.0     2.55E05   8.95E05
             0.0     0.030     0.040
! Stiff H-frame truck
! Warp resistance for bolster to side frame
!   14     3     0.0     1.275E06  1.915E06
!              0.0     0.030     0.040
! Lateral Stiffness of bolster to side frame connection divided by 4
   15    3     0.0     2.225E3   1.09E5
                     0.0     0.50     0.60
! Vertical Secondary Suspension
! 9-D5 outers and 5-D5 inners
!   16     5    -1.954E5 -9.5414E4  -3.50E2    0.0     0.0
!             -3.7875  -3.6875     0.0      0.0625   1.0
! stiffness divided by 4
!   16     5    -0.4885E5 -2.38535E4 -8.75E1    0.0     0.0
!             -3.7875  -3.6875     0.0      0.0625   1.0
! with initial offsets calculated for loaded static weight of -15403.78
!   16     6    -0.4885E5 -2.38535E4  -1.540378E4 -8.75E1   0.0     0.0
!             -1.39747  -1.29747     0.0       2.3900   2.4525   4.0
  16  6     -2.4487335E4     -2.3837335E4     -1.540378E4     -1.3122E2   0.0    0.0
           -1.39747       -1.29747         0.0           2.39       2.410  4.0
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
!   16     2     0.0   3.0E3
!              0.0    1.0
!
! Spring nest for the variable damped option (6 D5 Outers and 7 D5 Inners)
!  16     6    -4.48E+04 -1.98E+04   -1.22E+04   -1.23E+02 0.0     0.0
!            -1.5171   -1.4171     0.0       2.2704   2.3329   3.2079
!
!***********Optional control coils for a variably damped truck***************
!   17     6    -5.91E+04 -9.14E+03   -6.39E+03   -1.81E+02 0.0     0.0
!             -1.5171   -1.4171     0.0       3.2079   3.5204   4.5204
!
!****************** Bearing Adapter Side Frame to Axle ********************
! Vertical Bearing adapter connection with offset for static load
  18     3    -1.5691E4 0.0        0.0
             0.0     0.031382    1.0
! Vertical Bearing adapter damping
  19     2     0.0     1.E3
                     0.0     1.0
! Bearing adapter stops
! Lateral Stiffness with Stops
  21     3     0.0     1.0     1.E3
             0.0     0.250   0.251
! Yaw Stiffness with Stops
  22     3     0.0     0.0    6.4E5
             0.0     0.030  0.040
! NEW Displacement Input Stiffnesses
  23     2     0.0     1.0E6
             0.0     1.0
```

B.1.2. Input Files

Vertical input file entitled ‘bolst_displ_input3.inp’:

```
Input file (.INP) for NUCARS 2006
========================================
Vertical Displacement of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
-----------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-----------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 3 (Vertical) is defined as a swept sine with nat'l freq = 2rad/sec, with amp=1.0in
3  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1      4    2000.0       0.0         0.0  0.31831  0.31831  1.0
! History 4 (Roll) is Null for this input
4  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 6 (Yaw) is Null for this input
6  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
```

Yaw input file entitled ‘bolst_displ_input36.inp’:

```
Input file (.INP) for NUCARS 2006
========================================
Yaw Rotation of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection
```

Give the number of inputs and for each, the input number, the number of input segments, and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance. For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP, 2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and Newton-meters or Newtons for the metric system.

```
-----------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-----------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1     0    2000.0     0.0       0.0    0.0    0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1     0    2000.0     0.0       0.0    0.0    0.0    0.0
! History 3 (Vertical) is Null for this input
3  1  1
   1     4    2000.0     0.0       0.0    0.31831    0.31831   1.0
! History 4 (Roll) is Null for this input
4  1  1
   1     0    2000.0     0.0       0.0    0.0    0.0    0.0
! History 5 (Pitch) is Null for this input
5  1  1
   1     0    2000.0     0.0       0.0    0.0    0.0    0.0
! History 6 (Yaw) is defined as sine with nat'l freq = 2 rad/sec., with amp=0.0031645rad
6  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1     2    2000.0     0.0      0.0    0.1    100.0   0.012
```

B.1.3. Data Files

Data file entitled 'sngl_trk.dat':

```
Data file (.DAT) for NUCARS Version 2.0
=======================================

$\EQUILIBRIUM

SELECTION OF OUTPUT
===================

!\CURVATURE
!   1
!   8

!\SUPERELEVATION
!   1
```

```
!    8

  Body #    No. & List of DoF's
--------------------------------------------------------------------------
$\DOF DISPLACEMENT
  16
    7   5   1 2 3 4 5
    8   6   1 2 3 4 5 6
    9   5   1 2 3 4 5

$\DOF VELOCITY
  18
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6

$\DOF ACCELERATION

$\DOF FORCE
  18
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6

\CONNECTION FORCE
16
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
 119.1 119.2 121.1 121.2 123.1 123.2 125.1 125.2

\CONNECTION FORCE SUM
    2
    'Ld Trk Lft Vert Sprg Nest'  1   4  119.2 121.2 123.2 125.2  1.0 1.0 1.0 1.0
    'Ld Trk Lft Latl Sprg Nest'  1   4  119.1 121.1 123.1 125.1  1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Vt For'  1   6  119.2 121.2 123.2 125.2 127.1 129.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Vt For'  1   6  120.2 122.2 124.2 126.2 128.1 130.1  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Lft Spg Grp Lat Fr'  1   6  119.1 121.1 123.1 125.1 127.2 129.2  1.0 1.0 1.0 1.0 1.0 1.0
    'Ld Trk Rgt Spg Grp Lat Fr'  1   6  120.1 122.1 124.1 126.1 128.2 130.2  1.0 1.0 1.0 1.0 1.0 1.0
!    'LEAD TRK SPG GRP ROLL MOM'  2   2  13  14  39.5  -39.5

\CONNECTION STROKE
 12
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
 119.2 121.2 123.2 125.2

\CONNECTION VELOCITY
  8
 127.1 127.2 128.1 128.2 129.1 129.2 130.1 130.2
```

B.1.4. Run Files

Run file for the vertical bolster displacement input entitiled ‘Bolst_wedge_sf_bolst-vert-displ_68_constant.run’:

```
Run file (.RUN) for NUCARS Version 2.0
=======================================
\RUN TITLE
Bolster-wedge-side frame lhopr w/type 6.8 wedge toeout, Vertical bolster displacement as input

\SYSTEM FILE
   'Bolst_wedge_sf_68_constant.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input3.INP'

!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0    .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

Run file for the yaw input entitled ‘Bolst_wedge_sf_bolst-vert-displ-w-yaw_68_constant.run’:

```
Run file (.RUN) for NUCARS Version 2.0
=======================================
\RUN TITLE
Bolster-wedge-side frame lhopr w/type 6.8 wedge toeout, Yaw input

\SYSTEM FILE
   'Bolst_wedge_sf_68_constant.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input_36.INP'

!\REVERSE VIDEO

\CONTROL CONSTANTS
   1     0    .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

B.2 Type 6.9 Friction Wedge Model

B.2.1. System Files

Type 6.9 system file entitled ‘bolst_wedge_sf_69_const.sys’:

```
System file (.SYS) for NUCARS Version 2006
========================================

\SYSTEM TITLE
Bolster+Carbody combo - Wedge - Side Frame - Ground Connections, Tyoe 6.9 Wedge Connection
Details About Model
 - Half Carbody = Loaded 100T Hopper Car
 - Toe angle of 0.2degrees
 - Bolster + Carbody constrained to Lateral & Vertical Translation & Roll
 - No Longitudinal connections between side frame & ground

09/15/06  Type 6.9 3dof stick slip wedge - hollow column face wear, constant damped
        Values for longitudinal Gib clearance not confirmed,may require adjustment
        Includes empirical values for truck warp restraint from LHOPR-04

Give the number of bodies, then for each, list the number, name, up to 15
characters in single quotes, and c.g. position, relative to a chosen datum,
followed by the number and list of degrees of freedom required (from 1=x,
2=y, 3=z, 4=phi, 5=theta, 6=psi, 7=epsx, 8=epsy, 9=epsz), and the mass and
inertias in roll, pitch, and yaw.  The degrees of freedom required for each
axle are 2, 3, 4, and 6.  A longitudinal degree of freedom, 1, is optional.

 Body #  ' 15 Char Name  '         C.G. Posn in X, Y, & Z
            No. & DoF List          Mass, Roll, Pitch, & Yaw Inertia
--------------------------------------------------------------------------
\BODY DATA
   3
    1   ' Half Car+Bolst'        -35.0      0.0      83.0
          6   1  2  3  4  5  6    319.175    0.92276E06   0.8350204E07   0.835276E07
    3   'Lead Lft Sframe'         -35.0     39.5      18.0
      6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03
    4   'Lead Rgt Sframe'         -35.0    -39.5      18.0
      6   1  2  3  4  5  6    2.98    9.0E2     1.37E03   1.37E03

\INPUT BODY DATA
  3
    7  'Lft Input disp '  -35.0   39.5   18.0   5   1 2 3 4 5     1 2 3 4 5    .F.
    8  'Cntr Input disp'  -35.0   0.0    18.0   6   1 2 3 4 5 6   1 2 3 4 5 6  .F.
    9  'Rgt Input disp '  -35.0  -39.5   18.0   5   1 2 3 4 5     1 2 3 4 5    .F.

\CONNECTION DATA
  50
! No centerplate or contact bearings btwn carbody & bolster reqd
! Long.,Pitch, and Yaw bolster to side frame connections
  117   'Ld L Bol-SF LPY'   1.1   1  3 -35.0  39.5 18.0  3   1 5 6   8 9 10
  118   'Ld R Bol-SF LPY'   1.1   1  4 -35.0 -39.5 18.0  3   1 5 6   8 9 10
! Vertical bolster to side frame connections split into 4 seperate springs
! at each nest, dropped down 5"
  119   'Ld L Bol-SF V 1'   1.3   1  3 -31.25  35.75 13.0  3  2 3 4  11 12 13
  120   'Ld R Bol-SF V 1'   1.3   1  4 -31.25 -35.75 13.0  3  2 3 4  11 12 13
  121   'Ld L Bol-SF V 2'   1.3   1  3 -31.25  43.25 13.0  3  2 3 4  11 12 13
  122   'Ld R Bol-SF V 2'   1.3   1  4 -31.25 -43.25 13.0  3  2 3 4  11 12 13
  123   'Ld L Bol-SF V 3'   1.3   1  3 -38.75  35.75 13.0  3  2 3 4  11 12 13
```

```
  124  'Ld R Bol-SF V 3'   1.3   1  4 -38.75 -35.75 13.0  3  2 3 4  11 12 13
  125  'Ld L Bol-SF V 4'   1.3   1  3 -38.75  43.25 13.0  3  2 3 4  11 12 13
  126  'Ld R Bol-SF V 4'   1.3   1  4 -38.75 -43.25 13.0  3  2 3 4  11 12 13
! 3D Stick-Slip Friction wedge connection between bolster and side frame
  127  'Ld Bol-SF LL Wg'   6.9   1   3   -26.5    39.5    18.0   3 1 2  14
  128  'Ld Bol-SF LR Wg'   6.9   1   4   -26.5   -39.5    18.0   3 1 2  14
  129  'Ld Bol-SF TL Wg'   6.9   1   3   -43.5    39.5    18.0   3 1 2  114
  130  'Ld Bol-SF TR Wg'   6.9   1   4   -43.5   -39.5    18.0   3 1 2  114
! Vertical surface friction element for side frame to axle
! connections elements are placed +/- 3.0 inches apart to react roll, and
! pitch of the side frame
  131  'SdFm-Grd 1 LVL '  6.5   3   0     0.0    42.5    22.5   3 1 2  15
  132  'SdFm-Grd 1 LVR '  6.5   3   0     0.0    36.5    22.5   3 1 2  15
  133  'SdFm-Grd 1 RVR '  6.5   4   0     0.0   -42.5    22.5   3 1 2  15
  134  'SdFm-Grd 1 RVL '  6.5   4   0     0.0   -36.5    22.5   3 1 2  15
  135  'SdFm-Grd 2 LVL '  6.5   3   0   -70.0    42.5    22.5   3 1 2  15
  136  'SdFm-Grd 2 LVR '  6.5   3   0   -70.0    36.5    22.5   3 1 2  15
  137  'SdFm-Grd 2 RVR '  6.5   4   0   -70.0   -42.5    22.5   3 1 2  15
  138  'SdFm-Grd 2 RVL '  6.5   4   0   -70.0   -36.5    22.5   3 1 2  15
! Vertical dampers for surface friction elements
  139  'SdFm-Grd 1 LVL '  1.2   3   0     0.0    42.5    22.5   3  16
  140  'SdFm-Grd 1 LVR '  1.2   3   0     0.0    36.5    22.5   3  16
  141  'SdFm-Grd 1 RVR '  1.2   4   0     0.0   -42.5    22.5   3  16
  142  'SdFm-Grd 1 RVL '  1.2   4   0     0.0   -36.5    22.5   3  16
  143  'SdFm-Grd 2 LVL '  1.2   3   0   -70.0    42.5    22.5   3  16
  144  'SdFm-Grd 2 LVR '  1.2   3   0   -70.0    36.5    22.5   3  16
  145  'SdFm-Grd 2 RVR '  1.2   4   0   -70.0   -42.5    22.5   3  16
  146  'SdFm-Grd 2 RVL '  1.2   4   0   -70.0   -36.5    22.5   3  16
! Side frame to Ground lateral and yaw Stops
  147  'SdFm-Grd 1 LVL '  1.1   3   0    0.0   39.5 22.5  2  2 6  18 19
  148  'SdFm-Grd 1 RVR '  1.1   4   0    0.0  -39.5 22.5  2  2 6  18 19
  149  'SdFm-Grd 2 LVL '  1.1   3   0  -70.0   39.5 22.5  2  2 6  18 19
  150  'SdFm-Grd 2 RVR '  1.1   4   0  -70.0  -39.5 22.5  2  2 6  18 19
! NEW Bolster Input Connections used to displace bolster using Input Body Data
  201  'Lft Long Disp  '   1    1  7    -35.0   39.50    18.0   1   21
  202  'Lft Latl Disp  '   1    1  7    -35.0   39.50    18.0   2   21
  203  'Lft Vert Disp  '   1    1  7    -35.0   39.50    18.0   3   21
  204  'Lft Roll Disp  '   1    1  7    -35.0   39.50    18.0   4   21
  205  'Lft Pitch Disp '   1    1  7    -35.0   39.50    18.0   5   21
!  206  'Lft Yaw Disp   '   1    1  7    -35.0   39.50    18.0   6   21
  211  'Cntr Long Disp '   1    1  8    -35.0   0.0      18.0   1   21
  212  'Cntr Latl Disp '   1    1  8    -35.0   0.0      18.0   2   21
  213  'Cntr Vert Disp '   1    1  8    -35.0   0.0      18.0   3   21
  214  'Cntr Roll Disp '   1    1  8    -35.0   0.0      18.0   4   21
  215  'Cntr Pitch Disp'   1    1  8    -35.0   0.0      18.0   5   21
  216  'Cntr Yaw Disp  '   1    1  8    -35.0   0.0      18.0   6   21
  221  'Rgt Long Disp  '   1    1  9    -35.0  -39.50    18.0   1   21
  222  'Rgt Latl Disp  '   1    1  9    -35.0  -39.50    18.0   2   21
  223  'Rgt Vert Disp  '   1    1  9    -35.0  -39.50    18.0   3   21
  224  'Rgt Roll Disp  '   1    1  9    -35.0  -39.50    18.0   4   21
  225  'Rgt Pitch Disp '   1    1  9    -35.0  -39.50    18.0   5   21
!  226  'Rgt Yaw  Disp  '   1    1  9    -35.0  -39.50    18.0   6   21
```

For each connection characteristic, list its number, identification numbers for the piecewise linear stiffness and damping characteristics, respectively, zero if absent, and the force, moment, or stroke limits in extn and compn, (if no limit exists, set the values outside the expected range).

```
 Pair #  Stiffness & Damping  F/S-extn.  F/S-comp.    K/D-parameters
--------------------------------------------------------------------------
\CHARACTERISTIC DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
   8  11          12       1.0E09    -1.0E09
! Pitch stiffness and stops
   9  13          0       1.0E09     -1.0E09
! Warp/torsion
  10  14          0       1.0E09    -1.0E09
! Lateral stiffness and stops
  11  15          0        1.0E09     -1.0E09
! Vertical Springs
  12  16          0       0.0       -1.0E09
! Dummy roll characteristic for type 1.3 connection
  13   0          0       0.0       -1.0E09
! # 4 is a 6.3 wedge element with pwl numbers, wedge angle, force, LVB,
! and friction, Constant damped truck is 1979 lb/in in the control coils
! at zero wedge rise the control coils are compressed 1.8393 inches
! 0.0 inch wedge rise
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      3.640E03  1.0E04  0.40
! 0.25 inch wedge rise (1.8393 - 0.25 = 1.5893 * 1979 = 3145)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      3.1450E03 1.0E04  0.40
! 0.375 inch wedge rise (1.8393 -.375=1.4643*1979=2898)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!    14      0        0       37.5      2.898E03  1.0E04  0.40
! modified for new type 6.7, MU1 for slope Mu2 for Face, T=Toe out, F=Toe in
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force    LB      Mu1    Mu2    Toe
!    14      0        0       37.5   2.898E3  1.0E04  0.40   0.40   .T.
! 0.50 inch wedge rise (1.8393 - 0.50 = 1.3393 * 1979 = 2650)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      2.650E03 1.0E04  0.40
! 0.75 inch wedge rise (1.8393 - 0.75 = 1.0893 * 1979 = 2155)
!   Ch #  Pwl Stiff Pwl Damp Wedge Angle    Force   LB      Mu
!   14      0        0       37.5      2.155E03 1.0E04  0.40
!
! Option for a VARIABLE DAMPED TRUCK design
!   Ch #  Pwl Stf Pwl Damp  Wedge Ang  Force    LB      Mu1    Mu2    Toe
!    14     17        0     32.0     0.0    1.0E04   0.40   0.40   .T.
!
!  NEW Type 6.9 3D Stick-Slip Wedge
!  Pwl-toe is for cloumn wear face
!  V/C = .F. for constant damped
!  Ka and Ca are force accumulator stiffness and damping
!  XDIR = 1.d0 for leading wedges, -1.d0 for trailing wedges
!  Column Face Normal Force limit FWNMAX = 1.0D5
!
!   Ch #  Pwl-Stf Pwl-Toe  Wedge Ang  V/C    Ka     Ca     Mu1  Mu2  XDIR  FWNMAX
    14      23     24      37.5     .F.   1.0E6  1.0E3   0.40  0.4  1.D0   1.0D5
   114      23     24      37.5     .F.   1.0E6  1.0E3   0.40  0.4 -1.D0   1.0D5
!
!******************* Bearing Adapter Side Frame to Axle ********************
```

```
! Vertical side frame to axle connections with friction, type 6.5
   15   18          0       1.0E06      1.0E03  0.5
! Vertical damping for bearing adapters with gap element
   16    0          19        1000.0     0.031382
! Longitudinal stiffness and stops
!    17   20          0         1.0E09     -1.0E09
! Lateral stiffness and stops
   18   21          0         1.0E09     -1.0E09
! Yaw stiffness and stops
   19   22          0         1.0E09     -1.0E09
! NEW Bolster Displacement Input Connections
   21    25         0         1.0E06     -1.0E06
```

For each piecewise linear function, list the identification number, the number of break points, and the ordinate, lb or in-lb, over abscissa, inches or rad, at each break point.

Note - extension is assumed to be positive for both ordinate and abscissa and 0.0 for the first break point indicates symmetry about the origin.

```
   PWL    IBP    Ordinates over Abscissae
------------------------------------------------------------------------
\PWL DATA
! ********************** Bolster to Side Frame Connections *******************
! Longitudinal
! Includes shear stiffness of coils - same stiffness as lateral 17,800 lb/in
! Longitudinal clearances +/- 0.125 inches
! some damping for integration stability
!    11     3      0.0      1.225E3   1.02225E5
!             0.0      0.125     0.60
! variable Damped truck
!    11     3      0.0      1.808E3   1.01808E5
!                         0.0      0.125     0.60
!    12     2      0.0      1.E3
!                         0.0      1.0
   11     3      0.0      2.225E3   1.02225E5
                          0.0      0.125     0.60
   12     2      0.0      1.E3
                          0.0      1.0
! Pitch Stiffness and Stops Mid Tolerance is Approx +/- 2.4 Degrees=0.042mRad
   13     3      0.0      0.0    6.40E7
                0.0      0.042  1.042
! ****************** Warp resistance ****************************************
! these values are empirical to include the missing effects of wedging action
! worn truck
! Warp resistance for bolster to side frame
!   14     3      0.0      5.25E04   6.924E05
!               0.0      0.030     0.040
! New truck
! Warp resistance for bolster to side frame
   14      3      0.0      2.55E05   8.95E05
               0.0      0.030     0.040
! Stiff H-frame truck
! Warp resistance for bolster to side frame
!   14     3      0.0      1.275E06  1.915E06
!               0.0      0.030     0.040
```

```
! Lateral Stiffness of bolster to side frame connection divided by 4
! 17,800 lb/in
   15    3     0.0     2.225E3   1.022E5
                       0.0     0.50     0.60
! Lateral Stiffness of bolster to side frame connection divided by 4, Variable Damped truck
! 14,666 lb/in
!   15    3     0.0     1.808E3   1.018E5
!                      0.0     0.50     0.60
! Vertical Secondary Suspension
! 9-D5 outers and 5-D5 inners
!   16     5    -1.954E5 -9.5414E4  -3.50E2    0.0      0.0
!              -3.7875  -3.6875     0.0      0.0625   1.0
! stiffness divided by 4
!   16     5    -0.4885E5 -2.38535E4 -8.75E1    0.0      0.0
!              -3.7875  -3.6875      0.0      0.0625   1.0
! with initial offsets calculated for loaded static weight of -15403.78
!   16     6    -0.4885E5 -2.38535E4  -1.540378E4 -8.75E1   0.0     0.0
!              -1.39747  -1.29747     0.0        2.3900   2.4525   4.0
! MAMBO model uses spring stiffness of 3000lb/in for Variably Damped Wedge
!   16     2     -5.0E3    0.0
!               -1.0      0.0
!! with initial offsets calculated for loaded static weight of -15403.78
! Turned back on - 4/22/07 NGW
!   16     6    -0.4885E5 -2.38535E4  -1.540378E4 -8.75E1   0.0     0.0
!              -1.39747  -1.29747     0.0        2.3900   2.4525   4.0
  16   6     -2.4487335E4     -2.3837335E4     -1.540378E4     -1.3122E2   0.0    0.0
            -1.39747       -1.29747         0.0           2.39       2.410  4.0
! Spring nest for the variable damped option (6 D5 Outers and 7 D5 Inners)
!  16     6    -4.48E+04 -1.98E+04   -1.22E+04   -1.23E+02 0.0      0.0
!             -1.5171   -1.4171      0.0        2.2704   2.3329   3.2079
!
!***********Optional control coils for a variably damped truck***************
! 2 B353 outers and 2 B354 inners, zero wedge rise - this is different than LHOPR-04
!  17     8   -5.903E+04 -9.0314E+03 -6.303E+03 -1.89E+02 -1.767E3 -72.25   0.0    0.0
!            -1.5085    -1.4085      0.0        2.279    2.3415    3.2165  3.3415 4.3415
!******************* Bearing Adapter Side Frame to Axle ********************
! Vertical Bearing adapter connection with offset for static load
  18     3    -1.5691E4 0.0        0.0
             0.0     0.031382    1.0
! Vertical Bearing adapter damping
  19     2     0.0     1.E3
                       0.0     1.0
! Bearing adapter stops
! Longitudinal Stiffness with Stops
!   20     3     0.0     1.0     1.E3
!                      0.0     0.0468  0.0478
! Lateral Stiffness with Stops
  21     3     0.0     1.0     1.E3
             0.0     0.250   0.251
! Yaw Stiffness with Stops
  22     3     0.0     0.0    6.4E5
             0.0     0.030  0.040
!****************** Type 6.9 Wedge PWLs ********************
! Control Coil Stiffness - 100 ton constant damped truck theoretical data
! 3640 lbs at 0.0 wedge rise.   1908.3 lbs at 0.875 rise, 1979.3 lbs/in
!   23     2    -3640.2  -1908.3
```

```
!              0.0      0.875
! MAMBO control coil stiffness is 1979lb/in; 3661lb at 0.0in wedge rise (Preload)
!   2177lb at 0.75in wedge rise
!  23    2     -9204.7     -7473.25
!              0.0        0.875
  23     5     -5681.2    -3702.2   -1723.2    0.0        0.0
               -1.0       0.0       1.0     1.87064     10.0
! Column wear face - Hypothetical hollow, 0.1 inch deep centered on -0.75
  24     3     0.015708   0.0    -0.015708
              -4.5      0.0    4.5
! NEW Displacement Input Stiffnesses
  25     2     0.0      1.0E6
              0.0      1.0
```

B.2.2. Input Files

Vertical input file entitled ‘bolst_displ_input3.inp’:

```
Input file (.INP) for NUCARS 2006
=======================================
Vertical Displacement of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.
-----------------------------------------------------------------------
Segment Shape  Segment  End Start & End Base  Coef.1  Coef.2  Amp.
-----------------------------------------------------------------------
\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1  1  1
! History 1 (Longitudinal) is Null for this input
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 2 (Lateral) is Null for this input
2  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
! History 3 (Vertical) is defined as a swept sine with nat'l freq = 2rad/sec, with amp=1.0in
3  1  1
! Segment Shape Segment t  End Start & End Base  Coef.1  Coef.2  Amp.
   1      4    2000.0       0.0         0.0  0.31831  0.31831  1.0
! History 4 (Roll) is Null for this input
4  1  1
   1      0    2000.0       0.0         0.0     0.0     0.0    0.0
```

! History 5 (Pitch) is Null for this input
5 1 1
1 0 2000.0 0.0 0.0 0.0 0.0 0.0
! History 6 (Yaw) is Null for this input
6 1 1
1 0 2000.0 0.0 0.0 0.0 0.0 0.0

Yaw input file entitled 'bolst_displ_input36.inp':

Input file (.INP) for NUCARS 2006
==
Yaw Rotation of Bolster as an input to the system

\INPUT TITLE
Bolster Displacement as an Input Using Type 1 Connection

Give the number of inputs and for each, the input number, the number of input segments,
and an indicator determining whether it is time or distance based, ITD = 1 for time, 2 for distance.
For each segment, provide the segment number, the shape function number, 0 = NULL, 1 = CUSP,
2 = BEND, 3 = SIN, 4 = SSIN, the time or distance at the segment end, in seconds or feet and the shape
base level at the start and end of the segment, pounds or inches. Coef1 & Coef2 are two coefficients that
in general determine the wavelength and repeat distance of the shape.
In the case of the swept sine SSIN they are the start and end frequency in Hz.
Finally, the function amplitude, in pounds or inches for the English system and
Newton-meters or Newtons for the metric system.

Segment Shape Segment End Start & End Base Coef.1 Coef.2 Amp.

\INPUT HISTORY DATA
!Number of individual input histories
6
! Unique History number one, number of segments/history, and time=1/distance=2
1 1 1
! History 1 (Longitudinal) is Null for this input
1 0 2000.0 0.0 0.0 0.0 0.0 0.0
! History 2 (Lateral) is Null for this input
2 1 1
1 0 2000.0 0.0 0.0 0.0 0.0 0.0
! History 3 (Vertical) is Null for this input
3 1 1
1 4 2000.0 0.0 0.0 0.31831 0.31831 1.0
! History 4 (Roll) is Null for this input
4 1 1
1 0 2000.0 0.0 0.0 0.0 0.0 0.0
! History 5 (Pitch) is Null for this input
5 1 1
1 0 2000.0 0.0 0.0 0.0 0.0 0.0
! History 6 (Yaw) is defined as sine with nat'l freq = 2 rad/sec., with amp=0.0031645rad
6 1 1
! Segment Shape Segment t End Start & End Base Coef.1 Coef.2 Amp.
1 2 2000.0 0.0 0.0 0.1 100.0 0.012

B.2.3. Data Files

Data file entitled ‘sngl_trk.dat’:

```
Data file (.DAT) for NUCARS Version 2.0
========================================

$\EQUILIBRIUM

SELECTION OF OUTPUT
===================

!\CURVATURE
!   1
!   8
!\SUPERELEVATION
!   1
!   8

  Body #    No. & List of DoF's
----------------------------------------------------------------------
$\DOF DISPLACEMENT
  34
    1   6   1 2 3 4 5 6
    3   6   1 2 3 4 5 6
    4   6   1 2 3 4 5 6
    7   5   1 2 3 4 5
    8   6   1 2 3 4 5 6
    9   5   1 2 3 4 5

$\DOF VELOCITY
    52
    1       8      2 3 4 5 6 7.01 8.01 9.01
    2       4      2 3 4 6
    3       4      2 3 4 6
    4       5      1 2 3 5 6
    5       5      1 2 3 5 6
    6       5      1 2 3 5 6

$\DOF ACCELERATION

$\DOF FORCE
   18
     1   6   1 2 3 4 5 6
     3   6   1 2 3 4 5 6
     4   6   1 2 3 4 5 6

\CONNECTION FORCE
  20
  127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
  119.1 119.2 121.1 121.2 123.1 123.2 125.1 125.2

\CONNECTION FORCE SUM
   2
   'Ld Trk Lft Vert Sprg Nest'  1   4  119.2 121.2 123.2 125.2  1.0 1.0 1.0 1.0
   'Ld Trk Lft Lat Sprng Nest'  1   4  119.1 121.1 123.1 125.1  1.0 1.0 1.0 1.0
   'Ld Trk Lft Spg Grp Vt For'  1   6  119.2 121.2 123.2 125.2 127.1 129.1  1.0 1.0 1.0 1.0 1.0 1.0
```

```
   'Ld Trk Rgt Spg Grp Vt For'  1   6  120.2 122.2 124.2 126.2 128.1 130.1  1.0 1.0 1.0 1.0 1.0 1.0
   'Ld Trk Lft Spg Grp Lat Fr'  1   6  119.1 121.1 123.1 125.1 127.2 129.2  1.0 1.0 1.0 1.0 1.0 1.0
   'Ld Trk Rgt Spg Grp Lat Fr'  1   6  120.1 122.1 124.1 126.1 128.2 130.2  1.0 1.0 1.0 1.0 1.0 1.0
!    'LEAD TRK SPG GRP ROLL MOM'  2   2  13  14  39.5  -39.5

\CONNECTION STROKE
  16
  127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
  119.2 121.2 123.2 125.2

\CONNECTION VELOCITY
12
 127.1 127.2 127.3 128.1 128.2 128.3 129.1 129.2 129.3 130.1 130.2 130.3
```

B.2.4. Run Files

Run file for the vertical bolster displacement input entitled ‘bolst_wedge_sf_bolst-vert-displ_69_const.run’:

```
Run file (.RUN) for NUCARS Version 2.0
=====================================
\RUN TITLE
Single Truck with 1/2 car mass, type 6.9 wedge toeout w/vert displ of bolster as input
\SYSTEM FILE
   'bolst_wedge_sf_69_const.SYS'

\DATA FILE
   'sngl_trk.DAT'

\INPUT FILE
   'bolst_displ_input3.INP'


!\REVERSE VIDEO

\CONTROL CONSTANTS
   1      0     .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

Run file for the yaw input entitled ‘bolst_wedge_sf_bolst-vrt-displ-w-yaw_69_const.run’:

```
Run file (.RUN) for NUCARS Version 2.0
=====================================
\RUN TITLE
Single Truck with 1/2 car mass, type 6.9 wedge toeout w/yaw as input
\SYSTEM FILE
   'bolst_wedge_sf_69_const.SYS'

\DATA FILE
   'sngl_trk.DAT'
```

```
\INPUT FILE
   'bolst_displ_input_36.INP'

!\REVERSE VIDEO

\CONTROL CONSTANTS
   1      0     .F.

\STEPPING CONSTANTS
   0.01  20.0   0.1
```

APPENDIX C: STAND-ALONE MATLAB MODEL SIMULATION FILES

C.1. Variably-Damped Friction Wedge Model

Four files were required in order to run the simulations for the variably-damped stand-alone friction wedge model. Due to their large size, these files can be found on the CVeSS FTP server in folder "W:\Internal Publications\Theses\Jennifer Steets Spring 07\Var Damped ode". The file entitled 'variabledampkin.src' is the source file, which was used to derive the equations for the force vector and mass matrix for the model. In order to read this file, the software program MATLAB must be used. Type "procread('variabledampkin.src') in the "Command Window", and the file will be accessed. The MAPLE kernel inside MATLAB was used to output the equations from the source file to be used in other m-files. The force vector and mass matrix solved for using this source file were then inserted into the 'vdampodefun.m' file, which is called the function file. The function file calculates the state variables at each time step, which determine the equations of motion, for the system based on which contact points are in contact with the interaction surfaces. Determining which contact points are in contact with the side frame or bolster is performed using a series of 'if' statements. The points are in contact if the longitudinal component of the vector from the contact points to the side frame or bolster is less than 0. When the contact points detect contact, the variable representing that contact point is equal to 1. The points are not in contact if the longitudinal component of the vector from the contact points to the side frame or bolster is greater than 0. When the contact points do not detect contact, the variable representing that contact point is equal to 0.

The 'vdforces.m' file calculates the forces and moments acting on each point, based on whether they are in contact with the side frame or bolster. The points detect contact in the same manner described for the function file, which is through a series of 'if' statements. The file calculates a matrix of forces, moments, rate of energy dissipated, velocities and displacements for each time step, which is defined in the 'vardiffeqintegrate.m' file. The 'vddiffeqintegrate.m' file integrates 'vdampodefun.m' using the 'ode15s' command, which solves variable order differential equations, and calls on 'vdforces.m' for each toe and yaw rotation specification tested in the simulations. The main purpose of this file is to output and save the data outputted in each simulation as a .MAT-file, which is used for analysis of the data.

C.2. Constantly-Damped Friction Wedge Model

Four files were required in order to run the simulations for the constantly-damped Stand-Alone friction wedge model. Due to their large size, these files can be found on the CVeSS FTP server in folder "W:\Internal Publications\Theses\Jennifer Steets Spring 07\Const Damped ode". The file entitled 'constantdampkin.src' is the source file, which was used to derive the equations for the force vector and mass matrix for the model. In order to read this file, the software program MATLAB must be used. Type "procread('constantdampkin.src') in the "Command Window", and the file will be accessed. The MAPLE kernel inside MATLAB was used to output the equations from the source file to be used in other m-files. The force vector and mass matrix solved for using this source file were then inserted into the 'cdampodefun.m' file, which is called the function file. The function file calculates the state variables at each time step, which determine the equations of motion, for the system based on which contact points are in contact with the interaction surfaces. Determining which contact points are in contact with the side frame or bolster is performed using a series of ‘if’ statements. The points are in contact if the longitudinal component of the vector from the contact points to the side frame or bolster is less than 0. When the contact points detect contact, the variable representing that contact point is equal to 1. The points are not in contact if the longitudinal component of the vector from the contact points to the side frame or bolster is greater than 0. When the contact points do not detect contact, the variable representing that contact point is equal to 0.

The ‘cdforces.m’ file calculates the forces and moments acting on each point, based on whether they are in contact with the side frame or bolster. The points detect contact in the same manner described for the function file, which is through a series of ‘if’ statements. The file calculates a matrix of forces, moments, rate of energy dissipated, velocities and displacements for each time step, which is defined in the ‘cdiffeqintegrate.m’ file. The ‘cddiffeqintegrate.m’ file integrates ‘cdampodefun.m’ using the ‘ode15s’ command, which solves variable order differential equations, and calls on ‘cdforces.m’ for each toe and yaw rotation specification tested in the simulations. The main purpose of this file is to output and save the data outputted in each simulation as a .MAT-file, which is used for analysis of the data.

APPENDIX D: COMPARISON PLOTS FOR NUCARS® VS MATLAB MODEL M- FILES

The MATLAB m-files shown here were used to plot the results of both the NUCARS® and stand-alone models all in Toe Out against each other. The results of the models were saved as MATLAB MAT-files and loaded into the following M-files. The vertical and longitudinal forces were plotted, and the rate of energy dissipation was calculated and plotted. The vertical force hysteresis plot was created by plotting the vertical forces against the vertical displacement of the wedge.

D.1. Variably-Damped Model

D.1.1. Vertical Bolster Displacement Input

```
% Toe OUT
close all
clear all

load('var_vrt_69_out.mat')
load('var_vrt_68_out.mat')
% load('run0_psi_0.mat')
load('vdrun_toe_-0.2_psi_0.mat')

 q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

t_vrt = t;
Fx_vrt = Fx;
Fz_vrt = Fz;
EsideframeT_vrt = EsideframeT;
FsideframeNormal_vrt =  FsideframeNormal;
FsideframeTangent_vrt = FsideframeTangent;
FbolsterNormal_vrt = FbolsterNormal;
Momentsideframex_vrt = Momentsideframex;
Momentsideframey_vrt = Momentsideframey;
Momentsideframez_vrt = Momentsideframez;
```

```
%%%% Plots Type 6.8 & 6.9 damping forces on one plot
figure(1)
plot(var_vrt_69_out(:,1),var_vrt_69_out(:,2))
hold on
plot(var_vrt_68_out(:,1),var_vrt_68_out(:,2),'--r')
plot(t_vrt,-Fz_vrt,'g')
hold off
xlim([0 10])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')

saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\vert_wdg_force','jpg')

figure(2)
plot(var_vrt_69_out(:,1),var_vrt_69_out(:,3))
hold on
plot(t_vrt,Fx_vrt,'g')
hold off
xlim([0 10])
ylim([0 8000])
% title('Longitudinal Forces for Variably-Damped Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Type 6.9', 'MATLAB')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\long_force','jpg')

%%% Rate of Energy Dissipation %%%
vel_69=abs(var_vrt_69_out(:,8));
vel_68=abs(var_vrt_68_out(:,6));
energy_dissip_69=var_vrt_69_out(:,2).*vel_69;
energy_dissip_68=var_vrt_68_out(:,2).*vel_68;

figure(3)
plot(var_vrt_69_out(:,1), energy_dissip_69)
hold on
plot(var_vrt_68_out(:,1), energy_dissip_68,'--r')
plot(t_vrt,EsideframeT_vrt,'g')
hold off
xlim([0 10])
% ylim([-6000 0])
% title('Energy Dissipated due to vertical friction')
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\rate_energy_dissip','jpg')

figure(4)
plot(var_vrt_69_out(:,1), energy_dissip_69)
hold on
plot(var_vrt_68_out(:,1),energy_dissip_68,'--r')
```

```
plot(t_vrt,EsideframeT_vrt,'g')
hold off
xlim([4 7])
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southeast')
saveas(figure(4),'C:\Documents and Settings\Jenn\Desktop\Friction
Wedge\MATLAB Outputs\Var vrt inp out\zoom_e_dissip','jpg')

figure(5)
plot(t_vrt,q5)
xlim([0 10])
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Bolster Displacement, (in)','FontSize',16)
legend('z=sin(2t)')
% text(['z=sin(2t)'],['$\psi=0\']);
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\bolst_vrt_disp','jpg')

mambo_displ=q2(1:400)-10.25;
figure(6)
plot(var_vrt_69_out(1:50,5),var_vrt_69_out(1:50,2))
hold on
plot(var_vrt_68_out(1:50,4),var_vrt_68_out(1:50,2),'--r')
plot(mambo_displ,-Fz_vrt(1:400),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\hyst_vrt_force','jpg')

figure(7)
plot(var_vrt_69_out(:,1),var_vrt_69_out(:,2))
hold on
plot(var_vrt_68_out(:,1),var_vrt_68_out(:,2),'--r')
plot(t_vrt,-Fz_vrt,'g')
hold off
xlim([4 7])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\zoomed_vert_force','jpg')

figure(8)
plot(var_vrt_69_out(:,1),var_vrt_69_out(:,3))
hold on
plot(t_vrt,Fx_vrt,'g')
hold off
xlim([4 7])
ylim([0 8000])
% title('Longitudinal Forces for Variably-Damped Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
```

```
legend('Type 6.9', 'MATLAB')
saveas(8,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var vrt inp out\zoomed_long_force','jpg')
```

D.1.2. Vertical Bolster Displacement with Yaw Input

```
% Toe OUT
close all
clear all

load('var_yaw_68_out.mat')
load('var_yaw_69_out.mat')
load('vdrun_toe_-0.2_psi_0.012.mat')


q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

t_yaw=t;
Fx_yaw = Fx;
Fz_yaw = Fz;
EsideframeT_yaw = EsideframeT;
FsideframeNormal_yaw = FsideframeNormal;
FsideframeTangent_yaw = FsideframeTangent;
FbolsterNormal_yaw = FbolsterNormal;
Momentsideframex_yaw = Momentsideframex;
Momentsideframey_yaw = Momentsideframey;
Momentsideframez_yaw = Momentsideframez;


%%%% Plots Type 6.8 & 6.9 damping forces on one plot
figure(1)
plot(var_yaw_69_out(:,1),var_yaw_69_out(:,2))
hold on
plot(var_yaw_68_out(:,1),var_yaw_68_out(:,2),'--r')
plot(t_yaw(5:1000),-Fz_yaw(5:1000),'g')
hold off
xlim([0 10])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\vert_force','jpg')

figure(2)
```

```
plot(var_yaw_69_out(:,1),var_yaw_69_out(:,3))
hold on
plot(t_yaw(5:1000),Fx_yaw(5:1000),'g')
hold off
xlim([0 10])
ylim([0 6000])
% title('Longitudinal Forces for Variably-Damped Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Type 6.9', 'MATLAB')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\long_force','jpg')

%%% Rate of Energy Dissipation %%%
vel_69=abs(var_yaw_69_out(:,8));
vel_68=abs(var_yaw_68_out(:,6));
energy_dissip_69=var_yaw_69_out(:,2).*vel_69;
energy_dissip_68=var_yaw_68_out(:,2).*vel_68;

figure(3)
plot(var_yaw_69_out(:,1), energy_dissip_69)
hold on
plot(var_yaw_68_out(:,1), energy_dissip_68,'--r')
plot(t_yaw(5:1000),EsideframeT_yaw(5:1000),'g')
hold off
xlim([0 10])
% ylim([-6000 0])
% title('Energy Dissipated due to vertical friction')
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\rate_energy_dissip','jpg')

figure(4)
plot(var_yaw_69_out(:,1), energy_dissip_69)
hold on
plot(var_yaw_68_out(:,1),energy_dissip_68,'--r')
plot(t_yaw,EsideframeT_yaw,'g')
hold off
xlim([4 7])
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southeast')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\zoom_e_dissip','jpg')

mambo_displ=q2(300:700)-10.25;
figure(5)
plot(var_yaw_69_out(30:70,5),var_yaw_69_out(30:70,2))
hold on
plot(var_yaw_68_out(30:70,4),var_yaw_68_out(30:70,2),'--r')
plot(mambo_displ,-Fz_yaw(300:700),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
```

```
legend('Type 6.9','Type 6.8','MATLAB','Location','southeast')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\hystersis','jpg')

figure(6)
plot(var_yaw_69_out(:,1),var_yaw_69_out(:,2))
hold on
plot(var_yaw_68_out(:,1),var_yaw_68_out(:,2),'--r')
plot(t_yaw(5:1000),-Fz_yaw(5:1000),'g')
hold off
xlim([4 7])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB','Location','southeast')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\zoomed_vert_force','jpg')

figure(7)
plot(var_yaw_69_out(:,1),var_yaw_69_out(:,3))
hold on
plot(t_yaw(5:1000),Fx_yaw(5:1000),'g')
hold off
xlim([4 7])
ylim([0 5000])
% title('Longitudinal Forces for Variably-Damped Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Type 6.9', 'MATLAB')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Var yaw inp out\zoomed_long_force','jpg')
```

D.2. Constantly-Damped Model

D.2.1. Vertical Bolster Displacement Input

```
close all
clear all

load('const_vrt_69_out.mat')
load('const_vrt_68_out.mat')
load('cdrun_toe_-0.2_psi_0.mat')

t_out=t;
q_vert_out=y(:,2);
Momentsideframex_out=Momentsideframex;
Momentsideframey_out=Momentsideframey;
Momentsideframez_out=Momentsideframez;
Fx_out=Fx;
Fz_out=Fz;
Fspring2_out=Fspring2;
Esideframe_out=Esideframe;
```

```
spring_displ_out=vector;  % Control Coil length

%%%% Plots Type 6.8 & 6.9 & MAMBO damping forces on one plot %%%%%
figure(1)
plot(const_vrt_69_out(:,1),const_vrt_69_out(:,2))
hold on
plot(const_vrt_68_out(:,1),const_vrt_68_out(:,2),'--r')
plot(t_out,Fz_out,'g')
hold off
xlim([0.5 10])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\vert_wdg_force','jpg')


figure(2)
plot(const_vrt_69_out(:,1),const_vrt_69_out(:,3))
hold on
plot(t_out,Fx_out,'g')
hold off
xlim([0.5 10])
ylim([0 8000])
% title('Longitudinal Forces for Variably-Damped Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Type 6.9', 'MATLAB')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\long_wdg_force','jpg')

%%% Rate of Energy Dissipation %%%
vel_69=const_vrt_69_out(:,8);
vel_68=const_vrt_68_out(:,6);
energy_dissip_69=const_vrt_69_out(:,2).*vel_69;
energy_dissip_68=const_vrt_68_out(:,2).*vel_68;

figure(3)
plot(const_vrt_69_out(:,1), -energy_dissip_69)
hold on
plot(const_vrt_68_out(:,1), -energy_dissip_68,'--r')
plot(t_out,Esideframe_out,'g')
hold off
xlim([0.5 10])
% ylim([-6000 0])
% title('Energy Dissipated due to vertical friction')
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\rate_energy_dissip','jpg')

figure(4)
plot(const_vrt_69_out(:,1), -energy_dissip_69)
hold on
```

```
plot(const_vrt_68_out(:,1),-energy_dissip_68,'--r')
plot(t_out,Esideframe_out,'g')
hold off
xlim([4 7])
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southwest')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\zoom_e_dissip','jpg')

amp=(max(y(:,2))-min(y(:,2)))/2;
initial=max(y(:,2))-amp;
mambo_displ=q_vert_out-initial;
figure(5)
plot(const_vrt_69_out(35:75,5), const_vrt_69_out(35:75,2))
hold on
plot(const_vrt_68_out(35:75,4),const_vrt_68_out(35:75,2), '--r')
plot(mambo_displ(350:750),Fz_out(350:750),'g')
xlim([-1.1 1.1])
ylim([-2100 2600])
xlabel('Vertical Displacement, (in)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9', 'Type 6.8', 'MATLAB')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\hyst_force','jpg')

figure(6)
plot(const_vrt_69_out(:,1),const_vrt_69_out(:,2))
hold on
plot(const_vrt_68_out(:,1),const_vrt_68_out(:,2),'--r')
plot(t_out,Fz_out,'g')
hold off
xlim([3.5 7.5])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const vrt inp out\zoomed_vert_force','jpg')
```

D.2.2. Vertical Bolster Displacement with Yaw Input

```
% Toe OUT
close all
clear all

load('const_yaw_69_out.mat')
load('const_yaw_68_out.mat')
load('cdrun_toe_-0.2_psi_0.012.mat')

%%% MAMBO Model Outputs %%%
t_out=t;
q_vert_out=y(:,2);
Fx_out=Fx;
```

```
Fz_out=Fz;
Esideframe_out=Esideframe;
Fspring2_out=Fspring2;
% FsideframeNormal_out=FsideframeNormal;
% FsideframeTangent_out=FsideframeTangent;
% FbolsterNormal_out=FbolsterNormal;
Momentsideframex_out = Momentsideframex;
Momentsideframey_out = Momentsideframey;
Momentsideframez_out = Momentsideframez;

load('cdrun_toe_-0.2_psi_0.mat')
t_vrt=t;
Fx_vrt=Fx;

%%%% Plots Type 6.8 & 6.9 damping forces on one plot
figure(1)
plot(const_yaw_69_out(:,1),const_yaw_69_out(:,2))
hold on
plot(const_yaw_68_out(:,1),const_yaw_68_out(:,2),'--r')
plot(t_out,Fz_out,'g')
hold off
xlim([0.5 10])
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\vert_wdg_force','jpg')


figure(2)
plot(const_yaw_69_out(:,1),const_yaw_69_out(:,3))
hold on
plot(t_out,Fx_out,'g')
hold off
xlim([0.5 10])
ylim([0 8000])
xlabel('Time, (s)','FontSize',16)
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Type 6.9', 'MATLAB')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\long_wdg_force','jpg')

%%% Rate of Energy Dissipation %%%
vel_69=const_yaw_69_out(:,8);
vel_68=const_yaw_68_out(:,6);
energy_dissip_69=const_yaw_69_out(:,2).*vel_69;
energy_dissip_68=const_yaw_68_out(:,2).*vel_68;

figure(3)
plot(const_yaw_69_out(:,1), -energy_dissip_69)
hold on
plot(const_yaw_68_out(:,1), -energy_dissip_68,'--r')
plot(t_out,Esideframe_out,'g')
hold off
xlim([0.5 10])
% ylim([-6000 0])
```

```
% title('Energy Dissipated due to vertical friction')
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\rate_energy_dissip','jpg')

figure(4)
plot(const_yaw_69_out(:,1), -energy_dissip_69)
hold on
plot(const_yaw_68_out(:,1),-energy_dissip_68,'--r')
plot(t_out,Esideframe_out,'g')
hold off
xlim([3.5 7.5])
xlabel('Time, (s)','FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB','Location','southwest')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\zoom_e_dissip','jpg')


mambo_displ=q_vert_out-9.95;
figure(5)
plot(const_yaw_69_out(35:75,5), const_yaw_69_out(35:75,2))
hold on
plot(const_yaw_68_out(35:75,4),const_yaw_68_out(35:75,2), '--r')
plot(mambo_displ(350:750),-Fz(350:750),'g')
xlim([-1.1 1.1])
xlabel('Vertical Displacement, (in)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9', 'Type 6.8','MATLAB')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\hysteresis','jpg')

figure(6)
plot(const_yaw_69_out(:,1),const_yaw_69_out(:,2))
hold on
plot(const_yaw_68_out(:,1),const_yaw_68_out(:,2),'--r')
plot(t_out,Fz_out,'g')
hold off
xlim([3.5 7.5])
% title('Vertical Wedge Force for Variably-damped, Toe Out Wedge')
xlabel('Time, (s)','FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Type 6.9','Type 6.8','MATLAB')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\zoom_vert_force','jpg')

figure(7)
plot(t_vrt,Fx_vrt)
hold on
plot(t_out,Fx_out,'g')
hold off
xlim([0.5 10])
ylim([0 8000])
xlabel('Time, (s)','FontSize',16)
```

```
ylabel('Longitudinal Force, (lb)','FontSize',16)
legend('Vertical', 'Yaw')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\Const yaw inp out\long_comp_input','jpg')
```

APPENDIX E: COMPARISON PLOTS ALL TOE CASES OF MATLAB MODEL M- FILES

The MATLAB m-files shown here were used to plot the results of the stand-alone MATLAB model for all toe cases against each other. The results of the models were saved as MATLAB MAT-files and loaded into the following M-files. The vertical and longitudinal forces and yaw and pitch moments were plotted, and the rate of energy dissipation was calculated and plotted. The vertical force hysteresis plot was created by plotting the vertical forces against the vertical displacement of the wedge.

E.1. Variably-Damped Model

E.1.1. Vertical Bolster Displacement Input

```
%%%% Creates Mambo Comparisons for same inputs, but 3 toe cases
%%%% (Toe In/No Toe/Toe Out)
close all
clear all

%%% Case 1= Toe OUT %%%
load('vdrun_toe_-0.2_psi_0.mat')

q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

t_out=t;
q_vert_out=y(:,2);
Momentsideframex_out=Momentsideframex;
Momentsideframey_out=Momentsideframey;
Momentsideframez_out=Momentsideframez;
Fx_out=Fx;
Fz_out=Fz;

EsideframeT_out=EsideframeT;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%% Case 2 = No Toe Version %%%
load('vdrun_toe_0_psi_0.mat')

q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Longitudinal Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

Fx_no = Fx;
Fz_no = Fz;
EsideframeT_no = EsideframeT;
Momentsideframex_no = Momentsideframex;
Momentsideframey_no = Momentsideframey;
Momentsideframez_no = Momentsideframez;
q_vert_no=q2;
u_vert_no=u2;
t_no=t;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 3 = Toe In %%%
load('vdrun_toe_0.2_psi_0.mat')

q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

Fx_in = Fx;
Fz_in = Fz;
EsideframeT_in = EsideframeT;
Momentsideframex_in = Momentsideframex;
Momentsideframey_in = Momentsideframey;
Momentsideframez_in = Momentsideframez;
q_vert_in=q2;
u_vert_in=u2;
t_in=t;

%%% PLOTS %%%
figure(1)
plot(t_out,-Fz_out)
hold on
plot(t_no, -Fz_no,'--r')
plot(t_in,-Fz_in,'g')
```

```
hold off
xlim([0 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(figure(1),'C:\Documents and Settings\Jenn\Desktop\Friction
Wedge\MATLAB Outputs\mambo var vrt inp\vert_wdg_force','jpg')

figure(2)
plot(t_out,-Fz_out)
hold on
plot(t_no, -Fz_no,'--r')
plot(t_in,-Fz_in,'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\zoomed_vert_force','jpg')


figure(3)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
xlim([0 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\long_wdg_force','jpg')

figure(4)
plot(t_out,EsideframeT_out)
hold on
plot(t_no,EsideframeT_no,'--r')
plot(t_in,EsideframeT_in,'g')
hold off
xlim([0 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\e_dissip','jpg')

figure(5)
plot(q_vert_out(1:400),-Fz_out(1:400))
hold on
plot(q_vert_no(1:400),-Fz_no(1:400),'--r')
plot(q_vert_in(1:400),-Fz_in(1:400),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Friction Force, (lb)','FontSize',16)
```

```
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\vert_force_hyst','jpg')

figure(6)
plot(t_out,-Fz_out)
hold on
plot(t_no, -Fz_no,'--r')
plot(t_in,-Fz_in,'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\zoom_vert_force','jpg')

figure(7)
plot(t_out(400:700),Fx_out(400:700))
hold on
plot(t_no(400:700),Fx_no(400:700),'--r')
plot(t_in(400:700),Fx_in(400:700),'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\zoomed_long_force','jpg')

figure(8)
plot(t_out,EsideframeT_out)
hold on
plot(t_no,EsideframeT_no,'--r')
plot(t_in,EsideframeT_in,'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(8,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var vrt inp\zoomed_e_dissip','jpg')
```

E.1.2. Vertical Bolster Displacement with Yaw Input

```
%%%% Creates Mambo Comparisons for same inputs, but 3 toe cases
%%%% (Toe In/No Toe/Toe Out)
close all
clear all

%%% Case 1= Toe OUT %%%
load('vdrun_toe_-0.2_psi_0.012.mat')

q1=y(:,1); %Wedge Long displacement
```

```
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

t_out=t;
q_vert_out=y(:,2);
Momentsideframex_out=Momentsideframex;
Momentsideframey_out=Momentsideframey;
Momentsideframez_out=Momentsideframez;
Fx_out=Fx;
Fz_out=Fz;

EsideframeT_out=EsideframeT;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 2 = No Toe Version %%%
load('vdrun_toe_0_psi_0.012.mat')

q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Longitudinal Velocity
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

Fx_no = Fx;
Fz_no = Fz;
EsideframeT_no = EsideframeT;
Momentsideframex_no = Momentsideframex;
Momentsideframey_no = Momentsideframey;
Momentsideframez_no = Momentsideframez;
q_vert_no=q2;
u_vert_no=u2;
t_no=t;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 3 = Toe In %%%
load('vdrun_toe_0.2_psi_0.012.mat')

q1=y(:,1); %Wedge Long displacement
q2=y(:,2); %Wedge Vertical Displacement
q3=y(:,3); %Wedge Pitch Displacement
q4=y(:,4); %Wedge Yaw Displacement
q5=y(:,5); %Bolster Displacement
u1=y(:,6); %Wedge Long Velocity
```

```
u2=y(:,7); %Wedge Vertical Velocity
u3=y(:,8); %Wedge Pitch Velocity
u4=y(:,9); %Wedge Yaw Velocity

Fx_in = Fx;
Fz_in = Fz;
EsideframeT_in = EsideframeT;
Momentsideframex_in = Momentsideframex;
Momentsideframey_in = Momentsideframey;
Momentsideframez_in = Momentsideframez;
q_vert_in=q2;
u_vert_in=u2;
t_in=t;

%%% PLOTS %%%
figure(1)
plot(t_out,-Fz_out)
hold on
plot(t_no, -Fz_no,'--r')
plot(t_in,-Fz_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\vert_wdg_force','jpg')


figure(2)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\long_wdg_force','jpg')

figure(3)
plot(t_out,EsideframeT_out)
hold on
plot(t_no,EsideframeT_no,'--r')
plot(t_in,EsideframeT_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate if Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\e_dissip','jpg')

figure(4)
```

```
plot(q_vert_out(300:700),-Fz_out(300:700))
hold on
plot(q_vert_no(300:700),-Fz_no(300:700),'--r')
plot(q_vert_in(300:700),-Fz_in(300:700),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Friction Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\vert_force_hyst','jpg')

figure(5)
plot(t_out,-Fz_out)
hold on
plot(t_no, -Fz_no,'--r')
plot(t_in,-Fz_in,'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\zoom_vert_force','jpg')

figure(6)
plot(t_out,Momentsideframey_out)
hold on
plot(t_no,Momentsideframey_no,'--r')
plot(t_in,Momentsideframey_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Pitch Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\pitch_mom','jpg')

figure(7)
plot(t_out,Momentsideframez_out)
hold on
plot(t_no,Momentsideframez_no,'--r')
plot(t_in,Momentsideframez_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Yaw Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\yaw_mom','jpg')

figure(8)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
```

```
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(8,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\zoomed_long_force','jpg')

figure(9)
plot(t_out,EsideframeT_out)
hold on
plot(t_no,EsideframeT_no,'--r')
plot(t_in,EsideframeT_in,'g')
hold off
xlim([4 7])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate if Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(9,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo var yaw inp\zoomed_e_dissip','jpg')
```

E.2. Constantly-Damped Model

E.2.1. Vertical Bolster Displacement Input

```
%%%% Creates Mambo Comparisons for same inputs, but 3 toe cases
%%%% (Toe In/No Toe/Toe Out)
close all
clear all

%%% Case 1= Toe OUT %%%
load('cdrun_toe_-0.2_psi_0.mat')

t_out=t;
q_vert_out=y(:,2);
Momentsideframex_out=Momentsideframex;
Momentsideframey_out=Momentsideframey;
Momentsideframez_out=Momentsideframez;
Fx_out=Fx;
Fz_out=Fz;
Fspring2_out=Fspring2;
% FbolsterNormal_out=FbolsterNormal;
% FsideframeNormal_out=FsideframeNormal;
% FsideframeTangent_out=FsideframeTangent;
Esideframe_out=Esideframe;

spring_displ_out=vector;  % Control Coil length

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 2 = No Toe Version %%%
load('cdrun_toe_0_psi_0.mat')
```

```
t_no=t;
q_vert_no=y(:,2);
Momentsideframex_no=Momentsideframex;
Momentsideframey_no=Momentsideframey;
Momentsideframez_no=Momentsideframez;
Fx_no=Fx;
Fz_no=Fz;
Fspring2_no=Fspring2;
% FbolsterNormal_no=FbolsterNormal;
% FsideframeNormal_no=FsideframeNormal;
% FsideframeTangent_no=FsideframeTangent;
Esideframe_no=Esideframe;

spring_displ_no=vector;  % Control Coil length

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 3 = Toe In %%%
load('cdrun_toe_0.2_psi_0.mat')

t_in=t;
q_vert_in=y(:,2);
Momentsideframex_in=Momentsideframex;
Momentsideframey_in=Momentsideframey;
Momentsideframez_in=Momentsideframez;
Fx_in=Fx;
Fz_in=Fz;
Fspring2_in=Fspring2;
% FbolsterNormal_in=FbolsterNormal;
% FsideframeNormal_in=FsideframeNormal;
% FsideframeTangent_in=FsideframeTangent;
Esideframe_in=Esideframe;

spring_displ_in=vector;  % Control Coil length

%%% PLOTS %%%
figure(1)
plot(t_out,Fz_out)
hold on
plot(t_no, Fz_no,'--r')
plot(t_in,Fz_in,'g')
hold off
xlim([0.5 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\vert_wdg_force','jpg')


figure(2)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
```

```
hold off
xlim([0.5 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\long_wdg_force','jpg')

figure(3)
plot(t_out,Esideframe_out)
hold on
plot(t_no,Esideframe_no,'--r')
plot(t_in,Esideframe_in,'g')
hold off
xlim([0.5 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\e_dissip','jpg')

figure(4)
plot(q_vert_out(350:750),Fz_out(350:750))
hold on
plot(q_vert_no(350:750),Fz_no(350:750),'--r')
plot(q_vert_in(350:750),Fz_in(350:750),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Friction Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\vert_force_hyst','jpg')

figure(5)
plot(t_out, Fspring2_out)
hold on
plot(t_no,Fspring2_no,'--r')
plot(t_in,Fspring2_in,'g')
xlabel('Time, (s)','FontSize',16)
ylabel('Control Coil Force, (lb)','FontSize',16)

figure(6)
plot(t_out,Fz_out)
hold on
plot(t_no, Fz_no,'--r')
plot(t_in,Fz_in,'g')
hold off
xlim([3.5 7.5])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\zoom_vert_force','jpg')

figure(7)
plot(t_out,Fx_out)
```

```
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
xlim([3.5 7.5])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\zoomed_long_force','jpg')

figure(8)
plot(t_out,Esideframe_out)
hold on
plot(t_no,Esideframe_no,'--r')
plot(t_in,Esideframe_in,'g')
hold off
xlim([3.5 7.5])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate of Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(8,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\zoomed_e_dissip','jpg')


figure(9)
plot(t_out,Momentsideframey_out)
hold on
plot(t_no,Momentsideframey_no,'--r')
plot(t_in,Momentsideframey_in,'g')
hold off
xlim([0 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Pitch Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(9,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\pitch_mom','jpg')


figure(10)
plot(t_out,Momentsideframez_out)
hold on
plot(t_no,Momentsideframez_no,'--r')
plot(t_in,Momentsideframez_in,'g')
hold off
xlim([0 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Yaw Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(10,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const vrt inp\yaw_mom','jpg')
```

E.2.2. Vertical Bolster Displacement with Yaw Input

```
%%%% Creates Mambo Comparisons for same inputs, but 3 toe cases
%%%% (Toe In/No Toe/Toe Out)
close all
clear all

%%% Case 1= Toe OUT %%%
load('cdrun_toe_-0.2_psi_0.012.mat')

t_out=t;
q_vert_out=y(:,2);
Fx_out=Fx;
Fz_out=Fz;
Esideframe_out=Esideframe;
Fspring2_out=Fspring2;
% FsideframeNormal_out=FsideframeNormal;
% FsideframeTangent_out=FsideframeTangent;
% FbolsterNormal_out=FbolsterNormal;
Momentsideframex_out = Momentsideframex;
Momentsideframey_out = Momentsideframey;
Momentsideframez_out = Momentsideframez;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 2 = No Toe Version %%%
load('cdrun_toe_0_psi_0.012.mat')

t_no = t;
q_vert_no = y(:,2);
Fx_no = Fx;
Fz_no = Fz;
Esideframe_no = Esideframe;
Fspring2_no = Fspring2;
% FsideframeNormal_no = FsideframeNormal;
% FsideframeTangent_no = FsideframeTangent;
% FbolsterNormal_no = FbolsterNormal;
Momentsideframex_no = Momentsideframex;
Momentsideframey_no = Momentsideframey;
Momentsideframez_no = Momentsideframez;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Case 3 = Toe In %%%
load('cdrun_toe_0.2_psi_0.012.mat')

t_in = t;
q_vert_in = y(:,2);
Fx_in = Fx;
Fz_in = Fz;
Esideframe_in = Esideframe;
Fspring2_in = Fspring2;
% FsideframeNormal_in = FsideframeNormal;
% FsideframeTangent_in = FsideframeTangent;
% FbolsterNormal_in = FbolsterNormal;
```

```
Momentsideframex_in = Momentsideframex;
Momentsideframey_in = Momentsideframey;
Momentsideframez_in = Momentsideframez;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% PLOTS %%%
figure(1)
plot(t_out,Fz_out)
hold on
plot(t_no, Fz_no,'--r')
plot(t_in,Fz_in,'g')
hold off
xlim([0.4 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(1,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\vert_wdg_force','jpg')

figure(2)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
xlim([0.4 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(2,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\long_wdg_force','jpg')

figure(3)
plot(t_out,Esideframe_out)
hold on
plot(t_no,Esideframe_no,'--r')
plot(t_in,Esideframe_in,'g')
hold off
xlim([0.4 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate if Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(3,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\e_dissip','jpg')

figure(4)
plot(q_vert_out(350:750),Fz_out(350:750))
hold on
plot(q_vert_no(350:750),Fz_no(350:750),'--r')
plot(q_vert_in(350:750),Fz_in(350:750),'g')
hold off
xlabel('Vertical Wedge Displacement, (in)','FontSize',16)
ylabel('Vertical Friction Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
```

```
saveas(4,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\vert_force_hyst','jpg')

figure(5)
plot(t_out,Momentsideframey_out)
hold on
plot(t_no,Momentsideframey_no,'--r')
plot(t_in,Momentsideframey_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Pitch Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(5,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\pitch_mom','jpg')

figure(6)
plot(t_out,Momentsideframez_out)
hold on
plot(t_no,Momentsideframez_no,'--r')
plot(t_in,Momentsideframez_in,'g')
hold off
xlim([0.1 10])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Yaw Moment, (lb-in)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(6,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\yaw_mom','jpg')

figure(7)
plot(t_out,Fz_out)
hold on
plot(t_no, Fz_no,'--r')
plot(t_in,Fz_in,'g')
hold off
xlim([3.8 7.2])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Vertical Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(7,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\zoom_vert_force','jpg')

figure(8)
plot(t_out,Fx_out)
hold on
plot(t_no,Fx_no,'--r')
plot(t_in,Fx_in,'g')
hold off
xlim([3.8 7.2])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Longitudinal Wedge Force, (lb)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In')
saveas(8,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\zoom_long_force','jpg')

figure(9)
```

```
plot(t_out,Esideframe_out)
hold on
plot(t_no,Esideframe_no,'--r')
plot(t_in,Esideframe_in,'g')
hold off
xlim([3.8 7.2])
xlabel('Time, (s)', 'FontSize',16)
ylabel('Rate if Energy Dissipation, (lb-in/sec)','FontSize',16)
legend('Toe Out', 'No Toe', 'Toe In','Location','southeast')
saveas(9,'C:\Documents and Settings\Jenn\Desktop\Friction Wedge\MATLAB
Outputs\mambo const yaw inp\zoome_e_dissip','jpg')
```