THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

TRACTOR TRAILER INSTABILITY OF VARIABLY LOADED CONTAINER TRUCKS

JONATHAN L. WEIDNER

Spring 2007

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

Reviewed and approved* by the following:

Dr. Sean N. Brennan
Asst. Professor of Mechanical Engineering
Thesis Supervisor

Dr. Domenic A. Santavicca
Professor of Mechanical Engineering
Honors Advisor

* Signatures are on file in the Schreyer Honors College.

We approve the thesis of Jonathan L. Weidner:

Date of Signature

Dr. Sean N. Brennan
Asst. Professor of Mechanical Engineering
Thesis Supervisor

Dr. Domenic A. Santavicca
Professor of Mechanical Engineering
Honors Advisor

Student ID # 958398218

ABSTRACT

The instability of tractor-trailer trucks has potential to have catastrophic effects to everyone who utilizes some form of automobile transportation. Due to the potential severity of accidents and the number of people who utilize automobiles, tractor-trailer stability is an important research sector.

This thesis uses a three-degree-of-freedom bicycle model to simulate the response of a tractor-trailer truck with regard to various inputs, such as steering angle, speed, and mass.

A 1/14 scale model tractor and trailer were assembled. The trailer is capable of accepting either a container with extra mass or a tank which can be filled with liquid. The completion of this along with the developed computer simulations will provide future students with opportunities to develop a better understanding of articulated heavy vehicle dynamics.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The author would like to thank Dr. Sean Brennan, and all of the members of the Intelligent Vehicles and Systems Group for their invaluable help and support throughout this process, as well as the Tamiya Corporation for donating a 1/14 scale tractor.

I would also like to thank my friends and family.

Chapter 1

Introduction

The object of this thesis is to investigate a novel way of studying the behavior of articulated heavy vehicles during jackknifing and instability using scaled vehicle experiments. Jackknifing is a compound event with many factors related to its occurrence. Some factors that work together to influence jackknifing are driving conditions such as weather and light, vehicle conditions, and driver characteristics. For example, a jackknife is 86 percent more likely to occur on a curved roadway, 43 percent more likely to occur during times of poor lighting, 49 percent more likely to occur with a 10 mile per hour increase in the posted speed, and a 14 percent *less* likely to occur with a 10 percent increase in total truck weight [1].

Motivation

A tractor-trailer often contains heavy goods to be delivered to multiple destinations. As the trailer is unloaded the gross weight and location of the center of gravity change. Table 1-1 shows that jackknifing fluctuates according to the gross weight of the vehicle. This has the potential to have disastrous consequences not only for the driver of the tractor-trailer truck, but also occupants of other motor vehicles traveling in the vicinity of the variably-loaded trailer.

Gross combination wt. (lbs)	No jackknife		First event		Subsequent event		Total	
	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
15,001-20,000	7	0.2	1	2.0	0	0.0	8	0.3
20,001-25,000	46	1.6	1	2.0	2	1.0	49	1.5
25,001-30,000	336	11.5	13	25.5	44	22.0	393	12.4
30,001-35,000	331	11.4	4	7.8	28	14.0	363	11.5
35,001-40,000	104	3.6	1	2.0	10	5.0	115	3.6
40,001-45,000	103	3.5	1	2.0	8	4.0	112	3.5
45,001-50,000	100	3.4	2	3.9	8	4.0	110	3.5
50,001-55,000	88	3.0	0	0.0	8	4.0	96	3.0
55,001-60,000	90	3.1	1	2.0	5	2.5	96	3.0
60,001-65,000	86	3.0	2	3.9	4	2.0	92	2.9
65,001-70,000	176	6.0	1	2.0	9	4.5	186	5.9
70,001-75,000	349	12.0	3	5.9	11	5.5	363	11.5
75,001-80,000	496	17.0	11	21.6	28	14.0	535	16.9
80,001-85,000	48	1.6	1	2.0	2	1.0	51	1.6
85,001-90,000	25	0.9	0	0.0	3	1.5	28	0.9
90,001-95,000	6	0.2	0	0.0	2	1.0	8	0.3
95,001-100,000	11	0.4	1	2.0	0	0.0	12	0.4
100,001-110,000	9	0.3	0	0.0	0	0.0	9	0.3
110,001-120,000	6	0.2	0	0.0	0	0.0	6	0.2
120,001-130,000	1	0.0	0	0.0	1	0.5	2	0.1
130,001-140,000	1	0.0	0	0.0	0	0.0	1	0.0
Unknown	494	17.0	8	15.7	27	13.5	529	16.7
Total	2913	100.0	51	100.0	200	100.0	3164	100.0

Table 1-1: Gross Combination Weight by Jackknife Occurrence from Trucks Involved In Fatal Accidents Factbook 2000 [3].

In 2005, jackknifes occurred in 210 fatal crashes, 1000 injury crashes and 3000 property crashes [2]. It is reasons such as this that a significant amount of resources are used to research the area of instability in heavy articulated vehicles.

Outline

Chapter two of this thesis discusses the equations of motion derived for the simulation, in chapter 3. Chapter four then discuses the build process for both the scale tractor and trailer. Chapter five then outline the determination of the scaled vehicle parameters.

1 Longthorne, A., Moonesinghe, R., Shankar, U., Singh, S., Subramanian, R., Tessmer, J., (2003) "Analysis of Fatal Large Truck Crashes" National Highway Traffic Safety Administration, DOT HS 809 569

2 Traffic Safety Facts 2005, National Highway Traffic Safety Administration, National Center for Statisitics and Analysis, DOT HS 810 631, 2005

3. Blower, D. Matteson, A. (2003) "Trucks Involved in Fatal Accidents Factbook 2000" Center for National Truck Statistics, The University of Michigan Transportation Institute, UMTRI-2003-20

Chapter 2

Equations of Motion

This chapter will outline the development of the equations of motion used to simulate the motion of a full sized tractor-trailer truck. The equations of motion will be a three-degree-of-freedom system to allow for accurate predictions of planar motion while preventing the simulation from getting too complicated. The three degrees of freedom are tractor yaw rate, trailer yaw rate, and articulation angle. The nomenclature for values used in equations in this chapter can be found in Table **2-1**.

Symbol		Description
a	=	Distance from truck front axle to truck cg
b	=	Distance from truck rear axle to truck cg
d	=	Distance from truck cg to fifth wheel
e	=	Distance from fifth wheel to trailer cg
h	=	Distance from the trailer cg to trailer rear axle
I_{1z}	=	Mass moment of Inertia about Z axis of truck
I_{2z}	=	Mass moment of Inertia about Z axis of trailer
r_1	=	Yaw rate of truck
r_2	=	Yaw rate of trailer
U_1	=	Forward velocity of truck
U_2	=	Forward velocity of trailer

V_1	=	Lateral Velocity of truck
V_2	=	Lateral Velocity of trailer
X_f	=	Braking Force at tractor front tires
X_r	=	Braking force at tractor rear tires
X_t	=	Braking force at trailer tires
F_f	=	Tire force at tractor front tires
F_r	=	Tire force at tractor rear tires
F_t	=	Tire force at trailer tires
δ	=	Steering angle at front wheel
$C_{\alpha f}$	=	Cornering stiffness of front tires
$C_{\alpha r}$	=	Cornering stiffness of rear tires
$C_{\alpha t}$	=	Cornering stiffness of trailer tires
X_{truck}	=	Global position of truck cg in X direction
Y_{truck}	=	Global position of truck cg in Y direction
X_h	=	Global position of fifth wheel in X direction
Y_h	=	Global position of fifth wheel in Y direction
$X_{trailer}$	=	Global position of trailer cg in X direction
$Y_{trailer}$	=	Global position of trailer cg in Y direction

Table **2-1**: a list nomenclature used in the derivation of the equations of motion.

To derive the equations, we consider the diagram of the fifth wheel depicted in Figure **2-1**. This connects the tractor to the trailer. It is this fifth wheel that affirms the tractor and trailer have common velocities while allowing a change in articulation angle between the tractor and trailer, ψ , Figure 2-2 .

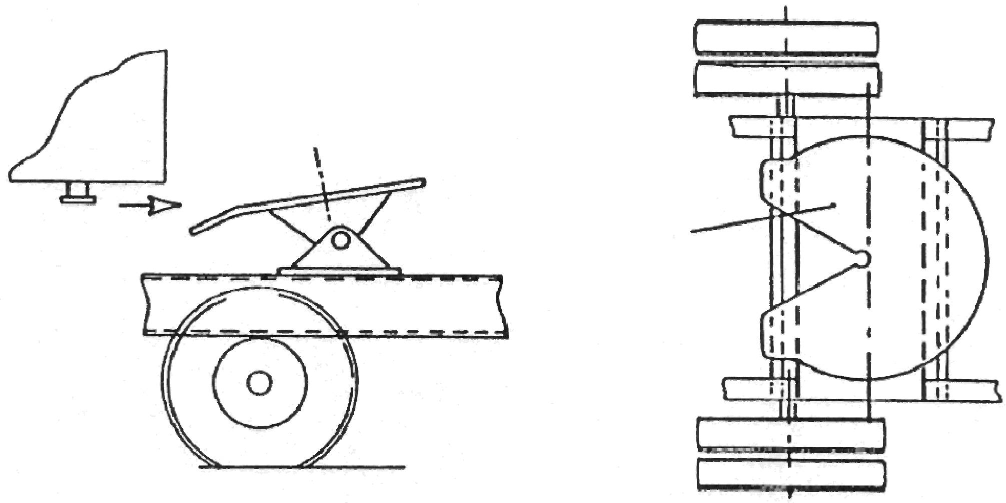

Figure 2-1: The fifth wheel connects the trailer to the tractor, from Road Vehicle Dynamics by J R Ellis[2]

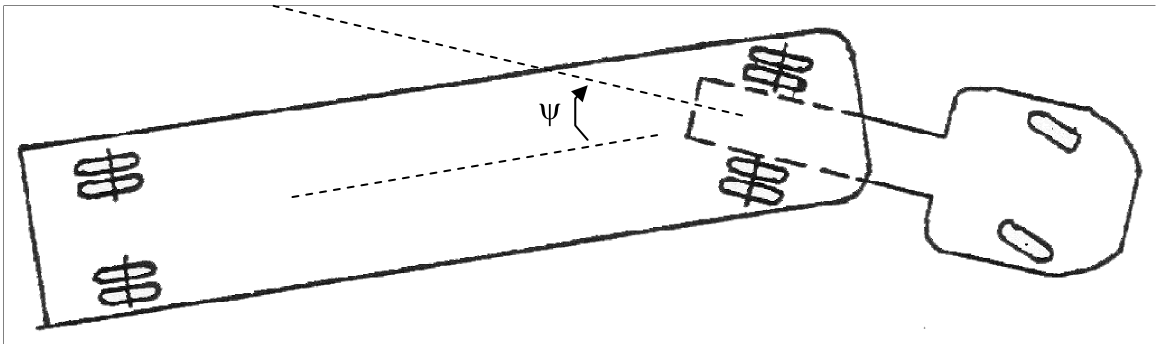

Figure 2-2: A tractor and trailer combination with an articulation angle $\neq 0$, from Road Vehicle Dynamics by J R Ellis[2]

The velocities of the trailer and the articulation angle of the trailer relative to the tractor can be written in terms of the tractor variables, as illustrated in Eq. 2.1. The third equation in Eq. 2.1 assumes the articulation angle at the initial time is equal to zero. Figure 2-3 shows the articulated vehicle, with an articulation angle equal to zero, and the notation used to derive the equations of motion for this thesis. This particular notation was used to assist in verifying the derived equations of motion of the tractor-trailer truck in comparison to established equations of motion for a motor vehicle; the MATLAB m-file used to analyze the equations of motion determined that the equations were correct. This was accomplished by substituting vehicle parameters for a typical passenger car into the m-file. A further description of this can be found in the following chapter, which overviews the simulation.

The relation of the velocities of the tractor and trailer about the fifth wheel are shown in Figure 2-4.

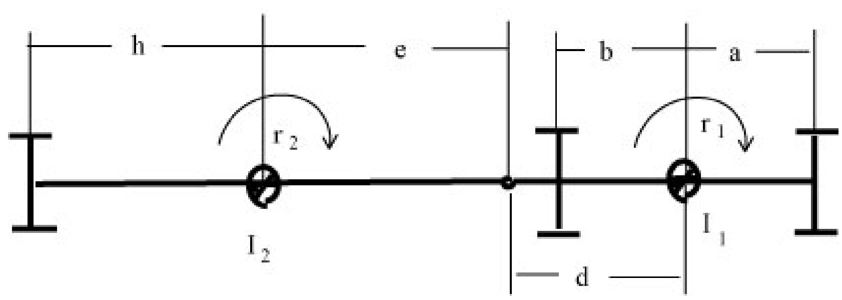

Figure 2-3: Critical distances and positive direction of yaw rate used in the derivation of equations of motion.

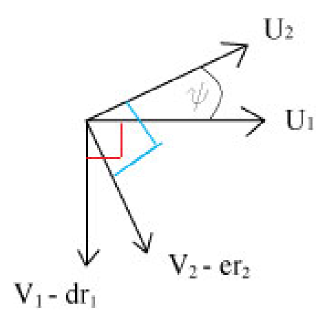

Figure 2-4: Velocities at the fifth wheel for both the tractor and trailer.

$$U_2 = U_1 \cos\psi - (V_1 - dr_1)\sin\psi$$
$$V_2 = U_1 \sin\psi + (V_1 - dr_1)\cos\psi - er_2 \qquad \mathbf{2.1}$$
$$\psi = \psi_o + \int_0^t (r_2 - r_1)dt$$

The accelerations in Eq. **2.2** can then be found for the trailer by taking the time derivative of the above velocities in Eq **2.1**.

$$\dot{U}_2 = \dot{U}_1 \cos\psi - U_1(r_1 - r_2)\sin\psi - (\dot{V}_1 - d\dot{r}_1)\sin\psi - (V_1 - dr_1)(r_1 - r_2)\cos\psi$$
$$\dot{V}_2 = \dot{U}_1 \sin\psi + U_1(r_1 - r_2)\cos\psi + (\dot{V}_1 - d\dot{r}_1)\cos\psi - (V_1 - dr_1)(r_1 - r_2)\sin\psi \qquad \mathbf{2.2}$$

The equations of motion can be determined by summing the forces and moments about the tractor and the trailer in Figure **2-5**. The trailer forces in the x and y direction can be found in Eq. **2.3** and Eq. **2.4**, respectively, while the moments in the Z direction, summed around the center of gravity can be found in Eq. **2.5**

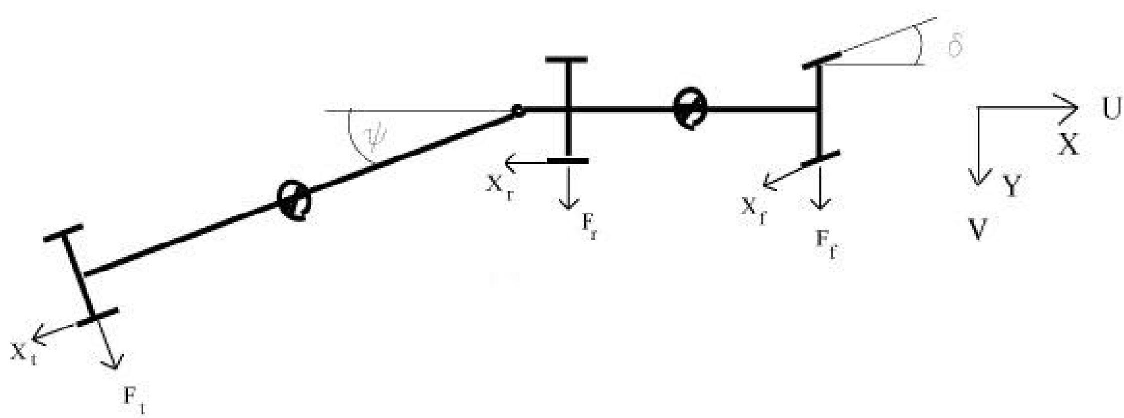

Figure **2-5**: Forces acting on the tractor-trailer system

$$\sum F_x \quad + \rightarrow \quad m_1(\dot{U}_1 - V_1 r_1) = -X_f \cos\delta - X_r + X \qquad \mathbf{2.3}$$

$$\sum F_y \quad +\downarrow \quad m_1(\dot{V}_1 + U_1 r_1)_1 = F_f + F_r + X_f \sin\delta - Y \qquad \textbf{2.4}$$

$$\sum M_z \quad \cap + \quad I_{1z}\dot{r}_1 = aF_f - bF_r + aX_f \sin\delta + dY \qquad \textbf{2.5}$$

Likewise, the forces and moments for the trailer can be found in Eq. **2.6**, **2.7**, **2.8,**

$$\sum F_x \quad +\rightarrow \quad m_2(\dot{U}_2 - V_2 r_2) = -X_t - Y\sin\psi - X\cos\psi \qquad \textbf{2.6}$$

$$\sum F_y \quad +\downarrow \quad m_2(\dot{V}_2 + U_2 r_2) = F_t + Y\cos\psi - X\sin\psi \qquad \textbf{2.7}$$

$$\sum M_z \quad \cap + \quad I_{2z}\dot{r}_2 = -hF_t + e(Y\cos\psi - X\sin\psi) \qquad \textbf{2.8}$$

where F_f, F_r and F_t are the forces at the tractor front, tractor rear and on the trailer tires, which are shown in Eq. **2.9**, **2.10**, and **2.11**

$$F_f = c_{\alpha f}\left(\frac{V_1 + ar_1}{U_1} - \delta\right) \qquad \textbf{2.9}$$

$$F_r = c_{\alpha r}\left(\frac{V_1 - br_1}{U_1}\right) \qquad \textbf{2.10}$$

$$F_t = c_{\alpha t}\left(\psi + \frac{V_1(d+e+h)r + (h+e)\dot{\psi}}{U_1}\right) \qquad \textbf{2.11}$$

These six equations, Eq. **2.3** through **2.8,** can be reduced to 3 equations after making practical assumptions and combining equations. The steps to simplify the equations are:

1. The combination tractor and trailer are traveling at a constant forward speed. As a result $\dot{U} = 0$
2. The combination tractor and trailer are subject to small disturbances. As a result Eq. **2.3** and **2.6** can be removed. Also, $\sin\psi = \psi$ and $\cos\psi = 1$

3. Combine Eq. 2.4 and 2.7 .

The resulting three equations can then be written as Eq. **2.12,** Eq. **2.13, and** Eq. **2.14**.

$$(m_1+m_2)\dot{V}_1 - m_2\dot{r}_1 - m_2 e\dot{r}_2 = -\left(\frac{c_f+c_r+c_t}{U_1}\right)V_1 + \left[(m_1+m_2)U_1 + \left(\frac{-ac_f+bc_r+dc_t}{U_1}\right)\right]r_1 + \left(\frac{(h+e)c_t}{U_1}\right)r_2 - (c_t)\psi - (c_f)\delta \qquad \textbf{2.12}$$

$$-m_2 d\dot{V}_1 + (I_1+m_2 d^2)\dot{r}_1 + m_2 ed\dot{r}_2 = \left(\frac{-ac_f+bc_r+dc_t}{U_1}\right)V_1 + \left[m_2 dU_1 - \left(\frac{a^2c_f+b^2c_r+d^2c_t}{U_1}\right)\right]r_1 - \left(\frac{d(h+e)c_t}{U_1}\right)r_2 - (dc_t)\psi - (ac_f)\delta \qquad \textbf{2.13}$$

$$-m_2 e\dot{V}_1 + m_2 ed\dot{r}_1 + (I_2+m_2 e^2)\dot{r}_2 = \left(\frac{(h+e)c_t}{U_1}\right)V_1 + \left[-m_2 eU_1 - \left(\frac{d(h+e)c_t}{U_1}\right)\right]r_1 - \left(\frac{(h+e)^2c_t}{U_1}\right)r_2 - ((h+e)c_t)\psi \qquad \textbf{2.14}$$

These three equations – Eq. **2.12,** Eq. **2.13,** Eq. **2.14 –** can then be written in matrix form: Eq. **2.15,** with the third equation from series Eq. 2.1 and simulated in MATLAB and Simulink.

$$M\dot{\bar{x}} = A'\bar{x} + B'\bar{y} \qquad \textbf{2.15}$$

Equation 2.15 utilizes a state vector defined as $\bar{x} = \begin{bmatrix} V_1 \\ r_1 \\ r_2 \\ \psi \end{bmatrix}$ and input $\bar{u} = \delta$. Equation **2.15** is equal to Eq. **2.16**. Equation **2.16** is written in matrix form.

$$\begin{bmatrix} m_1 + m_2 & -m_2 d & -m_2 e & 0 \\ -m_2 d & I_{1z} + m_2 d^2 & m_2 ed & 0 \\ -m_2 e & m_2 ed & I_{2z} + m_2 e^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{r}_1 \\ \dot{r}_2 \\ \dot{\psi} \end{bmatrix} =$$

$$\begin{bmatrix} -\frac{c_{\alpha f} + c_{\alpha r} + c_{\alpha t}}{U_1} & (m_1 + m_2)U_1 + \left(\frac{-ac_{\alpha f} + bc_{\alpha r} + dc_{\alpha t}}{U_1} \right) & \frac{(h+e)c_{\alpha t}}{U_1} & -c_{\alpha t} \\ \frac{-ac_{\alpha f} + bc_{\alpha r} + dc_{\alpha t}}{U_1} & -m_2 dU_1 - (\frac{a^2 c_{\alpha f} + b^2 c_{\alpha r} + d^2 c_{\alpha t}}{U_1}) & -\frac{d(h+e)c_{\alpha t}}{U_1} & dc_{\alpha t} \\ \frac{(h+e)c_{\alpha t}}{U_1} & -m_2 eU_1 - \frac{d(h+e)c_{\alpha t}}{U_1} & -\frac{(h+e)^2 c_{\alpha t}}{U_1} & (h+e)c_{\alpha t} \\ 0 & -1 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r_1 \\ r_2 \\ \psi \end{bmatrix} \quad \textbf{2.16}$$

$$+ \begin{bmatrix} -c_{\alpha f} \\ -ac_{\alpha f} \\ 0 \\ 0 \end{bmatrix} [\delta]$$

1. Ellis, J. R. (1969) *Vehicle Dynamics, John R Ellis, London.*

2. Ellis, J. R. (1989) *Road Vehicle Dynamics, John R Ellis, Akron, OH.*

3. Ellis, J. R. (1994) *Vehicle Handling Dynamics, Page Bros., Norwich, UK.*

4. Karnopp, Dean. (2004)*Vehicle Stability*, Marcel Dekker, Inc., New York, NY.

5 Pacejka, H. B. (2002) *Tyre and Vehicle Dynamics*, MPG Book Ltd, Bomin, Cornwall

Chapter 3

Simulation

In this chapter, MATLAB and Simulink are used to model the trucks' behavior in response to various inputs. The m file and Simulink block diagrams can found in Appendix B and C.

MATLAB is used to perform the following operation to convert Eq. **2.16** to state space, Eq. **3.1** .

$$\dot{\bar{x}} = M^{-1}A'\bar{x} + M^{-1}B'\bar{y} \tag{3.1}$$

The expression can then be rewritten as Eq. **3.2**

$$\dot{\bar{x}} = A\bar{x} + B\bar{y} \tag{3.2}$$

At this point, the eigenvalues of the A matrix in Eq. **3.2** can be plotted. The eigenvalues, if stable, should reside to the left of the real axis and have positive and negative imaginary values. This condition is shown in Figure **3-1**.

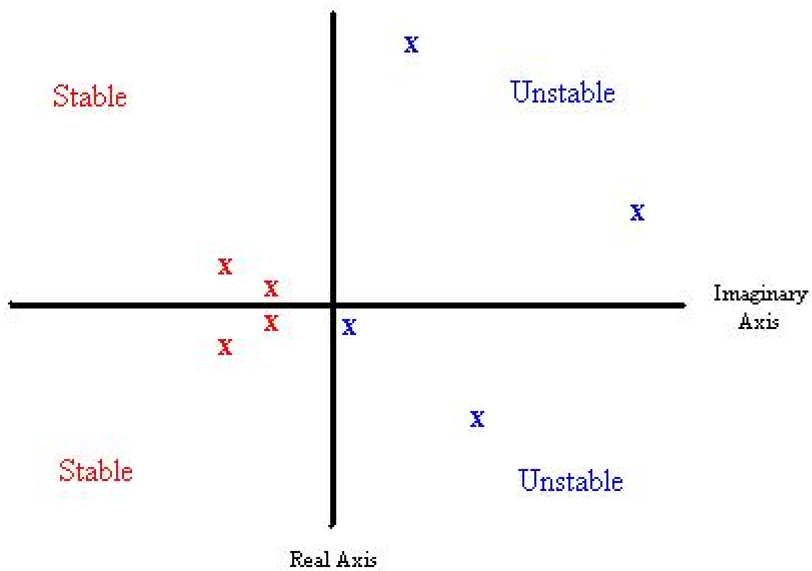

Figure 3-1: Eigen values plotted on the Imaginary and Real axes. The values in red demonstrate system stability while the values in blue demonstrate system instability.

In an effort to verify that the equations of motion and m-file derived for this thesis are correct, vehicle parameters were chosen that are commonly used in other research related to passenger vehicles. These parameters generate known, (and correct) eigenvalues. This parameter change was accomplished by setting all of the truck parameters equal to the commonly used car parameters, and the trailer parameters equal to negligible values. For example, if m_2 was set equal to zero, I_{2z} cannot be set equal to zero and must be set to the negligible value of 0.00001. Setting both of these values equal to zero would prevent MATLAB from calculating the inverse of the M matrix because this matrix becomes singular.

For analysis, a simple state space block can be used in Simulink to represent the equations of motion and parameter information. However, to see the effects of varying methods of tire force calculations, it is easier to use a Simulink model with subsystem blocks that separately calculate slip angles, tire forces, and the equations of motion used to describe basic physics. The outputs of the slip angle block would become the inputs for the tire force block. Likewise, the outputs for the tire force block would then be used as the inputs for the basic physics block. Regardless of whether the subsystem methodology or the state space block methodology is used to represent the equations of motion, the outputs should be equivalent if the same assumptions and parameters are used for each model.

Additionally, the output of either of the above models must be converted from a body-fixed coordinate system to a global coordinate system. A body-fixed coordinate system is a coordinate system that is perpendicularly attached to an object, maintaining its X-Y-Z coordinate structure regardless of the vehicle's movements: the X axis is directed toward the front of the vehicle, while the Y axis is perpendicular to the X axis, stretching from the center of gravity, outward; the Z axis is vertical from the center of gravity. (See Figure **3-2**) A global coordinate system allows one to plot the position of multiple objects on one plot relative to the same origin for all of the plots. This is comparable to an aerial view of the objects position – see Figure **3-3**. Equations **3.3**, and

3.4 convert the outputs, truck velocity, V_1 and truck yaw rate, r_1, into the global X and Y coordinates of the truck's center of gravity.

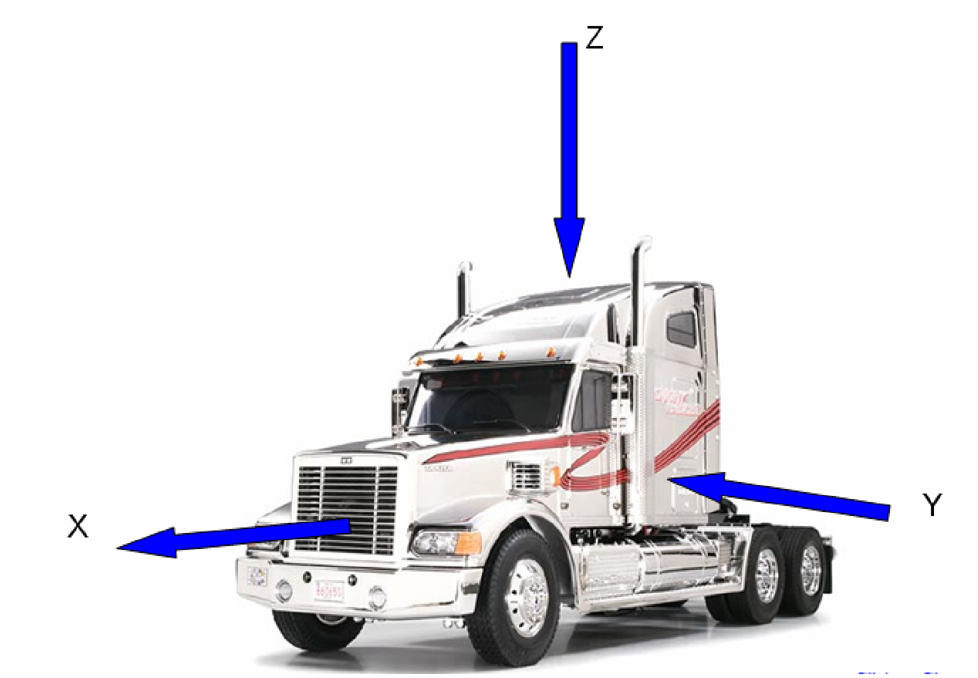

Figure 3-2: Body-fixed coordinate system

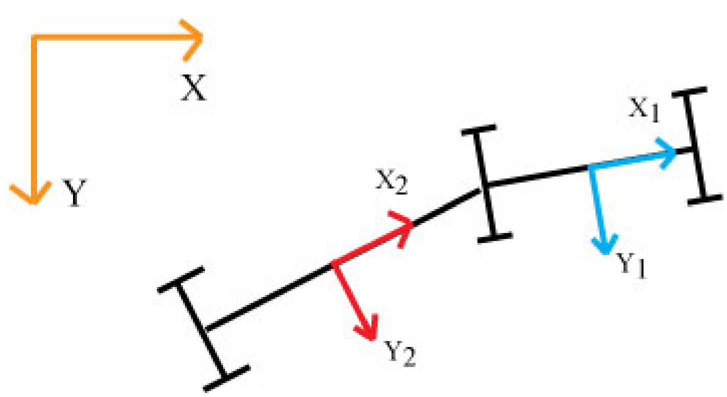

Figure 3-3: The global coordinates are shown in orange, while the body-fixed coordinates are shown in both blue and red.

$$X_{truck} = \int V_x = \int\left(-V_1 \sin\psi_1 + U_1 \cos\psi_1\right) \quad \textbf{3.3}$$

$$Y_{truck} = \int V_y = \int\left(V_1 \cos\psi_1 + U_1 \sin\psi_1\right) \quad \textbf{3.4}$$

The above equations, **3.3** and **3.4** both assume initial conditions are equal to zero. Equations **3.5** and **3.6** geometrically find the location of the fifth wheel in global coordinates relative to the center of gravity of the truck using the position of the truck's center of gravity and the yaw angle of the truck, ψ_1 .

$$X_h = X_{truck} - d\cos\psi_1 \quad \textbf{3.5}$$

$$Y_h = Y_{truck} - d\sin\psi_1 \quad \textbf{3.6}$$

Equations **3.7** and **3.8** find the center of gravity for the trailer relative to the fifth wheel using the position of the of fifth wheel and the yaw angle of the trailer.

$$X_{trailer} = X_h - e\cos\psi_2 \quad \textbf{3.7}$$

$$Y_{trailer} = Y_h - e\sin\psi_2 \quad \textbf{3.8}$$

Chapter 4

Scale Vehicle Construction

Scale Tractor

This chapter presents an overview of the scale vehicle and its parameters. The Tamiya Corporation donated a 1/14 scale Tamiya Knight Hauler Tractor Truck. The scale tractor includes an aluminum chassis with a planetary gear system for the rear differential. The steering of the scaled vehicle is controlled via a Tower Hobbies System 3000 STD-TS53 servo. The specifications for this servo can be found in Appendix D. The nomenclature for the values used in equations in this chapter can be found in Table **4-1**.

Symbol		Description
I_Z	=	Mass moment of Inertia about the Z axis
m	=	Mass of the object
r_g	=	Distance from the center of gravity to the pivot point
g	=	Gravitational constant
τ	=	Time period for 1 oscillation
π	=	

Table **4-1**: Nomenclature for mass moment of inertia

Scale Trailer

A scale sized trailer was made with the assistance of Dan Kaiserian another student performing research on the effects of slosh on tractor-trailer stability, and Carson Baird, the Pennsylvania State University Learning Factory Supervisor. The trailer chassis pieces were first designed using Pro/Engineering and the three-dimensional drawings can be found in Appendix D.

The trailer chassis is a rectangular box made from welded 6061 T6 Aluminum flat stock (see Figure 4-1). Each piece is one inch wide and 1/8 of an inch thick. The lengths of each individual piece designed in order to make the scaled dimensions accurate. The six cross pieces below are welded in order to ensure that the thickness of the chassis is 1/8 of an inch.

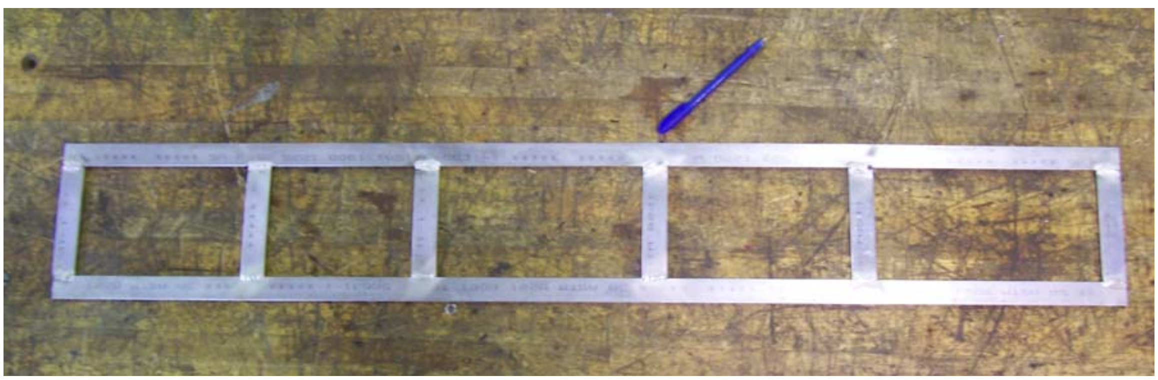

Figure 4-1: The 1/14 scale trailer chassis

The suspension utilizes a leaf spring suspension system (see Figure 4-2). The leaf springs were made from 0.050-inch thick sheet metal. Four 3.6-inch by 0.5-inch strips were cut from the original sheet. These strips were then formed around a uniform pipe with a diameter of eight inches. The final spring length after bending is 3.3 inches. Each end of the leaf springs then had a steel tube 0.5 inches long welded parallel to the end.

Figure 4-2: Two formed leaf springs on the top and bottom with one unformed strip in the center.

After testing, it was then determined that these leaf springs would plastically deform, instead of elastically deform, under the loads of the tank and container. A second strip of steal from the same stock, 3.5 inches long and 0.5 inches wide, was then welded to reinforce the leaf spring, Figure 4-3. Before welding the second strip of steal to the existing leaf spring, the initial bead of weld was ground where the tube was attached and a new weld was made to connect both leaf springs to the tube.

The leaf springs are attached to the chassis via two different styles of mounts (see Figure 4-3). Since two of the leaf springs are attached, making their ends close to each other, as illustrated on the right side of Figure 4-3, and the mount that holds each end of the springs together is a rigid pin connection, the leaf spring can then only rotate around the tube. The other mounts at the front of the forward leaf spring and rear of the rear leaf spring allow for both rotation and movement in the X direction: Figures 4-3 and 4-4.

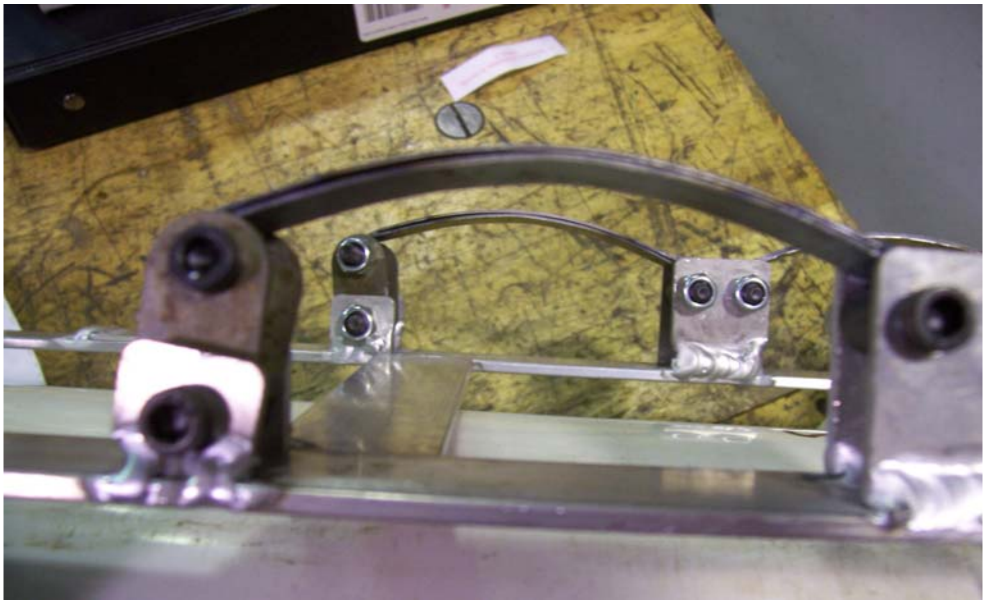

Figure 4-3: Front leaf spring and its connections to the chassis

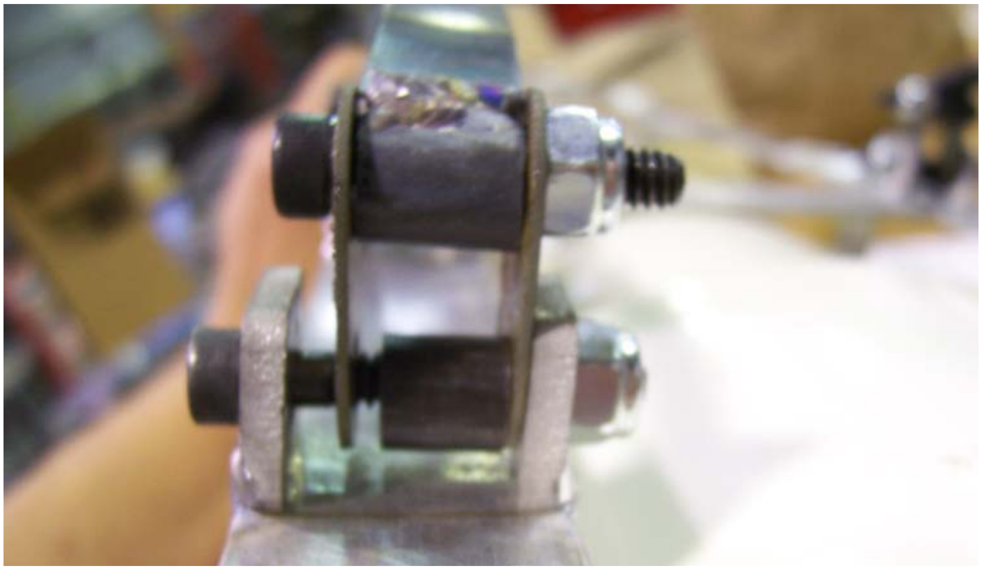

Figure 4-4: A rear view of the rear passenger side leaf spring

The wheels used on the trailer are rubber model airplane wheels, three-inches in diameter (see Figure **4-5**). Tires could have been made by cutting circles out of a solid sheet of rubber, however, it was felt that the aircraft tires are more similar to the true scale tire size and would react more like a regular air-filled tire, rather than a solid piece of rubber.

Figure **4-5**: 2 of the 4, 3 inch model airplane wheels

The wheels were mounted on A228 spring steel, also known as *music wire*, with a diameter of 5/32 inches. The music wire passed through a piece of ¼ inch steel round-stock, machined to allow the axle to fit without a wobble or excess friction. Each wheel was free to rotate at different speeds, as on a regular trailer. The sleeves were then welded to the front leaf springs, parallel to the front and rear of the trailer chassis, as well as perpendicular to the sides of the chassis (see Figure **4-6**). The rear leaf springs were then welded a distance of 4.1 inches behind the front leaf spring on both sides (see Figure **4-7**).

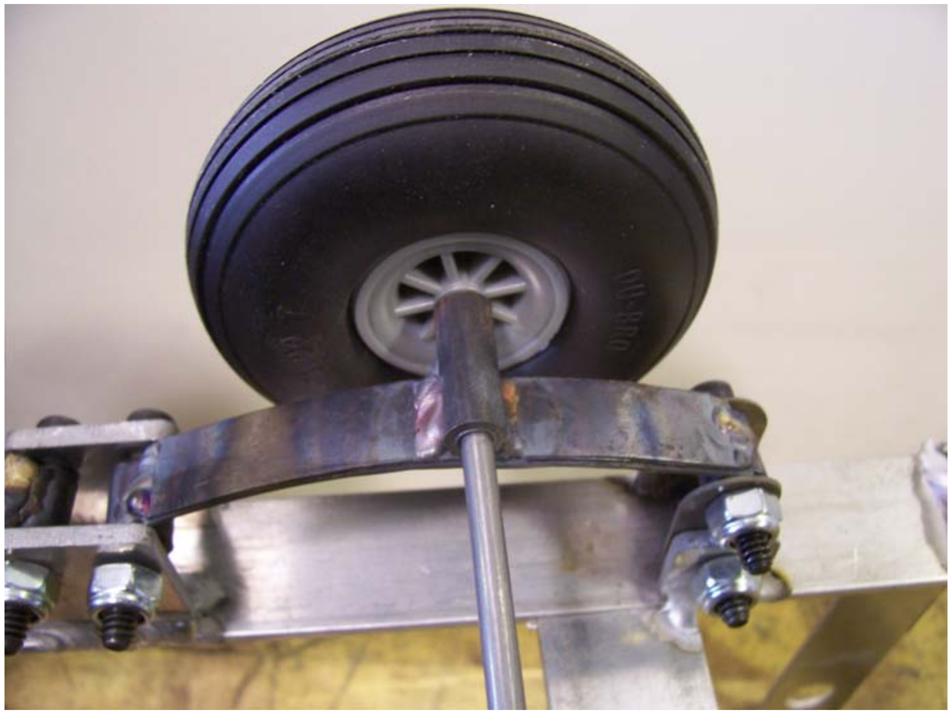

Figure 4-6: The axle running through the sleeve on the front driver side leaf spring

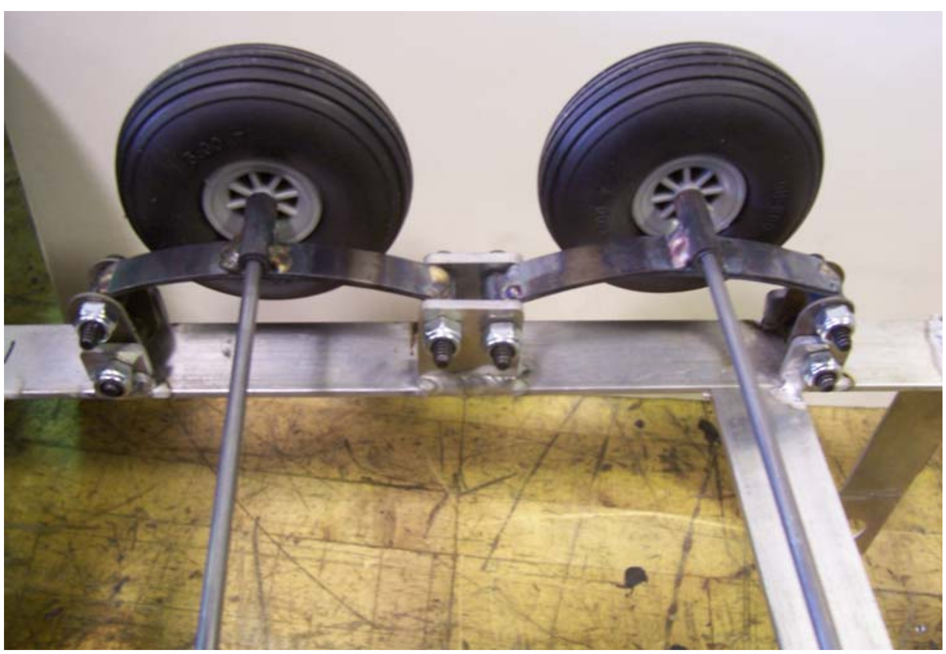

Figure 4-7: The two parallel axles on the trailer

Since 5/32 of an inch is conveniently close to the diameter of a gauge 10 bolt, the ends of each axle were ground and tapped with a 10-32 die allowing each axle end to accept a nut. A number 6 washer and nut, and liquid thread lock were then used to secure the wheels to each axle (see Figure 4-8).

Figure 4-8: The trailer wheel and a washer secured with a nut

In order to allow Dan and myself to interchange a PVC tank and a box container, aluminum L shaped brackets were welded directly to the chassis. The L shaped brackets were cut one inch, by six inches from a 1/8-inch thick sheet of aluminum. A slightly-greater-than-90-degree bend was then placed one inch from one of the ends of the aluminum, forming an “L.” The brackets were bent slightly past 90 degrees to promote a clamping action on both the tank and the container. Holes were then punched in the brackets with a one-half inch diameter punch, centered one inch in from the long end, allowing for a strap to go from one bracket, over the tank or container, then down to the other bracket. The brackets were then welded to the chassis by lap welding the one inch bend to the underside of the chassis (see Figure 4-9).

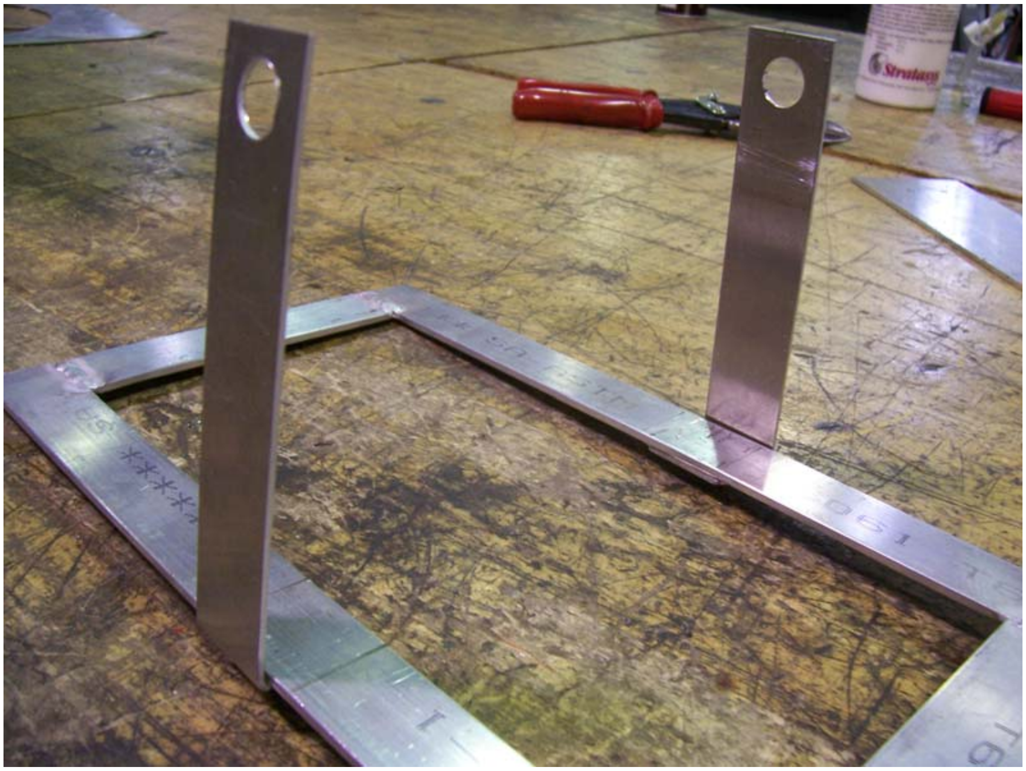

Figure 4-9: L brackets for securing the tank and container.

For the fifth wheel connection, also known as a *king pin*, another piece of 1/8-inch aluminum, the same as the chassis material, was welded to the underside of the chassis (see Figure 4-10). The center of this piece was placed 4.5 inches behind the front of the trailer. At the center, in both the X and Y direction of this piece, a hole was drilled with a number 21-drill bit. This hole was then tapped to 10-32 UNF. A Phillips head screw was then threaded through the hole and a nut was placed on with liquid thread lock.

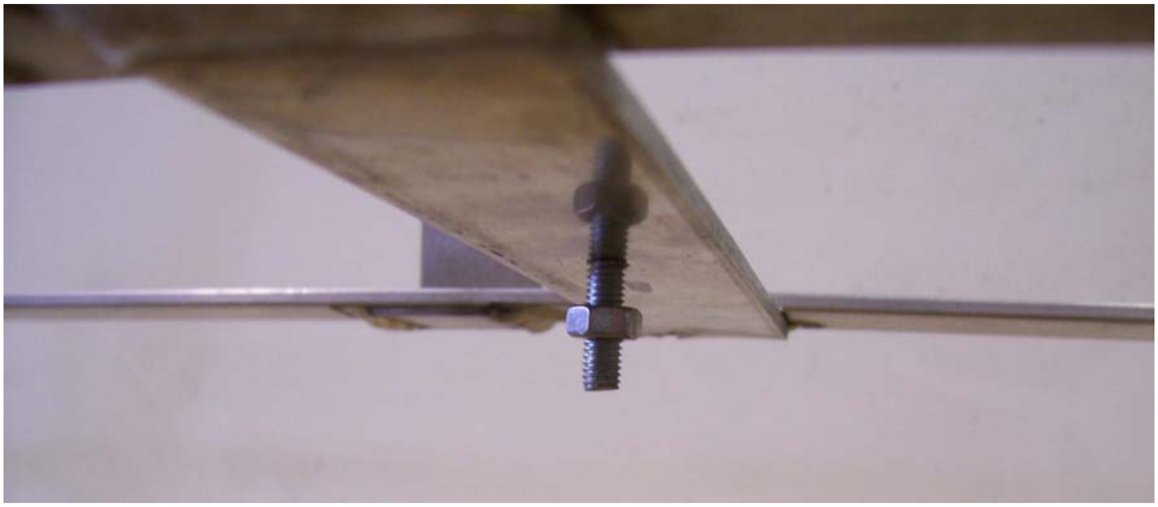

Figure 4-10: The king pin connection connects the trailer to the tractor via the fifth wheel.

Container

The container was designed using SolidWorks and the three-dimensional drawing can be found in Appendix D. The container was manufactured entirely from .075-inch thick 5052 Aluminum. This particular alloy was chosen because it is a softer alloy of Aluminum, which allows for 90 degree bends. A sheet of Aluminum had two 90-degree bends placed in it, forming two upright parallel sides. End pieces were then sheared to the proper dimensions. The bottom left and bottom right corners were then rounded off to fit smoothly in the 90-degree bends. The end pieces were then welded to the "U" shaped container, closing all sides of the container except for the top (see Figure 4-11). Two pieces of aluminum were then centered across the top of the container with a six-centimeter gap between them, and welded to the container in order to keep the container square (see Figure 4-12).

Figure 4-11: One of the end pieces welded inside the “U” shaped container.

Figure **4-12**: The finished container with two braces in the middle to help keep the container from deforming.

The container dimensions were selected to represent a fifty three foot long trailer that is one hundred and two inches wide. This is the largest container trailer size listed by the World Trade Press [1].

1. World Trade Press. *Truck Trailers*. 2006. Retrieved January 25, 2007 from http://www.worldtraderef.com/wtr_nl/WTR_site/Truck_Trailers/Guide_to_Truck_Trailers.asp.

Chapter *5*

Vehicle Parameter Estimation

The parameters of a vehicle represent the vehicle's physical characteristics, and therefore their estimation and/or measurement is important. This chapter explains how the parameters of the scaled vehicle were estimated. The actual values of the scaled parameters can be found in Appendix D. Assuming the governing equations of motion are correct the more accurately the parameters are estimated to be, the more accurate response one can predict.

Tractor Parameter Estimation

The parameters such as mass and lengths are relatively easy to estimate with a scale and a linear measuring device. The first step is to place the vehicle on the scale and record the mass. The next step is to balance the vehicle on a level-thin rigid surface, such as the ruler in Figure **5-1**. If the vehicle is balanced in the same plane with different orientations, the intersection of the lines formed by the ruler will be the location of the center of gravity in that plane: for example, the XY plane in Figure **5-1**.

Figure 5-1: The scale tractor being balanced at different orientations to find the location of the center of gravity in the XY plane

After the center of gravity is located in the XY plane, several parameters can simply be measured with a ruler or calipers. These parameters include the distance from the center of gravity to the axles, as well as the distance from the center of gravity to the fifth wheel.

The center of gravity in the XZ plane can be measured in a similar manner. However, for the XZ plane, the truck is suspended from the front and rear axles as shown in Figure **5-2**. Once the location of the center of gravity in the XZ plane is determined, the overall center of mass of the vehicle is known. The center of mass is at the intersection of the center of gravity in both the XY and XZ planes. The distance from the ground to the center of mass can simply now be measured.

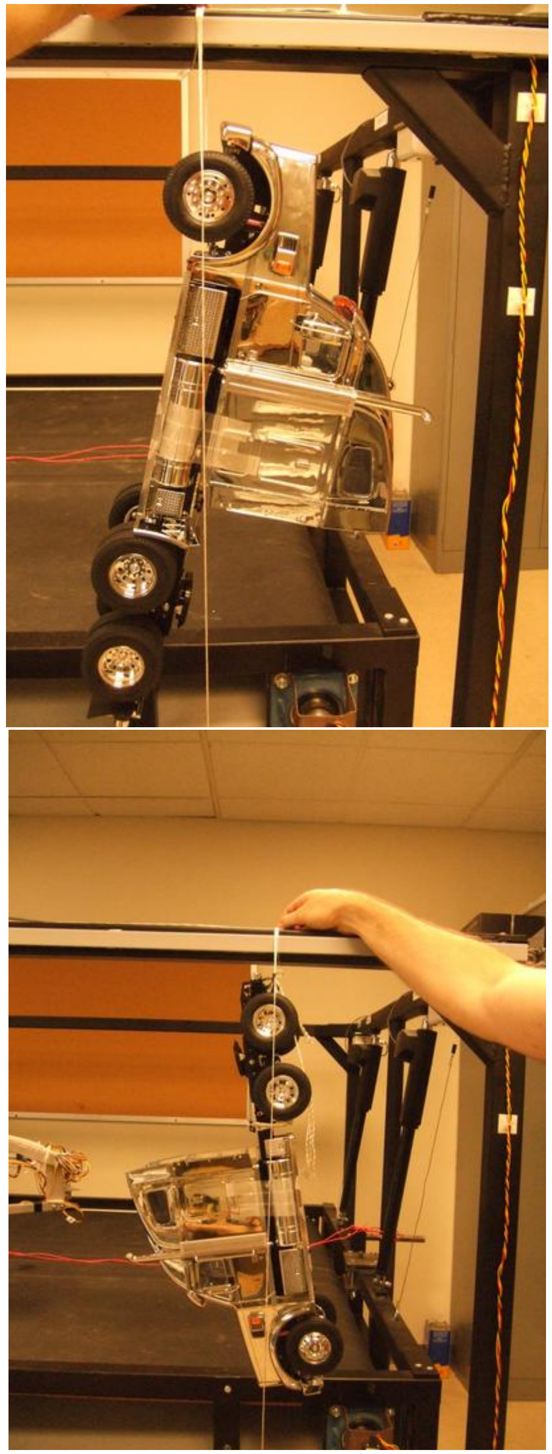

Figure 5-2: Estimating the height of the center of gravity by hanging the scaled vehicle from the front and rear axles.

To calculate the mass moment of inertia, the scaled vehicle is suspended in the air from one pivot point, as in Figure 5-3. The vehicle is then moved by a small angle measure, approximately equal to five degrees from bottom center. As shown in Figure 5-3, the scaled vehicle would swing into and out of the page to measure the period of oscillation. This measurement allows one to calculate the mass moment of inertia about the Z-axis. The number of oscillations and the time period for the oscillations is then recorded several times and an average period is calculated. Twenty oscillations repeated ten times is used in this study. The moment of inertia can then be calculated using Eq. 5.1.

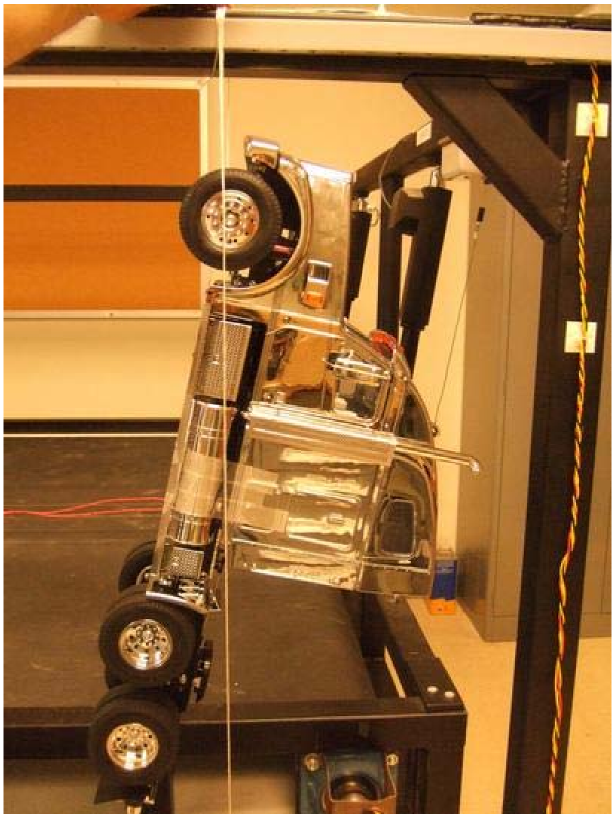

Figure 5-3: Estimating the mass moment of Inertia

$$I = mr_g(g(\frac{\tau}{2\pi})^2 - r_g) \quad \textbf{5.1}$$

Where m = scaled vehicle mass, r_g = the distance from the center of gravity to the pivot point, g = gravity, and τ = the period for one oscillation. A similar process was used to calculate the mass moment of inertia about the X-axis. The only difference is the truck is suspended from the front and rear axles with the truck hanging horizontally.

Trailer and Container Parameters

The methods for determining the parameters of the trailer are performed in the same manner as determining the parameters for the tractor. The only difference is, the container was secured to the trailer to prevent any movement of the container relative to the trailer chassis. The container was then marked with several reference points on each side of the "L" brackets, allowing the container to be removed and placed back in the same location (see Figure **5-4**). This combination of the container and chassis were then analyzed through the same steps as the tractor (see Figures **5-5**, **5-6**, and **5-7**). The estimated parameters for the combined container and chassis can be found in Appendix D.

Figure 5-4: Two of the twelve marks placed on the container to ensure the container has not slid relative to the chassis

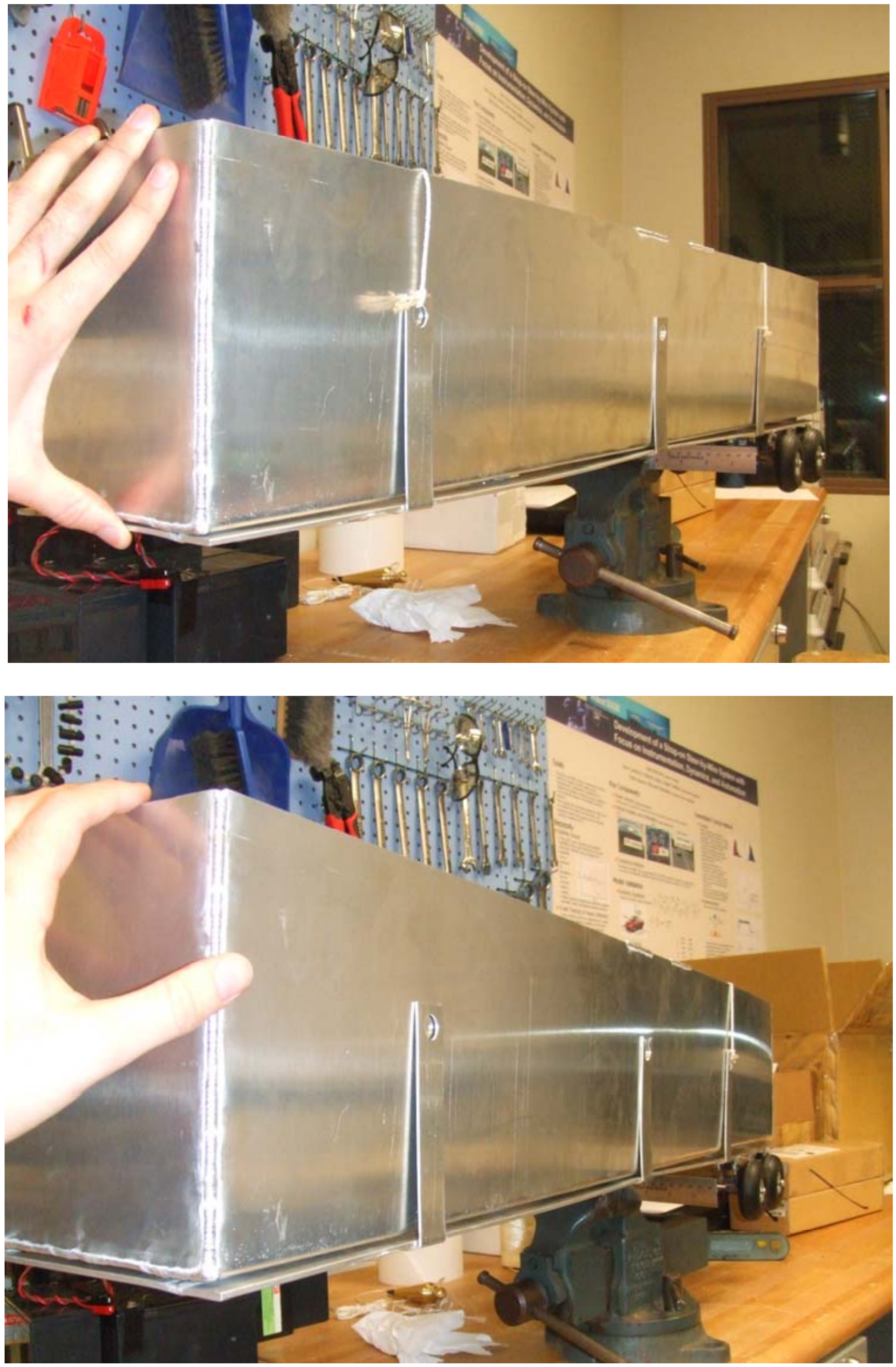

Figure 5-5: Estimating the location of the center of gravity in the XY plane for the combination container and chassis

Figure 5-6: Estimating the height of the center of gravity for the combination container and chassis.

Figure 5-7: Estimating the moment of inertia about the Z-axis for the combination container and chassis.

1. Pennock, G. R., Shigley, J. E. Uicker, J. J. (2003) Theory of Machines and Mechanisms, Third Edition, Oxford, New York.

2. Lapapong, C. (2007) Vehicle Similitude Modeling and Validation of the Pennsylvania State University Rolling Roadway Simulator. Masters Thesis, The Pennsylvania State University

Chapter 6

Conclusion and Future Work

Conclusion

Unfortunately we were unable to collect the test data we originally hoped to. However, some areas of potential future work were observed and, the tractor and trailer are both currently fully assembled and sitting on the rolling roadway simulator in room 321 of the Leonhard building awaiting testing. (See Figure 6-1 and 6-2.)

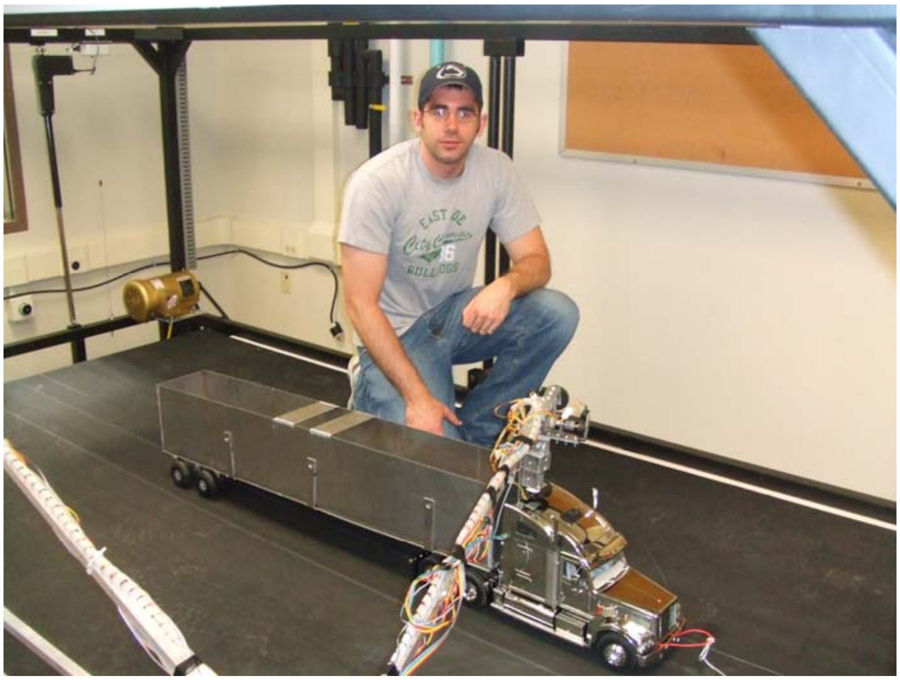

Figure 6-1: Myself next to the assembled scale tractor-trailer.

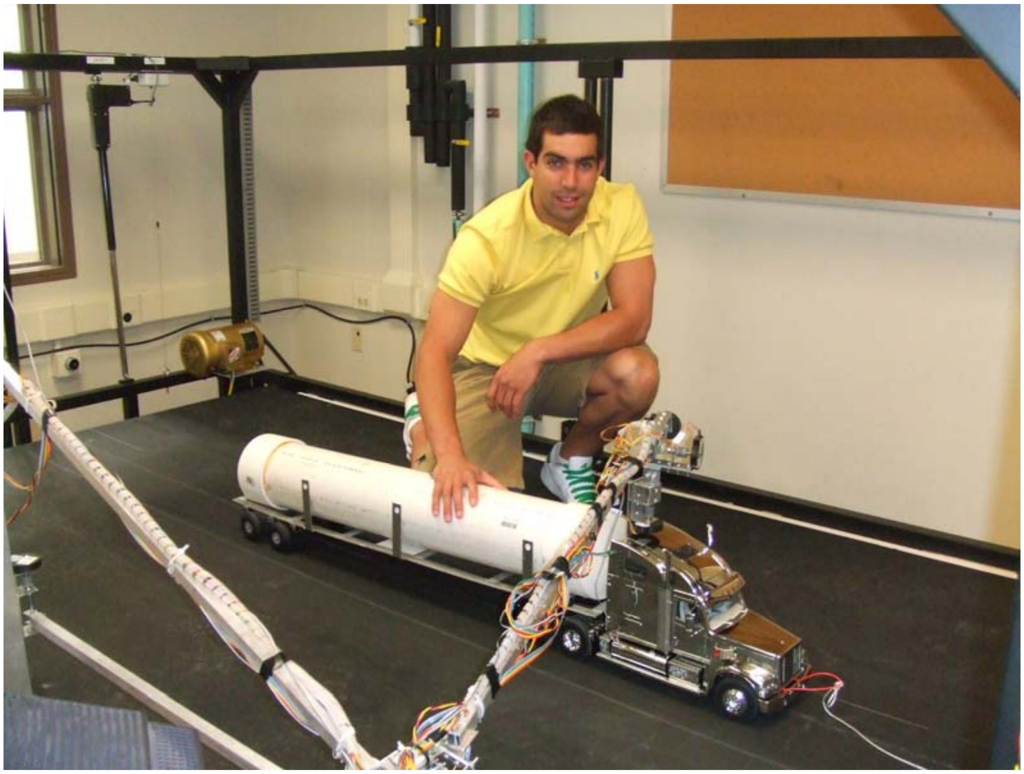

Figure 6-2: Dan Kaiserian next to the assembled scale tractor-trailer

Future Work

First the steering linkage is not robust. While the steering servo is kept at a constant value the front wheels exhibit a wobble behavior. This inadvertently causes the tractor to produce a sinusoidal response, which is undesirable for the constant steering input.

Secondly, the arm which attaches to the truck to measure the X and Y position, as well as the yaw rate, adversely affects the response of the vehicle. During testing, if the tractor deviated from the center of the track, the steering system was unable to make the tractor recover and come back to the center of the track. Possible ways of correcting could involve redesigning the arm or using a different system altogether to monitor the behavior of the vehicle, perhaps GPS and cameras.

Thirdly, a 1/14 scale model might be slightly too small. Another observation made during the initial testing of the tractor was a tendency to rollover under what would be considered normal driving conditions, for example slow-speed turns and slow-speed-straight line driving. A 1/10 scale model would have a longer track width and could possibly be less likely to roll over. Another possibility would be to add anti-sway bars or a more rigid suspension to help reduce body roll.

Finally a method for measuring the difference in articulation angle between the tractor and trailer would have to be developed. This could possibly be phased in along with replacing the arm that monitors the position and articulation angle of the tractor.

Appendix A

Full Scale Tractor Trailer Parameters

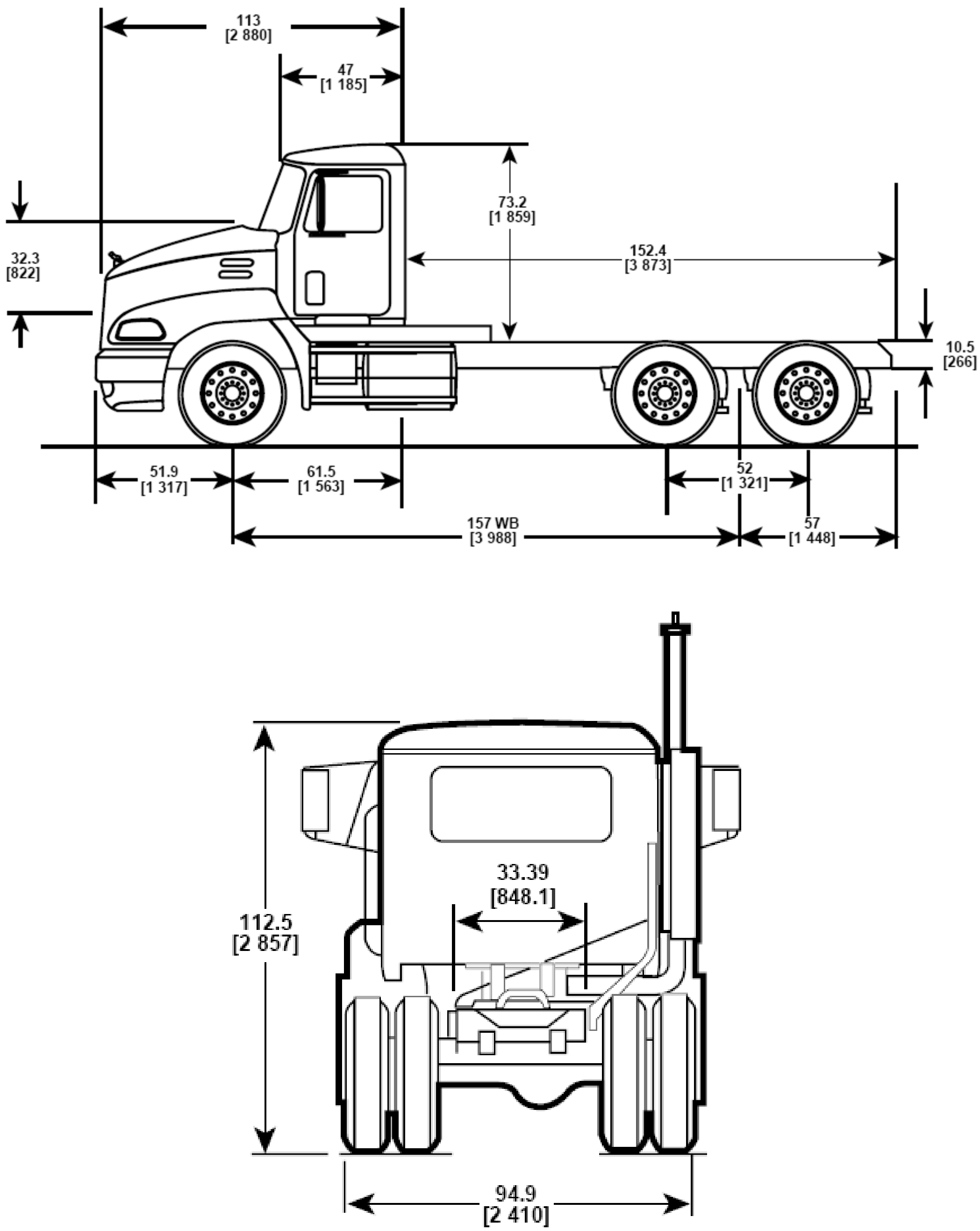

Figure **A-1**: The parameters from the Mack Truck specifications [1]

Tractor

Variable Name	Qualitative Definition	Value
w	track width	2.41 m
l	length	6.75 m
m1	mass	6417 kg
d	hitch point to center of mass	3.3765 m
b	rear axle to center of mass	3.3765 m
a	front axle to center of mass	4.217 m
c_f	front tire cornering stiffness	-100000 N/rad
c_r	rear tire cornering stiffness	-300000 N/rad
I1	mass moment of inertia	27521.79 kgm^4

Trailer

Variable Name	Qualitative Definition	Value
w	track width	2.41 m
e	hitch to trailer center of mass	8.075 m
h	trailer center of mass to rear axle	2.93 m
m1	mass	41846 kg
I2	mass moment of inertia	kgm^4
c_t	trailer tire cornering stiffness	-300000 N/rad

Table **A-1**: Tabulation of parameters used in mathematical model and simulation, and to decide on model trailer dimensions

1 Mack Trucks. *Standard Specifications for the CXN 603 Series.* October 14, 2005. Retrieved January 25, 2007 from http://www.macktrucks.com/assets/mack/Datasheets/Chassis%20Sheets/CHN6030020696.pdf

Appendix B

MATLAB Script and Plots

```
%This is used to verify the equations of motion derived for
%a heavy articulated vehicle (tractor trailer truck)

%Written by Jon Weidner with the assistance of Joe Yutko
%
clear all
clc


%tractor and trailer parameters
m1 = 6417;          %kg          = mass of tractor
m2 = 41846;         %kg          = mass of trailer
I1 = 27521.79;      %kg*m^4      = mass moment of inertia of tractor
I2 = 932923.79;     %kg*m^4      = mass moment of inertia of trailer
U  = 10             %m/s         = tractor forward speed
a  = 4.217          %m           = tractor front axle to cg
b  = 3.3765         %m           = tractor cg to rear axle
d  = 3.3765         %m           = tractor cg to fifth wheel
e  = 8.075          %m           = trailer fifth wheel to cg
h  = 2.93           %m           = trailer cg to rear axle
cf = -100000;       %N/rad       = front tire cornering stiffness
cr = -300000;       %N/rad       = rear tire cornering stiffness
ct = -300000;       %N/rad       = trailer tire cornering stiffness


Ma= m1+m2;
Mb= -m2*d;
Mc= -m2*e;
Md= -m2*d;
Me= I1+m2*d*d;
Mf= m2*e*d;
Mg= -m2*e;
Mh= m2*e*d;
Mi= I2+(m2*e*e);

Aa =-(cf+cr+ct)/U;
Ab = (m1+m2)*U+(-a*cf+b*cr+d*ct)/U;
Ac =(h+e)*ct/U;
Ad =-ct;
Ae =(-a*cf+b*cr+d*ct)/U;
Af =-m2*d*U-(a*a*cf+b*b*cr+d*d*ct)/U;
Ag =-d*(h+e)*ct/U;
Ah =d*ct;
Ai =(h+e)*ct/U;
Aj =-(m2*e*U)-d*(h+e)*ct/U;
```

```
Ak =-(h+e)*(h+e)*ct/U;
Al =(h+e)*ct;
Am = 0;
An = -1;
Ao = 1;
Ap = 0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   |       | |  .   |       |       | |      |   |     | |     |  %
%   |   M   |*|  X   |   =   |   A   |*|  X   | + |  B  |*|  U  |  %
%   |       | |      |       |       | |      |   |     | |     |  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

M = [Ma Mb Mc 0; Md Me Mf 0; Mg Mh Mi 0;0 0 0 1]
A = -[Aa Ab Ac Ad; Ae Af Ag Ah; Ai Aj Ak Al;Am An Ao Ap]
B = [-cf;-a*cf;0;0]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   |  .   |   =   |   M'A   | |  X   | + |  M'B   | |  U  |   %
%   |  X   |   =   |   M'A   |*|  X   | + |  M'B   |*|  U  |   %
%   |      |       |         | |      |   |        | |     |   %
%                   Matrix A              Matrix B             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

matrixA = inv(M)*A
eig(matrixA)
matrixB = inv(M)*B;
matrixC = [1 0 0 0 ; 0 1 0 0; 0 0 1 0;0 0 0 1];
matrixD = [0;0;0;0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%          Plotting          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

sim('bicycle_model_truck_sine');    %Plots a lane change maneuver

figure(1)
plot(X_truck,Y_truck,X_h,Y_h,X_trailer,Y_trailer)
title('Tractor Position Lane Change')
xlabel('X position'), ylabel('Y position')
legend('truck','hitch','trailer')

sim('bicycle_model_truck_step');    %Plots a constant radius turn

figure(2)
plot(X_truck,Y_truck,X_h,Y_h,X_trailer,Y_trailer)
title('Tractor Position Constant Radius Turn')
xlabel('X position'), ylabel('Y position')
legend('truck','hitch','trailer')
```

Verification of Equations of Motion

These are the parameters for the passenger car, which was used to verify the equations of motion

```
m1 = 1031.92;     %kg          = mass of tractor
m2 = 0;           %kg          = mass of trailer
I1 = 1850.5;      %kg*m^4      = mass moment of inertia of tractor
I2 = .0000001;    %kg*m^4      = mass moment of inertia of trailer
U  = 40           %m/s         = tractor forward speed
a  = .9271        %m           = tractor front axle to cg
b  = 1.5621       %m           = tractor cg to rear axle
d  = .0001        %m           = tractor cg to fifth wheel
e  = .0001        %m           = trailer fifth wheel to cg
h  = .0001        %m           = trailer cg to rear axle
cf = -77500;      %N/rad       = front tire cornering stiffness
cr = -116250;     %N/rad       = rear tire cornering stiffness
ct = -0;          %N/rad       = trailer tire cornering stiffness
```

This code estimates the response of the tractor and trailer system during both a turn of constant radius and a lane change maneuver. In the following Figures, **B-1** through **B-4,** the tractor center of gravity, hitch, and trailer center of gravity responses are plotted using a global coordinate system.

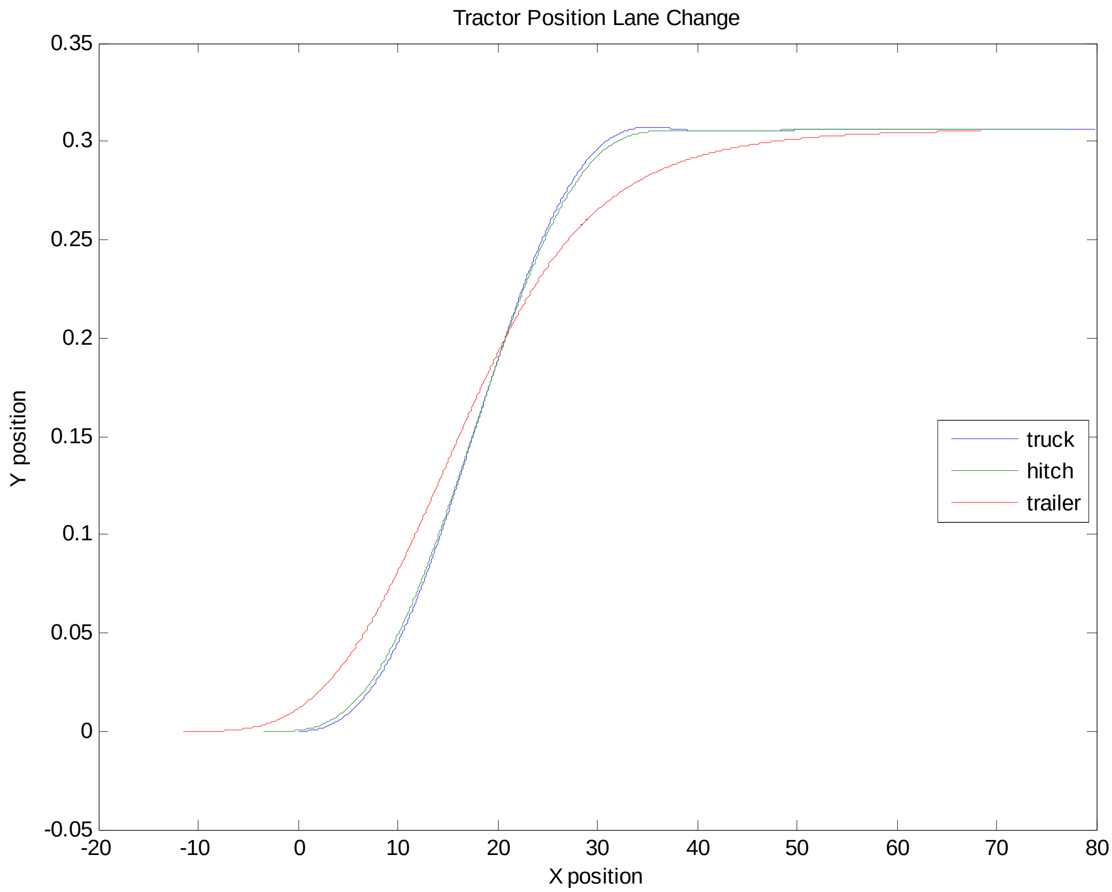

Figure **B-1**: The simulated response to a lane change maneuver at 4 m/s and a steering angle of 7 degrees = 0.1221 radians The tractor trailer system behaves as expected. At low speeds, the trailer will track to the inside of the tractor during a turn.

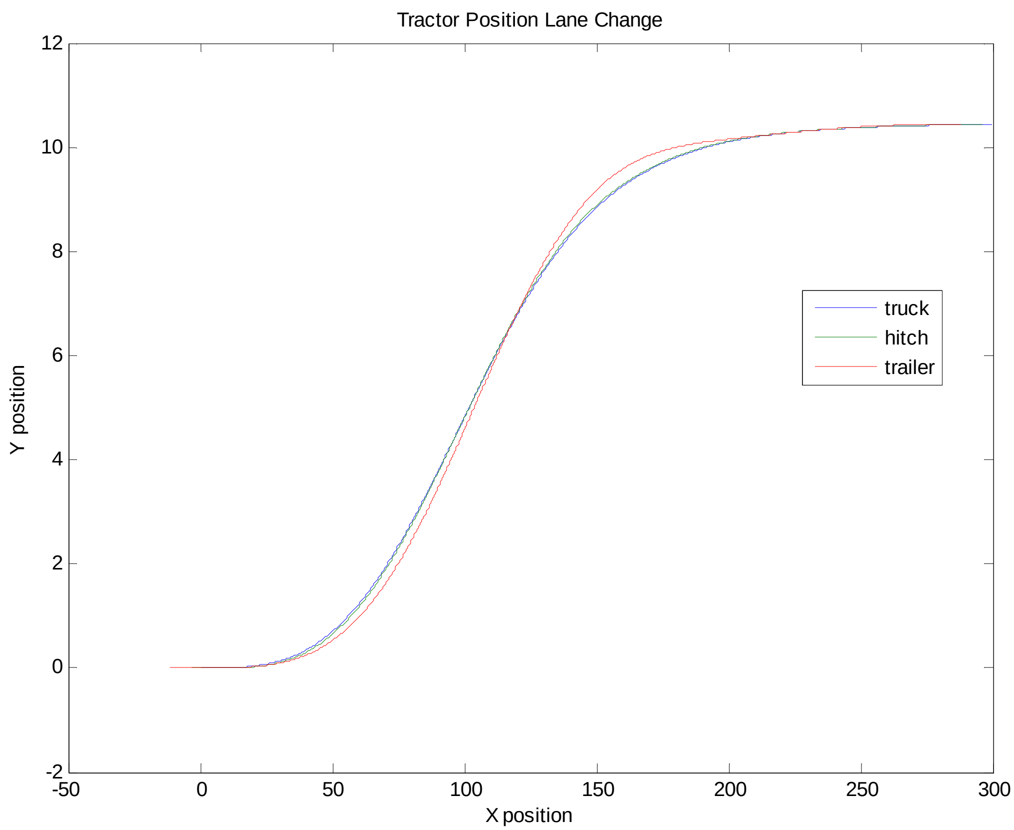

Figure **B-2**: The simulated response to a lane change maneuver at 15 m/s and a steering angle of 0.5 degrees = 0.0087 radians. The tractor trailer system again responds as expected. As the speed of the tractor trailer increases, the trailer will begin to follow a path similar to the truck.

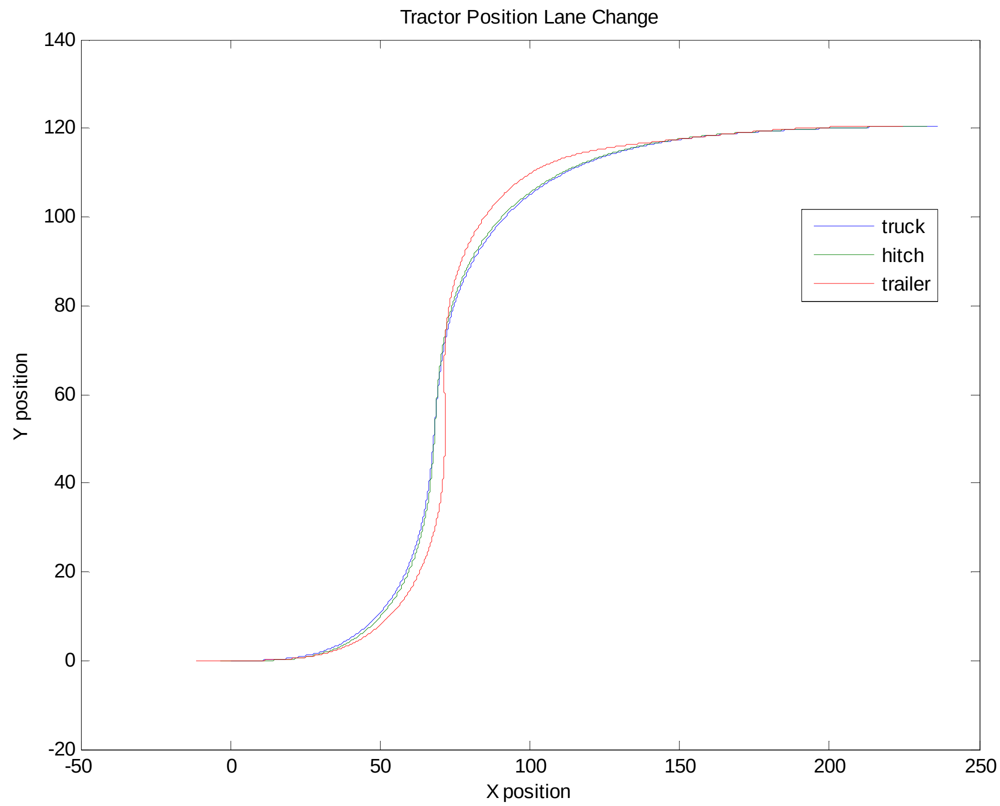

Figure **B-3**: The simulated response to a lane change maneuver at 25 m/s and a steering angle of 0.5 degrees = 0.0087 radians. Once again the tractor trailer system responds as expected. As the speed of the tractor trailer continues to increase the trailer continues to follow a path closer and closer to that of the truck. However, at excessive speeds as in the graph above, the trailer eventually swings out past the path followed by the truck.

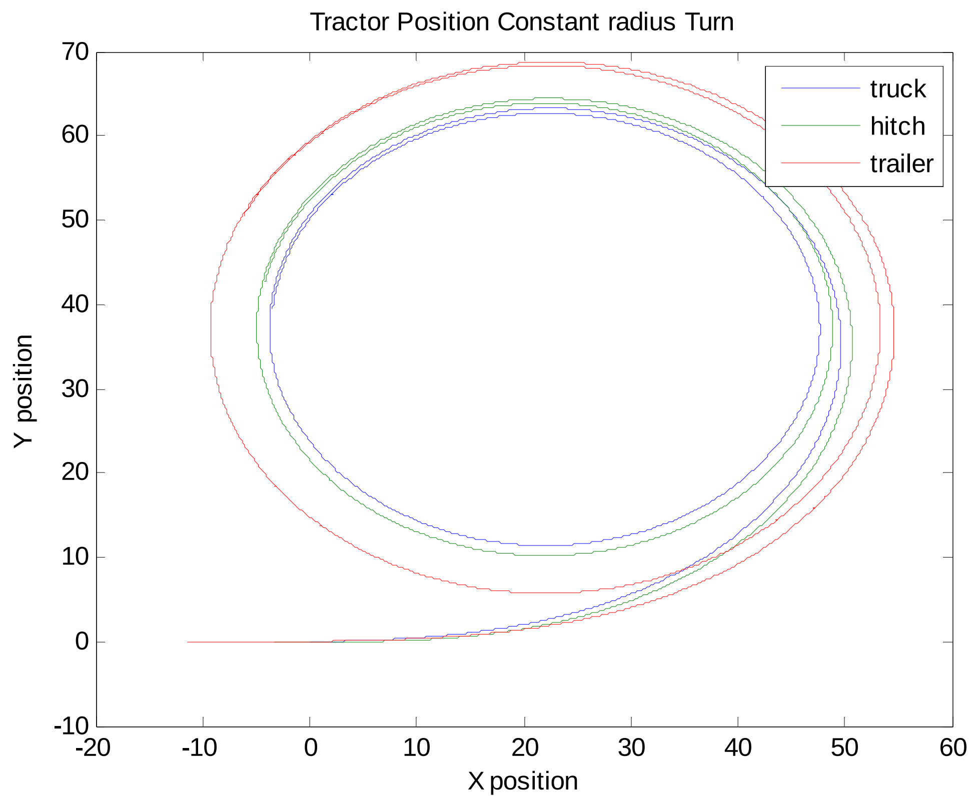

Figure **B-4**: The simulated response for a constant radius turn at 15 m/s and a constant steering angle of 7 degrees =0.122 radians

Appendix C

Simulink Block Diagrams

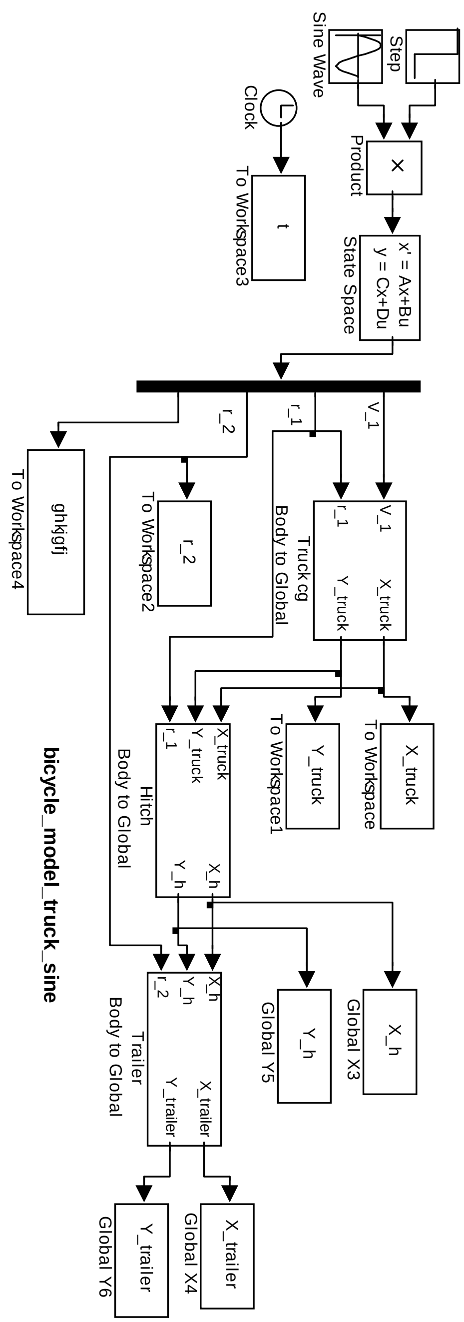

Figure C-1: Simulates a lane change maneuver.

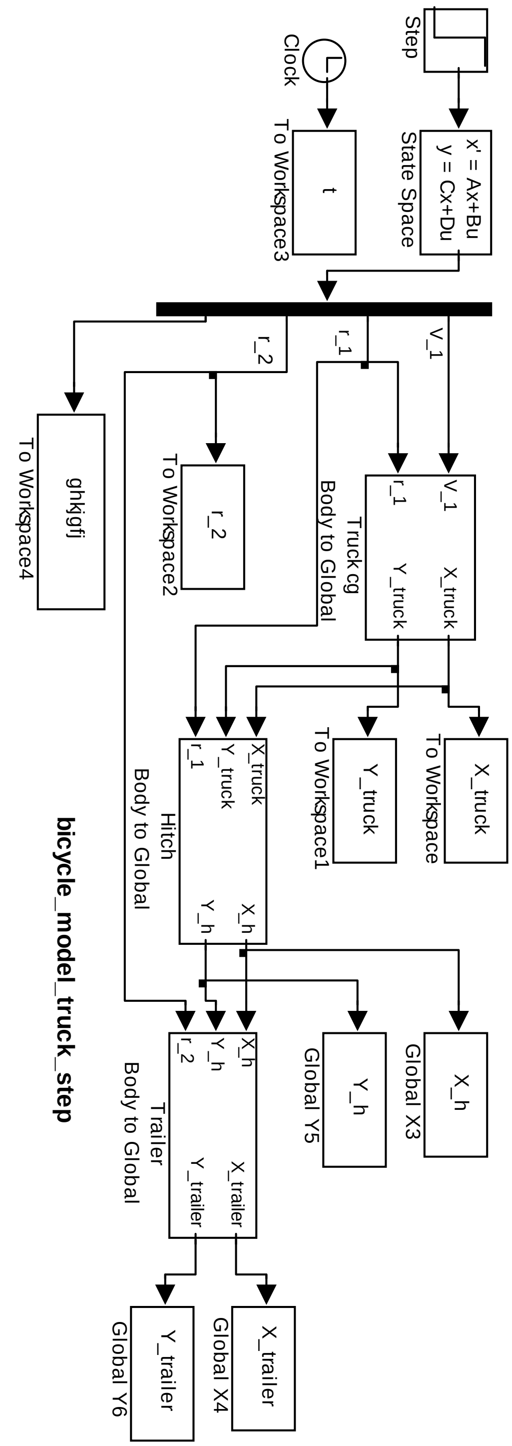

Figure C-2: Simulates a constant radius turn.

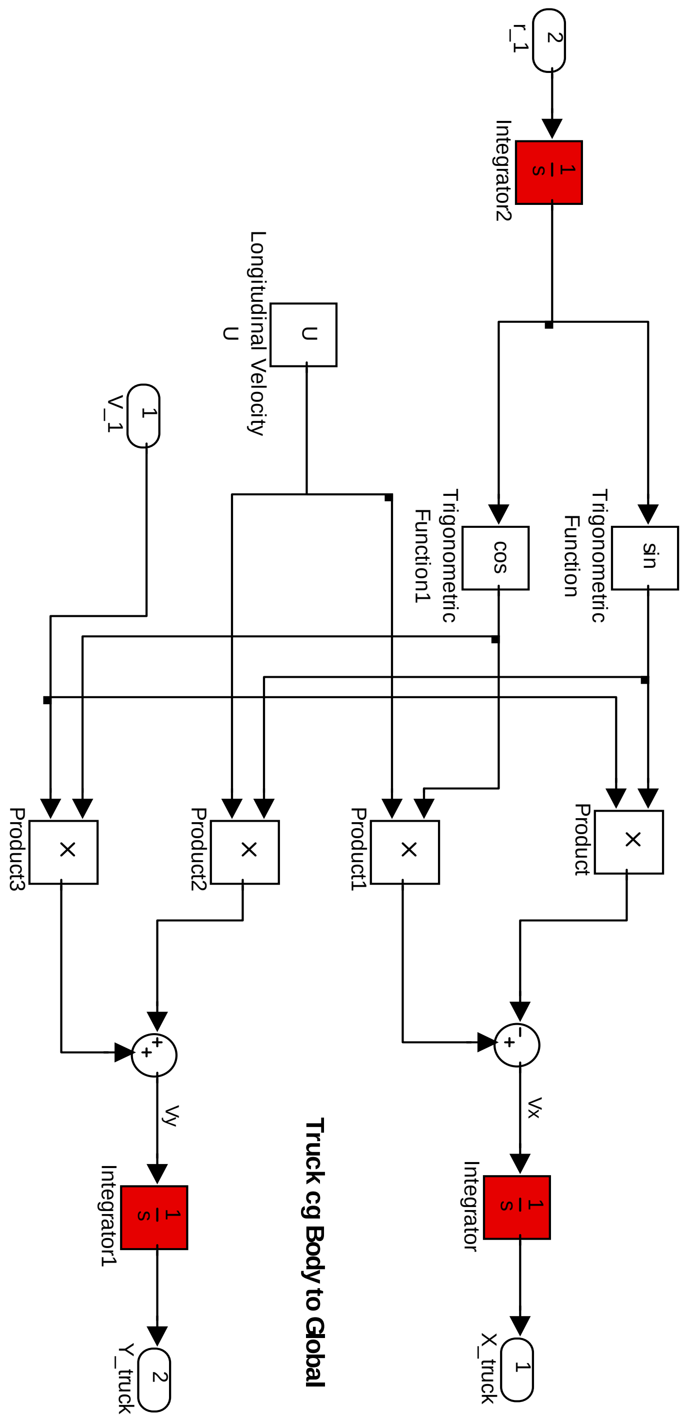

Figure **C-3**: Converts the body coordinates of the truck center of gravity to global coordinates.

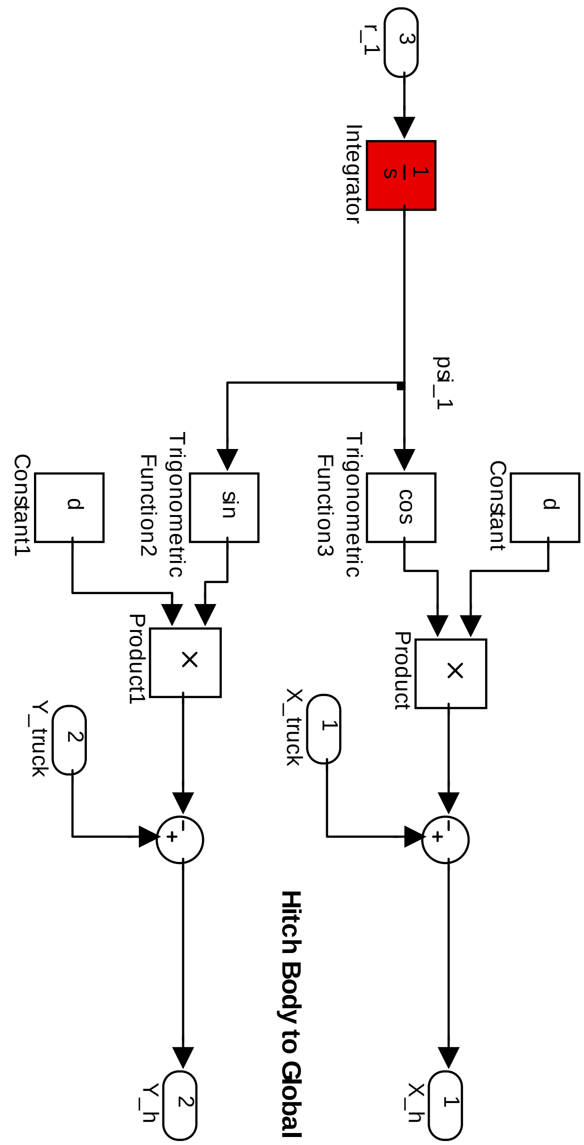

Figure C-4: Converts the position of the fifth wheel (hitch) to global coordinates

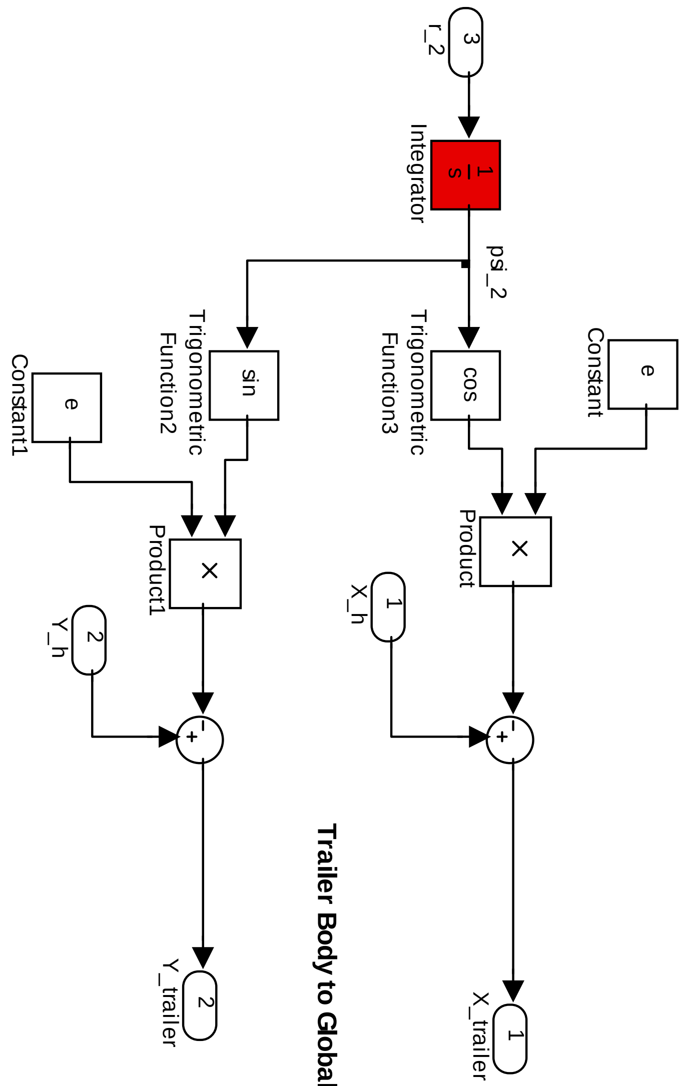

Figure C-5: Converts the position of the trailer center of gravity to global coordinates

Appendix D

Scale Vehicle Parameters

Steering Servo

Specification	Value	Units
Torque	42.0	oz-in
Speed	0.22	Sec to 60^o
Weight	1.50	oz
Length	1.60	in
Width	0.77	in
Height	1.40	in

Table **D-1**: Tower Hobbies System 3000 STD-TS53 steering servo specifications.

Tractor

trial #	Oscillations	time (s)	τ
1	20	31.57	1.58
2	20	31.03	1.55
3	20	31.10	1.56
4	20	31.44	1.57
5	20	31.47	1.57
6	20	31.22	1.56
7	20	31.22	1.56
8	20	31.53	1.58
9	20	31.32	1.57
10	20	31.29	1.56
average	**20**	**31.32**	**1.57**

Table **D-2**: Data used for calculating the mass moment of Inertia about the Z axis for the tractor.

Symbol		Value	Units
r_g	=	0.53	m
g	=	9.81	m/s^2
m	=	3.08	kg
τ	=	1.57	$1/s$

Table **D-3**: Data used for calculating the mass moment of Inertia about the Z axis for the tractor.

$$I = mr_g(g(\frac{\tau}{2\pi})^2 - r_g)$$

Equation **D-1**: Equation used for calculating the mass moment of Inertia about the Z axis for the tractor. (Also, Equation **5-4**)

Symbol	Description		Value	Units
m_1	mass of truck	=	3.080	kg
a	Distance from truck front axle to truck center of gravity	=	0.217	m
b	Distance from truck center of gravity to truck rear axle	=	0.257	m
d	Distance from truck center of gravity to fifth wheel	=	0.257	m
I_{1z}	Mass moment of inertia about the z axis	=	0.129	$kg \cdot m^4$
$C_{\alpha f}$	Front tire cornering stiffness	=	-	-
$C_{\alpha r}$	Rear tire cornering stiffness	=	-	-

Table **D-4**: The calculated parameters for the scale truck

Trailer

trial #	Oscillations	time (s)	τ
1	20	39.06	1.95
2	20	38.82	1.94
3	20	38.68	1.93
4	20	39.80	1.99
5	20	39.18	1.96
6	20	38.24	1.91
7	20	38.70	1.94
8	20	38.64	1.93
9	20	39.01	1.95
10	20	38.74	1.94
average	**20**	**38.89**	**1.94**

Table **D-5**: Data used for calculating the mass moment of Inertia about the Z axis for the trailer

Symbol		Value	Units
r_g	=	0.64	m
g	=	9.81	m/s^2
m	=	5.21	kg
τ	=	1.94	$1/s$

Table **D-6**: Data used for calculating the mass moment of Inertia about the Z axis for the trailer

$$I = mr_g(g(\frac{\tau}{2\pi})^2 - r_g)$$

Equation **D-2**: Equation used for calculating the mass moment of Inertia about the Z axis for the trailer (Also, Equation **5-4**)

Symbol	Description		Value	Units
-	Mass of trailer chassis	=	1.39	kg
-	Mass of container	=	3.82	kg
m_2	Combined mass	=	5.21	kg
e	Distance from fifth wheel to trailer center of gravity	=	0.50	m
h	Distance from trailer center of gravity to rear axle	=	0.39	m
w	Trailer track width	=	0.17	m
I_{2z}	Mass moment of inertia about the z axis	=	0.98	$kg \cdot m^4$
C_t	Trailer tire cornering stiffness	=	-	-

Table **D-7**: The estimated parameters for the combined scale container and scale trailer chassis

Scale Vehicle Drawings

Pro/Engineer Modeled Parts

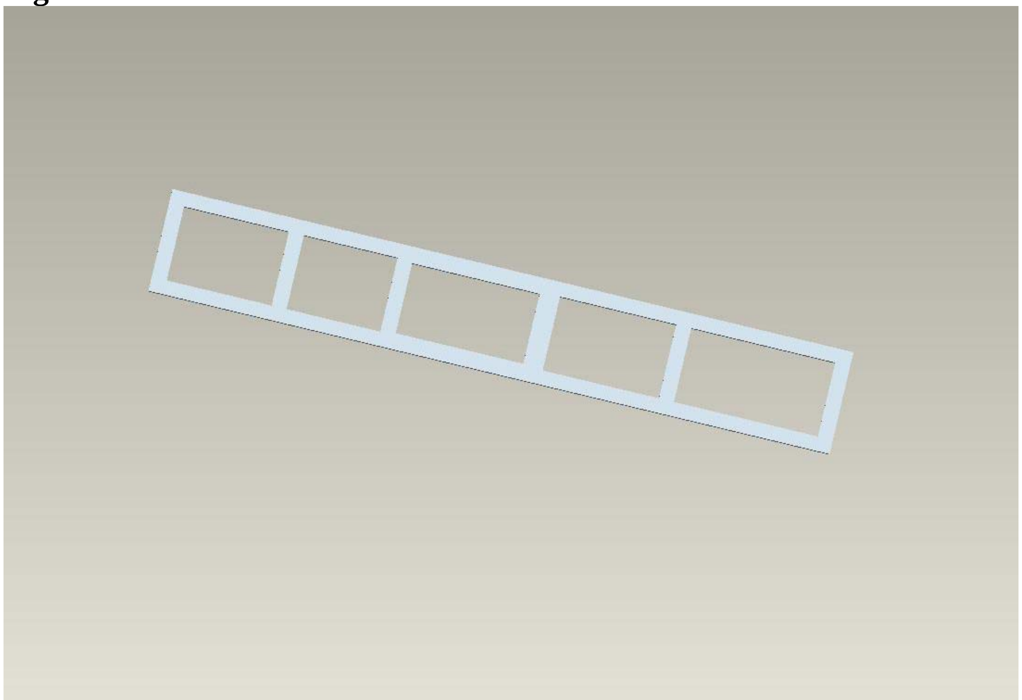

Figure **D-1**: Pro/Engineer Model of the Trailer Chassis

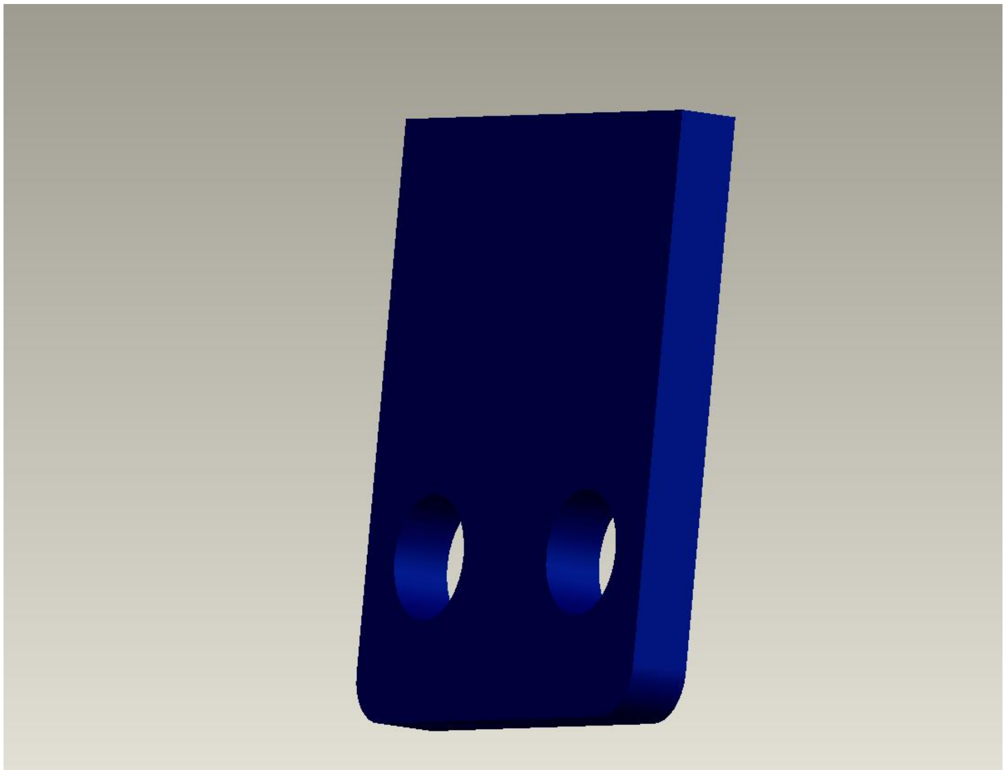

Figure **D-2**: Pro/E Model of the Center Spring Mounts

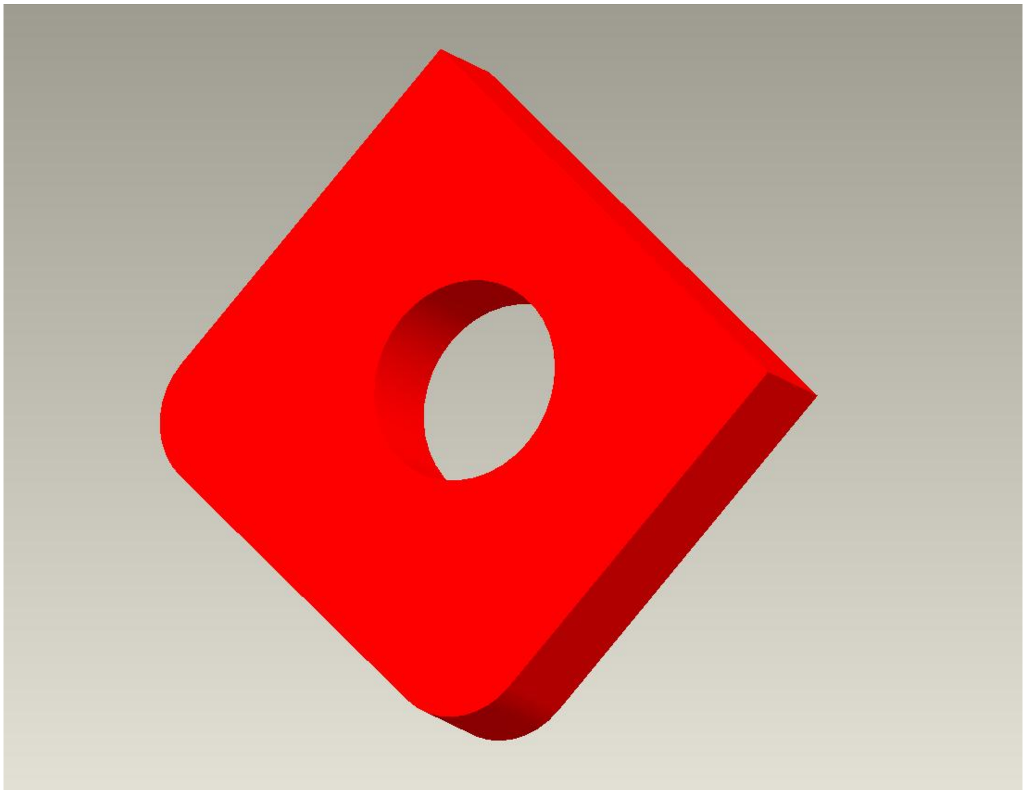

Figure **D-3**: Pro/E Model of the front and rear spring mount that attaches to the pivot (below Figure D-4)

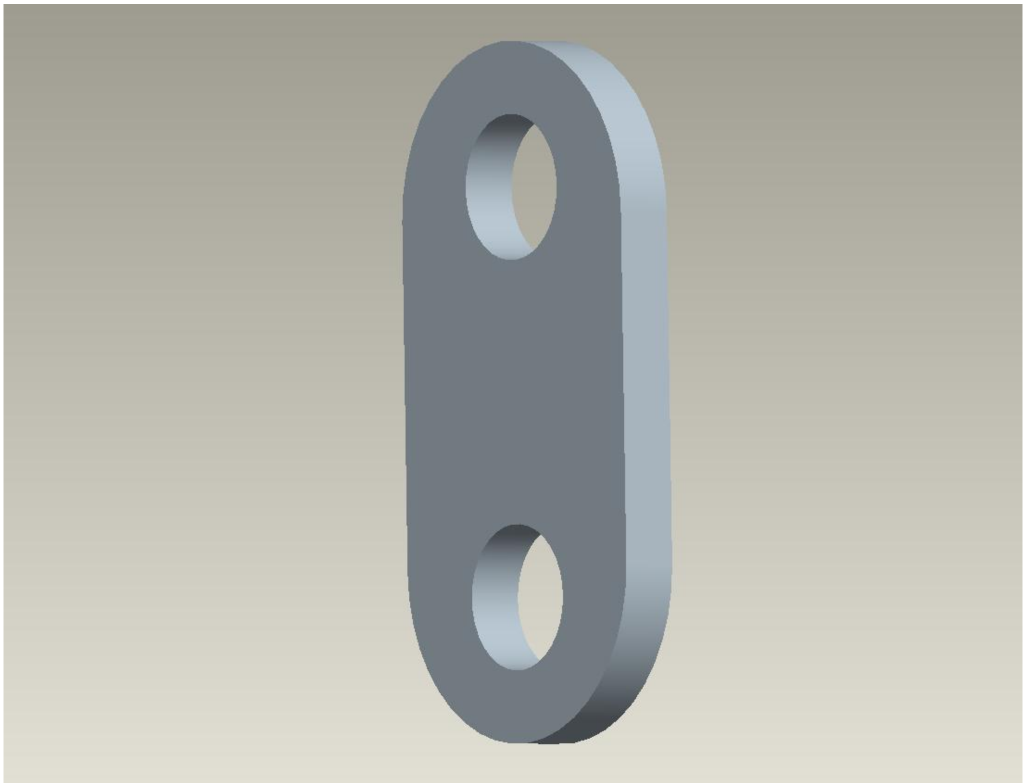

Figure **D-4**: Pro/E Model of the pivot allowing the leaf springs to deform

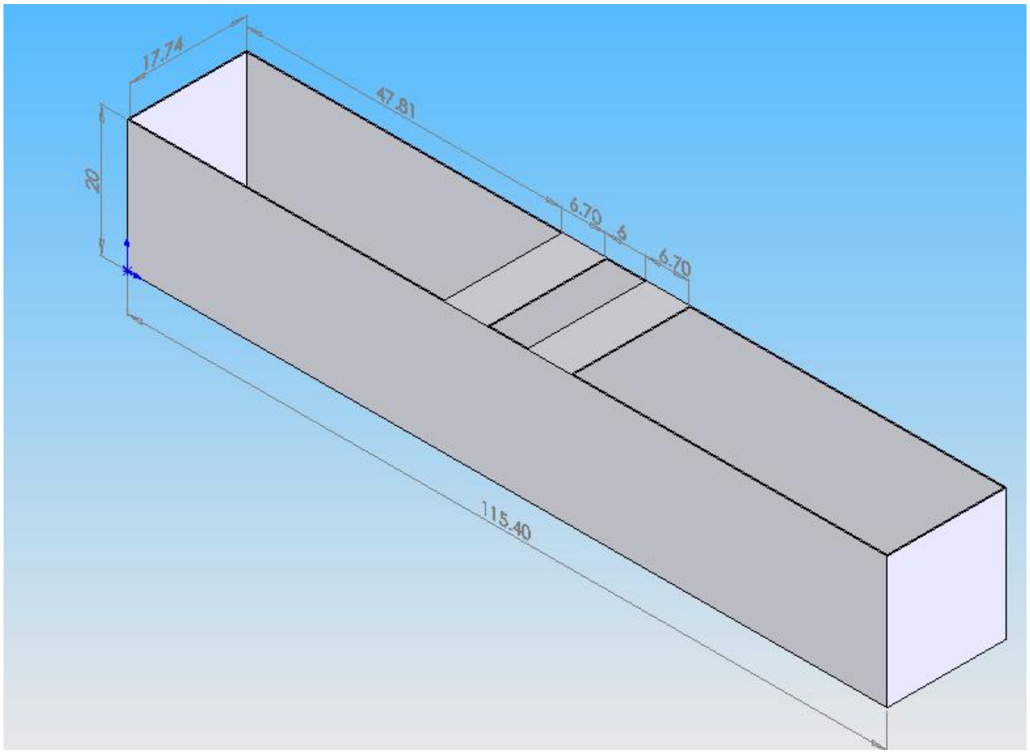

Figure D-5: SolidWorks Model of the container with dimensions in centimeters

Appendix E

Academic Vita

Jonathan Leo Weidner
jon.weidner@gmail.com
One Shipton St.
Mifflinburg, PA 17844
(570) 966-1502

Education:

The Pennsylvania State University
Schreyer Honors College
College of Engineering
Department of Mechanical and Nuclear Engineering
Bachelor of Science in Mechanical Engineering
Minor in Engineering Leadership and Development
Graduation Date: May 2007

Thesis:

Tractor Trailer Instability of Variably Loaded Container Trucks
Honors in Mechanical Engineering
Thesis Supervisor: Dr. Sean Brennan

Engineering Experience

General Electric Consumer and Industrial – Lighting, Winchester, VA
Technical Co-op **August 2005 – December 2005**

- Calculated and analyzed machine efficiencies, shrinkage, and yields
- Organized, created, and updated Manufacturing Process Instructions
- Improved downtime logging, and replaced production floor computers
- Created a detailed instruction manual for future co-ops

Work Experience

The Pennsylvania State University, University Park, PA
Earth and Mineral Sciences Library Assistant **June 2006 – Present**

- Managed service desk
- Assisted patrons with problems

The Pennsylvania State University, University Park, PA
PC Lab Monitor **June 2004 – August 2004**

- Monitored the Mechanical & Nuclear Engineering PC Studio computer labs
- Ensured proper working order of software and hardware
- Distributed student accounts and assisted in solving problems

Mifflinburg Area School District, Mifflinburg, PA
Maintenance Assistant **Summers 2002 - 03**

- Performed several maintenance duties including mowing, painting, and deliveries

Honors, Awards, and Activities

Phi Kappa Phi all discipline Honor Society, Spring 2006
Daniel R. Crowley, Jr. Memorial Scholarship, Spring 2006
Pi Tau Sigma Mechanical Engineering Honor Society, Fall 2004
Tau Beta Pi Engineering Honor Society, Fall 2004
Louis A. Harding Memorial Scholarship, Awarded Fall 2004 & Spring 2005
Boy Scouts of America, Assistant Scout Master, Spring 2004 – Spring 2005
President’s Freshman Award, June 2003
Eagle Scout, Bronze Eagle Palm, November 2001