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SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING AND
THE COLLEGE OF ENGINEERING

# TRACTOR TRAILER INSTABILITY DUE TO LIQUID SLOSH IN A PARTIALLY FILLED TANK

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## Abstract

The instability of tractor semitrailers is well documented. However, the models that have been designed to help truck drivers avoid instability conditions have only been developed for trailers that carry solid cargo. Thus, these models do not apply to partially filled liquid tanker-type semitrailers, and only qualitative methods for preventing rollover exist for such trailers. Using the three degree of freedom bicycle model, I developed a mathematical model of a tractor trailer in which various inputs were tested. Liquid slosh was not accounted for in the analysis due to the complexities of its mathematical analysis. In an effort to quantify the inputs and loading situations that are most dangerous, a scale model of a tanker tractor trailer was built for use on a roadway simulator. My work focused on the development of the hardware required to perform the scale model tests. Data will begin to be collected in the following weeks, and the trailer response will be compared to the response predicted in the mathematical model and simulation. Finally, the data collected will be used to develop methods of slosh mitigation, and techniques to prevent slosh-based trailer instability.

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# Chapter I—Introduction

## Objective and Motivation

The main objective of this thesis is to use scale model testing to collect some of the first data ever for tractor trailer rollover due to liquid sloshing in a partially filled tank. Because of the sloshing liquid, the three degree of freedom model for tractor trailers does not do an adequate job predicting instability conditions. To show that sloshing causes unforeseen instability conditions, we will employ the three degree of freedom model in a mathematical simulation, and compare the predicted results with the results that we observe and collect from the scale model test.

Because quantitative test data has never been acquired for a trailer with a sloshing tank, there are only qualitative ways to avoid rollover. The research and data acquired from the scale model studies will help to better understand the phenomenon of slosh-based instability. Questions we hope to answer include which driving inputs are most likely to cause a rollover, what level of liquid in the tank is the most unstable, and how to avoid rollover if any of these conditions exist. By discovering and quantifying these properties, we hope to be able to decrease the number of trailer rollovers due to sloshing tanks.

A trailer's tank will never be filled to more that the maximum capacity, and when full, the trailer behaves like a solid mass. However, if a trailer is only partially filled, such as in the case of a truck hauling milk, orange juice, clay slurry, or cooking oils, the risk of a sloshing tank arises. Slosh is generally not a concern in transport of volatile substances, as those trailers run full to the drop point and then unload all of their cargo. The partially filled tank allows the fluid to move, and if it hits a harmonic, the movement will continue uncontrollably, possibly causing the trailer to flip.

**Literature Review**

Tractor trailers, regardless of cargo, have a very low roll stability because of their high centers of gravity when loaded [3]. "Because of this characteristic, tractor semitrailers are susceptible to rollover during rapid lane-change or cornering as for instance on highway exit ramps,"[3]. Therefore, we will test steady-state cornering and lane change situations to discover rollover conditions. Though there have been electronic systems developed to warn a driver of a potential roll condition, they can be unreliable or even over-reliable, issuing warnings too often [3]. Thus quantitative evidence is necessary to help reduce rollovers on a large scale.

Ma and Peng have quantified some worst-case conditions that will cause a trailer to roll over [4]. However, the worst case inputs may be less severe when working with a sloshing liquid cargo. For example, if 2.5 degrees of tire steering angle in a sinusoidal steering input (i.e. a lane change) will cause a tractor trailer to flip at 60 mph [4], less steering angle could cause the same response if the tank was sloshing.

In *Lateral Control of Commercial Heavy Vehicles* [1], it is shown that by deriving the equations of motion for a tractor trailer by applying Lagrange's equations, a model can be developed that predicts the response of an apportioned vehicle to a specific steering input. The simulation employs a spring/damper model suspension to eliminate the need for experimentally determining suspension characteristics. The model was validated for forward tractor velocities of 30-46 mph.

Currently, the most accepted way to reduce the chances of tractor trailer rollover is braking. Due to the dependence of roll, yaw, and lateral dynamics upon each other, braking reduces the amount of roll when a tractor trailer is negotiating a turn. Applying the brakes also helps to reduce the roll angle by reducing lateral acceleration because pneumatic tires do not react linearly [2]. However, if the fluid in the tank begins to slosh, these tradeoffs will no longer yield a stable trailer.

To design a tank for a valid liquid slosh analysis, several guidelines must be followed. The fluid used to fill the tank must be dynamically similar; namely the Reynolds number and Cauchy number must be the same. It is also important to make the vessel of scale dimensions. Finally, due to the differences in slosh period for a small tank and a large tank, time scaling must be done to allow for a valid analysis of inputs that cause slosh [6].

**Outline of Coming Chapters**

In chapter 2 of this thesis I will discuss the equations of motion used to develop the mathematical model and simulation. Chapter 3 will follow the build process of the scale model trailer, including hardware development. Finally, chapter 4 will discuss how we found the scale model vehicle parameters.

# Chapter II—Equations of Motion and Simulation

## Introduction

Using the three degree of freedom model, a state space model was created in Simulink, using the parameters found in Mack Truck publications [5], on the internet from the World Trade Press [7], and through our own calculations, which are discussed later. These parameters are tabulated in Appendix A, along with other parameters relevant to the model. The simulation is used to predict tractor trailer response for a step input, such as a quick swerve to avoid debris or a lane change, as well as a constant speed, constant radius turn. The goal behind creating the simulation was to use various sets of parameters that predict stability for a solid cargo tractor trailer, and compare them to the actual response of a scale model of a tanker tractor trailer, to see if, and how much, a sloshing fluid in a tank will affect vehicle stability.

The first-principles simulation cannot be used to predict the response of a partly filled tanker tractor trailer because of the complexities of mathematically analyzing liquid slosh. However, parameters of a tanker tractor trailer can be used in the lumped mass simulation. With this assumption, only the dimensions and masses of the tractor trailer components are pertinent to the mathematical simulation. The results of this simulation are later compared with the experimental results of the scale model testing.

## Mathematical Model Parameters

In the design of the model as well as in the Simulink/MATLAB simulation, dynamic similarity is extremely important. For both the tractor and the trailer, moments of inertia must be calculated to perform the simulation. Since the moment of inertia in question is the moment about the z-axis (using a body-fixed coordinate system), the tractor and trailer were each approximated at steel plates with length and width equal to the length and width of the actual vehicle, but with a thickness such that the weight of the vehicle and the plate are equal.

$$I_{tractor} = I_{plate}$$

$$I_{plate} = \frac{m(w^2 + l^2)}{12}$$

$$I_{tractor} = \frac{(6417.3kg)[(2.421m)^2 + (6.753m)^2]}{12}$$

$$I_{tractor} = 27521.79kg \cdot m^4$$

As can be seen from the above analysis, the thickness of the plate and the density of the metal do not figure into the moment of inertia calculation, thereby validating the assumption that a steel plate can be used to approximate the moment of inertia of the tractor and trailer. Similarly, it can be calculated that $I_{trailer} = 932912.79kg \cdot m^3$.

**Equations of Motion**

Using the equations for a 3 degree of freedom model for tractor trailer vehicle dynamics, a series of differential equations can be written. These are shown here.

$$m(\dot{V} + U_1 r_1) + m_1 \bar{x}_1 \dot{r}_1 - m_2 \bar{x}_2 \dot{r}_2 = y_f + y_r + y_t$$

$$m_1 \bar{x}_1 (\dot{V} + U_1 r_1) + I_1 \dot{r}_1 = a_1 y_f - b_1 y_r$$

$$-m_2 \bar{x}_2 (\dot{V} + U_1 r_1) + I_2 \dot{r}_2 = -b_2 y_t$$

To be able to use a simple state space block for the simulation, we rearranged the equations and made them into two matrices to follow the form

$$\dot{X} = [M'A][X] + [M'B][U]$$

where, when before $\dot{X}$ is isolated, the matrix equation is defined in terms of tractor trailer parameters as shown below.

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

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

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

**Global Conversion Equations**

The outputs of the equations pertain only to the SAE coordinate system. To better understand the behavior of the tractor and trailer, the outputs of the simulation must be modified to reflect the global coordinate system, rather than the truck's local coordinate system. Three subsystems (shown expanded in Appendix B) complete this task, by converting the local coordinates of the trailer, hitch point, and trailer to global coordinates. The conversion equations for the tractor, hitch point, and trailer are shown below.

**Tractor**

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

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

**Hitch Point/Fifth Wheel**

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

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

**Trailer**

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

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

This applies when *d* is equal to the distance from the hitch point to the tractor's center of mass, *e* is the distance from the trailer's center of mass to the hitch point, and $\psi_1$ is the articulation angle between the tractor and the trailer.

The locations of the tractor, the fifth wheel, and the trailer were plotted in terms of x and y location in the global coordinate system for both a constant radius turn and a lane change input. The plots can be found in Appendix B with the m file and Simulink block diagrams.

# Chapter III—Construction of Scale Model

## Introduction

Due to the complexities and challenges of mathematically determining the effects of slosh, it was decided that the best way to proceed with the analysis would be to build a scale model of an entire tractor trailer system. The generally accepted model scales are 1:10 and 1:14. Initially, we decided that the 1:10 scale would be a better choice, as the calculations would be easier, and the dimensions simpler to work with. We were able to have a 1:14 scale model tractor donated, and thus decided to build the trailer to the corresponding specifications (Tabulated in Appendix C).

Pro/Engineer was used to design some of the simpler components of the model, and the three-dimensional drawings can be found in Appendix C. Originally, the Pro/Engineer model was to be used to determine component spacing, but measurements of a full-sized trailer were scaled by a factor of 1/14 to allow for the most realistic response possible. As such, solid modeling was only used for the frame and the parts needing rapid prototyping on the water jet machine.

## Construction

The chassis of the trailer was constructed from 6061-T6511 aluminum in the form of 1/8 inch x 1 inch flat stock. Pieces were cut using a sheet metal shear and the parts connected using a TIG welder set at 60A, DC. Shown below are the assembled outer chassis, the bracings, and the completed chassis itself.

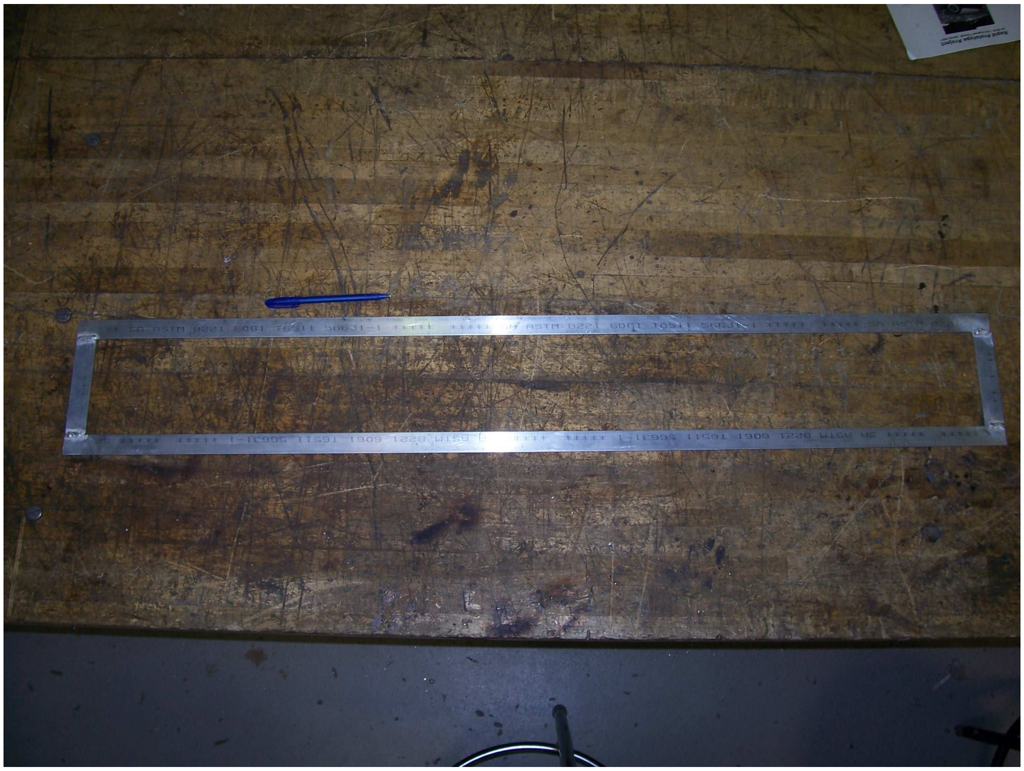

Figure 3.1: Shown above is the welded outside of the chassis, the pen is placed there for a reference of scale.

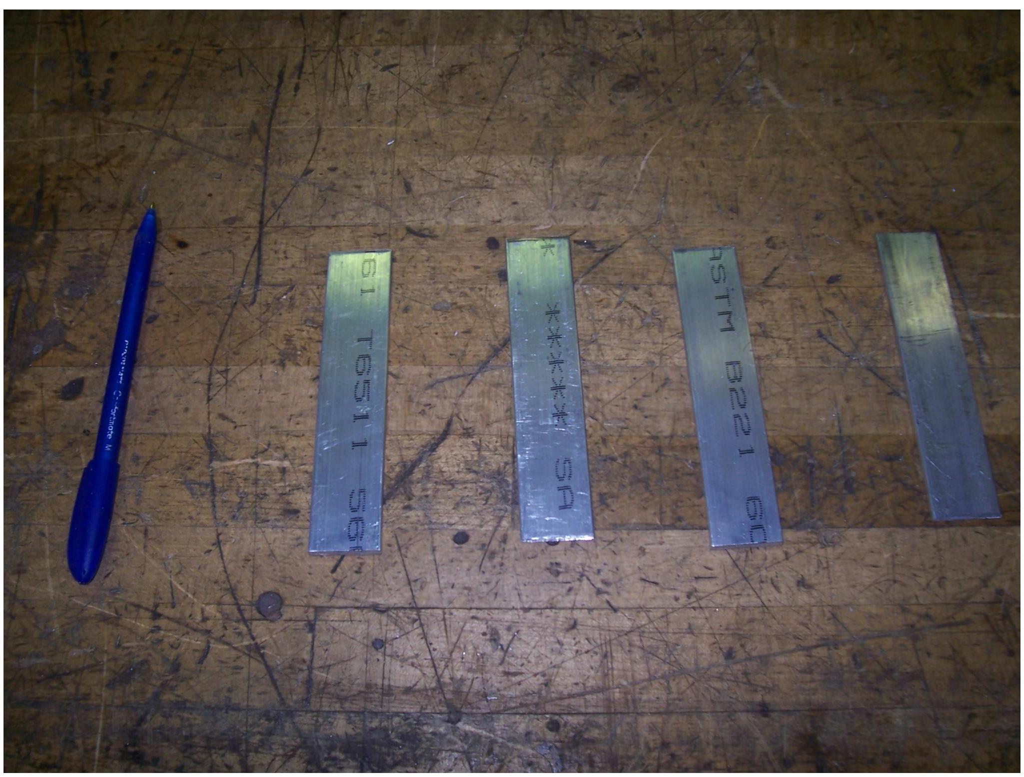


Figure 3.2: These are the cross bracings, used to increase the torsional stiffness of the chassis. Again, the pen is placed there for scale

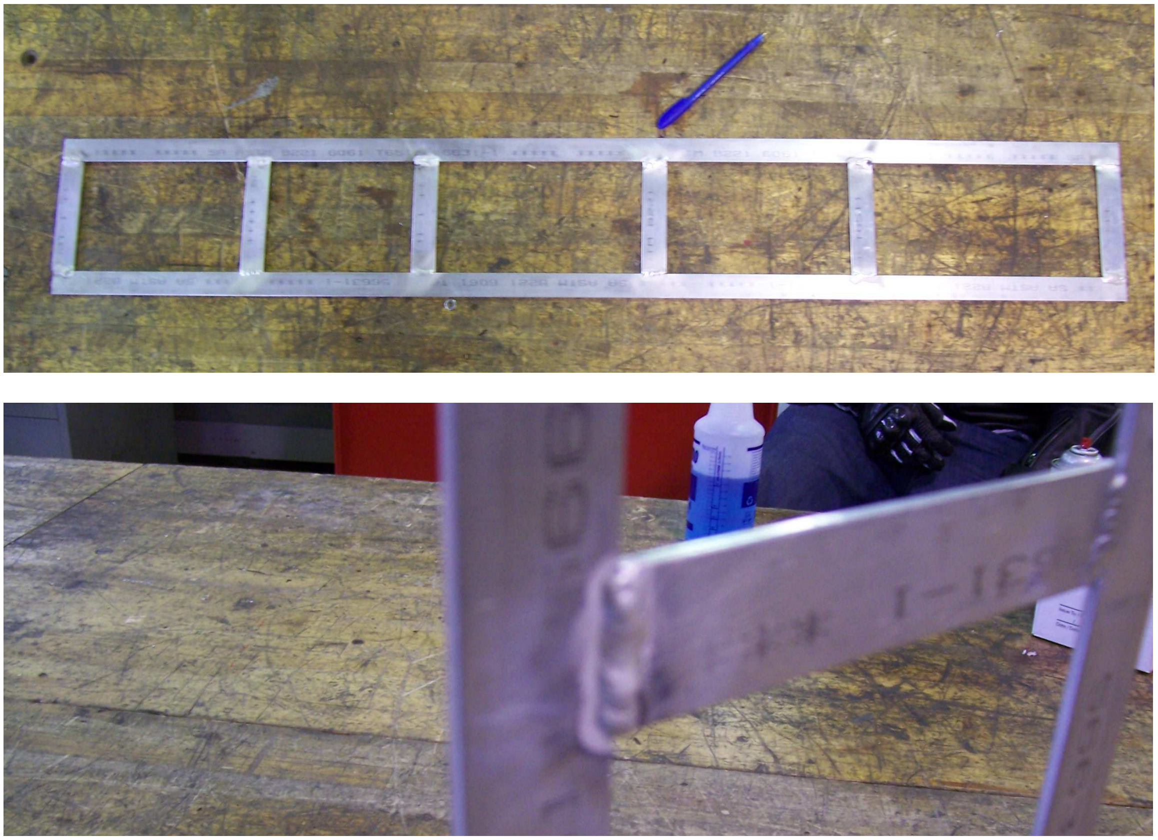

Figure 3.3: Above are the completed chassis and a close up of one of the welds.

After the construction of the chassis, a suspension system had to be designed and fabricated. Referencing an actual trailer suspension show in the picture below, a 1:14 scale leaf spring suspension was devised using 0.050” sheet steel and 0.50” tubing. The sheet metal was cut into four strips 0.50” in width and 3.6” in length. This length was chosen to give the final springs a spring length of 3.3” after curvature, which matches the length of leaf springs on a full-sized truck. Each strip was then hammered on an 8” diameter steel cylinder to give them uniform curvature, and spring constant. Two strips were made for each trailer axle, as each wheel has its own leaf spring, as can be seen in the pictures of the full size trailer.

The steel tubing was then cut into 0.5” lengths on the horizontal band saw. Finally, the bent metal strips were each welded to two 0.5” pieces of the steel tubing, with the opening perpendicular to the length of the strip, to allow the pieces to be attached to the suspension braces.

Figure 3.4: A leaf spring attached to the axle on the full size trailer

Figure 3.5: Note the two leaf springs on each side of the trailer, one on each axle

Figure 3.6: This picture shows the original size of the metal strip along with two completed leaf springs. Note that though the strip is bent, the finished springs are longer due to the connectors.

Figure 3.7: This picture shows three finished leaf springs from three different views. All are the same overall length, and they have the same radius of curvature.

To attach the leaf springs to the trailer chassis, mounts were designed in Pro/Engineer. There are two different types of mounts, due to the way leaf springs work. The mount between the rear wheels, which both leaf springs connect to, have a pin connection, restricting both translational degrees of freedom at the connection. However, the springs can still rotate about the pin. This rotational motion is important because the other mounts, which attach behind the rear wheel and in front of the front wheel, have a pivot, which allows the spring to deflect as disturbances are encountered. One end of each spring must be able to pivot with a degree of freedom along the length of the trailer, so that the spring can flex. Pictures of both the part and the assembly are shown below. The mounts were machined on the water jet machine, and they were made from 0.25" aluminum sheet metal. The use of aluminum allows the mounts to be welded directly to the frame, increasing the stability over a glued or riveted approach. Due to spacing issues, the pivots were made of 0.1 inch steel sheet.

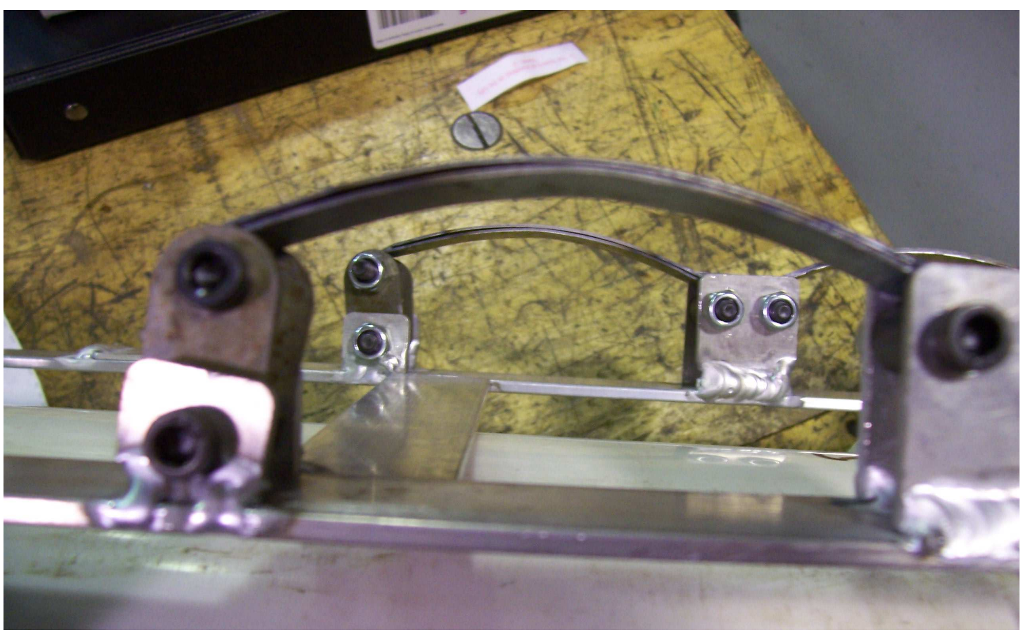

Figure 3.8: The left hand side of these springs allows the spring to deform, and deflect the steel pivot. The right side remains fixed in position.

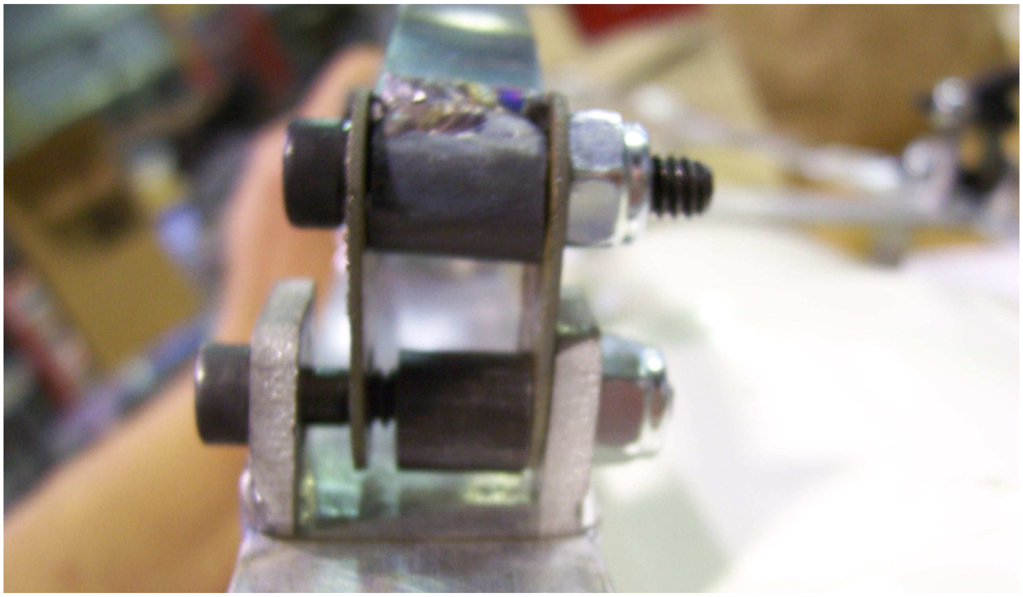

Figure 3.9: This is the rear view of the suspension. The spacer on the bottom bolt keeps the suspension pivots vertical, allowing for a consistent ride height on each spring

After initial testing of spring stiffness on the nearly completed trailer, we determined that the springs were too likely to plastically deform under the weight of the trailer. To increase the stiffness of the springs, an additional leaf of 3.5x0.5-inch 0.1 inch steel was welded to the existing springs. The added stiffness comes from load sharing between the two leaves of metal, and eliminates plastic deformation under the weight of the tank and trailer. This can be seen in Figure 3.8. To get the new leaves to sit flush against the original springs, they were grinded down to fit between the weld beads that attach the original springs to the tubing. These new leaves were then welded into the same bead, increasing strength, and allowing the leaves to laminate properly.

The trailer's wheels are 3" model airplane wheels. These were chosen for a number of reasons. They are rubber tires, which simulates the actual material used on truck tires. The wheel to tire size ratio is fairly close to those of actual trucks, which will help to yield better results, as tire behavior will be more similar. Finally, the tires are air-filled. Solid tires would alter trailer response significantly, as saturation properties would change.  The three inch wheels were used to simulate the 42” diameter wheels used on the largest trailers.  The wheels accept an axle 5/32 of an inch in diameter, and can rotate freely about the axle.  We chose to use A228 spring steel, also known as music wire, for the axles.  The free rotation allows the wheels to turn at different speeds as the tractor is cornering.  Commercial trailers use this same setup, since no engine input is transmitted to the trailer wheels, and therefore, there is no differential on the trailer.

Figure 3.10: These are the tires used for the trailer.

In designing a way to attach the axles to the suspension system, the main issue was finding a sleeve through which the 5/32 inch axle would fit without room to vibrate, but with enough room to spin freely.  Using ¼ inch steel round stock, four mounts were machined into tubes on a lathe, having an interior diameter of 5/32 inches.  Because the leaf springs are ½ inch wide, the sleeves were cut to 0.85 inches so that the wheel was spaced an adequate distance from the spring and the frame.  Pieces of music wire were then fed through the sleeves to align them on the leaf springs.  The sleeves were then clamped to the springs and welded into place.  The front set of sleeves was welded first, and then, with two pieces of axle material, we measured a constant 4.1 inches between the axles on each side to insure that the axles would be parallel.  We then welded the second set of ties to the leaf springs.

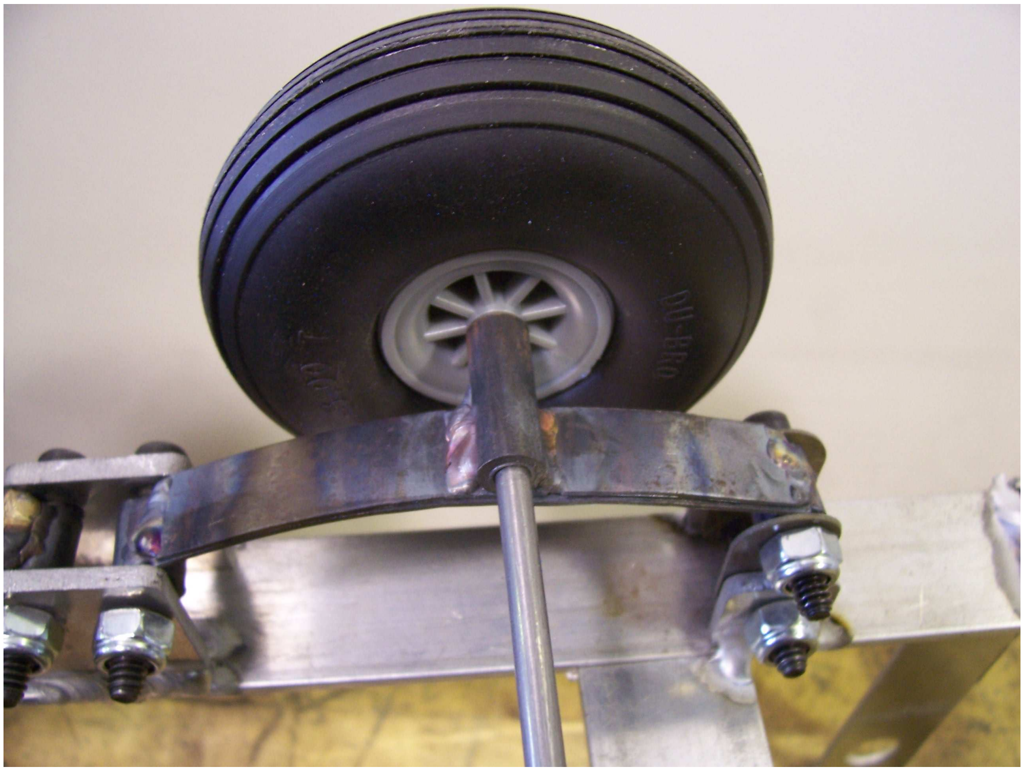

Figure 3.11: This shows the sleeve, welded to the front right leaf spring, and the spacing effect that it has for the wheel itself.

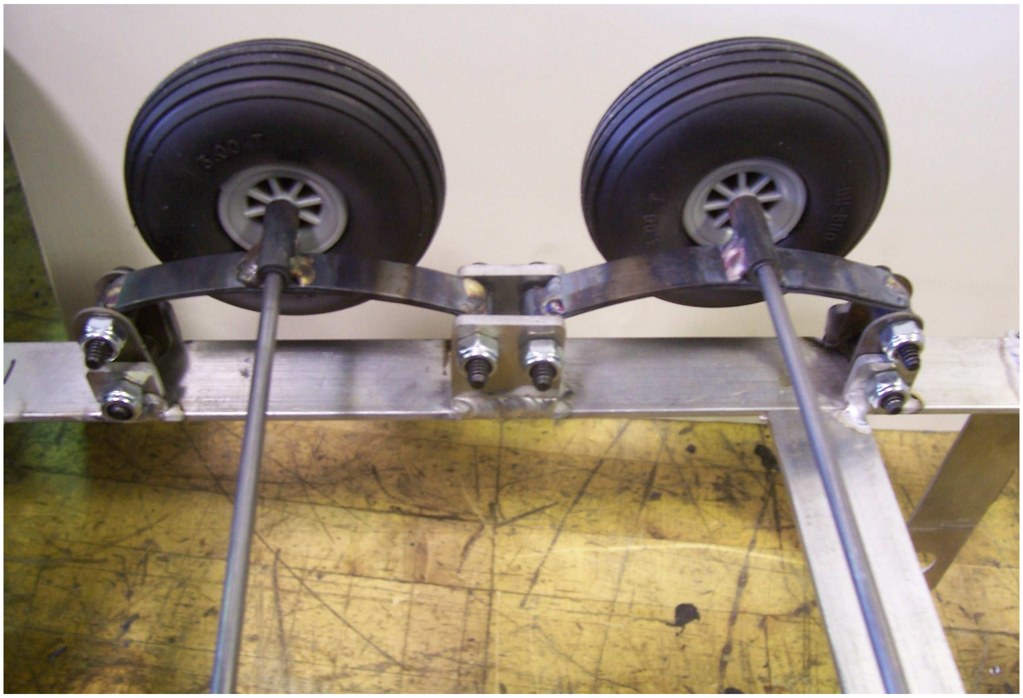

Figure 3.12: The two axles, welded parallel to each other.

The axles needed to be slightly modified so that we could attach the wheels to the axles.  Because 5/32” is close to the size of a gauge 10 bolt, we decided to tap the ends of the axles to allow us to secure each wheel with a washer and a nut secured with liquid thread lock, to prevent vibration-loosening of the nut. We first ground down the each end of both axles to the correct diameter, then used a 10-32 die to tap the axle rods. Then, using a #6 washer for spacing, we secured the wheels on the axle with a 10-32 nut and applied liquid thread lock.

Figure 3.13: A close up of the fastening mechanism on one of the axles.

To build the tank, we used 6" schedule 40 PVS pipe. Because the PVC only comes in 10' long sections, it was necessary to cut it to the correct length. Using the horizontal band saw, we cut the length to 100 cm, which allowed the tank to be centered on the trailer bed, as well as giving the proper scale volume of the largest tank commonly used in liquid cargo shipping. These calculations are shown in the Appendix, with the trailer parameters. The PVC was capped with 6" end caps to hold the liquid cargo. The ends were sealed with PVC sealant, which makes the tube water tight. To allow us to add liquid later, we drilled a hole to with a U bit and then tapped it with 7/16-14 (UNC) tap. This allowed us to plug the hole with a 7/16-14 machine screw. We applied Teflon tape to the threads to make the bolt and threads watertight. The tank is shown later assembled on the trailer.

We also decided to vent the trailer for ease in filling and draining the tank. To accomplish this, we drilled a hole in on of the PVC end caps. This hole was drilled with an F bit and tapped to 5/16-18 (UNC). The hole was plugged with a 5/16-18 machine screw, wrapped in Teflon tape, again, to seal the threads and make them watertight.

In the design of the trailer, it was important to develop a trailer system that could be used for both a solid cargo model as well as a sloshing liquid model. Therefore, Jon Weidner and I worked closely with each other to develop as system for which we could interchange the container. We examined various methods to connect the two different types of containers to the bed of the truck. It was determined that the best choice of attachment was to make L-shaped mounting brackets, shown below, which would be able to constrain the liquid tank in the lateral direction, as well as allow us to fasten it down to prevent it from bouncing on the trailer chassis or sliding off to the rear.

To accomplish this, we cut two 1-inch wide strips off of a 1/8-inch aluminum sheet. We then cut these strips into 6-inch sections. These sections were bent one inch from one of the ends. They were bent to slightly past 90 degrees. This allows both trailer containers to snap into place on the trailer. Finally, the supports were welded to the chassis by way of the 1-inch bend sections.

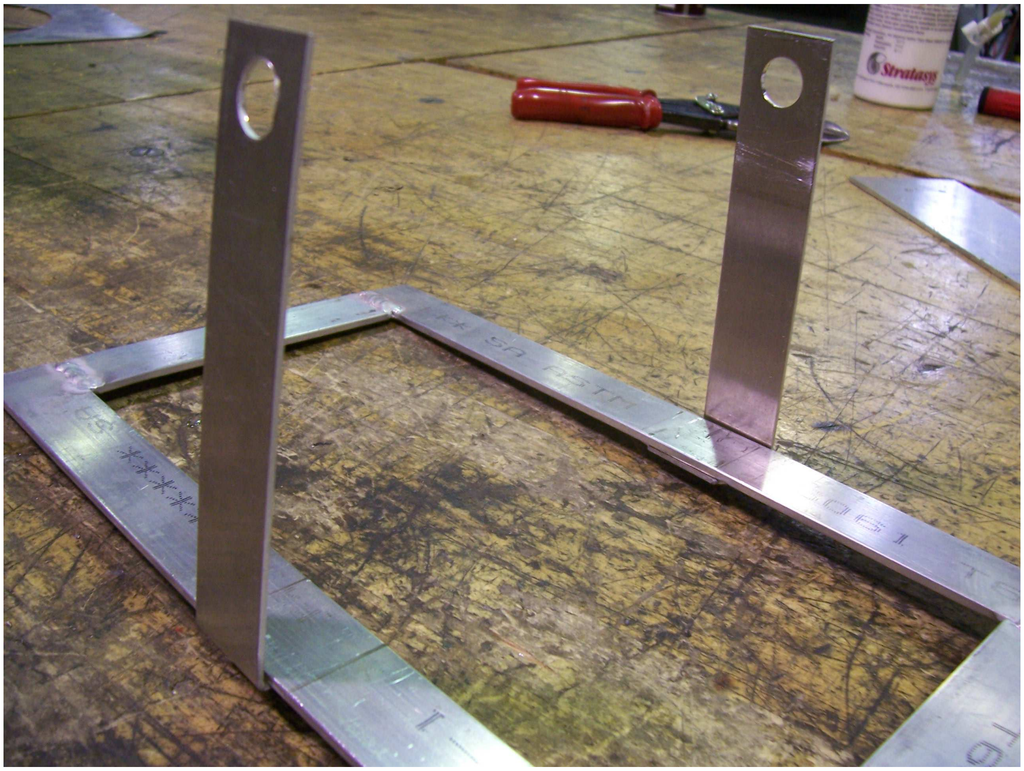

Figure 3.14: The lateral supports bent slightly past 90°, with holes punched to accommodate zip ties

As shown below, the brackets were attached to the aluminum chassis by a lap weld to the underside of the chassis. We welded them to the bottom of the chassis to allow the solid cargo container to remain flush with the chassis of the trailer. To further constrain the motion of the containers, we punched ½-inch holes half of an inch from the end of each bracket (Figure 3.14) to allow us to use zip ties to hold the containers down. In addition to constraining them in the z-direction, the friction from the ties against the containers prevents them from sliding backwards off of the chassis itself.

The last issue was the design of the attachment of the trailer to the tractor itself. We devised a hitch based on readily available materials. We used 1/8-inch 6061-T6 aluminum again, just as in the chassis. We measured the necessary offset of the hitch point from the front of the trailer from the tractor. We then welded the new crossbar with its center 4.5 inches from the front of the trailer. We then drilled a hole at the center point (measured from each side of the chassis) with a #21 drill bit. We tapped the hole to 10-32 (UNF) and screwed the 10-32 Phillips head screw through the hole. We then added a bolt and liquid thread lock to finish the hitch. This assembly is shown below in Figure 3.15.

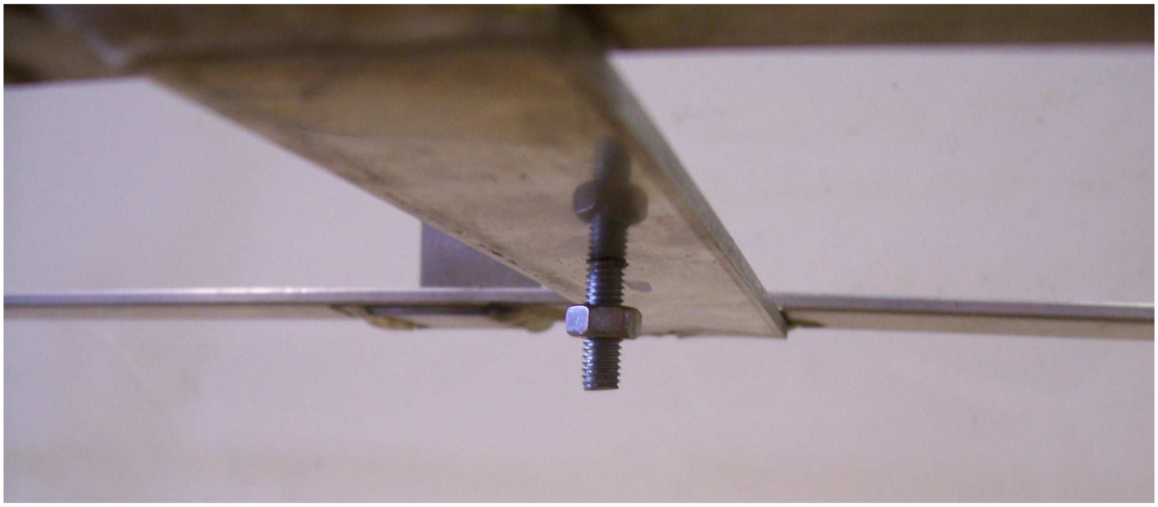

Figure 3.15: The kingpin assembly with the nut further up the screw for illustration purposes.

The last item was assembly of the tractor and trailer together. The final assemblies are shown below, with both the liquid cargo tank as well as the solid cargo shipping container. Note that zip ties were not used in these pictures to avoid waste, as each was only assembled to the trailer itself for enough time to take the pictures. In the pictures below, the trailer is in a testing setup on the rolling roadway simulator in 321 Leonhard Building. This setup allows for control of forward velocity and steering inputs as well as measurement of articulation angle, yaw rates, and lateral velocities of both the tractor and trailer. In each case, we will run another set of wires to the encoders that will be attached to the trailer. These were not set up yet when the pictures were taken.

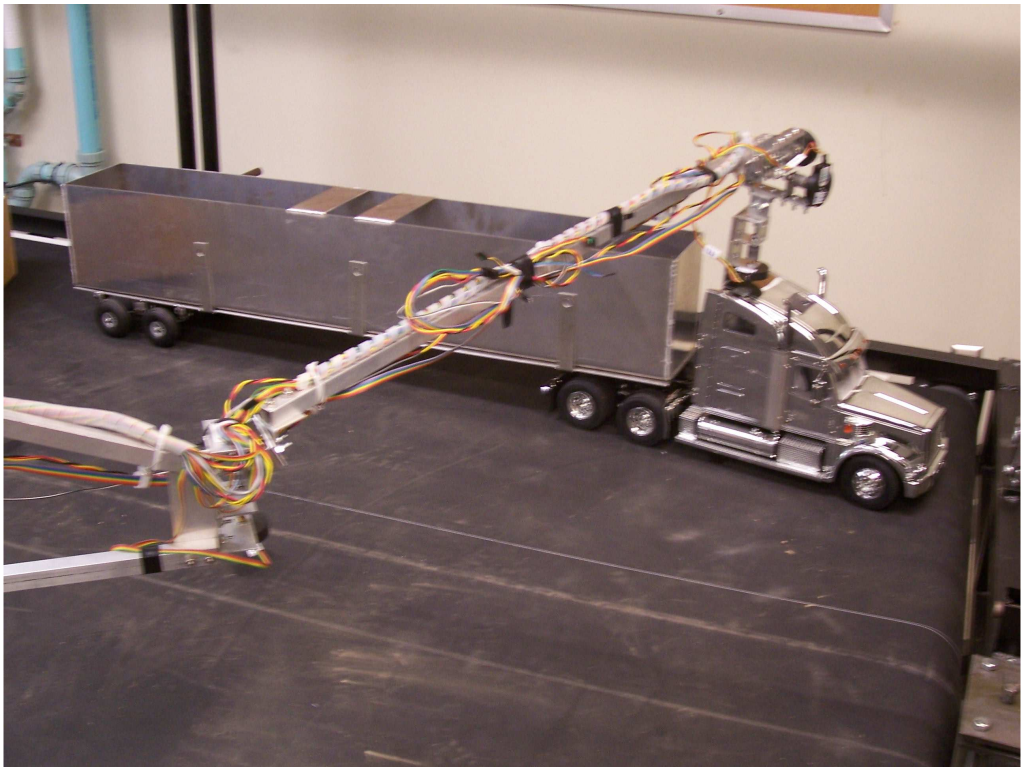

Figure 3.16: The trailer set up with the solid cargo tank

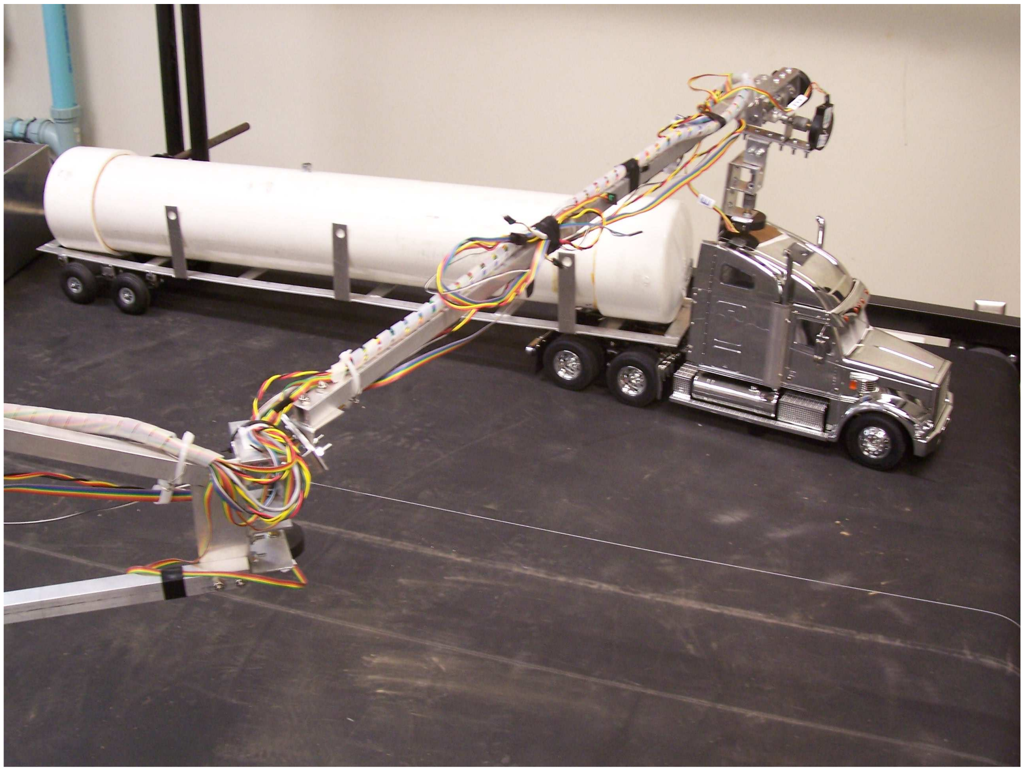

Figure 3.17: The trailer set up with the liquid tanker trailer.

# Chapter IV—Determination of Scale Model Parameters

## Introduction

Though the parameters for the mathematical model and simulation were determined earlier, they cannot be used in the scale model testing. The values obtained for inertias, centers of mass, and relevant geometry factors for the full sized tractor trailer do not correspond exactly to the model. Therefore, it was necessary to determine the vehicle parameters for the scale model. These parameters will be used in the mathematical simulation and the predicted response will be compared to the actual response to show that the three degree of freedom bicycle model does not apply for a semitrailer with a sloshing liquid in its tank.

All calculated parameters are tabulated in Appendix C with the rest of the scale model information.

## Methodology

Parameters to be determined for the tractor include the location of the center of mass, distance from the center of mass to the hitch point, and moment of inertia. The trailer is symmetrical, so it lies somewhere along the vehicle's centerline, but it's locations in the x-y plane (location front to back) and y-z plane (location up and down) plane are unknown. To accomplish this, two different methods were used—one for each plane.

First, to determine the location of the center of gravity in the x-y plane, the tractor was balanced as shown in Figure 4.1, below. We then measured the distance to the support from the front and rear of the tractor. Additionally, we measured the distance from the hitch to the center of gravity. Due to the geometry of the trailer, we could not balance it on its side to find the center of gravity in the y-z plane.

Figure 4.1: Balancing the tractor to locate its center of gravity

To find the height of the tractor's center of gravity, we suspended the tractor from the front and rear axles as shown in Figures 4.2 and 4.3. A plum bob was used to mark a line on the trailer when suspended from each axle. The intersection of the two lines is the vertical location of the center of gravity.

Finally, taking all of these tests into account, the location of the tractor's center of gravity can be determined. Additionally, the necessary lengths for the scale model simulation can be calculated. The ratios of these lengths may differ slightly from those of the full-sized tractor due to differences in construction and mass distribution, which is the main reason to perform these calculations.

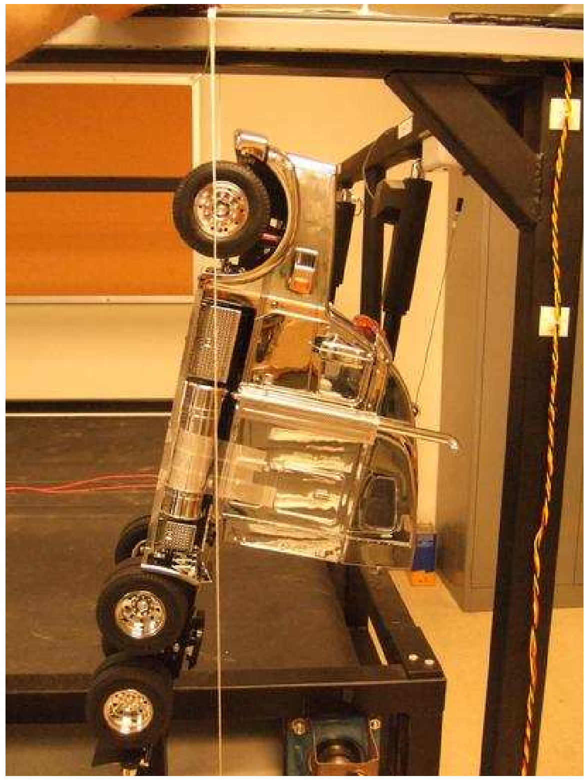

Figure 4.2: Suspending the Model from the front axle to determine the vertical location of center of gravity

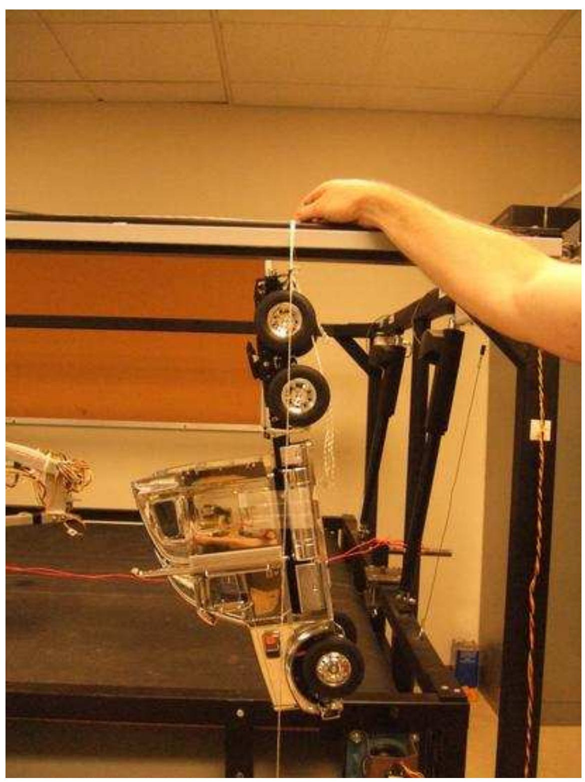

Figure 4.3: Suspending the model from the rear axle to determine vertical location of center of gravity

To determine the mass moment of inertia, the vehicle was again suspended as in

Figure 4.3. The vehicle was pulled about 5 degrees from bottom center, and was allowed to oscillate laterally in its x-y plane. We timed twenty oscillations and repeated the test ten times and averaged the results. Using the following equation, the moment of inertia about the z-axis can be calculated. In this calculation, $m$ is the vehicle's mass, $r_g$ is the distance from the pivot point to the center of mass, $g$ is the gravitational constant, and $\tau$ is the period for a single oscillation.

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

A similar approach was used for the calculation of trailer parameters. The trailer chassis was secured to the tank for this test. Securing the tank was imperative as any movement of the tank could have skewed the results, making the calculations invalid. Shown below in Figures 4.4 and 4.5 is the trailer with the solid cargo container attached to illustrate the process for the trailer. Figure 4.4 depicts the determination of the forward-backward location of the center of mass, while Figure 4.5 shows the process for finding mass moment of inertia about the z-axis.

Once all of these parameters were determined, a second m file with the new parameters was generated, to allow for the scale model to be tested. The predicted response will then be compared with the actual response, to see if they correlate. We predict that the solid cargo trailer will more closely resemble the predicted response, while the partially filled tanker semitrailer will experience instability and tip for some inputs that yield a stable condition for the solid cargo container.

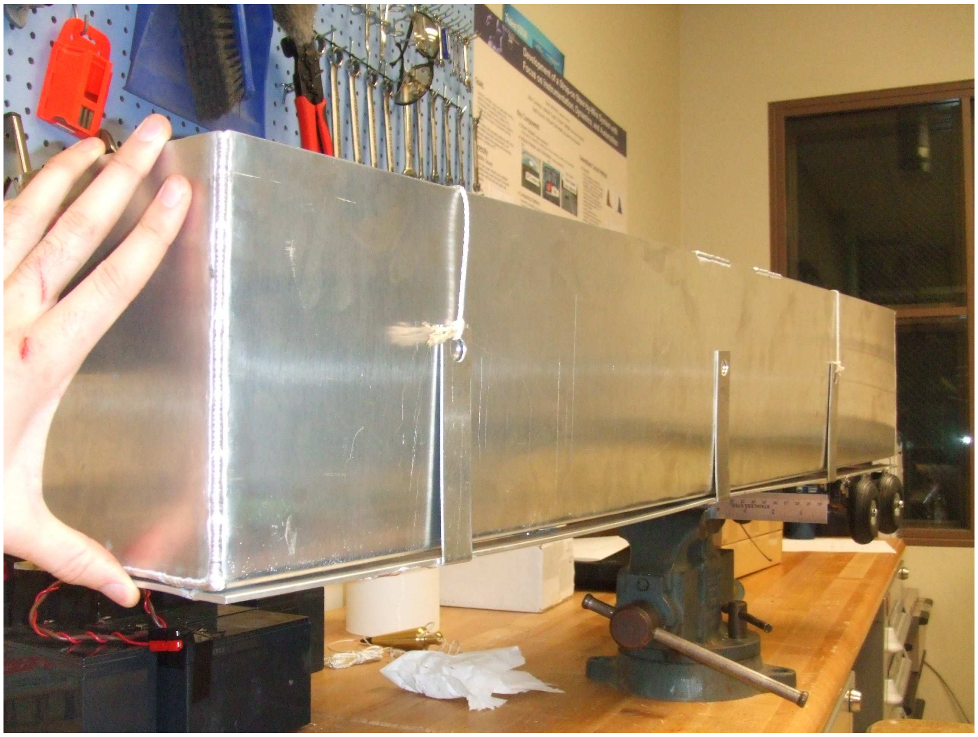

Figure 4.4: Balancing the trailer to determine location of center of gravity

Figure 4.5: Determination of the solid cargo trailer’s mass moment of inertia

## Chapter V—Future Work

Due to time constraints, we were unable to run tests to collect good data. However, we did notice several areas in which we can improve the hardware to make the scale testing run more smoothly and yield better results in the future. The steering servo currently installed on the tractor allows the front wheels to wobble slightly when set to zero displacement. Upgrading this steering system to a rack and pinion system would eliminate tire wobble. The trailer must be made heavier to allow us to measure cornering stiffnesses of tires. This is currently a main issue of concern, and progress is being made.

To measure the articulation angle between the tractor and the trailer, an encoder must be installed. While we have developed a system to do this, it has yet to be installed on the scale model itself. The encoder's laser will be mounted to the tractor, and the wheel will be mounted to the underside of the trailer chassis, allowing the same encoder system to work with either trailer. Additionally, we have yet to wire the trailer to the data acquisition system.

Finally, a fluid that meets the aforementioned parameters must be developed. This is especially important as a fluid that does not time scale properly will give invalid test results. The fluid must match in Cauchy and Reynolds number, and it will be developed using the Buckingham Pi Theorem. Currently, the time table for development and selection of a fluid is the middle of June, 2007.

I plan to continue working on the scale model system in the coming months and over the next few years as I pursue my Masters of Science in Mechanical Engineering at The Pennsylvania State University.

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1. Chen, Chieh and Tomizuka, Masayoshi. "Lateral control of commercial heavy vehicles." Vehicle System Dynamics, Vol. 33, no. 1, pg. 391—420, 2000.

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3. Hyun, Dongyoon and Langari, Reza. "Predictive Modeling for Rollover Warning of Heavy Vehicles." Proceedings of the 2002 ASME International Mechanical Engineering Congress and Exposition (IMECE), New Orleans, Louisiana, November 17—22, 2002,, 2002.

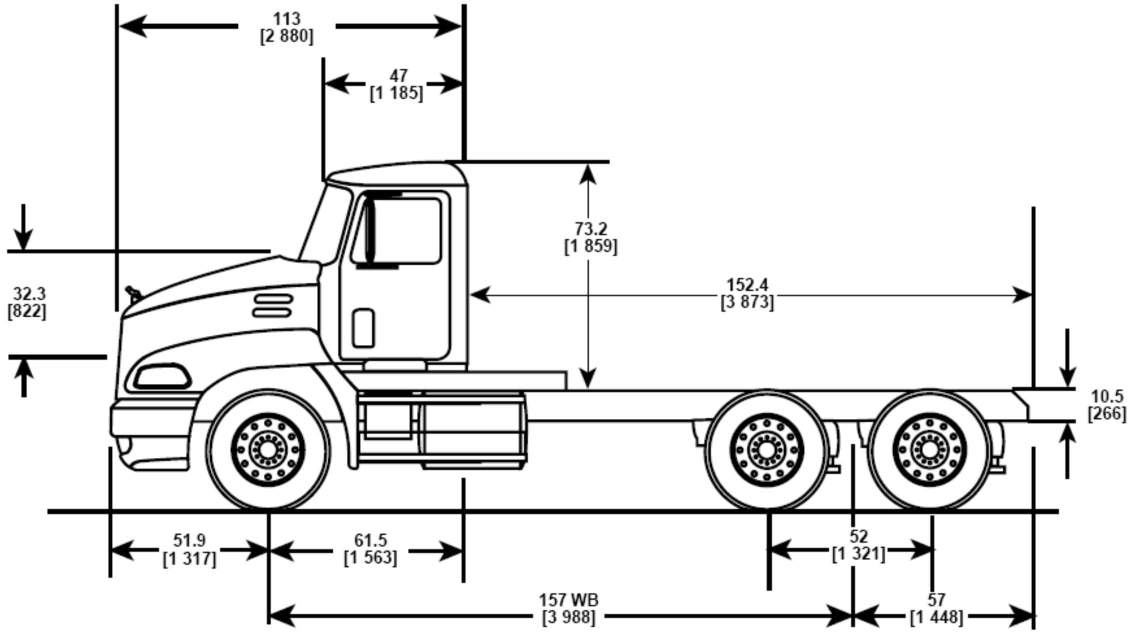
4. Ma, Wen-Hou and Peng, Huei. "Worst-case Maneuvers for the Roll-over and Jackknife of Articulated Vehicles." Proceedings of the 1998 American Control Conference, Philadelphia, Pennsylvania, June, 1998.

5. 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

6. Sandorff, Paul E. "Principles of Design of Dynamically Similar Models for Large Propellant Tanks." Report to the National Aeronautics and Space Administration, Washington D.C, January 1960.

7. 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

# Appendix A—Full Scale Tractor and Trailer Parameters



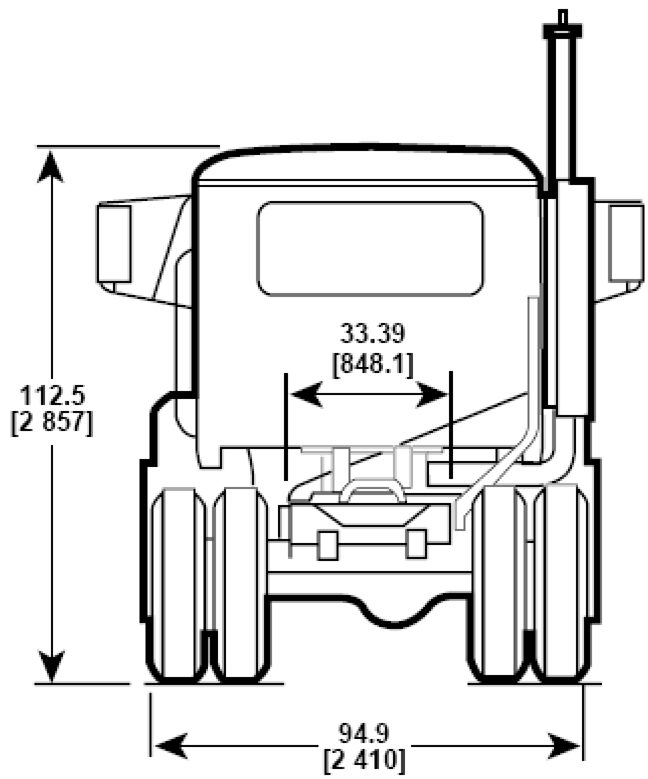




Figure A.1: The parameters from the Mack Truck specifications [5]

## 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 |

## Tanker

| 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 |
| d | diameter of tank | 96-102 in |
| l | length of tank | 40-53 ft |
| V | tank capacity | 3000-9500 gal |

Figure A.2: Tabulation of parameters used in mathematical model and simulation, and to decide on model trailer dimensions

# Appendix B

## Matlab Source Code

```
%This is used to verify the equations of motion derived for
%a tractor semitrailer articulated vehicle

%Written by Dan Kaiserian and 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%1.268   %m           = tractor cg to rear axle
d  = 3.3765%1       %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]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   |  .   |       |        | |      |   |       | |     |   %
%   |  X   |   =   |  M'A   |*|  X   | + |  M'B  |*|  U  |   %
%   |      |       |        | |      |   |       | |     |   %
%                   Matrix 1               Matrix 2          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

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];

sim('bicycle_model_truck_step');

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

figure(1)
plot(X_truck,Y_truck,X_h,Y_h,X_trailer,Y_trailer)
title('Tractor Position - Constant Radius Turn')
xlabel('X position (m)'), ylabel('Y position (m)')
legend('truck','hitch','trailer')

sim('bicycle_model_truck_sine');

figure(2)
plot(X_truck,Y_truck,X_h,Y_h,X_trailer,Y_trailer)
title('Tractor Position - Lane Change')
xlabel('X position (m)'), ylabel('Y position (m)')
legend('truck','hitch','trailer')
```

This code predicts the response of the tractor trailer system given a constant radius turn and a lane change scenario. Contained in Figures B.1 and B.2 are the tractor, hitch, and trailer responses given the lane change and step inputs, respectively. Following the outputs is the lane change block diagram. The only difference between it and the constant radius turn diagram is the additional sinusoidal input. The subsystems will be expanded to show their inner workings.

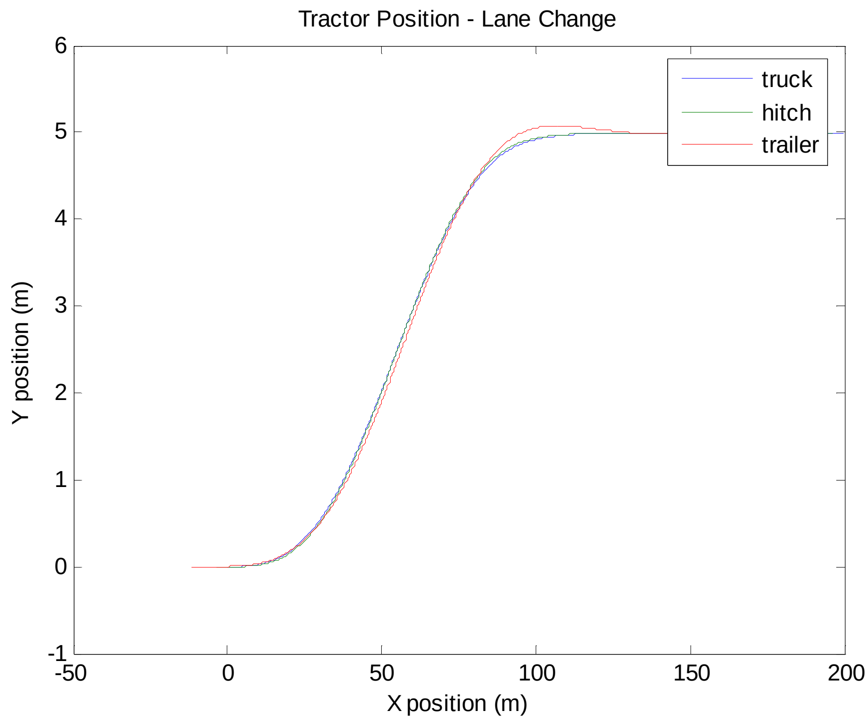



Figure B.1 The output from the m file for a lane change scenario

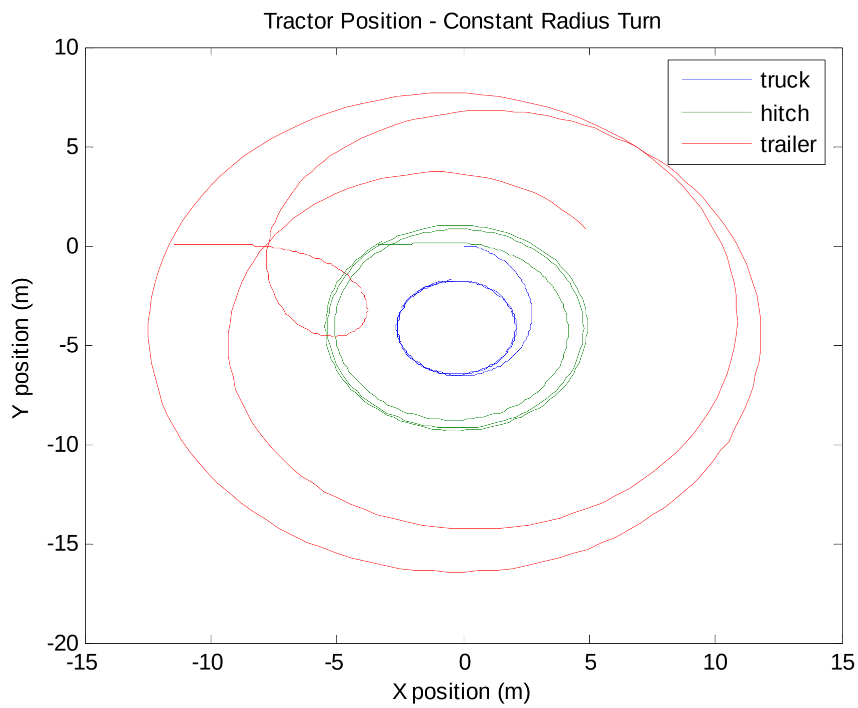



Figure B.2: The output for a constant radius turn

Attached in the following four pages are printouts of the Simulink block diagram. Figure B.3 shows the entire state space model of the lane change simulation. Figure B.4, B.5, and B.6 convert from body-fixed to global coordinates for the truck, hitch, and trailer, respectively.

# Appendix C

## Pro/Engineer Modeled Parts

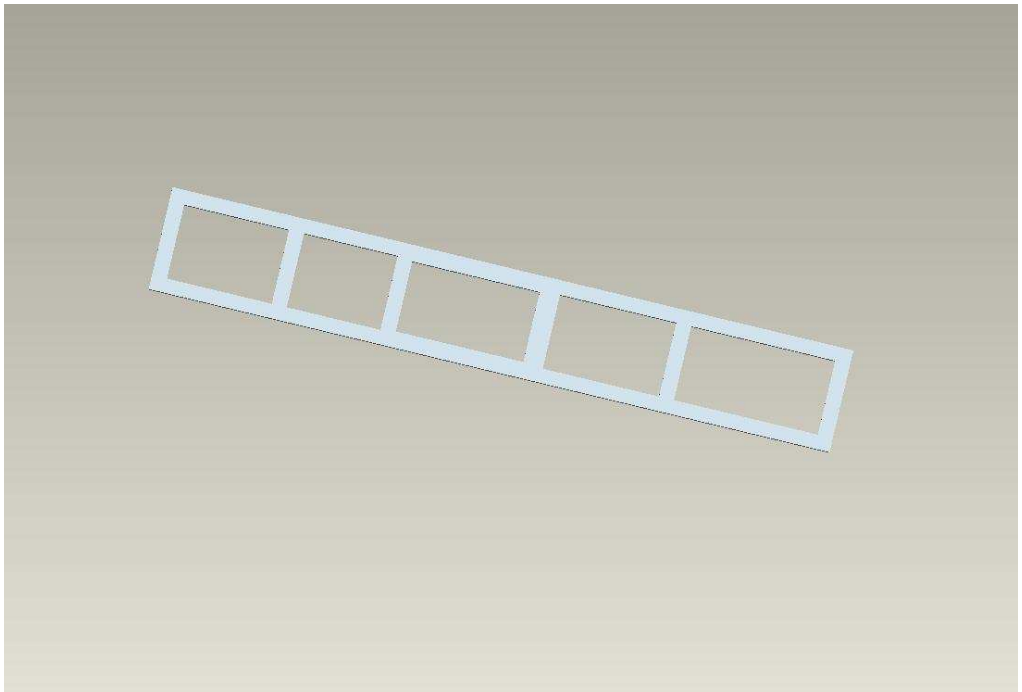


Figure C.1: Pro/Engineer Model of the Trailer Chassis

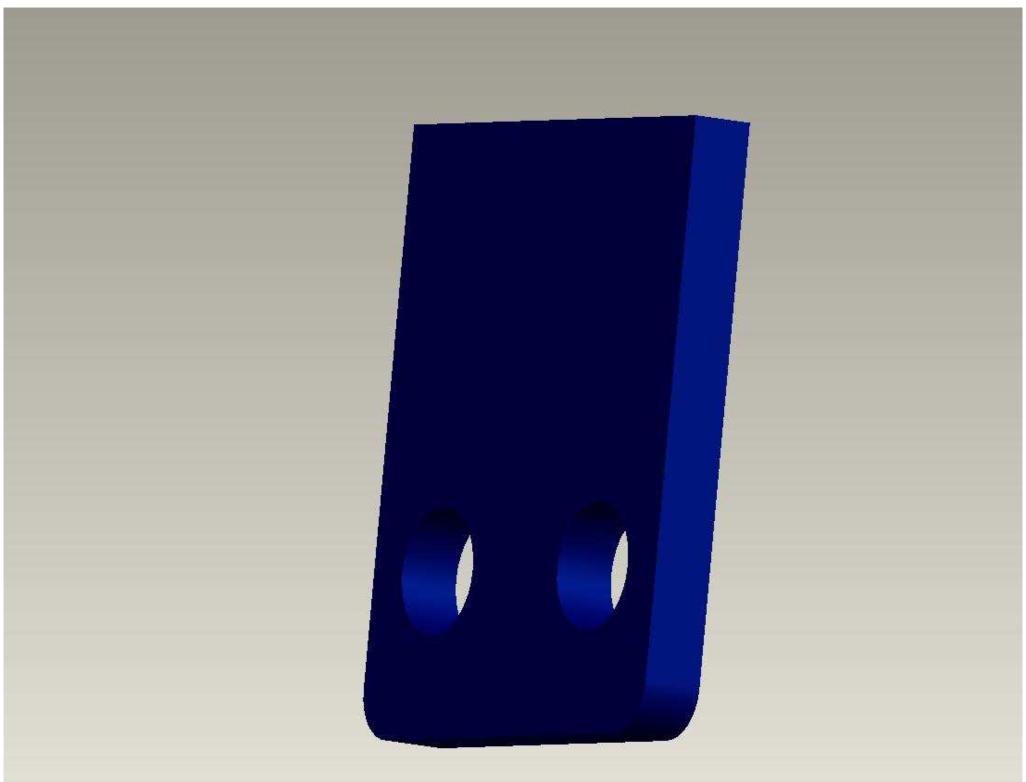


Figure C.2: Pro/E Model of the Center Spring Mounts

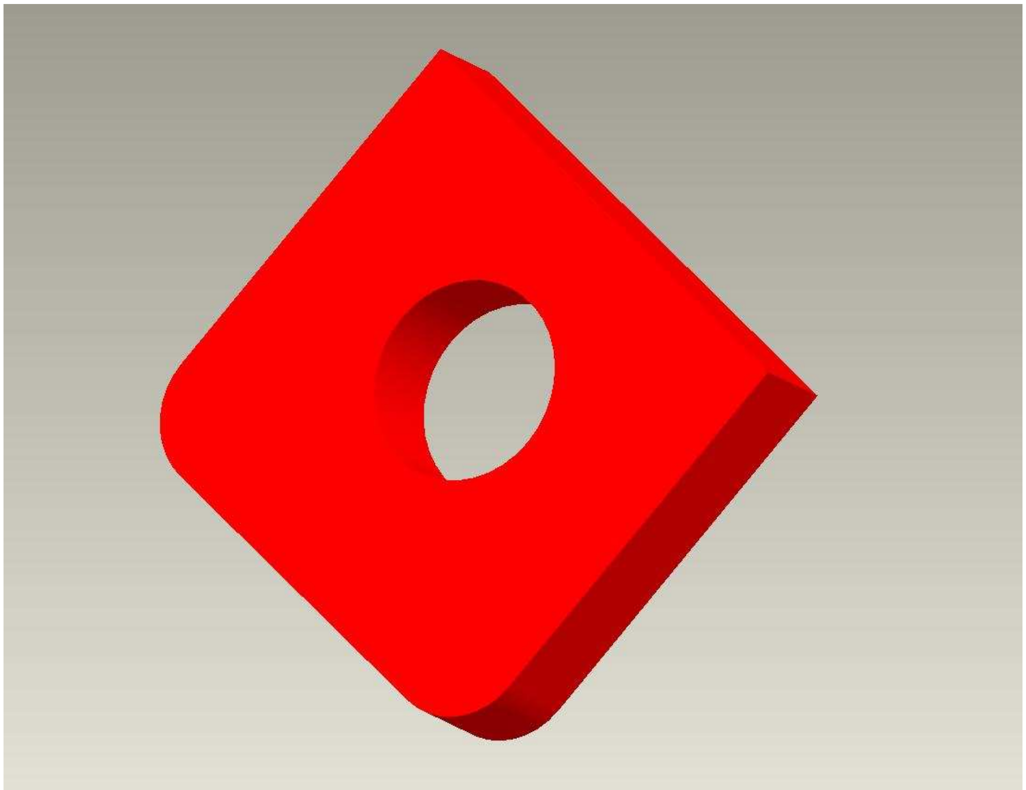


Figure C.3: Pro/E Model of the front and rear spring mount that attaches to the pivot (below)

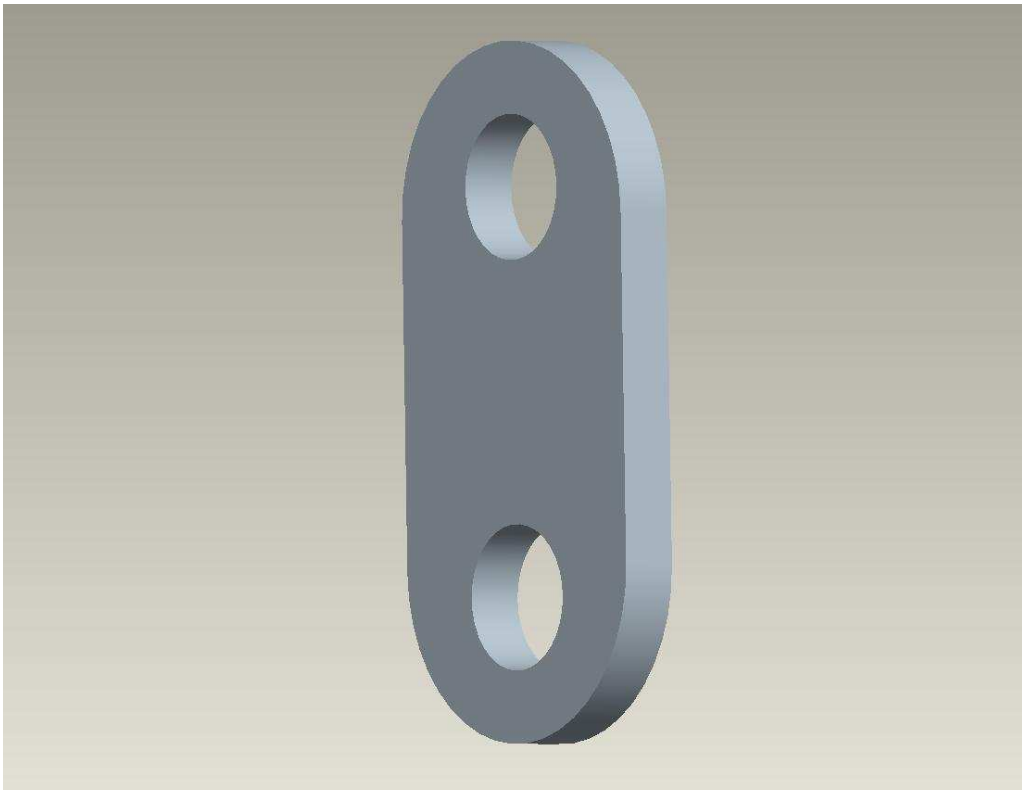


Figure C.4: Pro/E Model of the pivot to allow the leaf springs to deform

## Scale Model Parameters

### Trailer

| Quantity | Full size | Model Size |
|---|---|---|
| length | 16.15 m (53 ft) | 115 cm (45.5 in) |
| front of trailer to hitch | 1.6 m (5.25 ft) | 11.43 cm (4.5 in) |
| tire diameter | 43 in | 3 in |
| spring length | 4.3 ft | 3.5 in |
| volume | 35.96 cu m (9500 gal) | .019 cu m (3.5 gal) |
| tank diameter | 102 in | 6 in |
| tank length | 16.15 m (53 ft) | 1.05 m (41 in) |

Figure C.5: Trailer scale model parameters for build process

| trial # | oscilations | time (s) | period |
|---|---|---|---|
| 1 | 20 | 39.38 | 1.97 |
| 2 | 20 | 38.36 | 1.92 |
| 3 | 20 | 38.94 | 1.95 |
| 4 | 20 | 39.08 | 1.95 |
| 5 | 20 | 38.88 | 1.94 |
| 6 | 20 | 38.24 | 1.91 |
| 7 | 20 | 38.42 | 1.92 |
| 8 | 20 | 39.01 | 1.95 |
| 9 | 20 | 39.01 | 1.95 |
| 10 | 20 | 39.31 | 1.97 |
| average | 20 | 38.86 | 1.94 |

| | | | |
|---|---|---|---|
| rg | = | 0.64 | m |
| g | = | 9.81 | m/ss |
| m | = | 8.88 | kg |
| $\tau$ | = | 1.94 | 1/s |

Figure C.6: Data used to calculate the mass moment of inertia of the trailer about the z-axis

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

| Symbol | Description | | Value | Units |
|---|---|---|---|---|
| | Mass of trailer chassis | = | 1.39 | kg |
| | Mass of container | = | 7.5 | kg |
| $m_2$ | Combined mass | = | 8.88 | kg |
| $e$ | Distance from fifth wheel to trailer center of gravity | = | 0.485 | m |
| $h$ | Distance from trailer center of gravity to rear axle | = | 0.403 | m |
| w | Trailer track width | = | 0.20 | m |
| $I_{2z}$ | Mass moment of inertia about the z axis | = | 1.677 | kg m^4 |

Figure C.7: The estimated parameters for the combined scale container and scale trailer chassis

**Tractor**

| trial # | oscilations | time (s) | $\tau$ |
|---|---|---|---|
| 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** |

| Symbol | | Value | Units |
|---|---|---|---|
| $r_g$ | = | 0.53 | m |
| g | = | 9.81 | m/ss |
| m | = | 3.08 | kg |
| $\tau$ | = | 1.57 | 1/s |

Figure C.8: Data used for calculating the mass moment of Inertia about the Z axis for the tractor.

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

| Symbol | Description | | Value | Units |
|---|---|---|---|---|
| $m_1$ | mass of truck | = | 3.08 | 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 m^4 |

Figure C.9: The estimated parameters for the scale tractor

**Appendix D**

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Email: dkraus@psu.edu

**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 Mechanics

Graduation Date: May 2007

**THESIS:**

*Tractor Trailer Instability Due to Liquid Slosh in a Partially Filled Tank*
- Honors in Mechanical Engineering

Thesis Supervisor: Dr. Sean N. Brennan

**WORK EXPERIENCE:**

**Penn State Swim Camps** June 2006
*Assistant Swim Coach* State College, PA
- Worked with children ages 7-14 teaching stroke technique

**Conestoga Swim Club.** Summer 2005
*Head Swim Coach* Villanova, PA
- Was solely responsible for writing workouts, running practice, organizing lineups for swim meets
- Led team to best finish in 12 years

**Self Employed** Spring 2000—Spring 2003
*Landscaping* Bryn Mawr, PA
- Did various landscaping jobs for four local clients over the course of three years, including lawn maintenance, mulching, tree pruning
- Negotiated with local companies to reduce cost of supplies such as mulch

**LEADERSHIP EXPERIENCE:**

**Penn State Swimming and Diving** Fall 2003-Spring 2007
*Team Captain*

**Student Athlete Advisory Board** *Team Representative*
- Voted in the interest of the swim team at monthly meetings
- Was involved in voting on national issues affecting student athletes

**Engineering Mentorship Program** Fall 2006
*Mentor*
- Worked to introduce freshman engineering students to life at Penn State
- Kept in touch with mentees over the course of the first semester

**AWARDS:**

**The Pennsylvania State University**
- Ernest B. McCoy Scholar Athlete Award Spring 2007
- Dean's List 6 of 7 semesters, and 1 of 1 summer

**Penn State Swimming**
- Robert Krimmel Academic Achievement Award 2005-2007
- Academic All American 2007
- Academic All American Honorable Mention 2005, 2006
- Academic All Big Ten 2005-2007