2014

Frankie Wiggins
Alex Seitz
Justin Bautista

TeamNathan2014@gmail.com

Mechanical Engineering
California Polytechnic State University, San Luis Obispo

[TEAM NATHAN SUSPENSION]

THURSDAY, OCTOBER 16, 2014

The purpose of this document is to define our design solution to the current problems with the Standing Dani™ mobility device as well as provide relevant background information. This document also outlines the process by which we validated our design, manufactured and tested it, and the costs associated with it.

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Nathan Cooper is an 8-year old boy with Spinal Muscular Atrophy (SMA). SMA has affected Nathan's muscle development and requires him to use the Standing Dani™ mobility device. The Standing Dani is a motorized standing wheelchair, or Wheelstand. Nathan controls and uses it to get around. Though the Standing Dani performs well for most functions, it has some distinct issues. The primary issue that this project addresses is its lack of suspension and the discomfort that Nathan feels as a result. After talking with our client, we developed several specifications generally related to geometry, safety, vehicle dynamics, and reliability. Many possible suspension solutions were developed using three methods of idea generation. A rear trailing arm suspension paired with pneumatic casters in the front was chosen as the final concept. From this concept, we designed a system that was made up of four basic components: front casters, frame, trailing arm linkages, and a spring-shock assembly. The final design is supported with hand calculations involving the static system and a dynamic analysis of the suspension behavior using MATLAB®. The manufacturing and testing portions of the final design were completed in the final three months of the project. We are confident that the design that has been developed will suit the needs of Nathan and make his daily activities all the more enjoyable.

CHAPTER 1: INTRODUCTION

The goal of this report is to showcase our final design to increase Nathan Cooper's comfort while using his Standing Dani. It reviews the project problem definition, specifications, background, and methods of idea generation. Our objectives and design requirements remained the same since the conceptual design phase. We spent a considerable amount of time with the design of the suspension system and that is what we have presented in this report. All manufacturing and testing processes described involve the new suspension. We believed that focusing too much attention on increasing Nathan's vision and the range of the device might interfere with the success of the suspension so we made it a lower priority. For more information on the background, continue to Chapter 2: Background.

FIGURE 1. OUR DESIGN THAT WE PRESENTED AT THE SENIOR PROJECT EXPO.

In the concept design phase, we came up with solutions through different types of brainstorming, compared four of our favorite final concepts, and then objectively decided which concept was the best. The final concept we chose was the Rear Trailing Arm design for the rear suspension and larger, pneumatic casters for the front suspension. The details on the concept process are listed in Chapter 3: Design Development.

We developed this concept into a more complete suspension design. In the front, we have chosen 8-inch pneumatic casters for the suspension. In the rear, we are using Romic D coil-over mountain bike shocks. We made the switch from the FOX Float CTD air shocks after considering the reliability issues experienced by mountain bicyclist riders that used the air shocks. In addition, the springs that are being used have a lower spring rate than the Romic D stock springs. The frame and rear suspension trailing arms are largely the same, but they have been improved to look cleaner. Furthermore, we redesigned his arm rest (not shown) and created a new attachment sub-assembly that allows Nathan to recline. More detail is presented in Chapter 4: Description of the Final Design.

We have also completed the manufacturing and testing departments of the project. Our manufacturing plan is more explicitly described in Chapter 5: Product Realization. In addition, we completed baseline testing of the Standing Dani, the test rig, and our final design. We developed a Design Verification Plan & Report (DVP&R) to quantify our test results. Each DVP&R is provided for review. Our testing methods are described in Chapter 6: Design Verification Plan (Testing).

CLIENT BACKGROUND AND NEEDS

This section gives some background information on our client, Spinal Muscular Atrophy (SMA) and some of the benefits of using a standing mobility device instead of a conventional powered wheelchair.

NATHAN AND THE COOPERS

Our client is the Cooper Family of San Luis Obispo. Their family consists of Amy, Bob, and their two sons, Nathan & Nicholas. The Coopers have been clients of past Cal Poly Senior Projects all aimed at improving the quality of life of their oldest son, Nathan.

FIGURE 2. THE COOPER FAMILY.

Nathan is your typical eight-year old boy. He enjoys playing Minecraft, listening to music and his two favorite characters are Batman and Lightning McQueen from Cars. His favorite color is blue, much like the original Batman costume. Nathan loves emulating Lightning McQueen by popping wheelies and speeding around in his Standing Dani. Nathan is also extremely smart and demonstrates his intelligence at his school every day.

SPINAL MUSCULAR ATROPHY

Spinal Muscular Atrophy (SMA) is a motor neuron disease. Motor neurons are necessary to control muscles required for activities such as crawling, walking, head and neck control, and swallowing. It is relatively common. One in 6000 babies are affected and one in 40 people are carriers. Although the motor functions are weakened, the brain's cognitive functions and ability to feel objects and pain are not affected for people with SMA. Those affected with SMA can be grouped into one of four types (I, II, III, IV) based on their highest level of motor ability.

FIGURE 3. FAMILIES OF SMA LOGO. (FAMILIES OF SMA)

SMA is a recessive genetic disease and is caused by a missing or abnormal gene known as the survival motor neuron gene 1 (SMN1). This gene is responsible for producing the survival motor neuron (SMN) protein. Those with SMA have a lack or deficiency of the protein which causes severe problems for the motor neurons. The motor neurons send out nerve fibers to all the muscles throughout the body. Without the SMN protein, muscles become weaker. As a child with SMA grows, it becomes harder for the muscles to deal with demands of daily activities. Muscle weakness can lead to bone and spine changes that can cause breathing problems and more loss of muscle function. SMA is not considered a progressive disease, although most individuals affected with SMA typically lose muscle function over time. The loss in muscle function can occur gradually or suddenly, but many individuals can retain stable muscle function over prolonged periods of time.

In regards to caring for someone affected by SMA, it is important to remember that cognitive ability and brain function is not affected and that individuals with SMA are very intelligent. Children with SMA should be encouraged to participate in as many age and developmentally-appropriate activities as possible, while keeping in mind necessary adaptations. (Families of SMA, 2013)

BENEFITS OF STANDING

Most people are used to seeing seated assistive devices for people with disabilities, but it is important that there are assistive devices that allow their users to get on their feet, if possible. Standing has many benefits associated with it and many of the benefits are worth the extra design work needed in order to find ways to allow users to stand.

Some benefits are for health or medical reasons. They include things such as pressure relief, improved circulation and respiration, improved flexibility and digestion, and reduced spasticity. Standing allows people to enjoy their daily life in places such as home, school, work, or just when they are out and about. Being able to stand has financial benefits in the sense that it reduces the requirement for assistive needs, home modification, and loss of jobs. Standing also has psychological benefits as it improves independence, self-esteem, social status, communication, access level, and quality of life. (Quest Magazine Online, 2013)

FORMAL PROBLEM DEFINITION

Nathan is a young boy with Spinal Muscular Atrophy (SMA) that requires assistance with moving around. His Standing Dani device is crucial to his execution of daily activities, but the device can cause discomfort when moving over uneven terrain and it limits Nathan's awareness of his surroundings. An improved system design would address these concerns and improve the quality of Nathan's life.

FIGURE 4. NATHAN COOPER.

OBJECTIVE & SPECIFICATION DEVELOPMENT

Our main objective was to develop a suspension system to make the Standing Dani™ more comfortable. We decided to design a new frame to accommodate a suspension and focus on the lower risk requirements after we get a solid foundation for our frame. We would've liked to improve Nathan's awareness of his surroundings and the range of the device, but we didn't have adequate time to design solutions. These additional mini-projects are issues with the device that we see as areas of needed improvement, and recommend future groups to look at if they continue with this project.

Through the use of a Quality Functional Deployment (QFD) matrix (Appendix A – Quality Function Diagram), we were able to determine what our main objectives of the project would be and the importance of each. The QFD is a design tool commonly used in industry. We first inputted the customer requirements and ranked how important each requirement is on a scale of 1 to 5. We then gave each requirement a target value. For example, the requirement "must have a smaller footprint than the current Standing Dani™" had a target, or specification, overall length of 29 inches and a greatest width of 25 inches. In the center portion of the chart, we assigned a value that represented how much one requirement affected another. For example, the "smaller footprint" was strongly affected by the overall length and greatest width specifications, so this relationship received a '9'. On the other hand, the overall length and width weakly affect the comfort and received a value of 1 representing a weak relationship. The QFD will then tell us which specifications are most important in our designs.

OBJECTIVE DESCRIPTIONS

The following points highlight our main objectives and their importance:

- Design a cost-effective system that is safe for Nathan. This objective has *high risk* due to the human factors involved with this project and our customer requirements. We also have a pretty set budget and would like to stay under budget with our design.
- Build a system with a geometry and weight no greater than the existing design. This objective has *high risk* because of its strong correlation with customer requirements and the engineering specifications. The Coopers stated that keeping the new design as small as or smaller than the current design was very important to them.
- Develop a suspension system that will be safe and comfortable for Nathan. This suspension addition will allow him to go over more terrain and be comfortable. This objective has *high risk* because it was the reason for the project's commission and because it plays a large role in the customer's requirements. This is the main goal of our project and one of the most limiting factors of the current Standing Dani™.
- Accommodate Nathan's desires regarding device aesthetics. We really want Nathan to enjoy our improvements to the Standing Dani™ and looks plays a distinct role in that. For this reason, this objective has *high risk*.
- We wanted to design a system that had relatively portable. We decided that it would be useful if an average adult were to be able to easily place our design into a vehicle to be transported. We decided this was of *high risk* since it is one of Nathan's main methods of travel, the Coopers would need to be able to bring it with them wherever they go easily and without too much effort.
- Create a system that has easily repairable and replaceable parts. This is very important for Nathan's family and anyone who needs to repair the Standing Dani™. Custom parts will be avoided when possible. This objective has *medium risk* because it will be accomplished to the best of the team's ability, but may be sacrificed for the sake of other design parameters.
- Design a user awareness system to help Nathan operate the Standing Dani™ more safely and to decrease the probability of colliding with an object or person. This objective has *low risk* because it will be done if time permits, but it is not guaranteed to be completed.

- Improve the range of the Standing Dani device. It was found that the Standing Dani's batteries are often insufficient for the purpose it has been utilized for. This objective has a *low risk* because it will be done if time permits, but it is not guaranteed to be completed.

Table 1 is a compliance matrix that summarizes the above objectives, their corresponding risk, and related specifications. This visual is intended to make the design objectives more clear. It also includes a detailed list of our engineering specifications.

TABLE 1. COMPLIANCE MATRIX.

Objective	Risk	Compliance	Specification
Low Cost	H	A, I	≤ $2500
Safe	H	T, I	≤ 10 pinch points and no sharp edges, no electrical hazards
Weight	H	I	≤ Current Weight
Greatest Width	H	I	≤ 25 inches
Overall Length	H	I	≤ 29 inches
Suspension	H	A, T, S, I	≥ 50% reduction in transmitted G-force
Aesthetics	H	S, I	Design look approved by Nathan
Portability	H	T, S, I	Loaded into vehicle by average adult
Reliability	M	A, S	Component design life of ≥ 10 years
Repairable	M	S, I	Maintenance requires std. tools only; ≥ 50% off-the-shelf parts
F/R Tiltover Angle	M	A, T, I	≥ 25 degrees
L/R Tiltover Angle	M	A, T, I	≥ 25 degrees
User Awareness	L	T, I	≥ 90° rear field of view
Range Improvement	L	A, T	≥ 50% increase

Risk Level: High (H), Medium (M), Low (L)
Compliance: Analysis (A), Test (T), Similarity to existing designs (S), Inspection (I)

PROJECT MANAGEMENT

As stated in the objective section, we plan on improving Nathan's life, so that he enjoys using the Standing Dani™ even more. This project has required determination, plenty of planning and working with individuals outside of our team of three students to achieve that. In this section, we will discuss how we have done at hitting project milestones, how we plan on reaching the remaining milestones, and the responsibilities of team members.

PROJECT MILESTONES

Our final design was very focused on adding a suspension system to the Standing Dani™. Given the time constraints and our actual progress, improving user awareness and device battery range were secondary concerns and did not get addressed. Our complete plan is presented in our Appendix G – Gantt Chart.

GENERAL PROJECT ACHIEVEMENTS

We achieved many things in our project. These achievements fall into three basic categories: design, manufacturing, and testing.

The achievements that we made in the design category are as follows:

- Finalized our design (including, but not limited to, the frame design, trailing arms, arm rest, and attachment sub-assembly)
- Chose the materials that would be utilized
- Added detail to our SolidWorks® model
- Created SolidWorks drawings for the system
- Created a detailed cost analysis
- Powder coated our final assembly

The achievements that we made in the manufacturing category are as follows:

- Manufactured the test rig
- Manufactured the final design

The achievements that we made in the testing category are as follows:

- Created a test plan (DVP&R) with corresponding procedures
- Created mathematical models to predict system behavior
- Completed baseline testing & testing on the test rig
- Analyzed the results & quantified the success of our design

RESPONSIBILITIES

Certain tasks were specifically assigned to each team member in order to facilitate the timely and effective completion of this project as a whole. Each specific responsibility was assigned as the project progressed, so that we more naturally fell into roles that we were comfortable with.

FIGURE 5. FRANKIE AND ALEX AT THE SENIOR PROJECT EXPO.

Alex took on the role as the manufacturing specialist & solid modeling lead as well as developed the testing software. As the resident expert in manufacturing, Alex was the main resource inside the team when it came to prototype fabrication. He developed all of the team's most of the team’s solid models and updated them. He combined his manufacturing expertise with his experience in suspension design to create models that were realistic and represent actual function. Furthermore, he created the drawings for most of the solid models. Finally, he developed the Arduino© software used for the accelerometer testing.

Justin was the team research expert, secretary, and treasurer. Nathan is affected by SMA and it was important that we had a background of how individuals deal with it. In addition to being informed on SMA, Justin also was in charge of finding out as much about the Standing

Dani™ and competitor devices as possible. As team secretary, he took notes in team meetings and weekly status report updates with Professor Harding as well as maintained the team Gmail® account. Justin was also in charge of maintaining the budget and purchasing the materials for manufacturing.

FIGURE 6. OUR POSTER AT THE SENIOR PROJECT EXPO.

Frankie took on the role as the center of communications, task manager, technical analysis lead, and testing lead. He was the main contact with the Coopers and the Mechanical Engineering (ME) Department, the client and sponsor of the project, respectively. When needed, he was also the contact for outside entities/sponsors (i.e. Cambria Bicycle Outfitters). In addition, he was the reference for old projects involving the Coopers. As task manager, he kept the Gantt chart up-to-date and planned out the weekly and long-term tasks for the team. Frankie completed all of the technical analysis required by the project. Furthermore, he ensured that testing was carried out appropriately by creating and implementing the project's test procedures. Finally, Frankie provided design support for Alex. He developed the solid models for the attachment sub-assembly and the arm rest.

FIGURE 7. PICTURE OF THE FINAL MANUFACTURED & POWDER-COATED DESIGN.

CHAPTER 2: BACKGROUND

EXISITING PRODUCTS

This section discusses some of the current solutions available on the market today.

LEVO® COMBI JR.

The powered LEVO Combi Jr. (Figure 8) is a powered wheelchair with standing capability. It has the capability to be mobile while in the standing position. It also has adjustable growth plates, components, and a wide range of accessories that allow for child growth. It has simple handling and is very user-friendly. The movement of the seat is smooth when converting from seated to standing of vice versa. It has a turning radius of 43 inches and can support up to 265 lbs. It has adjustable foot position, back angle, and can elevate between 0 and 85 degrees. It is available in multiple colors and has easy accessibility for maintenance and service updates. (Levo, n.d.)

Some issues with the LEVO Combi Jr. are that is it very expensive – the base model is $13,000. In addition, it has a large footprint and is relatively heavy and difficult for adults to lift safely. (Cooper A. , 2013)

FIGURE 8. LEVO COMBI JR. (LEVO, N.D.)

GO-BOT

FIGURE 9. NATHAN IN HIS GO-BOT. (TRASK, JOHNSON, & GARCIA)

The Go-Bot (Figure 9) is a powered cart that is designed to provide mobility and independence for children who have mobility disabilities. It supports a range of children as young as 12 years old and the height can be adjusted to support users up to 43 inches tall. The device is designed for indoor use and level surfaces outdoors.

The cart can accommodate a child in a seating, semi-standing, or standing position. The controls are electronic and can be adjusted to suit a child's needs. The Go-Bot is joystick-operated, runs off of two 12-volt batteries, and it can be turned on & off with an emergency remote. It includes chest support, wide saddle-style seat, adjustable footrest with straps, and has a weight capacity of 100 lbs. (AbleData, n.d.)

Some issues with the Go-Bot are that it is uncomfortable after extended use, it has no suspension, and is relatively heavy & difficult to transport. (Cooper A. , 2013)

STRIDER 1 & 2

FIGURE 10. NATHAN IN STRIDER 2. (CUMMINGS, KREIDLE, LEE, & STEEN)

The Strider is a mobile walker developed by two different Cal Poly Senior Project Teams. The Strider was designed to allow Nathan to exercise and propel himself in an upright position. The first iteration of the Strider, nicknamed Strider 1, was heavy and was not able to be disassembled easily. (Trask, Johnson, & Garcia, 2010) Nathan had trouble propelling it because it weighed about as much as he did. The appearance of the original Strider was not very aesthetically pleasing either. (Kreidle, 2013)

The second iteration of the strider, nicknamed Strider 2, was lightweight, but was still bulky and difficult to transport. (Cummings, Kreidle, Lee, & Steen) Nathan doesn't use the Strider because he doesn't have time and it is hard to transport and find a place to use it. Both Striders use human power for propulsion (Cooper, Cooper, & Cooper, 2013).

ALBER ADVENTURE

The Alber Adventure is a mobility Scooter developed by the German company, Ulhrich Alber GmbH. It is primarily for comfortable outdoor use, but can be used indoors as well. It incorporates a modular design with easily replaceable components and can also be assembled or disassembled without tools. The main selling point of the adventure is its trailing link suspension design. This allows for independent shock absorption on each side. The Adventure is also advertised as being portable enough to comfortably fit into a vehicle. A wide selection of components is available for users of different backgrounds. (Ulrich Alber GmbH, n.d.)

FIGURE 11. ALBER ADVENTURE TRAILING LINK SUSPENSION. (ULRICH ALBER GMBH, N.D.)

FIGURE 12. ALBER ADVENTURE. (ULRICH ALBER GMBH, N.D.)

TWELL AIRLESS TIRES

FIGURE 13. TWELL AIRLESS TIRE. (GRABIANOWSKI)

The Twell Airless Tires are tires made completely out of rubber with no pneumatic air tube supporting it. It contains spines that connect the inner wheel with the outside rim of the tire. The Twell was designed as an alternative to pneumatic tires and works well except for the fact that it is very noisy at high speeds. They are being developed for low speed application such as construction or military use. These would be a good alternative to solid front wheels except that they are not in production and are still in the testing phase. (Grabianowski, 2007)

CURRENT STATE OF THE ART: THE STANDING DANI™

The Standing Dani™ Wheelstand (Figure 14) is a mobile stander for children with special needs and the focus of this project. It was designed to assist children with medical conditions that require assistance to achieve mobility while standing, but is no longer in production. It supports the child in an upright position, while their hands are left free to interact with others. The Standing Dani™ helps achieve benefits of dynamic weight bearing through the lower extremities. Some of these benefits include strengthening of bones, joint development, stretching of the ankle, knee hip flexors and abdominal muscles. It improves respiration and digestion, while it reduces constipation and the risk of bladder infection. It consists of two primary components: a wheeled base frame and an attached board to keep the user upright. It includes several adjustable components to accommodate different users. The Standing Dani™ will accommodate users between two and five & a half feet tall. It comes in manual and power versions. (Kettering University, n.d.)

FIGURE 14. NATHAN'S STANDING DANI.

FIGURE 15. STANDING DANI DRIVE WHEELS AND CASTERS.

The Standing Dani™ currently uses a system with two drive wheels and two caster wheels. The drive wheels are pneumatic (air-filled) tires with electric motors and safety brakes built in. The front casters have a metal rim with a solid rubber tire. The caster design has a pivoting arm with a rubber bushing to provide some shock absorption, but the bushing is too stiff and does not function as it was intended to function. Additional issues that currently exist with the Standing Dani™ system include low battery life, very limited user awareness, and uncomfortable extended use for Nathan. (Cooper, Cooper, & Cooper, 2013)

CHAPTER 3: DESIGN DEVELOPMENT

When engineering a solution to any problem, it is important to consider all possible ways of solving that issue before moving into the advanced design and building phases. This aspect of the engineering design process is aptly named idea generation. A commonly-known type of idea generation that we utilized was brainstorming. After our ideas had been generated, a decision matrix was used to compare the ideas. A decision matrix is a tool commonly used by engineers to objectively compare different concepts by scoring them on their ability to meet project requirements.

METHODS OF IDEA GENERATION

We employed three general methods of idea generation with the mindset that all ideas were accepted. The first method involved constructing physical models out of foam core, string, and other similar materials. The second method we used was morphological analysis. This required us to come up with different solutions for each aspect of the problem. The results from this are shown in Appendix B – Morphological Analysis. Our third approach involved brainstorming solutions based on existing suspension styles.

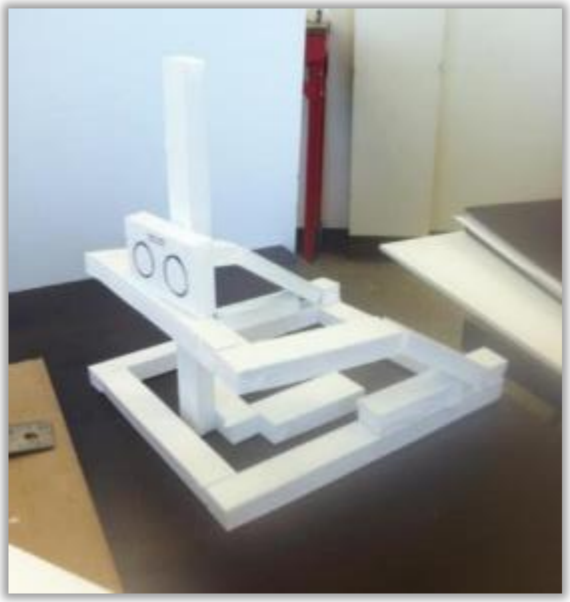


FIGURE 16. FOAM CORE MODEL OF CANTILEVER WITH SPRING CONCEPT.

The results from physical modeling, morphological analysis, and specialized brainstorming were refined and four final concepts emerged. At this stage, we made the decision to concentrate our efforts on developing suspension system concepts. This helped us narrow down our lengthy list of options. In addition, we reviewed our suspension ideas and discarded the unrealistic options. For example, one idea involved using magnets for levitation as a source of suspension. That was discarded, but using pneumatic casters (air-filled wheels) in the front was kept. After that, we individually developed and proposed detailed suspension concepts based off what remained from our modeling, morphological analysis, and brainstorming.

At the end of the day, the specialized brainstorming was the most useful form of idea generation for us. It was much more effective because it focused on looking at suspension systems that already existed and are well-researched. It allowed us to spend more time analyzing our specific problem of Nathan's discomfort.

DISCUSSION OF CONCEPTUAL DESIGNS

In total, we developed four final concepts: Low Pressure Tires, Twin A-Arm, Rear Trailing Arm, & Cantilever with Spring. The latter three are described below in terms of the rear part of the suspension only because it was decided that each would feature larger, pneumatic casters for the front suspension.

LOW PRESSURE TIRES

FIGURE 17. LOW PRESSURE TIRE DEFLECTING AROUND A 2X4 WOODEN BEAM. (DEFLECTION OF TIRE, N.D.)

This concept focused on using large air-filled tires that are partially deflated to absorb shock induced by bumps in the drive path of the Standing Dani™. It was the most simple, reliable, and cost-effective of each of our concepts. It also would provide an effective barrier between Nathan and rough terrain because the tires could deform around bumps as shown in Figure 17.

There are some serious drawbacks to this concept however. The required larger tires and low operating air pressure would be detrimental for the Standing Dani™'s maneuverability. In addition, the tires may flex and make the Standing Dani™ unstable when Nathan attempts a turn. The battery life would also decrease because the low pressure tire would have an increased resistance to forward movement.

TWIN A-ARM

The Twin A-Arm concept was derived from a common type of suspension used in cars sometimes called a Wishbone or A-Arm suspension. A sketch is shown in Figure 18. It would allow each of the rear wheels to move independently, which would increase Nathan's comfort. This quality would also be beneficial for going over different types of terrain. In these two categories, the Twin A-Arm outperformed each of the other concepts. In addition, this concept had added aesthetic appeal because of the "cool" look of a suspension system.

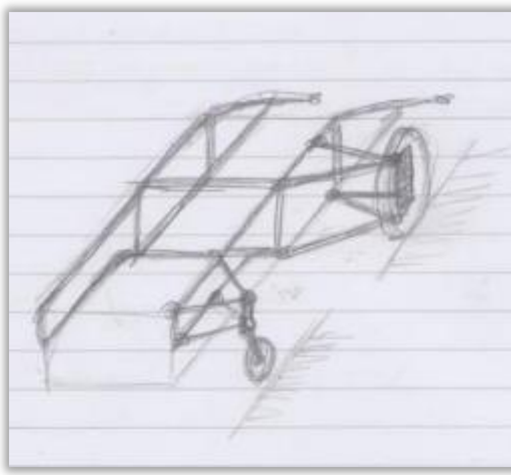


FIGURE 18. TWIN A-ARM CONCEPT SKETCH.

The drawbacks of this type of suspension were related to its geometry, weight, and overall complexity. This design would require an increase in the Standing Dani™ footprint. The increase in components due to the addition of a suspension system would be heavier as well. In addition, this suspension is system is relatively complicated, which would make mathematical modeling and manufacturing more difficult and costly. If a part needed to be replaced in the future, it would be more troublesome for the Coopers.

REAR TRAILING ARM

The name of this design, Rear Trailing Arm, was derived from an existing suspension style often seen in off-road vehicles. Each side of the suspension featured a wheel connected to two links. Each link is also attached to the frame at a pivot point. The pivot point allowed the wheel to move up and down over bumps. In order to control this movement, a spring & shock system (similar to something you would see on a mountain bike) was attached to the links.

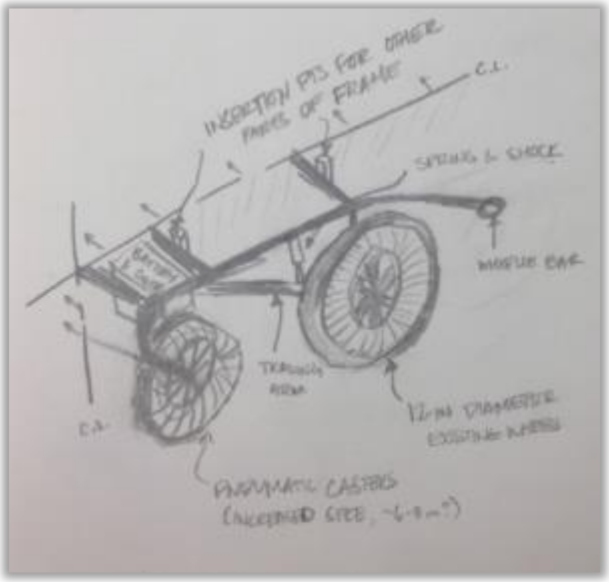


FIGURE 19. REAR TRAILING ARM CONCEPT SKETCH.

The simplicity, comfort, and attractiveness of this design were its strengths. It would feature only a few additional/new components from the existing Standing Dani™ design (i.e. the shocks and pivot arms). This suspension was mechanically simpler than the Twin A-Arm, but would still provide a satisfactory reduction in shocks from bumps. Like the Twin A-Arm, the added suspension system would be more attractive than the existing Standing Dani™ system.

The trailing arm had drawbacks, like each of the other concepts. The added spring & shock system would add overall weight to the Standing Dani™. It would not perform as well as the Twin A-Arm in reducing the road vibrations felt by Nathan. In addition, it would not be as effective at resisting roll (the shifting and rotation of Nathan left to right) as the Twin A-Arm when Nathan makes a turn.

CANTILEVER WITH SPRING

The Cantilever with Spring design focused on isolating Nathan from movement due to rough terrain by suspending him on a sideways-V frame. The frame would have springs that control his vertical movement as well. This concept was originally developed during the solid modeling stage of idea generation.

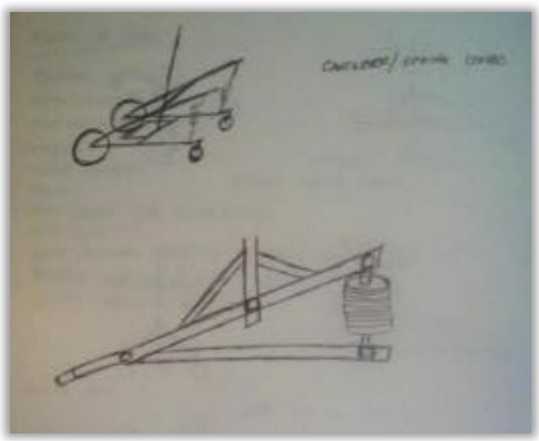


FIGURE 20. CANTILEVER WITH SPRING CONCEPT SKETCH.

This design was simple and would provide added comfort to Nathan's experience on the Standing Dani™. There were only a few required components and the added dynamic suspension system will provide Nathan with some isolation from the road.

This concept performed less well in the categories of aesthetics, system behavior, and weight. This design might have attracted negative attention to Nathan because of the oversized springs and beams that make up the suspension. If the front wheels hit a bump, then the rear wheels would react undesirably, and vice versa. Finally, the larger components required to make this design achievable would add a significant amount of weight to the Standing Dani™.

CONCEPT SELECTION

A decision matrix is a tool commonly used by engineers to objectively compare different concepts by scoring them on their ability to meet project requirements. We developed our own decision matrix (shown in Table 2) and were able to come to the conclusion that the most appropriate concept would be the Rear Trailing Arm.

TABLE 2. DECISION MATRIX OF CONCEPT DESIGNS.

Requirements	Weight	What is Better?	Datum - Standing Dani™		Cantilever w/ Spring		Low Pressure Tires		Rear Trailing Arm		Twin A-Arm	
			Non-Wt	Wt	Non-Wt	Wt	Non-Wt	Wt	Non-Wt	Wt	Non-Wt	Wt
Cost-Effective	**2**	**Less**	0	0	-1	-2	1	2	-1	-2	-1	-2
Safe for Nathan	**5**	**More**	0	0	0	0	0	0	0	0	0	0
Geometry	**5**	**Less**	0	0	0	0	0	0	0	0	-1	-5
Weight	**4**	**Less**	0	0	-1	-4	0	0	-1	-4	-2	-8
Comfortable	**5**	**More**	0	0	1	5	1	5	1	5	2	10
Terrain Capabilities	**5**	**More**	0	0	1	5	1	5	1	5	2	10
Aesthetics	**5**	**More**	0	0	0	0	-1	-5	1	5	1	5
Reparability	**3**	**More**	0	0	1	3	2	6	1	3	-1	-3
Reliable	**4**	**More**	0	0	-1	-4	0	0	-1	-4	-1	-4
User Awareness	**3**	**More**	0	0	0	0	0	0	0	0	0	0
Battery Range per Charge	**2**	**More**	0	0	0	0	-2	-4	0	0	0	0
Maneuverability	**4**	**More**	0	0	0	0	-1	-4	0	0	0	0
Operability	**5**	**More**	0	0	0	0	0	0	0	0	0	0
Likelihood of Rollover	**5**	**Less**	0	0	0	0	0	0	0	0	0	0
Transportability	**5**	**More**	0	0	0	0	0	0	0	0	0	0
Total			***0***	***0***	***0***	***3***	***1***	***5***	***1***	***8***	***-1***	***3***

There are a few important takeaways from our decision matrix. The datum, or what we used as a baseline for each comparison, was the existing Standing Dani™. The scoring system was on a scale of -2 to +2 and is explained in Table 3. There were also a few important results. The Rear Trailing Arm performed well in the same areas as other concepts. Likewise, other concepts performed poorly when the Rear Trailing Arm performed poorly. Hence, the Rear Trailing Arm was a happy medium of each of the concepts and came out on top.

Table 4 gives a more detailed description of each requirement used in the decision matrix. Each of these requirements can be referenced back to the QFD Matrix (Appendix A – Quality Function Diagram).

TABLE 3. SCORING SYSTEM FOR DECISION MATRIX.

Scoring System	
Much worse than the Datum	-2
Worse than the Datum	-1
Same performance as Datum	0
Better than the Datum	1
Much better than the Datum	2

TABLE 4. EXPLANATION OF REQUIREMENTS USED FOR DECISION MATRIX.

Description of each Requirement	
Cost-Effective	Cost of the entire system (thinking about raw materials and how each component is manufactured)
Safe for Nathan	Must not cause the Nathan any type of bodily injury
Geometry	Concerned with the footprint, height, use of existing body support, and other frame design
Weight	Weight of system without Nathan
Comfortable	Must be able to provide a comfortable ride across varying terrain (i.e. grass, trails, boardwalk)
Terrain Capabilities	Ability to go over different types of terrain without affecting user negatively
Aesthetics	Should look aesthetically pleasing so as to not draw negative attention to the user
Repairability	Number of off-the-shelf components, Ease of repair by outside party
Reliable	Must be low-maintenance and have high reliability
User Awareness	Ability of Nathan to see or be informed of what is near him
Battery Range per Charge	The time the system could run under average load (currently two hours, aiming for three hours)
Maneuverability	Ability of Standing Dani to move through tighter spaces with acceptable response time
Operability	Ability of Nathan to control the Standing Dani during operation
Likelihood of Rollover	Chance that the device will rollover in standard operating conditions, No rollover is acceptable
Transportability	Must be easily transported by van or small SUV and lifted by a maximum of two people.

NOTE: The weighting of the different requirements came from our QFD.

CHAPTER 4: DESCRIPTION OF THE FINAL DESIGN

OVERALL DESCRIPTION AND SOLID MODEL

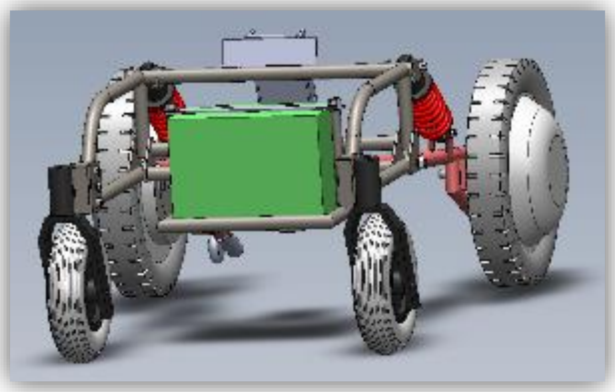


FIGURE 21. FINAL DESIGN MODEL (FRONT VIEW).

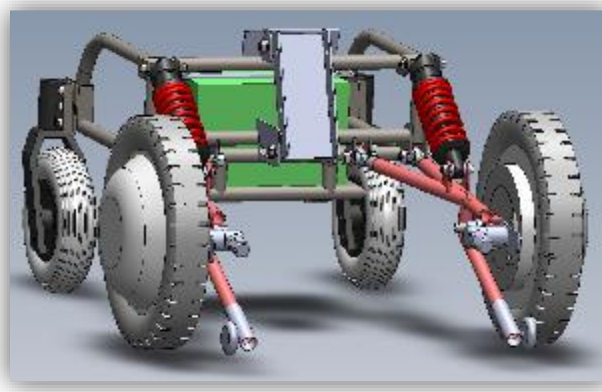


FIGURE 22. FINAL DESIGN MODEL (REAR VIEW).

As discussed in the above section, we decided to go with the Rear Trailing Arm design. Different views of a three-dimensional solid model of the final design are shown in Figure 21 through Figure 24. Some refining took place after deciding to go with the Rear Trailing Arm concept. We looked into what components it would require, basic sizing of the system, and locations for wheels and the insertion area for the Standing Dani™ frame parts that would be reused.

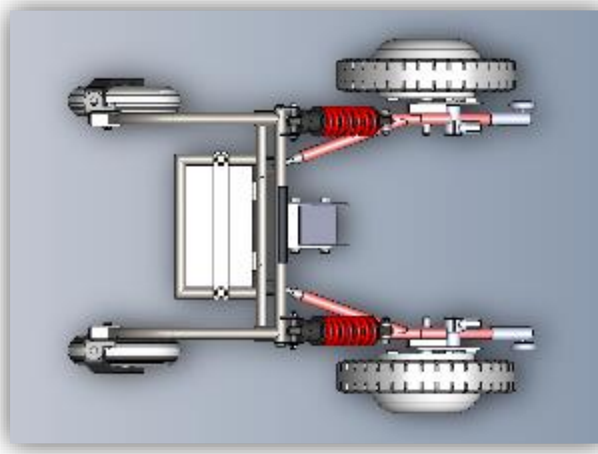


FIGURE 23. FINAL DESIGN MODEL (TOP VIEW).

There are a few components and design features from the existing Standing Dani™ that we will be reusing in our design. We will be reusing the original drive system, which includes a controller, battery, charger and wheels with the motor built into the hub. This decision will allow us to focus our efforts on areas that need improvement (i.e. the suspension system). In our design, the rear wheels will be bolted directly to a flat plate on the frame. The motor and gearing is built in to the rear wheel, which means we do not have to worry about any power transmission components. This gives us the ability to keep all the suspension components simple and lightweight.

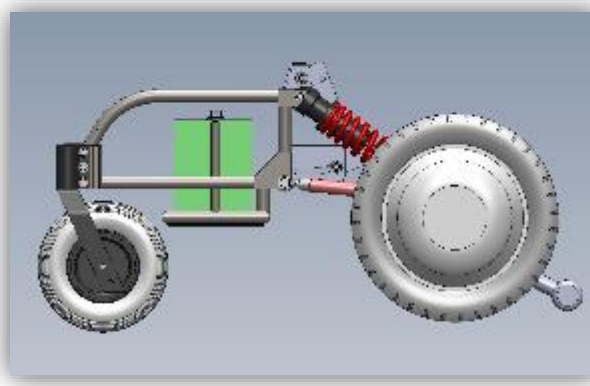


FIGURE 24. FINAL DESIGN MODEL (SIDE VIEW).

We will also be reusing all of the components used to support Nathan. The system works fairly well for him with the exception of a few areas. Our list of secondary projects included improving these areas. Nathan's support system is all mounted off of one vertical support mounted to the horizontal cross member of the frame. For the frame, we decided to build it out of ¾ inch steel tubing. This is similar tubing found on the current Standing Dani™ so we were comfortable using it for our design. We also did stress analysis to double-check our assumption and from the results, we believe that the tubing will be more than adequate. When purchasing the tubing, we were only able to find Electric Resistance Welded (ERW) Steel Tubing. We preferred Drawn-Over Mandrel (DOM) Steel Tubing but we settled for the ERW for our test rig because of ease of availability and cost. For the final design, we purchased DOM Tubing from online.

DETAILED DESIGN DESCRIPTION

In this section, we will discuss the front caster, the frame design, the suspension linkages, the attachment assembly, the arm rest, the wheelie bars as well as the shocks we plan to use.

FRONT CASTER

It turned out to be more challenging than we had initially anticipated coming up with a solution to reduce the shock coming from the front wheels. The drive system that we used works by varying the speed on each of the drive wheels (the same way a tank steers). It's a very simple and compact system which allowed for excellent maneuverability. For this system to work properly, the non-powered wheels must have a 360-degree range of motion, which was very easily achieved by caster wheels.

For a caster wheel to work properly, the pivot axis must be perfectly vertical, or perpendicular to the ground. If there is any small misalignment, it will cause the caster to turn in that direction. This is why old shopping carts at the grocery store never want to go straight. This sensitivity to changing angles made adding a suspension very difficult because it would have to maintain this perfect alignment while moving up and down.

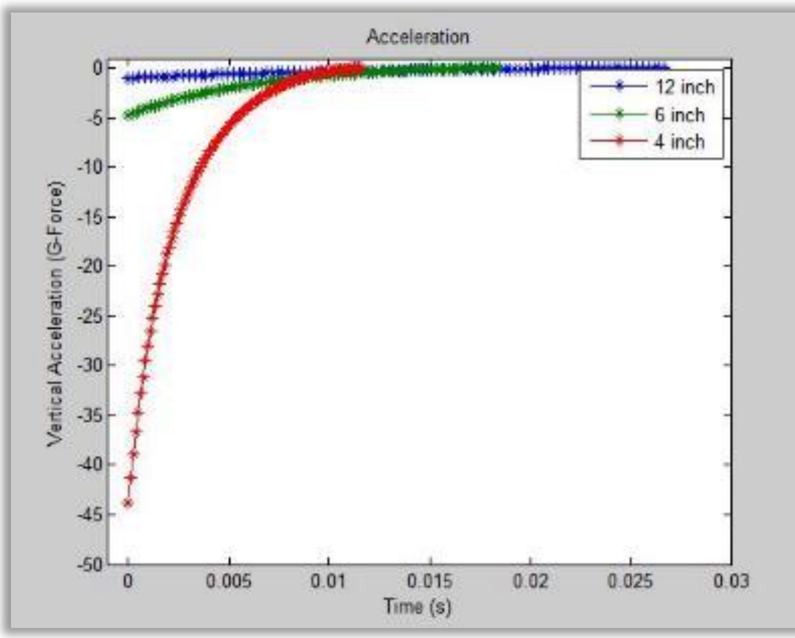


FIGURE 25. VERTICAL ACCELERATION OVER 1/2" BUMP.

We tried to think of other solutions to the problem so we decided to see what effect a simple change in wheel diameter would have on reducing shock. Theoretically, a larger wheel will be better. We did some rough calculations to compare a 4, 6, and 12-inch wheel rolling over a ½-inch curb at 5 mph. The current front wheel is four inches and the rear is 12 inches in diameter. We felt that a 6-inch wheel could be a reasonable front wheel size considering the effects larger wheels have on maneuverability. Figure 25 shows the accelerations felt over ½-inch bump. The larger negative values indicate a much harsher ride. Our calculations showed that a 50% increase in wheel diameter would dramatically reduce the transmitted shock.

We wanted to go with Semi-Pneumatic Casters to assist with increasing the suspension of the front. This would increase the shock absorption that the Standing Dani™ would have while also having the advantage of being longer lasting and having no risk of air leaks or punctures that regular pneumatics face.

FIGURE 26. FOAM FILLED SEMI-PNEUMATIC CASTERS

After doing some research, we found two caster options that could have potentially satisfied our needs. Caster City had Semi-Pneumatic Foam filled casters that came in 6-inch, 8-inch, or 10-inch sizes and could support anywhere between 200 and 350 pounds (size-dependent). They provided the same ride as regular air-filled pneumatic tires but they were not at risk for air leaks. They would have cost us slightly more.

Caster City also stock their Super Cushion Semi-Pneumatic caster. These casters are often used in hospitals and hotels to reduce vibration and noise from uneven ground. They absorb shock and vibration better than the foam filled semi-pneumatic wheels, but they also cost nearly twice as much. They are offered in similar sizes to the foam filled casters, but can handle higher loads on a smaller diameter wheel. We considered these casters in case we had needed more shock absorption.

FIGURE 27. SUPER CUSHION SEMI-PNEUMATIC CASTERS

In the end, we used the set of eight-inch rubber casters from the Coopers that they donated at the beginning of our project. After some research, we found that they were Primo Spirit scooter tires. We used them for testing and were satisfied with their results. When we purchased the replacement wheels from Caster City, we found that the center hubs did not match our existing design. For this reason, we chose to continue to use the donated casters from the Coopers. A vendor that sells replacements or these casters are listed in Appendix D – List of Vendors, Contact Information, and Pricing.

FRAME DESIGN

The original Standing Dani™ frame has a very simple construction made out of approximately six tubular steel sections which are welded together. We decided to make our own frame (Figure 28) for a couple reasons:

- Simple, low-cost design
- We had limited access to the Standing Dani
- More convenient geometry for the new suspension

FIGURE 28. FRAME DESIGN.

It is important to note that the attachment points for the trailing suspension linkages & shock assembly are also known as mounting tabs. They are single pieces of steel that were welded on to the frame after being machined from stock metal.

We built two frames over the course of our project. The first was a part of our test rig. We used it settle the geometry for the final frame design. For our test rig, we used ¾-inch Electric Resistance Welded (ERW) steel tubing because of how cheap it was. We believed that it would still hold up to our weight specifications. For the final design, we used Drawn Over Mandrel (DOM) steel tubing, which is a lot stronger, but also more expensive. We cut the tubing to length, bent it, and welded it together to create our frame.

SUSPENSION LINKAGES

FIGURE 29. SUSPENSION TRAILING ARM.

FIGURE 30. TRAILING ARM ATTACHED TO FRAME AND SHOCK.

The suspension links created the connection between the main frame, the rear wheels, and the shocks. We have designed them as simple triangular structures made of welded steel tubing. We used off-the-shelf spherical rod ends for the attachment points because of their high strength and low cost. They were easy to work with and readily available which helps us meet our reparability objective. The narrow end of the arm has a flat plate for mounting the drive wheels. The drive wheels were mounted to the plate with four bolts.

ATTACHMENT ASSEMBLY

In order to attach Nathan's existing body support to our new frame design, we needed to design an attachment piece to be welded to our new frame. We had two options: a fixed design (like the one he currently has) or a reclining design (more complex, but more flexible).

After some miscommunications in manufacturing, we were forced to choose the reclining design. Nathan's current body support leans forward at an angle of 20 degrees from the vertical. After the first part of the frame was manufactured, we realized that achieving that 20 degree angle would be impossible because one mounting point was directly above the other. For this reason, we developed a reclining design.

The reclining design required extra time in a few areas. First, we had to develop a solid model in SolidWorks. Whereas the fixed design required two unique parts, the reclining design required five unique parts. In addition, we were required to use Computer Numerical Control (CNC) machines to manufacture our parts. This was completed by Alec Bialek with some assistance from Carter Wilson (Appendix H – Helpful Resources & Points of Contact). CNC machining requires programming and a machinist with an open schedule. Finally, we had another manufacturing miscommunication. The attachment design was sized for a vertical tube offset of five inches (from an earlier revision for the design), but the frame tubing was manufactured with an offset of four inches. During welding, additional pieces were added to the frame to make up for the one inch of space.

FIGURE 31. EXISTING ATTACHMENT DESIGN (BLUE PIECE WITH BUTTONS).

The attachment assembly worked relatively well, but there are a couple adjustments that would improve it. First, it would be lighter if the attachment was designed for the correct tube offset. Also, if a bicycle quick release skewer was used instead of fasteners for the curved slot, it would be easier to adjust for the Coopers. The final design is shown in Appendix C – Bill of Materials and Drawing Packet.

ARM REST

Nathan's existing acrylic arm rest was not functioning as intended and was breaking down leading to greater discomfort for Nathan. In response, we developed a new, symmetric arm rest made out of Polycarbonate for greater durability and better body control of Nathan. The design was done with the help of Bob Cooper and the materials and cutting were donated by Brian Kerns & Robert Kilbride (Appendix H – Helpful Resources & Points of Contact). After the arm rest was completed, it was given to the Coopers to be attached. Excluding some minor changes, the arm rest is working very well.

FIGURE 32. NEW POLYCARBONATE ARM REST WITH ANTI-SCRATCH PROTECTIVE SHEETING ON IT.

WHEELIE BARS

One of the important features that we needed to keep on our new design from the original design was the set of wheelie bars. It is a safety

FIGURE 33. WHEELIE BAR NEXT TO FRAME.

feature that prevents Nathan from tilting too far back when he first accelerates from a dead stop. A pair of wheelie bars were supplied to us at no cost by A-1 Mobility Scooters in Atascadero. They are pictured in Figure 33. The wheelie bars were then welded on to the existing frame to be used by Nathan.

SHOCKS

The most important part of any suspension is having the correct spring and shock combination. We had very limited space in the frame so it needed to be as compact as possible. We did not anticipate needing more than one to two inches of travel (related to the size of bumps in the road) to meet our terrain requirements. Still, we needed adjustable spring and shock settings to achieve our desired performance.

The shocks we initially selected are made by FOX and designed for mountain bikes. They use compressed air instead of a conventional coil spring. This allows them to be much lighter and more compact. The spring rate and damping rate (shock stiffness) can be adjusted over a wide range which would have given us more freedom in our suspension geometry. They also have an electronic control module for adjusting the damping remotely by a switch. This would have been an excellent feature for Nathan because it would allow him to adjust the ride stiffness to match the terrain he was driving over.

The particular model we were interested in was the Float CTD from FOX. They are 5.5-inches long with 1-inch of travel, which suited our application. They are very lightweight (0.46 pounds each) relative to overall system weight. Figure 34 shows the actual shock and Figure 35 shows the three-dimensional model we used to represent it in our conceptual design.

FIGURE 34. FOX FLOAT CTD. (FOX FACTORY, N.D.)

FIGURE 35. FOX FLOAT CTD (SOLIDWORKS RENDITION).

FIGURE 36. ROMIC D SHOCK AND SPRING.

FIGURE 37. ROMIC D SHOCK AND SPRING (SOLIDWORKS RENDITION).

After more research, we discovered that the FOX Float shocks weren't the safest option. We found out that they had the potential to be rendered useless by a simple scratch on the cylinder. We did not want to risk this as they would have been very expensive to replace ($300). We decided to buy a more conventional spring and shock combo to use for our suspension and found the Romic D for a good price. After some analysis, we determined that the spring rate for the Romic D was too high for our application (rated 300 lbs/in), but we have found alternative springs that will suit our needs.

We placed an order for two different replacement springs with different springs rates (97 lbf/in and 42 lbf/in) that would fit our shock. After some analysis and testing, we decided to stick with the 97 lbf/in replacement spring as we thought it would work best for our application. Each of the new springs were powder coated in black paint.

All of the springs were given to the Coopers upon final delivery of all hardware.

ANALYSIS RESULTS

We completed technical analysis to confirm the validity of our original design. We took the measurements of our design and applied engineering principles to check for system deflection and suspension behavior, among other parameters. The analysis that we completed involved deflection of the system when it was not moving, worst-case stress prediction in the rear trailing arm, tiltover angle, and the suspension's natural frequency. After the original design was completed, we re-evaluated our design using the test results and feedback from the Coopers. All of our supporting analysis can be found in Appendix F – Detailed Supporting Analysis.

STATIC DEFLECTION

We analyzed the new design for a simplified loading condition to determine how much sag we could expect. The loads that were used were the weight of Nathan, the controller & battery, and the rear wheels. The modeled spring rate was 300 lbf/in (the stock spring rate for the Romic D shock).

In the analysis, each applied load was multiplied by five. This implied a safety factor of 5 and was recommended by Dr. Mello (Mello, 2014). The thought was to design around this increased load in the static analysis, so that – in the case of a more extreme load (i.e. a two-foot drop from a car) – the system would not fail.

The results of the analysis are summarized below. Please note that the rear wheel deflection assumed that the trailing arm-frame connection pin remained fixed and that the tire was rigid. In reality, the pin moves and the tire deflects a little. In addition, the spring was assumed to behave linearly.

- Deflection at rear wheel, $\delta_{rw,in} = 4.98\ inches$
- Deflection at rear wheel without safety factor, $\delta_{rw,in,noF.S.} = 0.996\ inches$
- Spring travel, $\Delta x_{in} = 1.598\ inches$
- Angle between horizontal and trailing arm, $\theta_1 = 24.53°$
- Angle between trailing arm and shock assembly, $\theta_2 = 34.64°$
- Normal force at the rear wheel, $N_R = 172.9\ lbf$

STRESS IN TRAILING ARM

After completing the static deflection analysis, we looked at the expected stress in the trailing arm component. The analysis looked at axial and bending stresses while considering shear and torsional stress to be negligible (the trailing arm is considered a long rod and there was no applied torque). The resulting stresses were used to find the principal stresses in the trailing arm. Using the Ductile Material Stress Theory (Budynas, Nisbett, & Shigley), we found that our design was safe for loading factors of up to four (the static deflection analysis assumed a loading factor of five).

TITLTOVER ANGLE

General calculations were done for the tiltover angle, but the most important thing that was found regarded actual testing of the device. For more information, see Appendix F – Detailed Supporting Analysis: Tiltover angle.

SUSPENSION NATURAL FREQUENCY

Based off of a recommendation from Dr. Mello, we did basic calculations regarding the natural frequency of the suspension. This was done to predict how stiff it would be. It predicted a natural frequency of 3.13 Hz, which showed that the system was a little stiffer than we would like (Mello, 2014). Consequently, our testing of the original spring rate (300 lbf/in) proved that our system was, in fact, too stiff. As discussed in Detailed Design Description (Chapter 4: Description of the Final Design), we ended up purchasing springs with lower spring rates.

MANUFACTURING DRAWINGS

All pertinent drawings can be found in Appendix C – Bill of Materials and Drawing Packet. This includes, but is not limited to, the system assembly & sub-assemblies with a Bill of Materials (BOM) and detailed part drawings.

SAFETY CONSIDERATIONS

Most of our safety considerations are laid out in our testing methods in Chapter 6: Design Verification Plan (Testing). Overall, we wanted this device to be safe for Nathan so that his family is comfortable when he is operating it. We wanted to be sure that there were no possible pinch points or sharp edges on the unit. We were not too afraid of electrical concern because there was not too much that can cause shock, but we were sure to check that there were no exposed wires that could cause electrical harm. We also checked the incline and tiltover limits of the device to ensure that it would not tilt over under expected operating conditions.

PROCUREMENT & COST ANALYSIS

The Mechanical Engineering Department at Cal Poly allotted us $2500 for our project. For our test rig, we obtained the ERW tubing from Precision Machine in San Luis Obispo, and the material for our mounting tabs was purchased at McCarthy's Tank and Steel in San Luis Obispo. We ordered rod ends and connecting rods from McMaster-Carr.com and had them shipped to the Mustang 60 Machine shop. Our spring/shock combo was purchased from Cambria Bicycle Outfitters for a fantastic price. The Coopers were kind enough to donate some of their extra components so that we could use them for testing purposes. We received the battery, controller, and drive wheels from the old Standing Dani™ and they also gave us a pair of pneumatic casters (replacements can be purchased at MonsterScooterParts.com).

For our final design, we purchased mounting hardware, rod ends and connecting rods from McMaster-Carr and reused everything that was salvageable from our test rig. For casters, we purchased Foam-Filled Semi-Pneumatic casters from Castercity.com. We decided to instead just keep using the casters provided to us by the Coopers because the hub size didn't match with our available casters. Furthermore, we purchased ¾"-DOM tubing from SpeedyMetals.com and our spring replacements from CenturySpring.com.

As seen in Table 6, we had spent a little under $250 for our test rig and the total projected cost of the project was significantly lower than our budget. Our budget allowed us to build two iterations of our design. We also planned to use some of the savings on aesthetics and are going to get the frame powder coated. We wanted to talk to Nathan and ask him if there were any components that he would have liked to see on his Standing Dani™ to make it cool. A few options that the Coopers said would be nice are rear view mirrors and a carrying basket. We did not end up purchasing these items, but they could be easily added on by the Coopers. Table 5 gives a summary of our cost analysis presented on the following page.

TABLE 5. SUMMARY OF COST ANALYSIS.

Total Spent	**1125.16**
Total Remaining	**1374.84**
Absolute Projected Cost	**1255.16**
Absolute Projected Remaining	**1244.84**

TABLE 6. COST ANALYSIS.

Team Nathan Cost Analysis

	Item Description	Purpose	Retailer	Quantity	Price/Item	Total Price	Tax/Shipping	Date Purchased	Date Received	Payment Method	Reimbursed
Test Rig	1/8" x 1" Flat Bar 20'	Mounting Tab Manufacture	McCarthy's Tank and Steel	1	5.51	5.51	0.00	1/22/14	1/22/14	Credit Card (F)	Yes
	3/4" Electric Reistance Welded Steel Tubing 15'	Frame and Trailing Link Manufacture	Precision Machine	1	20.00	20.00	0.00	1/16/14	1/16/14	Cash (A)	Yes
	Romic D Shock 7.875" x 2.25"	Suspension	Cambria Bicycle Outfitters	2	61.71	123.42	0.00	1/17/14	1/17/14	Credit Card (F)	Yes
	PTFE-Line Stailness Steel Ball Join Rod End, 3/8"-24 Right-Hand Male Shank, 3/8" Ball ID, 1-1/4" L Thread	Connection Points	McMaster-Carr	4	17.14	80.84	12.28	1/23/14	1/24/14	Pro-Card	N/A
	Alloy Steel Tube-End Weld Nut, Fits 3/4" Tube OD, .065" Wall Thickness, 3/8"-24 Right-Hand Thread			4	5.04	20.16		1/23/14	1/24/14	Pro-Card	N/A
	8" x 2" Primo Spirit Wheel + Caster	Wheel	Donated from Coopers	2	0.00	0.00	0.00		12/10/13		N/A
	Standing Dani Drive Wheels	Drive System		2	0.00	0.00	0.00		12/10/13		N/A
	Standing Dani Battery	Power Supply		1	0.00	0.00	0.00		12/10/13		N/A
	Standing Dani Controller	Control System		1	0.00	0.00	0.00		12/10/13		N/A
	Hardware	Mounting	Home Depot	1	30.00	30.00	0.00			(A)	No
Final Design	3/8" x 2" Flat Bar 5'	Mounting	McCarthy's Tank and Steel	1	19.66	21.23	1.57	5/15/14	5/15/14	Credit Card (J)	Yes
	3/8" x 4" Flat Bar 4'	Center Column Mount		1	30.74	30.74	0.00	6/3/14	6/3/14	RAPD Acct	N/A
	3/16" x 2" Flat Bar 20'	Mounting Tab Manufacture		1	12.30	13.28	0.98	5/15/14	5/15/14	Credit Card (J)	Yes
	3/4" OD {A} x 0.606" ID {B} x .072" Wall {C} DOM Steel Tube-60"	Frame and Trailing Link Manufacture	Speedy Metals	6	25.38	152.28	41.72	4/23/14	4/30/14	Pro-Card	N/A
	1/2" OD {A} x 0.370" ID {B} x .065" Wall {C} DOM Steel Tube-60"	Battery Support Manufacture		1	17.04	17.04		4/23/14	4/30/14	Pro-Card	N/A
	1.937" OD x 4.5" Compression Spring. 97 lbs/in	Spring Replacement	Century Spring	2	41.55	83.10	18.47	4/1/14	4/15/14	Pro-Card	N/A
	1.687" OD x 3.5" Compression Spring. 42 lbs/in			2	19.07	38.14		4/1/14	4/15/14	Pro-Card	N/A
	8" Pneumatic Wheel - Black Tire	Replacement Wheel	Caster City	2	13.66	25.95	17.02	4/23/14	5/2/14	Pro-Card	N/A
	8" Foam Filled Pneumatic Wheel - Black Tire			2	29.10	55.29		4/23/14	5/2/14	Pro-Card	N/A
	PTFE-Line Stailness Steel Ball Joint Rod End, 3/8"-24 Right-Hand Male Shank, 3/8" Ball ID, 1-1/4" L Thread	Connection Points	McMaster-Carr	4	17.14	68.56	17.13	4/23/14	4/30/14	Pro-Card	N/A
	Alloy Steel Tube-End Weld Nut, Fits 3/4" Tube OD, .065" Wall Thickness, 3/8"-24 Right-Hand Thread			4	5.04	20.16		4/23/14	4/30/14	Pro-Card	N/A
	Zinc Plated Steel Serrated Flange Cap Screw 1/4"-20 Thread 2-1/4" Length, Fully Threaded	Mounting Hardware		1	7.58	7.58		4/23/14	4/30/14	Pro-Card	N/A
	Grade 8 Steel Serrated-Flange Hex Locknut 3/8"-16 Thread Size, 9/16" Width, 11/32" Height			1	12.73	12.73		4/23/14	4/30/14	Pro-Card	N/A
	Zinc Plated Steel Serrated Flange Cap Screw 3/8"-16 Thread 1-1/2" Length, Fully Threaded			1	14.65	14.65		4/23/14	4/30/14	Pro-Card	N/A
	Type 316 Stainless Steel Type A SAE Flat Washer, 1/4" Screw Size, 5/8" OD, .05"-.08" Thick			1	7.55	7.55		4/23/14	4/30/14	Pro-Card	N/A
	Grade 8 Steel Serrated-Flange Hex Locknut 1/4"-16 Thread Size, 7/16" Width, 15/64" Height			1	6.66	6.66		4/23/14	4/30/14	Pro-Card	N/A
	CNC Machining Labor	Center Column Mount	Cal Poly Machine Shop	9	16.00	144.00	0.00	6/5/14	6/5/14	RAPD Acct	N/A
	Powder Coat Finish	Finish	Central Coast Powder Coating	1	100.00	100.00	0.00	6/25/14	6/25/14	Cash (J)	No
Testing	0.451 in 15/32 CAT BC Project Panel	Bump Test	Home Depot	2	19.98	43.54	3.58	3/8/14	3/8/14	Credit Card (F)	Yes

MAINTENANCE AND REPAIR CONSIDERATIONS

FIGURE 38. DEBURRING TOOL (DIRECT INDUSTRY)

The only maintenance that we foresee is that the battery will require recharging as always. There should not be any regularly scheduled maintenance required for the final design. Some repair considerations include having to purchase new pneumatic casters, if they end up becoming dysfunctional. The other repair consideration that might occur is that the Coopers may need to buy another replacement spring if theirs happens to break. The provided appendices provide fully-detailed drawings and lists of vendors used to purchase materials. These should have enough information to find replacement parts.

FIGURE 39. METAL GRINDER (OXYGEN SERVICE CO)

FIGURE 40. DRILL PRESS (HARBOR FREIGHT)

CHAPTER 5: PRODUCT REALIZATION

MANUFACTURING PROCESSED EMPLOYED

The manufacturing phases represent the time set aside to physically build a working model to test. In total we planned four manufacturing phases that were each going to last around two to three weeks.

During each manufacturing phase, we planned to complete five of the same tasks. First, we would develop or make changes to our system design based off our test results and feedback from the Coopers. Next, we would machine, find necessary hardware, and do anything else required to get a working prototype for testing. While the prototype was being produced, we would ensure that safety of the device was maintained by eliminating pinch points & ball joints and ensuring that all components were strong enough to ensure that Nathan would be safe then and in the future. Each manufacturing phase would commence with updates to engineering technical analysis and computer-aided solid modeling files. After we compiled the testing data, we could use our models to create a more optimal design and improve upon the flaws of each previous design. Ideally, we wanted to do two iterations of the frame, but we planned out room for up to four iterations.

FABRICATION METHODS

We developed our initial frame fabrication. We used this first iteration as a test rig to test and finalize the geometry of our fixtures. In order to build a modular frame we decided to purchase flat steel bar to use as our mounting points. We used a metal grinder (Figure 42) to cut the steel into different sized tabs. The two sizes were to be used for connecting the rod ends as well as connecting our spring/shock combination. The rod ends were to have a single hole drilled through at a .375 in. diameter while the shock tabs were to be drilled with a .230 in. diameter hole. We used a drill press (Figure 40) with fractional drill sizes to make the holes. The problem with this is that there wasn't a .230 in. drill bit, so we went with the next closest bit which was a .234 in. drill bit. After drilling the holes, we used an air grinder and a de-burring tool to get rid of all of the sharp edges and burrs on our metal. Our next step in the test rig manufacturing phase was to create the frame. We had three pieces of six foot electric resistance welded tubing that we used for the frame. Our calculations lead us to believe that a .75 in. diameter tube would be sufficient for our application. We used the metal grinder to cut our tube to the correct length, and a metal inert gas (MIG) welder (Figure 41) to hold the frame together. Once

FIGURE 41. MIG WELDER (MOPAR MUSCLE)

FIGURE 42. AIR GRINDER (KNUCKLE BUSTER INC)

this was completed, we were able to bolt the rest of the components on to the frame and begin our test phase.

For our final model, many of the same steps were taken. We were more careful in our manufacturing as we wanted the final design to be perfect for our customer. We were able to bend the tubes for the final design unlike the test rig where we just welded straight tubes together. It made for a much nicer finish.

MANUFACTURING RESOURCES

Our manufacturing was primarily done in the Cal Poly Machine Shops. Our tab manufacturing was done in the Cal Poly Hangar using a metal grinder, drill press, and an air grinder. We used the Cal Poly Hangar as a place to weld and bend our frame as well. Alex is our team welder. He has a lot of welding experience from his work on building drift cars. We ordered most materials online and had it shipped to the Mustang '60 Machine Shop.

FIGURE 43. TEST RIG TRAILING LINKS

OUTSOURCED MANUFACTURING

Almost all of the manufacturing, we planned to do in the Machine Shops at Cal Poly. One of the manufacturing processes that needed to be outsourced was the powder coating of the final design. We found a few local shops and decided on Central Coast Powder Coating as the place to get our frame powder coated.

Another aspect of manufacturing that we outsourced was our mounting tabs for the center column. We decided that we weren't able to manufacture these ourselves due to the curved nature of the slots. We decided to use the Mustang 60 Machine shop CNC machine to make this piece for us.

FIGURE 44. OUR TAB BEING MACHINED IN MUSTANG '60 HAAS CNC MILL.

The last outsourced machining process was to make a new arm rest for Nathan. Frankie had a contact that was able to cut polycarbonate for us. The final product can be seen in Figure 32 on page 30.

FIGURE 45. FIXTURES TO CREATE IDENTICAL TRAILING ARMS.

FIGURE 46. TRAILING ARM ATTACHMENT.

FIGURE 47. ATTACHING OUR TRAILING ARM TO OUR TEST RIG.

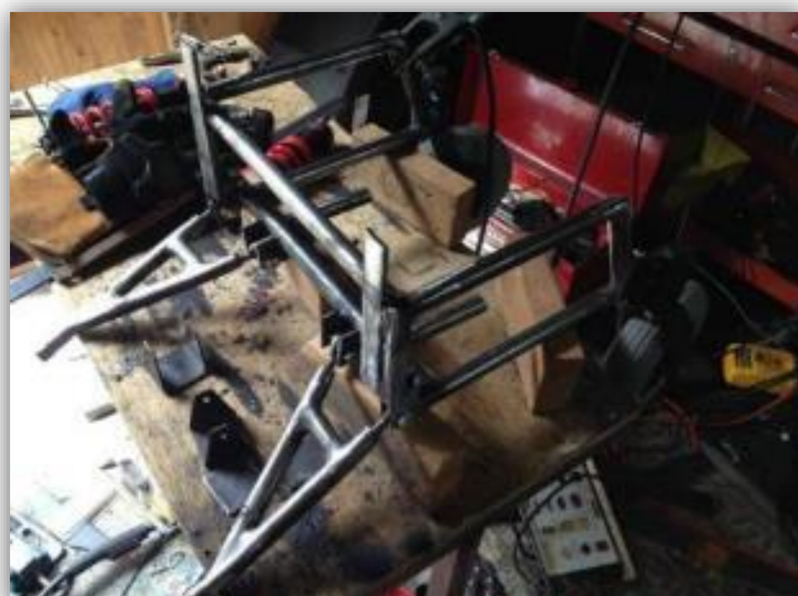


FIGURE 48. BOTH TRAILING ARMS ON OUR TEST RIG.

FIGURE 49. CENTER COLUMN MOUNTING PIECE.

FIGURE 50. CENTER COLUMN MOUNTING PIECE ATTACHED TO OUR FRAME.

MANUFACTURING FLOW DIAGRAM

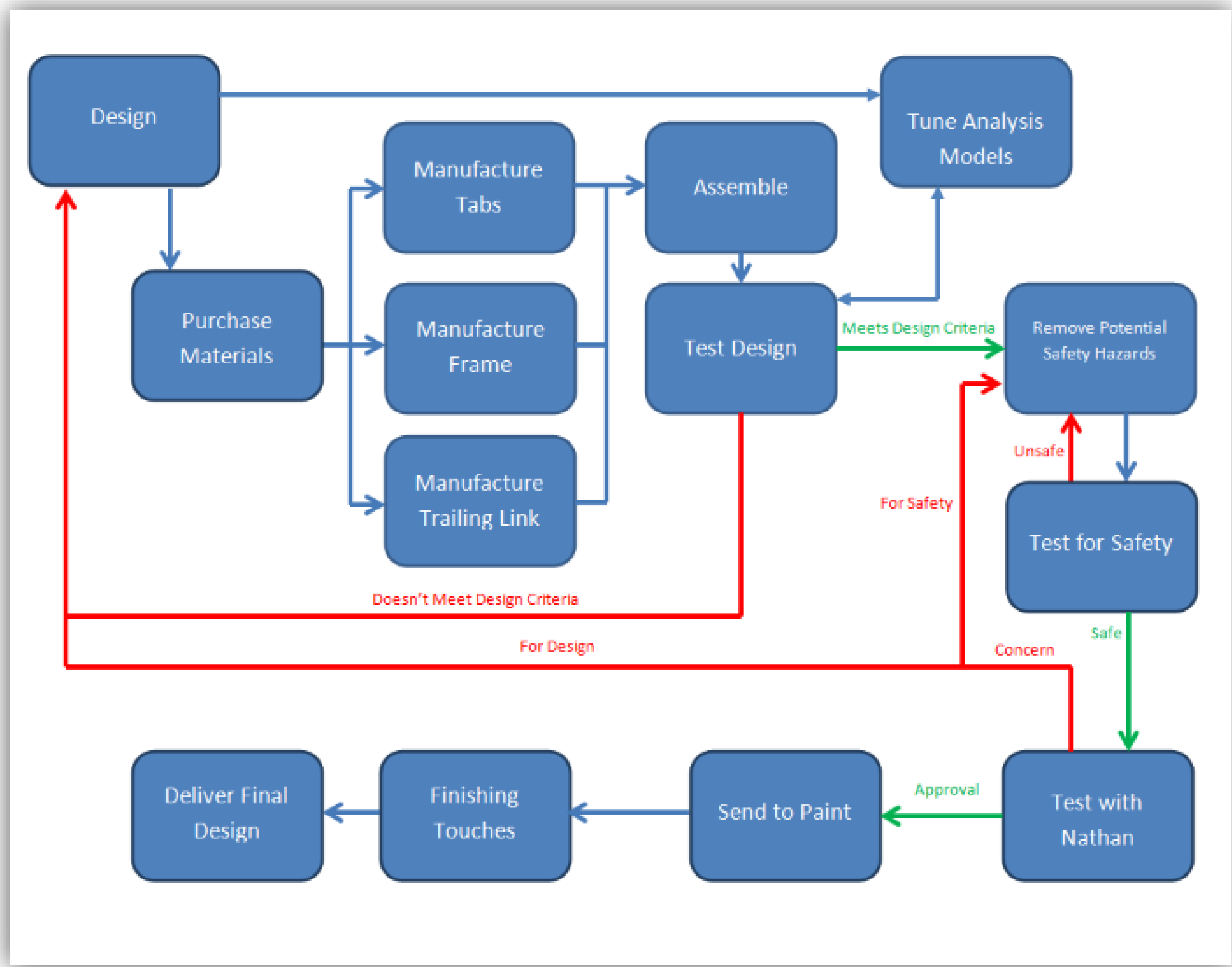


FIGURE 51. MANUFACTURING FLOW DIAGRAM

RECOMMENDATIONS FOR FUTURE MANUFACTURING

We do have a few recommendations for future manufacturing. We believe it would have been beneficial to begin manufacturing earlier than we did. We drastically underestimated the time it took to build a frame. The actual welding process was not the time consuming part, it was the preparation of the materials that took up our time. We also did not consider the mounting piece (or attachment assembly) for the center column until right before we wanted to mount it. We believed that the center column was easily mounted to the frame, but we didn't take into consideration the design it would take to manufacture the actual piece. The Coopers also wanted it to be able to lean forward and backward. We were able to accommodate this, but it took a little more design time than we had and we had to outsource the manufacturing in order to fulfill our timeline. We recommend taking everything into consideration and to not forget any pieces even if you believe they look simple. Some other things that we wanted to add are metal plates that could fill the open spaces on the side of the frame. We wanted to cutout the Batman symbol on one side and Lightning McQueen on the other side. This would fall into the aesthetics category and Nathan said that he would have enjoyed it if we had made it happen.

CHAPTER 6: DESIGN VERIFICATION PLAN (TESTING)

The priority of the test phases was to evaluate the prototypes we produced in the manufacturing phases. This was accomplished by completing a series of tests and inspections identifying how well we met the project's requirements and specifications (discussed in Objective & Specification Development section of this report). The results were presented to the Coopers at the same time we asked for their feedback on the design. Testing was completed on the existing Standing Dani (baseline testing) and on the test rig (both will be generally referred to as a prototype in this chapter).

TEST DESCRIPTIONS

PREPARATION

Before testing could begin, we needed to prepare appropriately. The following tasks were completed:

- Manufacture the prototype
- Create a Design Verification Plan & Report (DVP&R) Template
- Complete baseline tests, or benchmarks, on the existing Standing Dani™

SUPPLIES

The supplies required for all the tests are listed below. It should be noted that not every one of the above items is required for each test.

- Fully-assembled prototype and/or existing Standing Dani™
- 40lb. Bag of sand with covered bucket for holding the sand
- DVP&R test sheet
- Tape measure (minimum 12 feet)
- Weight scale
- Hand Truck
- Bill of materials (BOM)
- Arduino© controller
- Accelerometers
- Magnet & magnetic sensor
- Double-sided tape, zip ties, rubber bands, and scissors
- Two 4' x 4', 1/2" plywood sheets
- Computer for accelerometer analysis

FIGURE 52. TEST RIG.

SYSTEM GEOMETRY TEST

The objective of this test was to test out specifications related to the major dimensions of the system.

SCHEMATIC OF TEST SETUP

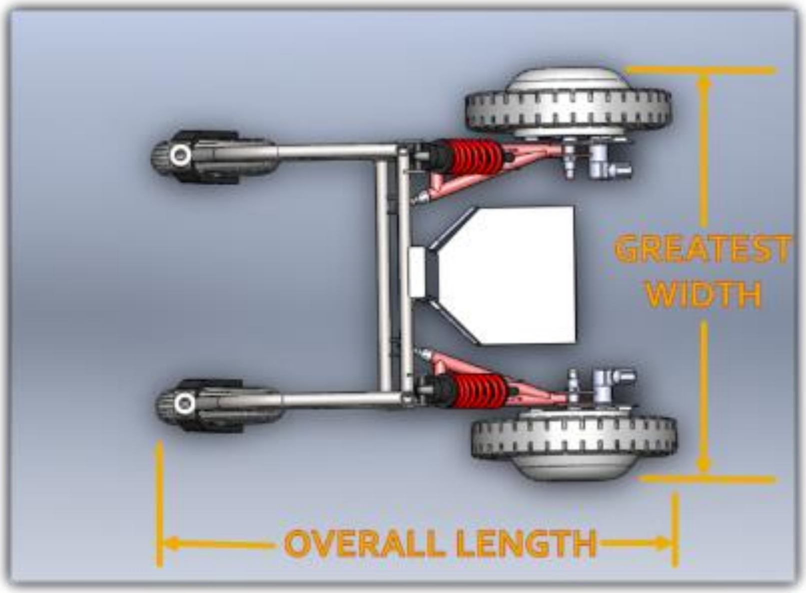


FIGURE 53. TOP VIEW OF PROTOTYPE WITH OVERALL LENGTH AND GREATEST WIDTH DIMENSIONS LABELED.

FIGURE 54. FRONT VIEW OF EXISTING STANDING DANI WITH HEIGHT DIMENSION LABELED.

MEASUREMENT INFORMATION

The measurements taken in this test and the corresponding measurement priority, units, and uncertainties are:

1. Overall length in inches with a maximum uncertainty of ± 0.5 inches
2. Greatest width in inches with a maximum uncertainty of ± 0.5 inches
3. Height in inches with a maximum uncertainty of ± 0.5 inches

PROCEDURE

MEASURE THE OVERALL LENGTH

1. Using a tape measure, measure the longest distance from the front to the back of the prototype. Make sure the tape measure is parallel to the centerline of the vehicle.
2. Write down the overall length in inches and any comments on the DVP&R sheet.

MEASURE THE GREATEST WIDTH

1. The greatest width is likely the track width. The track width of a vehicle is defined as the measurement from outside of one tire to the outside of the other tire (Suspension & Handling Glossary, 2013).
2. Using a tape measure, measure from the outside of the right rear drive wheel to the outside of the left rear drive wheel. This is the widest point of the vehicle. Make sure the tape measure is parallel to the line created between the geometric centers of the two drive wheels.
3. Write down the greatest width in inches and any comments on the DVP&R sheet.

MEASURE THE HEIGHT

1. Using a tape measure, measure from the ground up to the highest point on the Standing Dani™. Do not include Nathan. Make sure the tape measure is perpendicular to the ground.
2. Write down the height in inches and any comments on the DVP&R sheet.

SAFETY INSPECTION

The objective of this test was to test out specifications related to the safety of Nathan and anyone around him during use of the system.

PROCEDURE

PINCH POINT INSPECTION

1. A pinch point is defined as a point in between moving and stationary parts of a machine where an individual's body part or body may be placed such that when the machine is operating the body part may become caught, leading to an injury (Pinch Point, 2013).
2. Examine the entire frame for pinch points. Look especially in areas like the trailing arm links where there are fasteners and movement is expected.
3. Write down the number of pinch points found and any comments on the DVP&R sheet.
4. Complete this inspection twice.

FIGURE 55. PINCH POINT SIGN. (MYSAFETYSIGN.COM, 2014)

SHARP EDGE INSPECTION

1. A sharp edge is defined as an edge that is able to cut or pierce something (Definition of Sharp, 2014).
2. Examine the entire frame for any sharp edges. Look especially in areas where joints and ends are as burrs may have been left behind in manufacturing.
3. Write down the number of sharp edges found and any comments on the DVP&R sheet.
4. Complete this inspection twice.

ELECTRICAL HAZARD INSPECTION

1. An electrical hazard is defined as a dangerous condition such that contact or equipment failure can result in electric shock, arc flash burn, thermal burn, or blast (Arc Flash Terms, 2014).
2. Examine the entire frame for any electrical hazards. Look especially at areas where insulated wires are attached and they may be subject to abrasion. Also, be sure to look at the controller and battery input & output areas.

FIGURE 56. ELECTRICAL HAZARD SIGN. (ANSI DANGER ELECTRICAL HAZARD SIGN, N.D.)

3. Write down the number of electrical hazards found and any comments on the DVP&R sheet.
4. Complete this inspection twice.

WEIGHT INSPECTION

The objective of this test was to test out the weight specification of the system. The weight scale in the Cal Poly ME Engines Lab may be used for this test. Another option was to use the method shown in Figure 57.

SCHEMATIC OF TEST SETUP

FIGURE 58. PICTURE OF WEIGHT SCALE BEING USED IN TESTS. (WEIGHT SCALES, 2014)

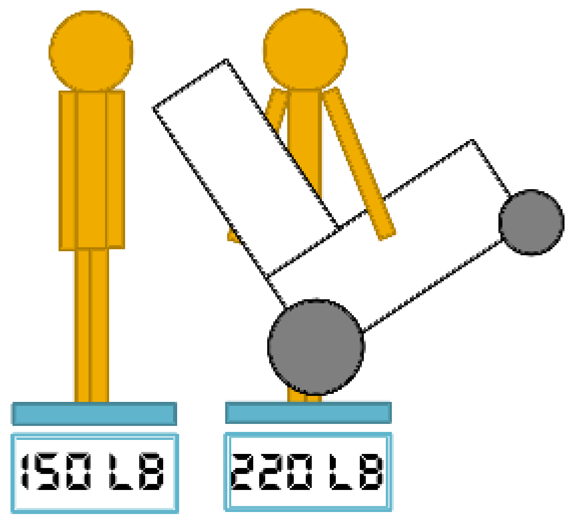


FIGURE 57. A METHOD OF MEASURING THE SYSTEM WEIGHT ON A SCALE.

MEASUREMENT INFORMATION

The measurement taken in this test is weight. It was measured in pounds with a maximum uncertainty of ± 1 pound.

PROCEDURE

1. Before weighing the system, make sure Nathan is not in the Standing Dani™ and the battery & controller are removed.
2. Zero/tare the weight scale.
3. Weigh the entire frame without Nathan, the battery, or the controller.
4. Write down the weight and any comments on the DVP&R sheet.
5. Repeat steps 2 – 5 a total of three times.

STATIC TILTOVER TEST

The objective of this test was to test out the specifications related to the tilt over characteristics of the system. Before each component of this test, be sure to set up the incline device used for measuring the device.

SCHEMATIC OF TEST SETUP

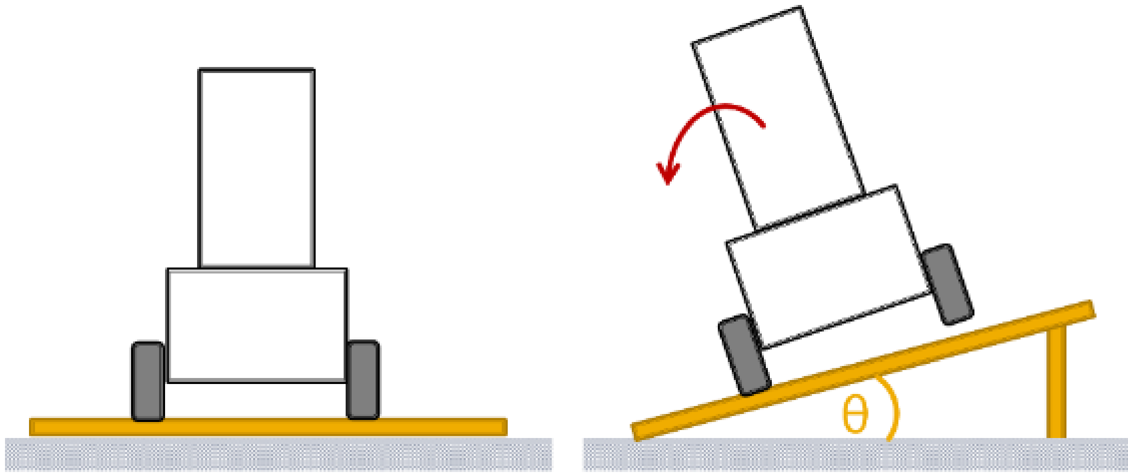


FIGURE 59. SCHEMATIC VIEW OF LATERAL TILTOVER TEST.

In Figure 60, the angle θ represents the lateral tilt over angle that is being tested for. This is a view of the rear/front of the prototype.

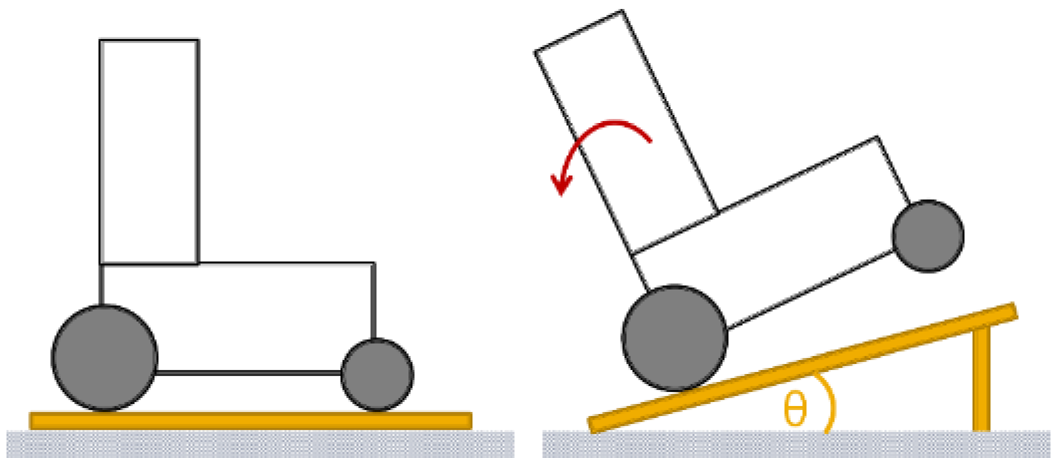


FIGURE 60. SCHEMATIC VIEW OF LONGITUDINAL TILTOVER TEST.

In Figure 59, the angle θ represents the longitudinal tilt over angle that is being tested for. This is a view of the side of the prototype.

MEASUREMENT INFORMATION

The measurements taken in this test and the corresponding measurement priority, units, and uncertainties are:

1. Lateral tiltover angle in degrees with a maximum uncertainty of ± 3 degrees
2. Longitudinal tiltover angle in degrees with a maximum uncertainty of ± 3 degrees

PROCEDURE

LATERAL TILTOVER ANGLE

1. A vehicle's tiltover angle is defined as the angle at which the vehicle will tip over onto its side or roof due to gravitational forces. The lateral tiltover angle specifically deals with roll-axis characteristics of the vehicle (Rollover, 2014).
2. Put the system on the incline device. The system should be complete and functional, but Nathan should be replaced with a representative weight for safety reasons. The system's roll axis should be parallel to the inclined surface pivot axis.
3. Now assign three people to each of the following responsibilities.
    a. Making sure that the inclined surface is raised and does not slide relative to the ground.
    b. Making sure that when the Standing Dani™ starts to tip, it is stopped. Also, responsible for making sure the Standing Dani™ stays stationary during test.
    c. Responsible for measuring the critical angle.
4. Person A should incrementally (or continuously) raise the surface, while Person B ensures that the system is kept still.
5. When the system starts to tip, the critical angle has been reached. Person A should stop raising the surface. Person B should stop the Standing Dani™ from tipping entirely.
6. Person C should write down the angle and any comments on the DVP&R sheet (see Figure 62).
7. Repeat steps 3 – 6 a total of three times.

FIGURE 61. FRANKIE COMPLETING THE TILTOVER TEST WITH CHRIS DALEY.

LONGITUDINAL TILTOVER ANGLE

1. A vehicle's tiltover angle is defined as the angle at which the vehicle will tip over onto its side or roof due to gravitational forces. The longitudinal tiltover angle specifically deals with pitch-axis characteristics of the vehicle (Rollover, 2014).
2. Put the system on the incline device. The system should be complete and functional, but Nathan should be replaced with a representative weight for safety reasons. The system's roll axis should be perpendicular to the inclined surface pivot axis with the system facing up the slope.
3. Now assign three people to each of the following responsibilities.
    a. Making sure that the inclined surface is raised and does not slide relative to the ground.
    b. Making sure that when the Standing Dani™ starts to tip, it is stopped. Also, responsible for making sure the Standing Dani™ stays stationary during test.
    c. Responsible for measuring the critical angle.
4. Person A should incrementally (or continuously) raise the surface, while Person B ensures that the system is kept still.

FIGURE 62. FRANKIE MEASURING THE TILTOVER HEIGHT.

5. When the system starts to tip, the critical angle has been reached. Person A should stop raising the surface. Person B should stop the Standing Dani™ from tipping entirely.
6. Person C should write down the angle and any comments on the DVP&R sheet.
7. Repeat steps 3 – 6 a total of three times.

BILL OF MATERIALS INSPECTION

The objective of this test was to test out the specifications related to the Bill of Materials (BOM), specifically the percentage of the off-the-shelf components used and the total cost of the system. The BOM will be required to complete this test. After looking at our bill of materials, we can break the system up into components:

- Frame
- Drive Wheels
- Front Casters
- Mounting Hardware
- Center Column
- Battery

Looking at this list, all of the components are considered off the shelf except for the frame. We only really anticipate failure for the mounting hardware so we aren't too worried about having the Coopers able to repair and maintain the device. We will provide them with a list of our vendors so that they could easily acquire all of the necessary parts. Putting into consideration the amount of each material, our off the shelf percentage of parts was found to be about 84%.

PROCEDURE

OFF-THE-SHELF COMPONENTS

1. Off-the shelf components are defined as parts that can be purchased and installed with basic tools and without any required modifications, including, but not limited to, machining or welding.
2. Count up the number of off-the shelf components used to build the system. This count should include everything that is a part of the system when Nathan operates it.
3. Count up the total number of parts used to build the system. This count should include everything that is a part of the system when Nathan operates it.
4. Divide the number from step 1 by the number in step 2 and use this as the test result.
5. Write down the result and any comments on the DVP&R sheet.

SYSTEM COST

1. Examine the BOM and ensure that includes all components on the prototype.
2. Calculate the total cost of the system.
3. Write down the total cost and any comments on the DVP&R sheet.

DYNAMIC SUSPENSION TEST

The objective of this test was to test out the specifications related to the comfort level of Nathan during operation as well as the accelerations that he experiences when he goes over a bump. This was accomplished by using a test setup including accelerometers. This is the most complex test that we will be completing.

ACCELEROMETER EXPLANATION

An accelerometer – a common electronic device that measures accelerations – will measure the "g-force" that is transmitted from the ground to the frame where Nathan will be positioned. G-force is simply a measurement of acceleration in terms of gravity. A g-force of 1.0 is what we experience standing still on planet Earth. In a plane during takeoff or a steep turn, we may experience higher g-forces, which is what causes us to feel like we are heavier. The job of the suspension in our case is to lower this value as much as possible. The lower the g-force, the smoother the ride will be for Nathan.

An accelerometer test setup was developed to evaluate the performance of our future suspension designs and to evaluate the current Standing Dani™. We used the test setup to find a number that will tell us how well the suspension works. We mounted the accelerometers to the Standing Dani™ and drove it over a simulated terrain environment. The simulated terrain was plywood of various thicknesses to simulate an environment like the pier in Pismo Beach. Of course, we did not want to subject Nathan to a situation which we already know is potentially harmful to him, so we used a weight to simulate him using the device.

SCHEMATIC OF TEST SETUP

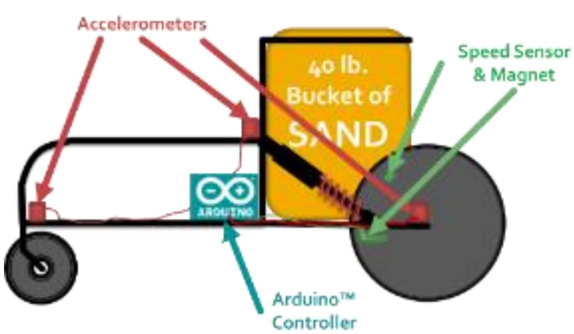


FIGURE 63. ACCELEROMETER TEST SETUP ON PROTOTYPE.

FIGURE 64. ATTACHING ACCELEROMETERS FOR THE TEST.

MEASUREMENT INFORMATION

The measurements taken in this test and the corresponding measurement priority, units, and uncertainties are:

1. Acceleration in g's with a maximum uncertainty of ± 0.1 g
2. Velocity in mph with a maximum uncertainty of ± 0.5 mph

PROCEDURE

INITIAL SETUP

1. Mount the accelerometers onto the test setup as shown in the diagram. This can be done using double-sided tape, zip ties, and/or rubber bands. If there are less than three accelerometers, mount the accelerometers in the following order: above caster, on trailing arm, and then on the top of the frame.
2. Mount the magnetic sensor onto the test setup as shown in the diagram. This can be done using double-sided tape, zip ties, and/or rubber bands.
3. Mount the magnet onto the test setup as shown in the diagram. This can be done using double-sided tape.
4. Connect the sensors to the Arduino Controller.
5. Fill a bucket with roughly 40 lbs of sand and place it in test fixture.
   NOTE: We do not want to subject Nathan to a situation that we know is potentially harmful to him, hence the sand is used to simulate his weight.

FLAT GROUND TEST

1. Find flat ground (i.e. carpet or hardwood).
2. Turn on the sensors and take measurements at rest for 2 seconds.
3. Now assign three people to each of the following responsibilities.
   a. Making sure that the path is clear for the test setup.
   b. Operate the sensors and data logging system.
   c. Operate the test setup and direct it over 12' of flat ground. *NOTE: The test assumes CONSTANT SPEED.*
4. Person A should measure out the test area and ensure that the test area is clear of any obstructions.
5. Person A should walk to the end of the test region.
6. Person B should turn on the sensor setup.
7. After two seconds, person B should indicate to person C to initiate the test.
8. After the test setup has passed person A, person C should allow the test setup to come to rest.
9. Take measurements at rest for 2 seconds and then person B should turn off data logging.
10. Repeat steps 2 – 9 three times.
11. After test, download accelerometer & magnetic sensor results to computer and check for any errors.
12. Write down the total reduction in acceleration after the results have been compared to the baseline results. Write down any comments on the DVP&R sheet as well.

BUMP TEST

1. Lay down one 4'x4', 1/2" sheet of plywood.
2. Now assign three people to each of the following responsibilities.
   a. Making sure that the path is clear for the test setup and stand on one side of the plywood.
   b. Operate the sensors & data logging system and stand on the other side of the plywood.

    c. Operate the test setup and direct it over 12’ of total ground (including the 4’ of the plywood). *NOTE: The test assumes CONSTANT SPEED.*
3. Person A should measure out the test area and ensure that the test area is clear of any obstructions. At the end of the measured test section, put a marker.
4. Person B should turn on the sensor setup.
5. Persons A & B should take their positions securing the plywood sheets. The sides of the plywood sheets should be parallel or perpendicular to the travel path of the test setup. The closest side should be 4’ from the test setup start.
6. After two seconds, person B should indicate to person C to initiate the test.
7. After the test setup has passed the marker at the end of test section, person C should allow the test setup to come to rest.
8. Take measurements at rest for 2 seconds and then person B should turn off data logging.
9. Repeat steps 3 – 8 three times.
10. After test, download accelerometer & magnetic sensor results to computer and check for any errors.
11. Write down the total reduction in acceleration after the results have been compared to the baseline results. Write down any comments on the DVP&R sheet as well.

FRAME ATTACHMENT INSPECTION

The objective of this test is to test out the requirement related to using the existing body support that Nathan uses on his Standing Dani™. This test was only be completed on the prototype as the test rig will not have an attachment point.

SCHEMATIC OF TEST SETUP

FIGURE 65. LOCATION OF ATTACHMENT POINT ON STANDING DANI.

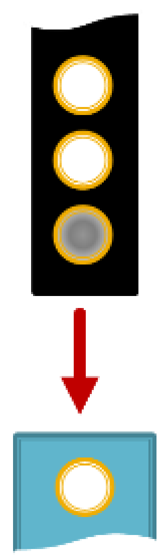


FIGURE 66. DIAGRAM ON HOW TO INSERT BODY SUPPORT INTO PROTOTYPE FRAME.

PROCEDURE

1. Take the upper part of the Standing Dani™ frame off of the existing Standing Dani™ device. Be careful as the release point is a pinch point.
2. Using the diagram above, attach the body support to the new frame. This task may require two people to complete
3. Write down whether the attachment was successful and any comments on the DVP&R sheet.

CAR TRANSPORT SIMULATION

The objective of this test was to test out the specifications related to lifting and transporting the prototype. This test requires the Coopers to complete.

SCHEMATIC OF TEST SETUP

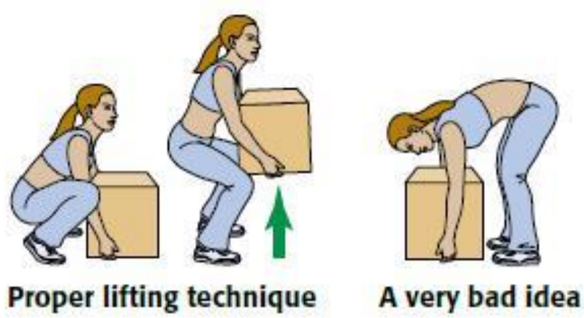


FIGURE 67. PROPER LIFTING TECHNIQUE. (SCIENCE KNOWLEDGE, 2010)

FIGURE 68. 2011 SUBARU FORESTER, THE COOPERS' CAR. (2011 SUBARU FORESTER, 2010)

PROCEDURE

EASY TO LIFT BY ONE PERSON

1. Set the prototype in an open area. Nathan should not be in it.
2. Have Bob lift it. It should be expressed to him that he should not strain herself and to use proper lifting technique.
3. After lifting it, have Bob set the prototype down and express how easy it was to lift the prototype.
4. Write down the results and any comments Bob has on the DVP&R sheet.

TRANSPORTABILITY

1. Set the prototype in an open area. Nathan should not be in it.
2. Have Amy or Bob lift the prototype. It should be expressed to them that they should not strain themselves and to use proper lifting technique.
3. After lifting it, have Amy or Bob put the prototype in their car.
4. After completing the task, have them express how easy it was to fit the prototype in the car.

5. Write down the results and any comments Amy or Bob has on the DVP&R sheet.

OPERATION FEEDBACK TEST

The objective of this test was to test out the specifications related to ease of operation and turning radius. This test required the Coopers to complete. It was important for Nathan to try operate the prototype like he would normally operate his Standing Dani™. This test was trying to figure out if the new prototype design affects operation in any way.

SCHEMATIC OF TEST SETUP

FIGURE 70. PHOTO COLLAGE OF NATHAN IN MOTION.

FIGURE 69. DIAGRAM DEFINING TURNING RADIUS FOR A VEHICLE. (WHAT IS TURNING RADIUS?, 2012)

PROCEDURE

EASE OF OPERATION

1. Make sure the prototype is entirely assembled and ready for Nathan to use.
2. Once Nathan is in the prototype, explain to him that he should just drive as normally as possible.
3. Once he has driven around for around 30 seconds, have him rate how easy it was to operate the new design. He should use a scale of 1 to 5, where 1 indicates that the prototype is very hard to control and 5 indicates that the prototype is very easy to control.
4. Write down the results and any comments Nathan has on the DVP&R sheet.

TURNING RADIUS

1. Make sure the prototype is entirely assembled and ready for Nathan to use.
2. Once Nathan is in the prototype, explain to him that he will attempt to make as tight of a turning radius as possible.
3. After he has completed one or two turns, have him rate how easy it was to operate the new design. He should use a scale of 1 to 5, where 1 indicates that the prototype is very hard to turn and 5 indicates that the prototype is very easy to turn.
4. Write down the results and any comments Nathan has on the DVP&R sheet.

COOPER APPROVAL

The objective of this test was to test out the specifications related to aesthetics and to get the prototype design approved by the Coopers. This test required the Coopers to complete. As the clients of the project, the Coopers' opinions on aesthetics and safety were crucial to the success of this project. The feedback that they gave us was taken into consideration when we updated our design.

PROCEDURE

AESTHETICICALLY PLEASING

1. Ask Coopers to rate the look of the Standing Dani™ on a scale of 1 to 10, where 1 represents the opinion of "please say that is going to look different" and 10 represents the opinion of "it could not be any better looking".
2. Write down the results and any comments the Coopers have on the DVP&R sheet.

SAFETY CONCERNS

1. Ask Coopers if they have any concerns regarding safety of the device.
2. Write down the results and any comments the Coopers have on the DVP&R sheet.

OTHER CONCERNS

1. Ask Coopers if they have any other concerns.
2. Write down the results and any comments the Coopers have on the DVP&R sheet.

DETAILED RESULTS

All of the testing results were tabulated and are presented in this report. Most of the data is listed on the following pages. However, only the most significant parts of the accelerometer data (Dynamic Suspension Test) are presented in this section given the amount of data collected. Each Design Verification Plan & Report (DVP&R) is provided in its respective section. Samples of the remainder of the collected accelerometer test data can be found in Appendix I – Supplementary Testing Information.

BASELINE TESTING RESULTS FOR THE STANDING DANI

TABLE 7. DVP&R FOR BASELINE TESTING.

Team Nathan Design Verification Plan & Report (DVP&R) - Baseline Test													
Report Date		April 16, 2014	Sponsor	The Cooper Family & ME Department				Component/Assembly		Team Nathan Suspension	REPORTING ENGINEER:	Frankie Wiggins	
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED Quantity	SAMPLES TESTED Type	TIMING Start date	TIMING Finish date	Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	WHEELBASE	GEOMETRY MEASUREMENT	≤ 27 INCHES	FRANKIE	DV	1	B	3/6/14	3/6/14	18"	1	0	29" Total length
2	TRACK WIDTH	GEOMETRY MEASUREMENT	≤ 19 INCHES	FRANKIE	DV	1	B	3/6/14	3/6/14	25"	0	1	Need to change criteria back to what it was
3	HEIGHT WITHOUT NATHAN	GEOMETRY MEASUREMENT	≤ 47 INCHES	FRANKIE	DV	1	B	3/6/14	3/6/14	46"	1	0	
4	NUMBER OF PINCH POINTS - SAFETY	SAFETY INSPECTION	0 PINCH POINTS	FRANKIE	DV	2	B	3/6/14	3/6/14	5	0	2	Footrest, frog legs (x2), casters (x2), Just looked at the lower parts
5	NUMBER OF SHARP EDGES - SAFETY	SAFETY INSPECTION	0 SHARP EDGES	FRANKIE	DV	2	B	3/6/14	3/6/14	0	2	0	
6	NO. OF ELECTRICAL HAZARDS - SAFETY	SAFETY INSPECTION	0 ELECTRICAL HAZARDS	FRANKIE	DV	2	B	3/6/14	3/6/14	0	2	0	
7	WEIGHT WITHOUT NATHAN & BATTERY	WEIGHT SCALE	≤ 50 POUNDS	FRANKIE	DV	3	B	3/6/14	3/6/14	78.5 +/- 0.2 lbs	0	3	Note that this included the whole upper frame as well, the controller and battery weighed 19 lbs.
8	LATERAL ROLLOVER ANGLE	STATIC ROLLOVER TEST	≥ 25° ABOVE HORIZONTAL	FRANKIE	DV	3	B	4/16/14	4/16/14	32°	3	0	
9	LONGITUDINAL ROLLOVER ANGLE	STATIC ROLLOVER TEST	≥ 25° ABOVE HORIZONTAL	FRANKIE	DV	3	B	4/16/14	4/16/14	30°	3	0	
10	NUMBER OF OFF-THE-SHELF PARTS	REVIEW OF BILL OF MATERIALS	≥ 50% OF TOTAL PARTS	JUSTIN	DV	1	B	N/A	N/A	This was weird to try to look at. It was not actually tested. May want to consider how this is measured. Do you consider weighting or special scoring? i.e. Does the drivetrain components account for more of the percentage?			
11	COST OF SYSTEM	REVIEW OF BILL OF MATERIALS	≤ $3000	JUSTIN	DV	1	B	N/A	N/A	This specification is more concerned with budget. For this reason, doing a baseline test for this would be trivial.			
12	WATER RESISTANCE	SPRAY TEST	FUNCTIONS AFTER WATER CONTACT	FRANKIE	DV	3	B	N/A	N/A	This requirement is to be an addition to the exisiting setup. The Standing Dani™ would not be expected to succeed in this. For this reason, baseline testing was foregone.			
13	BEACH USE	AVILA BEACH OPERATION	ACHIEVE 50% MAX SPEED ON SAND	FRANKIE	DV	3	B	N/A	N/A	This requirement is to be an addition to the exisiting setup. The Standing Dani™ would not be expected to succeed in this. For this reason, baseline testing was foregone.			
14	UTILIZATION OF BODY SUPPORT	ATTACH FRAME TO EXISTING BODY SUPPORT	BODY SUPPORT UPPER ATTACHES	FRANKIE	DV	1	B	3/6/14	3/6/14	YES	1	0	
15	EASY TO LIFT BY ONE PERSON	CAR TRANSPORT SIMULATION	AMY CAN LIFT W/O STRAINING BODY	FRANKIE	DV	1	B	3/6/14	3/6/14	NO	0	1	Amy cannot lift it and it is unhealthy and awkward for Bob to lift it (though he does everyday)
16	TRANSPORTABILITY	CAR TRANSPORT SIMULATION	FITS IN COOPERS' SMALL SUV	FRANKIE	DV	1	B	3/6/14	3/6/14	3 out of 5	1	0	Fits in the car, but barely. Hard to get in (Bob).
17	EASE OF OPERATION BY NATHAN	OPERATION FEEDBACK FROM NATHAN	AS EASY TO USE AS STANDING DANI	FRANKIE	DV	1	B	3/6/14	3/6/14	5 out of 5	1	0	Nathan loves using it and it works well for him.
18	USER AWARENESS	OPERATION FEEDBACK FROM NATHAN	≥ 90° REAR FIELD OF VISION	FRANKIE	DV	1	B	N/A	N/A	This requirement is to be an addition to the exisiting setup. The Standing Dani™ would not be expected to succeed in this. For this reason, baseline testing was foregone.			
19	TURNING RADIUS	OPERATION FEEDBACK FROM NATHAN	≤ 3 FEET OR NATHAN SAYS YES	FRANKIE	DV	1	B	3/6/14	3/6/14	5 out of 5	1	0	Nathan can turn on a dime using the two independent wheels. Not expected to change.
20	TRANSMITTED G-FORCE TO NATHAN	DYNAMIC SUSPENSION TEST	≥ 50% REDUCTION OF EXISITNG G'S	FRANKIE	DV	3	B	4/16/14	4/16/14	0%	0	3	The spec is based off the baseline performance so it is expected to fail.
21	AESTHETICALLY PLEASING	COOPER APPROVAL	NATHAN SAYS YES	FRANKIE	DV	1	B	4/16/14	4/16/14	5 out of 5	1	0	Nathan thinks it's cool-looking and gets a lot of positive comments.
22	RANGE IMPROVEMENT	RANGE DATA COLLECTION	LASTS LONGER THAN 3 HOURS ON ONE CHARGE	FRANKIE	DV	5	B	N/A	N/A	This requirement is to be an addition to the exisiting setup. The Standing Dani™ would not be expected to succeed in this. For this reason, baseline testing was foregone.			

As shown in Table 7, there were a few areas that the Standing Dani did not meet the requirements and specifications of the project. The track width, pinch point, weight, and lift tests resulted in failures, but not for the right reasons necessarily. It actually indicated that we needed to change our specifications (given that the Coopers wanted the new design to be the same or better than the current device in all areas). Finally, it was simply impossible for the Standing Dani to pass test #20 (Dynamic Suspension Test) because it cannot outperform itself, by definition.

It is also worth noting that the baseline testing took place on two separate days. The first round occurred in March. The tests completed at that required less supplies. The second round occurred in the middle of April. These tests were more complex (i.e. the tiltover test versus the geometry measurement test.

We completed four baseline Dynamic Suspension Test trials and each of them took place in the same area (the Cooper's backyard & putting green). It is important to note that each of the trials represents a different scenario. Trial 1 represents Nathan getting used to the Accelerometer (he was driving around uncontrolled). Trial 2 was the first controlled test where he drove over the 1/8" plywood sheet. At this point, his speed controller was set to about 50% of maximum power. Trials 3 & 4 were identical to Trial 2, except the speed controller setting. The controller was set to 70% and 90% of maximum power for Trials 3 and 4, respectively.

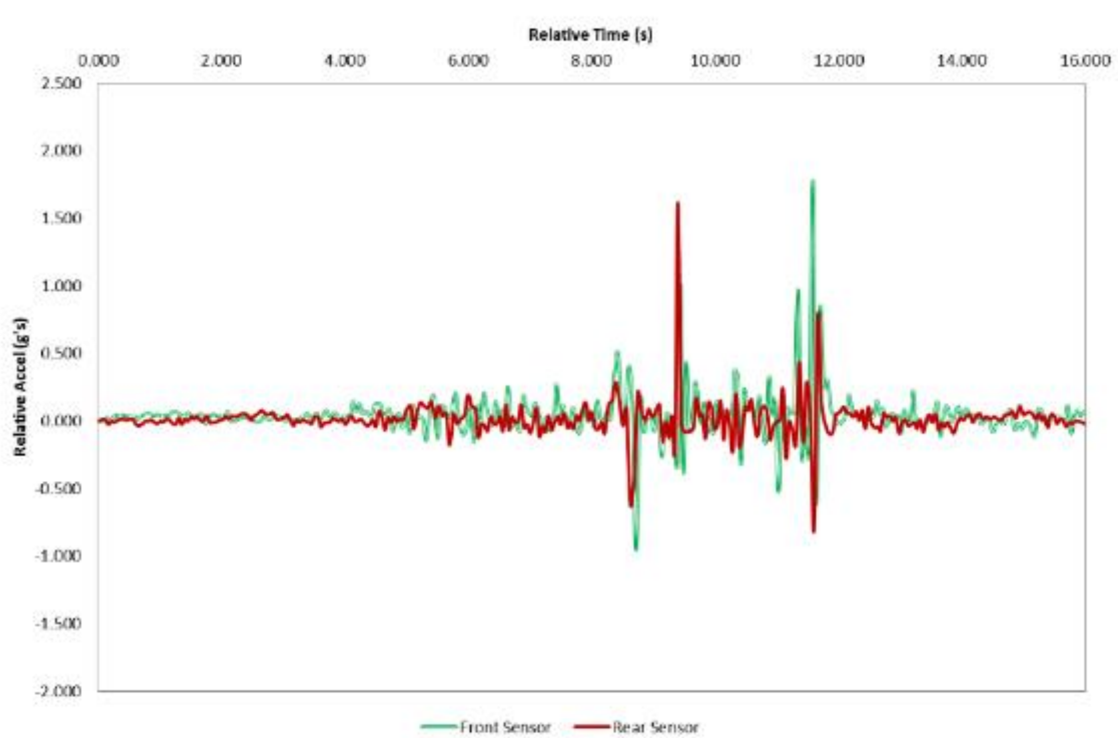


FIGURE 71. ACCELEROMETER OUTPUT FOR BASELINE DYNAMIC SUSPENSION TEST TRIAL 4.

The results from one of the trials is shown in Figure 71. The red, solid line represents the rear sensor output and the green, double line represents the front sensor. The disturbances between eight and twelve seconds represent Nathan going over the plywood sheet. The large spikes mark the beginning and end of the plywood sheet (or when the bump occurred). The maximum positive and negative accelerations for this trial were 1.776 & -0.952 g's, respectively, in the front and 1.616 & -0.808 g's, respectively, in the rear. This trial was used as a reference for the test rig testing results because, from observation, trial 4 represented the speed that Nathan generally drives the Standing Dani at.

Table 8 shows a summary of the maximum negative (-) and positive (+) accelerations[1] experienced by the Standing Dani during the Baseline Dynamic Suspension Testing.

TABLE 8. SUMMARY OF BASELINE DYNAMIC SUSPENSION TEST RESULTS.

Test Name	Front Sensor		Rear Sensor	
	Max (-) Accel. (g)	Max (+) Accel. (g)	Max (-) Accel. (g)	Max (+) Accel (g)
Baseline Test Trial 1	-1.272	1.096	-0.544	0.888
Baseline Test Trial 2	-0.704	0.576	-0.288	0.256
Baseline Test Trial 3	-1.376	1.136	-0.848	0.968
Baseline Test Trial 4	-0.952	1.776	-0.808	1.616

The graphs of the data represented in Table 8 can be found in Appendix I – Supplementary Testing Information along with samples of the raw and the fully manipulated data for baseline test trial 4.

TEST RIG RESULTS

The DVP&R for the test rig (Table 9, page 59) was important for three reasons. First, it proved that our suspension worked, but not well enough. Even though the best three of our six trials didn't pass our specification to reduce transmitted g-force by 50%, the test rig still performed really well. Second, it was a learning experience with regards to manufacturing and a reminder that everything that goes into building takes longer than one might expect. Finally, the test rig met most of the project's requirements and guidelines. It failed in a few areas, but succeeded in many areas and so we were confident with our design after testing. For example, we had too many sharp edges & it was difficult to maneuver. We did our best in the redesign to avoid these weak points (though there was still room for improvement at the end).

The results from one of the trials is shown in Figure 72 (page 60). The red, solid line represents the rear sensor output and the green, double line represents the front sensor. The disturbances between eight and ten seconds represent Nathan going over the plywood sheet. The large spikes mark the beginning and end of the plywood sheet (or when the bump occurred). The maximum positive and negative accelerations for this trial were 0.904 & -1.096 g's, respectively, in the front and 0.848 & -0.584 g's, respectively, in the rear. The maximum positive and negative accelerations changed by -49.1% & +15.1%, respectively, in the front and -47.5% & -27.7%, respectively, in the rear relative to baseline test trial 4. This trial marked one of the best performances of the test rig. Even then, transmitted g-force was not reduced in all areas.

Table 10 (page 60) shows a summary of each of the test rig's Dynamic Suspension Test results. Similar to Table 8, the table shows the maximum positive and negative accelerations measured (in g's). In addition,

[1] Negative acceleration represents downward vertical movement – and extension of the spring-shock assembly – and positive acceleration represents upward vertical movement – and compression of the spring-shock assembly.

it shows the percent difference between each number and the corresponding baseline test trial 4 value. There are two important patterns to notice in Table 10.

TABLE 9. DVP&R FOR TEST RIG.

Team Nathan Design Verification Plan & Report (DVP&R) - Test Phase 1													
Report Date		April 30, 2014	Sponsor	The Cooper Family & ME Department				Component/Assembly		Team Nathan Suspension	REPORTING ENGINEER:	Frankie Wiggins	
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED Quantity	SAMPLES TESTED Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	OVERALL LENGTH	GEOMETRY MEASUREMENT	≤ 29 INCHES	FRANKIE	DV	1	B	4/29/14	4/29/14	25"	1	0	
2	GREATEST WIDTH	GEOMETRY MEASUREMENT	≤ 25 INCHES	FRANKIE	DV	1	B	4/29/14	4/29/14	18.5"	1	0	
3	HEIGHT WITHOUT NATHAN	GEOMETRY MEASUREMENT	≤ 47 INCHES	FRANKIE	DV	1	B	4/29/14	4/29/14	17.5"	1	0	Measured to top of the battery; does not include top support, so it is expected to pass
4	NUMBER OF PINCH POINTS - SAFETY	SAFETY INSPECTION	≤ 10 PINCH POINTS	FRANKIE	DV	1	B	4/29/14	4/29/14	9	1	0	Wheels, springs, temporary seat
5	NUMBER OF SHARP EDGES - SAFETY	SAFETY INSPECTION	0 SHARP EDGES	FRANKIE	DV	1	B	4/29/14	4/29/14	≥ 10	0	1	Lots of sharp edges, but that was expected on test rig; it will be minimized in final iteration
6	NO. OF ELECTRICAL HAZARDS - SAFETY	SAFETY INSPECTION	0 ELECTRICAL HAZARDS	FRANKIE	DV	1	B	4/29/14	4/29/14	0	1	0	All wires insulated
7	WEIGHT WITHOUT NATHAN & BATTERY	WEIGHT SCALE	≤ 80 POUNDS	FRANKIE	DV	3	B	4/30/14	4/30/14	63.8 +/- 0.2 lbs	3	0	Includes a lot of excess weight from the seat & welds, but does include the battery, Nathan, or top support
8	LATERAL TILTOVER ANGLE	STATIC ROLLOVER TEST	≥ 25° ABOVE HORIZONTAL	FRANKIE	DV	1	B	4/30/14	4/30/14	> 27°	1	0	Assistant: Chris Daley (Frankie's roommate) "dangerously risked his life to better Nathan's life"
9	LONGITUDINAL TILTOVER ANGLE	STATIC ROLLOVER TEST	≥ 25° ABOVE HORIZONTAL	FRANKIE	DV	1	B	4/30/14	4/30/14	> 27°	1	0	Assistant: Chris Daley (Frankie's roommate) "dangerously risked his life to better Nathan's life"
10	NUMBER OF OFF-THE-SHELF PARTS	REVIEW OF BILL OF MATERIALS	≥ 50% OF TOTAL PARTS	JUSTIN	DV	1	B	4/29/14	4/29/14	≥ 75%	1	0	The frame was machined, but otherwise everything was off the shelf
11	COST OF SYSTEM	REVIEW OF BILL OF MATERIALS	≤ $2500	JUSTIN	DV	1	B	4/29/14	4/29/14	≤ $950	1	0	This is total money spent so far (may include extra costs)
12	WATER RESISTANCE	SPRAY TEST	FUNCTIONS AFTER WATER CONTACT	FRANKIE	DV	3	B	N/A	N/A	The current design is not concerned with the water resistance specification as it is low priority. This may be tested for later, but will not be tested now.			
13	BEACH USE	AVILA BEACH OPERATION	ACHIEVE 50% MAX SPEED ON SAND	FRANKIE	DV	3	B	N/A	N/A	The current design is not concerned with the beach use specification as it is low priority. This may be tested for later, but will not be tested now.			
14	UTILIZATION OF BODY SUPPORT	ATTACH FRAME TO EXISTING BODY SUPPORT	BODY SUPPORT UPPER ATTACHES	FRANKIE	DV	1	B	N/A	N/A	The test rig is not intended to be used with Nathan's body support, so this test was not completed.			
15	EASY TO LIFT BY ONE PERSON	CART TRANSPORT SIMULATION	BOB CAN LIFT W/O STRAINING BODY	FRANKIE	DV	1	B	4/29/14	4/29/14	Two people needed	0	1	Very heavy; difficult to maneuver
16	TRANSPORTABILITY	CART TRANSPORT SIMULATION	FITS IN COOPERS' SMALL SUV	FRANKIE	DV	1	B	4/29/14	4/29/14	Fits in back of small SUV	1	0	Fits easily in the trunk of a car
17	EASE OF OPERATION BY NATHAN	OPERATION FEEDBACK FROM NATHAN	AS EASY TO USE AS STANDING DANI	FRANKIE	DV	1	B	N/A	N/A	The test rig is not intended to be used by Nathan, so this test was not completed.			
18	USER AWARENESS	OPERATION FEEDBACK FROM NATHAN	≥ 90° REAR FIELD OF VISION	FRANKIE	DV	1	B	N/A	N/A	The test rig is focused on suspension and had no added user awareness benefit. For this reason this specification was not tested.			
19	TURNING RADIUS	OPERATION FEEDBACK FROM NATHAN	≤ 3 FEET OR NATHAN SAYS YES	FRANKIE	DV	1	B	N/A	N/A	The test rig is not intended to be used by Nathan, so this test was not completed.			
20	TRANSMITTED G-FORCE TO NATHAN	DYNAMIC SUSPENSION TEST	≥ 50% REDUCTION OF EXISITNG G'S OVER BUMP(S)	FRANKIE	DV	3	B	4/16/14	4/16/14	See Table in Report	0	3	See final report for further explanation. Significant reduction was experienced in some areas.
21	AESTHETICALLY PLEASING	COOPER APPROVAL	NATHAN SAYS YES	FRANKIE	DV	1	B	4/16/14	4/16/14	Yes	1	0	They loved it, can't wait to see the final product
22	RANGE IMPROVEMENT	RANGE DATA COLLECTION	LASTS LONGER THAN 3 HOURS ON ONE CHARGE	FRANKIE	DV	5	B	N/A	N/A	The current design is not concerned with the range improvement specification as it is low priority. This may be tested for later, but will not be tested now.			

The suspension responded better in the rear versus the front. The average percent change for negative maximum acceleration was -7.4% versus -4.3% (53% difference between the front to the rear). The average percent change for positive maximum acceleration was -42.3% versus -27.5% (43% difference between the front to the rear). This was somewhat expected considering the trailing arm suspension is located in the rear.

Furthermore, the suspension reduced the maximum positive acceleration more than it reduced the maximum negative acceleration. The average percent change was -4.3% versus -27.5% for the front sensor (145% difference between the negative and positive maximum acceleration). The average percent change was -7.4% versus -42.3% for the rear sensor (140% difference between the negative and positive maximum acceleration). This may have to do with the type of shock used.

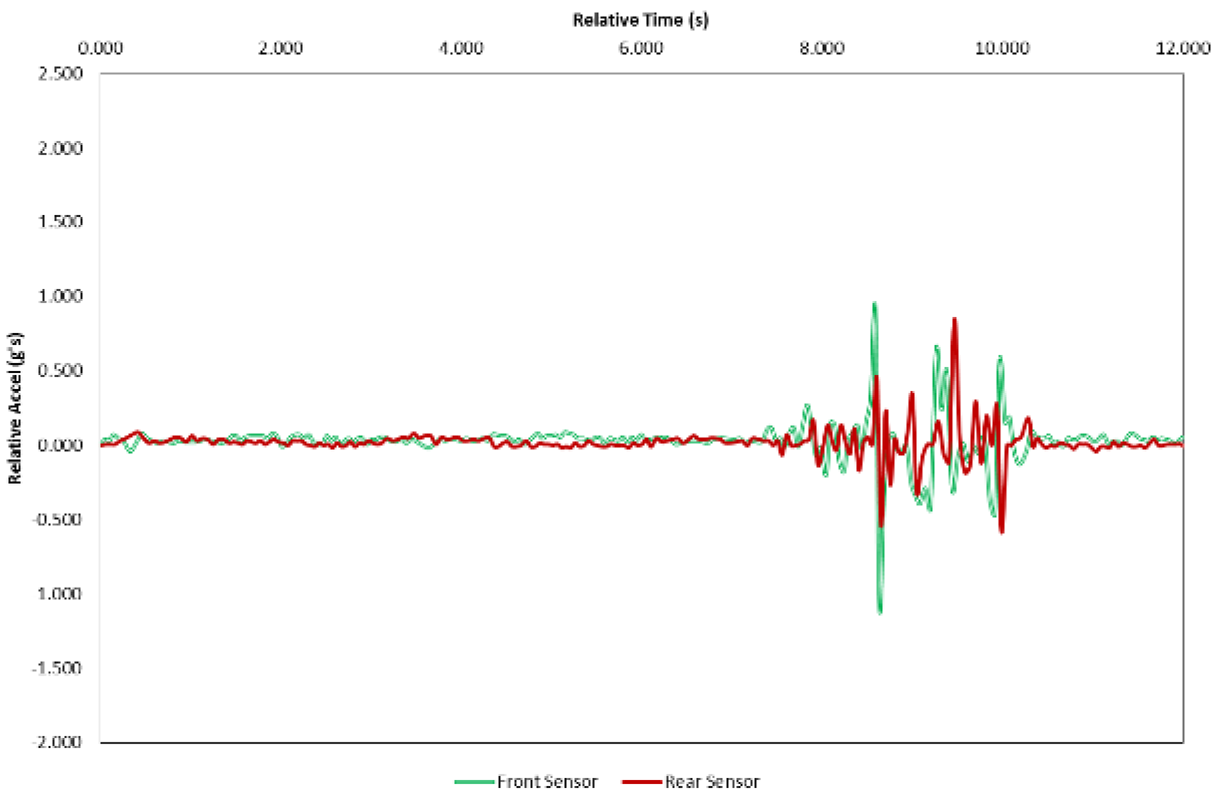


FIGURE 72. ACCELEROMETER OUTPUT FOR TEST RIG DYNAMIC SUSPENSION TEST TRIAL 6.

TABLE 10. SUMMARY OF TEST RIG DYNAMIC SUSPENSION TEST RESULTS.

Test Name	Front Sensor				Rear Sensor			
	Max (-) Accel. (g)	% Change[2]	Max (+) Accel. (g)	% Change	Max (-) Accel. (g)	% Change	Max (+) Accel. (g)	% Change
Test Rig Trial 1	-0.512	-46.2%	1.064	-40.1%	-0.832	3.0%	1.112	-31.2%
Test Rig Trial 2	-1.168	22.7%	0.648	-63.5%	-0.808	0.0%	0.976	-39.6%
Test Rig Trial 3	-0.792	-16.8%	1.520	-14.4%	-0.424	-47.5%	0.656	-59.4%
Test Rig Trial 4	-0.712	-25.2%	1.632	-8.1%	-0.936	15.8%	1.256	-22.3%
Test Rig Trial 5	-1.184	24.4%	1.960	10.4%	-0.904	11.9%	0.744	-54.0%
Test Rig Trial 6	-1.096	15.1%	0.904	-49.1%	-0.584	-27.7%	0.848	-47.5%
Average	***-0.911***	***-4.3%***	***1.288***	***-27.5%***	***-0.748***	***-7.4%***	***0.932***	***-42.3%***

The graphs of the data represented in Table 10 can be found in Appendix I – Supplementary Testing Information along with samples of the raw and the fully manipulated data for test rig trial 6.

[2] The percent change (% Change) is a measure of the acceleration reduction relative to Baseline Test Trial 4. A negative number indicates that there was a decrease in a transfer of acceleration. The equation used was -1*(Baseline Test Trial 4 – Test Rig Trial 'i')/ Baseline Test Trial 4.

COMMENTS ABOUT TESTING PROCEDURES & RESULTS

In presenting our results, it is important to note that were some distinct differences between the testing environments for baseline testing and the test rig testing. The differences are summarized in Table 11 below.

The spring rate differences are the biggest area of concern for us in Table 11 below. This is because the test rig accelerometer data showed a minimal reduction in transfer of g-force to Nathan, but we believe that – with the new springs – he will experience a much more comfortable ride, even with the different weights of the user.

TABLE 11. DIFFERENCES IN TESTING PROCEDURES.

Difference	Baseline Test	Test Rig
Spring Rates	Not applicable as the Standing Dani has no suspension.	The springs used had a stiffness of 300 lbf/in (our stiffest springs). We ended up testing with springs that had a stiffness of 94 lbf/in later, but no data was taken. A significantly less stiff ride resulted.
Users	Nathan rode the Standing Dani.	Alex drove the Test Rig instead of a representative weight. Alex is three to four times heavier than Nathan, but the body support weight was missing. The resulting difference in weight is unknown.
Testing Surfaces	Nathan rode the Standing Dani on his parent's putting green (made of artificial turf) and then drove over one full sheet of 1/8" plywood.	Alex drove the test rig over his garage's carpet and then over a sheet of plywood of similar thickness.

One other area that testing might have missed has to do with his body support. We measured the transfer of force through accelerometers mounted on the base of the frame, but some vibration made its way to Nathan due to the looseness of his body support attachment. Nathan may feel less (hopefully) or more vibration as a result of our new attachment design.

Finally, it is important to note that the Final Design was not tested. We completed the manufacturing of the final design with little time to test. We were able to do to simple testing to make sure it would work, but we did not do tests that were comparable to what was done on the Standing Dani and the Test Rig.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

In this report, we have presented our final design for increasing the comfort level of Nathan's Standing Dani™. Our methods of idea generation resulted in four different concepts. We then used a decision matrix comprised of project requirements to decide which concept was the best option. Our final concept will be the Rear Trailing Arm design. It features a trailing arm suspension for the rear wheels and larger diameter, pneumatic tires for the front casters. We proved that this design improves the ride comfort of the Standing Dani™. The first iteration of our design was built and helped us determine what worked & what didn't work with our design. It was tested and compared to the baseline testing of the Standing Dani™. We made a few design changes and built our final design. We ensured the safety of our device, got it painted and attached Nathan's old center column to our new design.

We do have some recommendations that can be made to our design. We weren't able to address our secondary projects that included increase the range, increase user awareness, and make the design waterproof. The Coopers would love it if these issues were resolved. We would also recommend trying and making the design more aesthetically pleasing by adding side panels that could be easily removed. These side panels could be made out of metal or polycarbonate and would feature things that Nathan enjoys (Batman, Lightning McQueen, and Minecraft). The panels could be interchangeable so that Nathan could swap them out when he felt like it. Some other things that Nathan said would be cool would be to add lights to it and possibly add an iPod/Speaker combo so that Nathan could listen to his favorite music while he rides along.

We largely achieved our objectives for this project and have developed a successful suspension design. Overall, we are excited with the product we are giving to the Coopers and hope that they are able to put it to good use.

FIGURE 73. FRANKIE, NATHAN, JUSTIN, ALEX AT DESIGN EXPO

WORKS CITED

(2010). Retrieved from Science Knowledge: http://4.bp.blogspot.com/_xu83mnX15Po/TCjDeW4YVJI/AAAAAAAAAMo/EEUSlPReemA/s320/Lifting+posture.JPG

2011 Subaru Forester. (2010, September 24). Retrieved from TopSpeed.com: http://pictures.topspeed.com/IMG/crop/201007/2011-subaru-forester_600x0w.jpg

(2014). Retrieved from mysafetysign.com: http://www.mysafetysign.com/img/lg/S/Pinch-Points-Watch-Danger-Sign-S-2877.gif

AbleData. (n.d.). *GO-BOT*. Retrieved October 5, 2013, from http://www.abledata.com/abledata.cfm?pageid=113583

ANSI Danger Electrical Hazard Sign. (n.d.). Retrieved from inkace.com: http://www.inkace.com/media/catalog/product/cache/1/image/9df78eab33525d08d6e5fb8d27136e95/d/a/dangh087_electrical_hazard.jpg

Arc Flash Terms. (2014). Retrieved from Galco.com: http://www.galco.com/circuit/arc_flash_terms.htm

Budynas, R., Nisbett, K., & Shigley, J. E. (n.d.). *Shigley's Mechanical Engineering Design* (9th ed.). McGraw-Hill Education.

Cooper, A. (2013, November 15). Feedback during a Phone Conversation. (F. Wiggins, Interviewer)

Cooper, N., Cooper, A., & Cooper, B. (2013, October 24). Background Research regarding Standing Dani. (F. Wiggins, A. Seitz, & J. Bautista, Interviewers)

Cummings, G., Kreidle, B., Lee, R., & Steen, C. (2011, December 6). Senior Design Report: Strider. (S. Harding, Ed.) San Luis Obispo, CA, United States: Cal Poly San Luis Obispo (Digital Commons). Retrieved from http://digitalcommons.calpoly.edu/mesp/132/

Davol, D. (2013, October 23). Background Research regarding Standing Dani & ME Department's Involvement. (F. Wiggins, A. Seitz, & J. Bautista, Interviewers)

Definition of Sharp. (2014, March 3). Retrieved from Google: https://www.google.com/search?q=sharp+edge&oq=sharp+edge&aqs=chrome..69i57j0l5.2480j0j4&sourceid=chrome&espv=2&es_sm=122&ie=UTF-8#q=define:+sharp

Deflection of Tire. (n.d.). Retrieved December 5, 2013, from neomatix.com: http://neomatix.com/wp-content/uploads/2013/07/deflaction.jpg

Direct Industry. (n.d.). Retrieved from http://img.directindustry.com/images_di/photo-g/manual-deburring-tools-countersinks-11972-2699869.jpg

Families of SMA. (2013, October 5). *Understanding Spinal Muscular Atrophy*. Retrieved from http://www.fsma.org/FSMACommunity/UnderstandingSMA/

FOX Factory. (n.d.). *Float CTD*. Retrieved December 5, 2013, from http://www.ridefox.com/product.php?m=bike&t=shocks&p=99106&ref=filter

Grabianowski, E. (2007, May 10). *How the Tweel Airless Tire Works*. Retrieved November 20, 2013, from How Stuff Works: http://auto.howstuffworks.com/tweel-airless-tire2.htm

Harbor Freight. (n.d.). Retrieved from http://www.harborfreight.com/media/catalog/product/cache/1/image/9df78eab33525d08d6e5fb8d27136e95/i/m/image_21484.jpg

Kettering University. (n.d.). *Getting Kids on Their Feet*. Retrieved October 5, 2013, from https://www.kettering.edu/news/getting-kids-their-feet

Knuckle Buster Inc. (n.d.). Retrieved from http://www.knucklebusterinc.com/features/wp-content/2008/06/diegrinder.jpg

Kreidle, B. (2013, October 13). Advice from the Past. (A. Seitz, J. Bautista, & F. Wiggins, Interviewers)

Leone, G. (2013, October 24). Background Research regarding Standing Dani & Working with the Coopers. (F. Wiggins, A. Seitz, & J. Bautista, Interviewers)

Levo. (n.d.). *LEVO COMBI JR.* Retrieved October 5, 2013, from http://levousa.com/combi-jr/combi-jr.html

Mello, D. J. (2014, February 5). Solving for Frame Loading. (F. Wiggins, Interviewer)

Mopar Muscle. (n.d.). Retrieved from http://image.moparmusclemagazine.com/f/miscellaneous/miller-electric-welding-gear/15230315/millermatic-212-auto-set-mig-welderone-of-the-miller-products-eligi.jpg

Oxygen Service Co. (n.d.). Retrieved from http://www.oxygenservicecompany.com/media/catalog/product/cache/1/image/9df78eab33525d08d6e5fb8d27136e95/J/a/Jancy_MCCS14.jpg

Percentage Difference. (n.d.). Retrieved June 11, 2014, from MathIsFun.com: http://www.mathsisfun.com/percentage-difference.html

Permobil USA. (n.d.). Retrieved October 1, 2013, from VS: Power Wheelchair Seating: http://www.permobilus.com/vs.php

Pinch Point. (2013, June 17). Retrieved from Wikitionary.com: http://en.wiktionary.org/wiki/pinch_point

Quest Magazine Online. (2013, October 1). *Stand Up!* Retrieved from http://quest.mda.org/article/stand

Rollover. (2014, March 2). Retrieved from Wikipedia: http://en.wikipedia.org/wiki/Rollover

Standing Dani. (n.d.). Retrieved October 5, 2013, from Facebook: https://www.facebook.com/pages/Standing-Dani/77819613913

Suspension & Handling Glossary. (2013). Retrieved March 4, 2014, from RockCrawler.com: http://www.rockcrawler.com/techreports/glossary/index.asp

Trask, A., Johnson, E., & Garcia, R. (2010, June). Strider Final Report. (L. Rosenburg, Ed.) San Luis Obispo, CA, United States: Cal Poly San Luis Obispo (Digital Commons). Retrieved from http://digitalcommons.calpoly.edu/mesp/26/

Ulrich Alber GmbH. (n.d.). *Alber Adventure*. Retrieved November 14, 2013, from http://responsive.alber.de/produkte-rollstuhl-zusatzantrieb/elektrorollstuhl-adventure.html

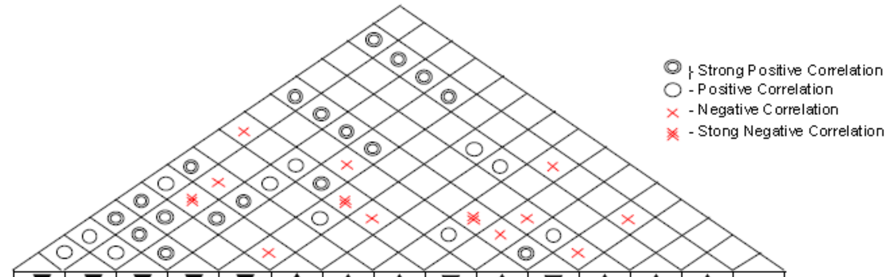
Van Allen, K., & Gavrilovic, N. (2014, January). Vehicle Half-Car Suspension and Roll Model. San Luis Obispo, California, United States of America.

Weight Scales. (2014, March 6). Retrieved from Overstock.com: http://www.overstock.com/Health-Beauty/Weight-Scales/6758/subcat.html

What is Turning Radius? (2012, April 6). Retrieved from WhatIsAll.com: http://www.whatisall.com/what-is-turning-radius/

Wheelbase. (2013, December 17). Retrieved March 3, 2014, from Wikipedia.org: http://en.wikipedia.org/wiki/Wheelbase

APPENDIX A – QUALITY FUNCTION DIAGRAM

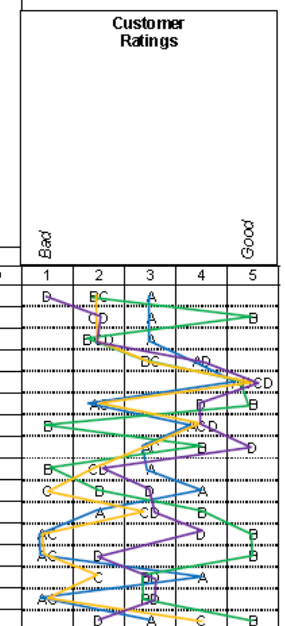


Larger is Better ▲
Nominal is Best ○
Smaller is Better ▼

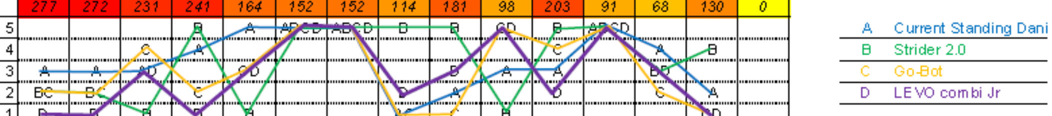
Customer Desciption (Whos):
1 = Nathan and the Cooper Family
2 = Repairmen and Companies that work with SMA families
3 = ME Department (Main Funding Source)

Customer Description (Whos)	Customer Requirements (Whats)	Importance	A: Overall Length	B: Greatest width	C: Height without Nathan	D: Weight without Nathan & Battery	E: Turning Radius (Radius needed to turn around)	F: Lateral Rollover Angle	G: Longitudinal Rollover Angle	H: Rear Vision	I: Low G-Force Transferred to Nathan	J: % of Off-the-shelf Components	K: Cost of System	L: Design Life (Excluding Consummable Items)	M: Aesthetically Pleasing	N: Easy to Lift	O
			▼	▼	▼	▼	▼	▲	▲	▲	▼	▲	▼	▲	▲	▲	
1	Must have the same or smaller footprint than the current Standing Dani	5	9	9	9	3	9	9	9		1		1		1	3	
1	Must have the same or smaller weight than the current Standing Dani	4	3	3	3	9		3	3		3		3			9	
1	Must have the same or greater maneuverability than the current Standing Dani	4	9	9	1	3	9	3	3	3			1				
1	Must have the same or greater user operability as the current Standing Dani	5	1	1	1					9	3						
1	Must not rollover in standard operating conditions	5	9	9	9	3	3	9	9								
1	Must not cause the user bodily injury due to accelerations or terrain	5	1			3	3				9		1	1			
1,2	Should have easy-to-replace parts and be easily repaired/replaced by outside party	3										9	9	3	1		
1,2	Must be low-maintenance and have high reliability	4				1		3	3	1	3	3	9	9			
1	Must be easily transported by van or small SUV	5	9	9	9	9										9	
1	Should utilize existing body support	2				9				3	9	3	3	1	3	1	
1	Should improve the comfort of the existing foot support	3	1	1		9					9	3	3	1	1	1	
1	Should have increased battery life (3 hours plus)	2	3	3	3	9	1	1	1			9	9	3		9	
1	Should have increased user awareness/vision	3	1	1	3		9			9		1	3	3	1		
1	Should look aesthetically pleasing so as to not draw negative attention to the user	3	3	3	9	1	3	3	3	3			3		9	3	
1	Must be able to provide a comfortable ride across varying terrain (i.e. grass, trails, boardwalk)	5	9	9	3	3	3	3	3	1	9	1	9	3	3		
1,3	Should cost the same or less than the current Standing Dani	2	9	9	9	9				3	1	9	9	3	3	1	
			277	272	231	241	164	152	152	114	181	98	203	91	68	130	0

Specifications (Hows)



Relationship Strength
Strong - 9
Medium - 3
Weak - 1



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Targets	≤ 29 in	≤ 25 in	≤ Existing Design	≤ 80 lbs	≤ 3ft	≥ 25deg	≥ 25deg	≥ 90deg	≥ 50% reduction from existing sys	≥ 50%	≤ $2,500	≥ 10 years	Nathan Likes It	Can be Lifted by Bob Cooper	
Weighted Importance	5	5	3	4	4	5	5	3	5	2	2	3	5	4	
% Importance	9.09%	9.09%	5.45%	7.27%	7.27%	9.09%	9.09%	5.45%	9.09%	3.64%	3.64%	5.45%	9.09%	7.27%	0.00%

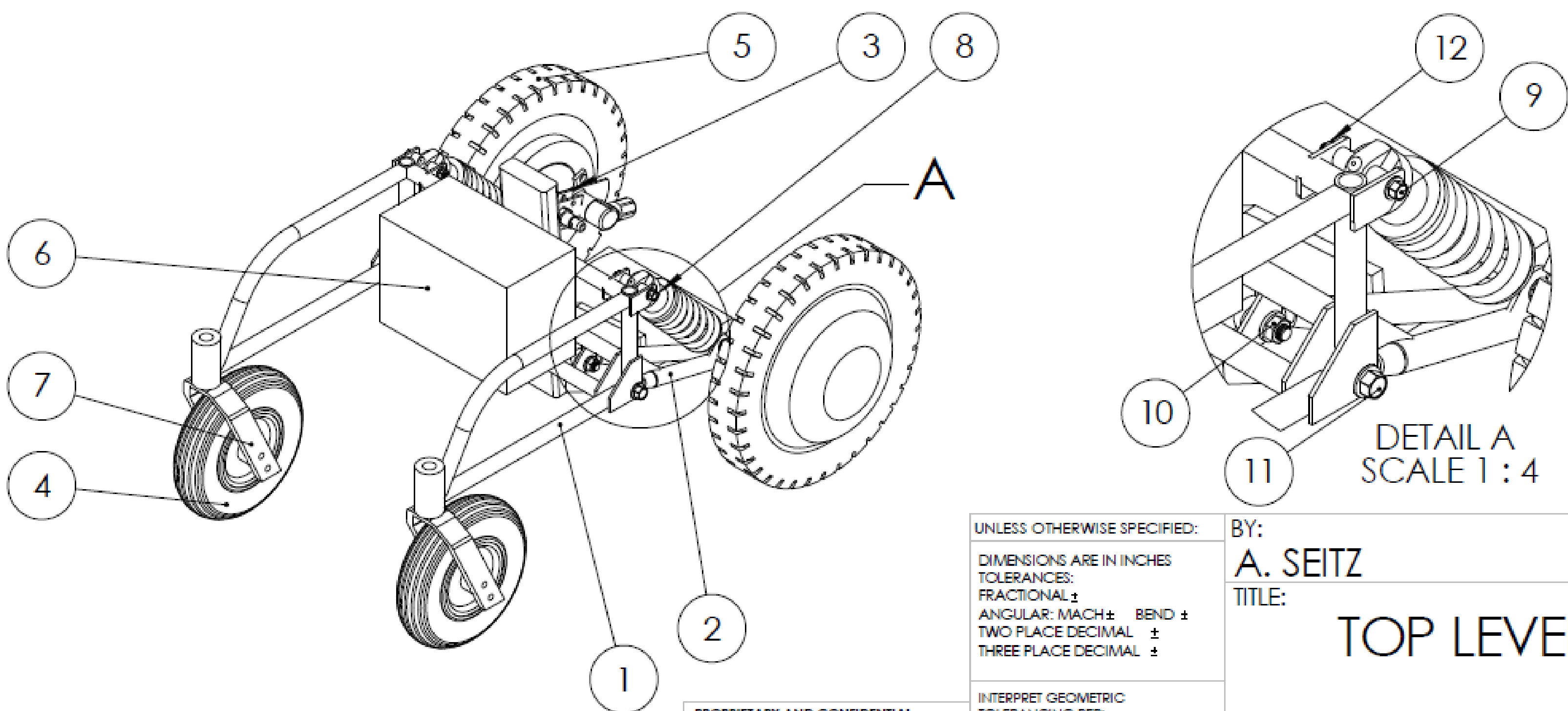
TABLE 12. MORPHOLOGICAL ANALYSIS TABLE.

Isolate Nathan From Terrain	Transport Easily	User Awareness	Increase Comfort	Maneuverability	Improve Range	Safety	Make It Cool
Shock/Spring Suspension	Collapsible	Mirrors	Water Bed	Hover Craft	More Batteries	Bubble Protection	Batman Wings
Bungee	Disassembles	Rear View Camera	Lay-Z-Boy®	Dynamic Suspension	Solar Powered	Force Field	Moon Shoes
Large Air Tires	Assisted Life	Gyroscopic Chair	Pillows	Flexible/Dynamic Frame	More Efficient Motors	Air Bags	Cup Holders
Levitation Via Magnets	Well-Placed Handles	Back Up Sensors	Blankets	Tri-Wheels	Lightweight	Bumpers	Lasers
Air Suspension	Hitch Mount	Beeping (i.e. Sensors)	Bungees (Strider 2)	Segway™ System	Human-Powered Mode	Impact Absorbers	Sound System
Hamster Ball Technology	Folding Wheelchair	Automated Assistive Voice	TempurPedic® Foam Supports	Spherical Two-Axis Wheels	Decrease Tire-Road Contact	GPS Location	Horn
Semi-Truck Captain's Chair	Telescoping (Like A Sprinkler)		Foot Massage	High Torque Setting	New Style Batteries	Headlights	Transforms Into Something
	Detachable Lift System		Air Conditioning	Casters	Material Distribution	Taillights	Sick Rims
			Lumbar Support			Nathan Fully-Enclosed	Sound System
			Closer Non-User Interaction			Rounded Edges	Sharp Features (i.e. Ferrari)
			Mental/Emotional /Physical				Red (Lightning McQueen)
			Hinged Design				Black (Batman)

ITEM NO.	DrawnBy	SW-File Name(File Name)	Part No	DESCRIPTION	QTY.
1	A. SEITZ	E – Frame	10	FRAME	1
1.1				TUBE, ROUND, 0.75 OD x 0.09	103.9
1.2					2
1.3				INNER SUSPENSION ARM MOUNT	4
1.4				INNER SPRING MOUNT	2
1.5				OUTER SUSPENSION ARM MOUNT	4
1.6				OUTER SPRING MOUNT	2
2	A. SEITZ	Trailing Arm assembly LEFT	20	ASSEMBLY – LEFT TRAILING ARM	1
2.1		94640A115	MCMASTER – 94640A115	THREADED WELD NUT	2
2.2		Rod end assembly	MCMASTER – 59915k274	3/8 THREADED ROD END	2
2.3	A. SEITZ	D – Trailing Arm Left	21	TRAILING ARM – LEFT	1
2.3.1				TUBE, ROUND, .75 OD x .09	17.82
2.3.2				SHOCK MOUNTING TAB 0.125 IN	1
2.3.3				WHEEL MOUNTING TAB 0.125 IN	2
3	A. SEITZ	Coilover assembly	103	ROMIC D – COILOVER	2
3.1		Shock			1
3.2		Coil Spring			1
3.3		Spring collar			1
3.4		Shock collar			1
4		Real caster fork	15	CASTER FORK	2

5		Real caster	11	6 INCH CASTER WHEEL	2
6	A. SEITZ	Trailing Arm assembly RIGHT	30	ASSEMBLY – RIGHT TRAILING ARM	1
6.1	A. SEITZ	D – Trailing Arm Right	31	TRAILING ARM – RIGHT	1
6.1.1				TUBE, ROUND, .75 OD x .09	17.82
6.1.2				SHOCK MOUNTING TAB 0.125 IN	1
6.1.3				WHEEL MOUNTING TAB 0.125 IN	2
6.2		94640A115	MCMASTER – 94640A115	THREADED WELD NUT	2
6.3		Rod end assembly	MCMASTER – 59915k274	3/8 THREADED ROD END	2
7		Actual drive wheel assembly	12	ALBER DRIVE WHEEL	2
7.1	A. SEITZ	Actual drive wheel	100	ALBER – DRIVE WHEEL	1
7.2		Wheel mount bolt			1
7.3	A. SEITZ	Motor controller to wheel	101	ALBER – DRIVE WHEEL CONTROL BRACKET	1
8		Battery	14	BATTERY	1
9		92323A526	MCMASTER – 92323A526	1/4-20 SERRATED FLANGE HEX CAP SCREW	4
10		95922A130	MCMASTER – 95922A130	3/8-16 SERRATED FLANGE HEX NUT	4
11		92323A558	MCMASTER – 92323A558	3/8-16 SERRATED FLANGE HEX CAP SCREW	4
12		95922A110	MCMASTER – 95922A110	1/4-20 SERRATED FLANGE HEX NUT	4

ITEM NO.	PartNo	DESCRIPTION	QTY.
1	010	FRAME	1
2	020	ASSEMBLY - LEFT TRAILING ARM	1
3	030	ASSEMBLY - RIGHT TRAILING ARM	1
4	011	6 INCH CASTER WHEEL	2
5	012	ALBER DRIVE WHEEL	2
6	014	BATTERY	1
7	015	CASTER FORK	2
8	103	ROMIC D - COILOVER	2
9	MCMASTER - 92323A526	1/4-20 SERRATED FLANGE HEX CAP SCREW	4
10	MCMASTER - 95922A130	3/8-16 SERRATED FLANGE HEX NUT	4
11	MCMASTER - 92323A558	3/8-16 SERRATED FLANGE HEX CAP SCREW	4
12	MCMASTER - 95922A110	1/4-20 SERRATED FLANGE HEX NUT	4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL ASSEMBLY

FINISH N/A

DO NOT SCALE DRAWING

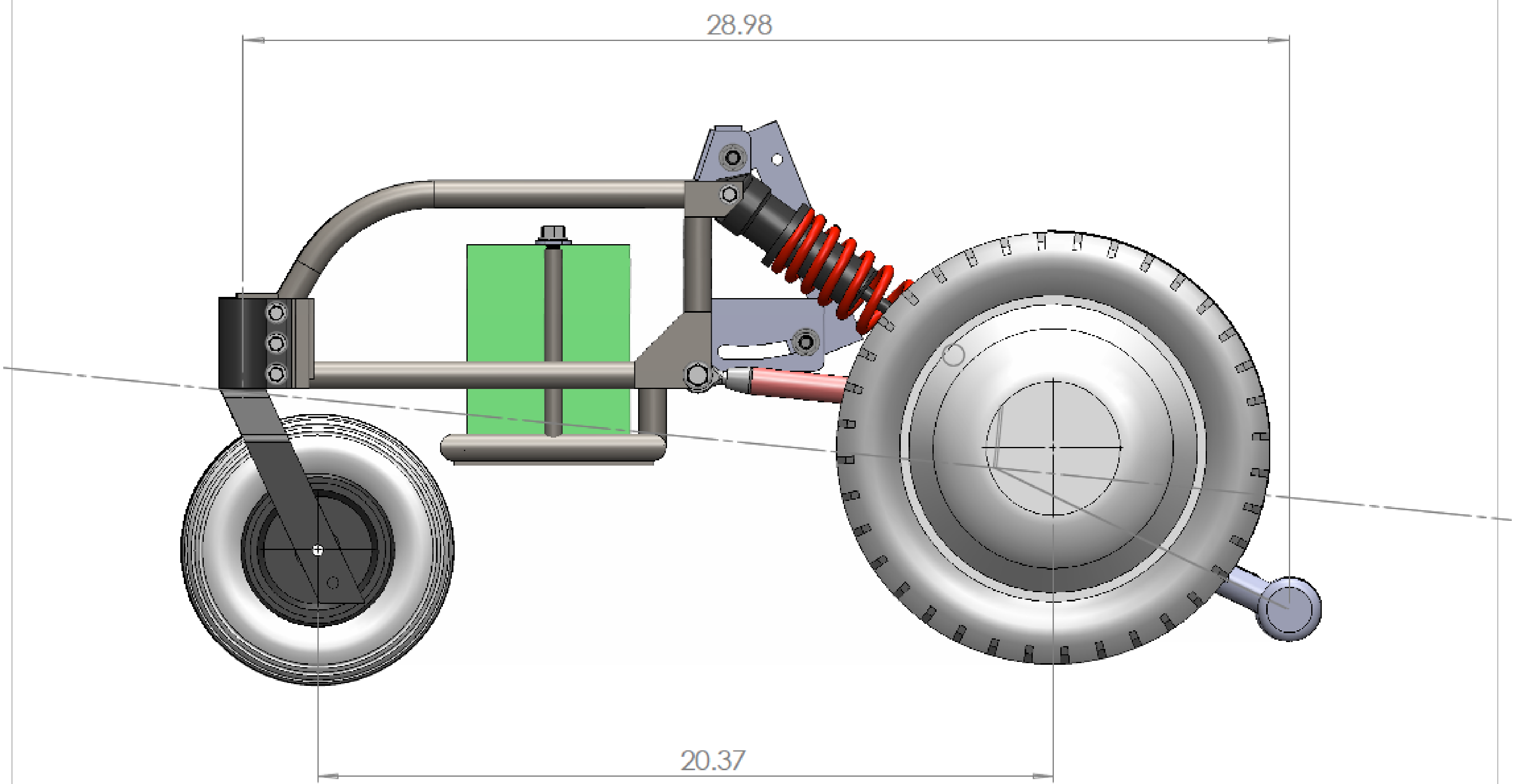
BY: A. SEITZ

TITLE: TOP LEVEL

SIZE A | DWG. NO. 100 | REV F

SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1

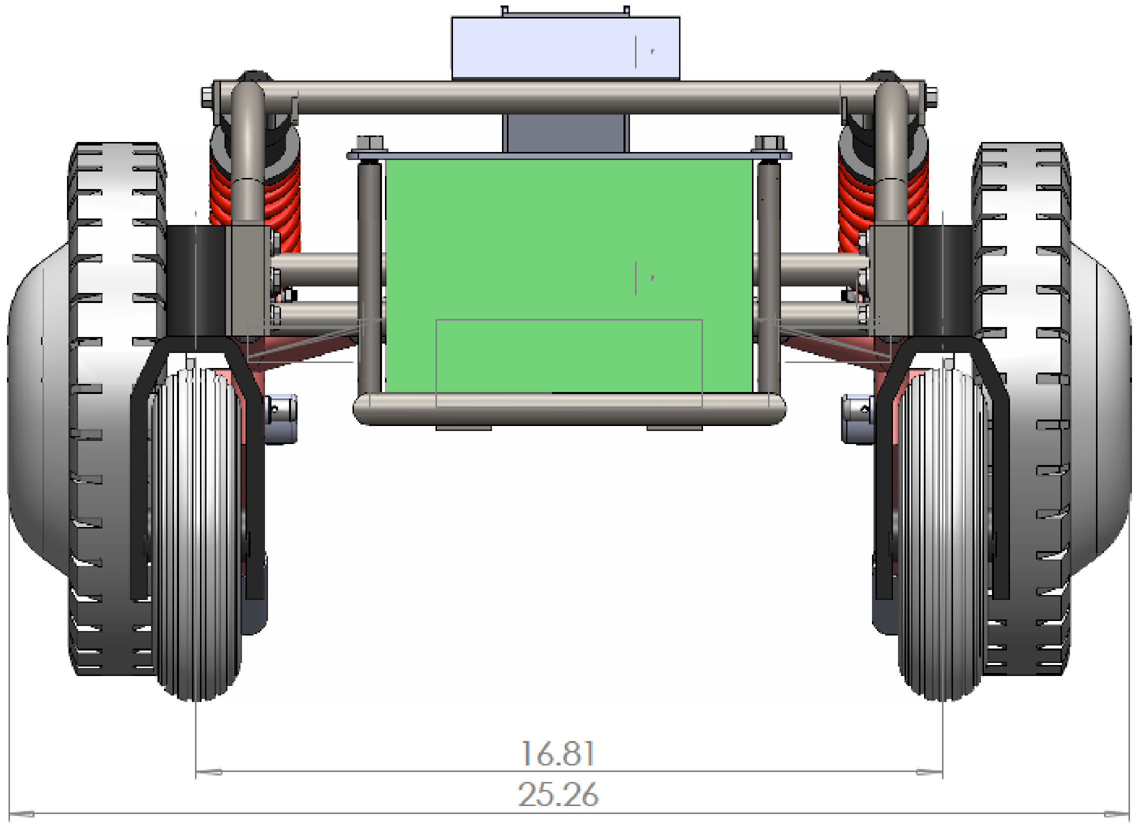
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:	BY: A. SEITZ
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: TOP LEVEL
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL ASSEMBLY	SIZE A / DWG. NO. 100 / REV F
FINISH N/A	
DO NOT SCALE DRAWING	SCALE: 1:12 / WEIGHT: / SHEET 2 OF 4

PROPRIETARY AND CONFIDENTIAL

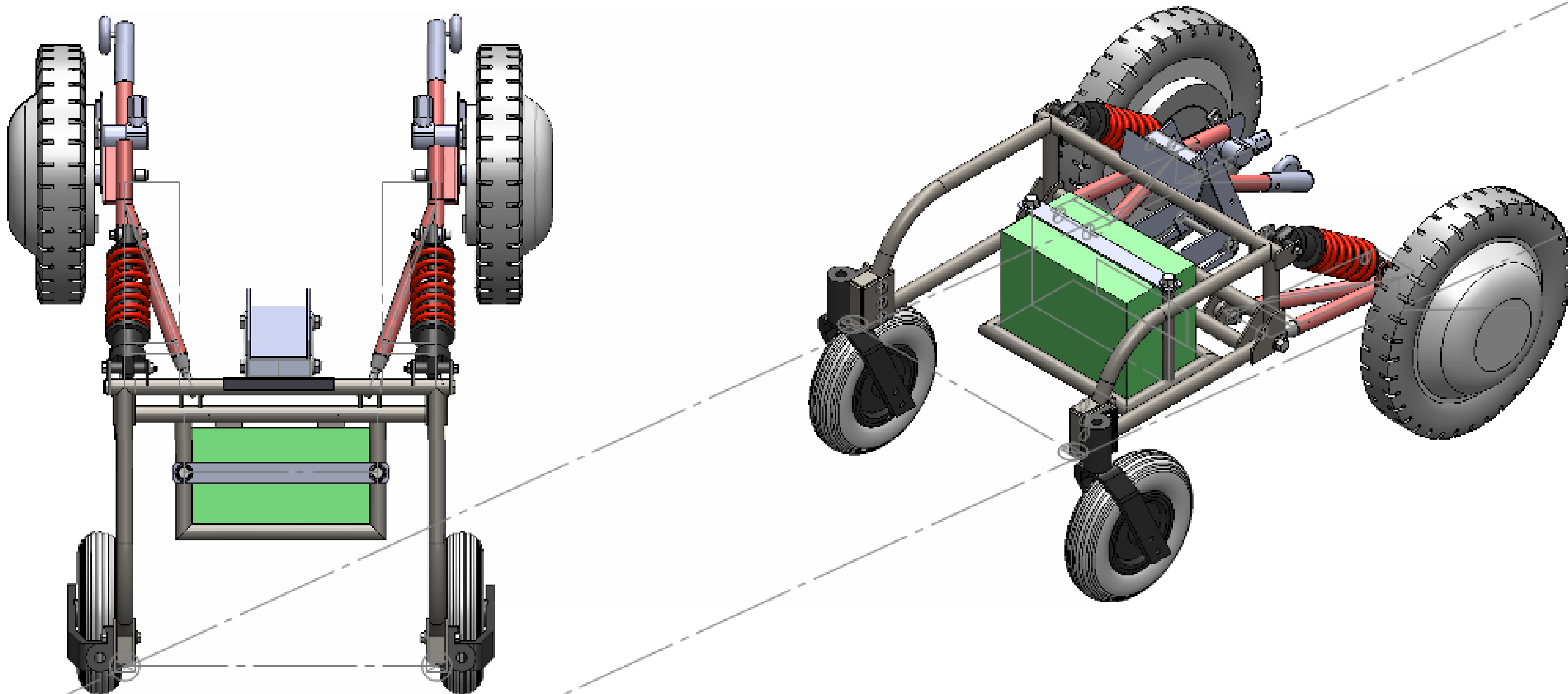
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.



UNLESS OTHERWISE SPECIFIED:	BY: A. SEITZ
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: TOP LEVEL
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL ASSEMBLY	SIZE A · DWG. NO. 100 · REV F
FINISH N/A	
DO NOT SCALE DRAWING	SCALE: 1:12 · WEIGHT: · SHEET 3 OF 4

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.

5 4 3 2 1



SolidWorks Student Edition for Academic Use Only

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL ASSEMBLY

FINISH N/A

DO NOT SCALE DRAWING

BY: A. SEITZ

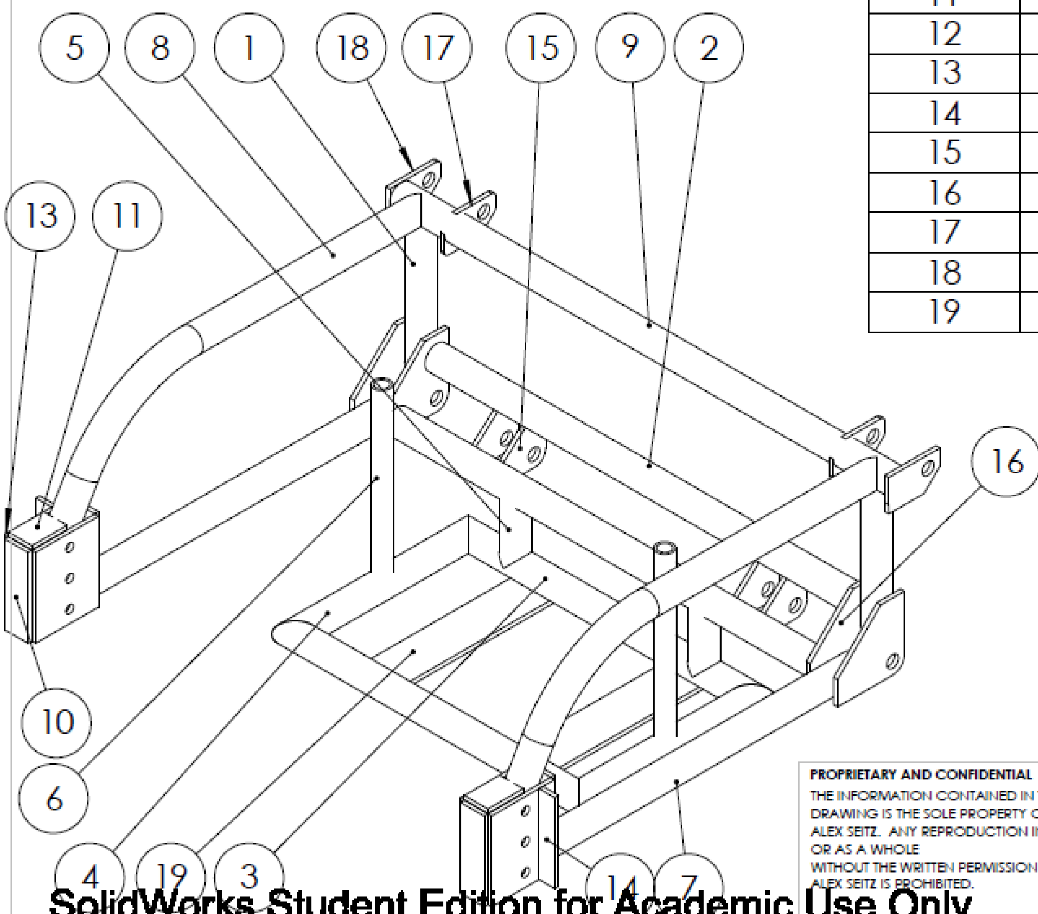
TITLE: TOP LEVEL

SIZE	DWG. NO.	REV
A	100	F

SCALE: 1:12	WEIGHT:	SHEET 4 OF 4

5 4 3 2 1

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	2	TUBE, ROUND, 0.75 OD x 0.09	4.25
2	2	TUBE, ROUND, 0.75 OD x 0.09	13.5
3	2	TUBE, ROUND, 0.75 OD x 0.07	9.75
4	2	TUBE, ROUND, 0.75 OD x 0.07	6.25
5	2	TUBE, ROUND, 0.75 OD x 0.07	2
6	2	TUBE, ROUND, 1.00 OD x 12.50	5.5
7	2	TUBE, ROUND, 0.75 OD x 0.09	12
8	2	TUBE, ROUND, 0.75 OD x 0.09	14.96
9	1	TUBE, ROUND, 0.75 OD x 0.09	15.75
10	2	BOX PLATE 1	
11	2	BOX PLATE 2	
12	2	BOX PLATE 3	
13	4	BOX PLATE 4	
14	2	CASTER SUPPORT TAB	
15	4	INNER SUSPENSION ARM MOUNT	
16	4	OUTER SUSPENSION ARM MOUNT	
17	2	INNER SPRING MOUNT	
18	2	OUTER SPRING MOUNT	
19	2	BATTERY SUPPORT	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL MILD STEEL

FINISH BLUE POWDER COAT

DO NOT SCALE DRAWING

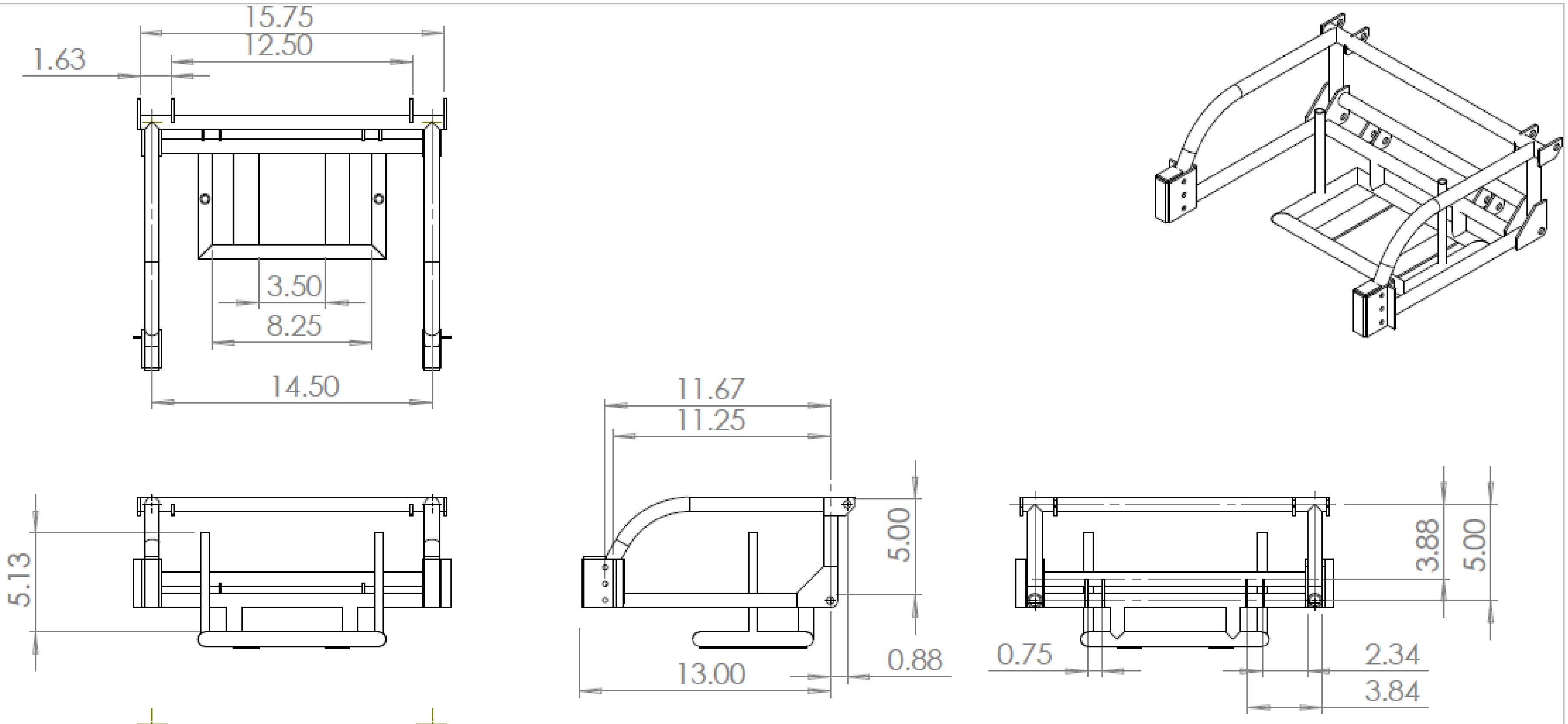
BY: A. SEITZ

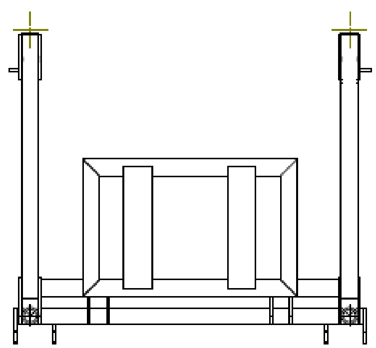
TITLE: FRAME

SIZE A | DWG. NO. 010 | REV G

SCALE: 1:8 | WEIGHT: | SHEET 1 OF 4

5 4 3 2 1





PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: MILD STEEL

FINISH: BLUE POWDER COAT

DO NOT SCALE DRAWING

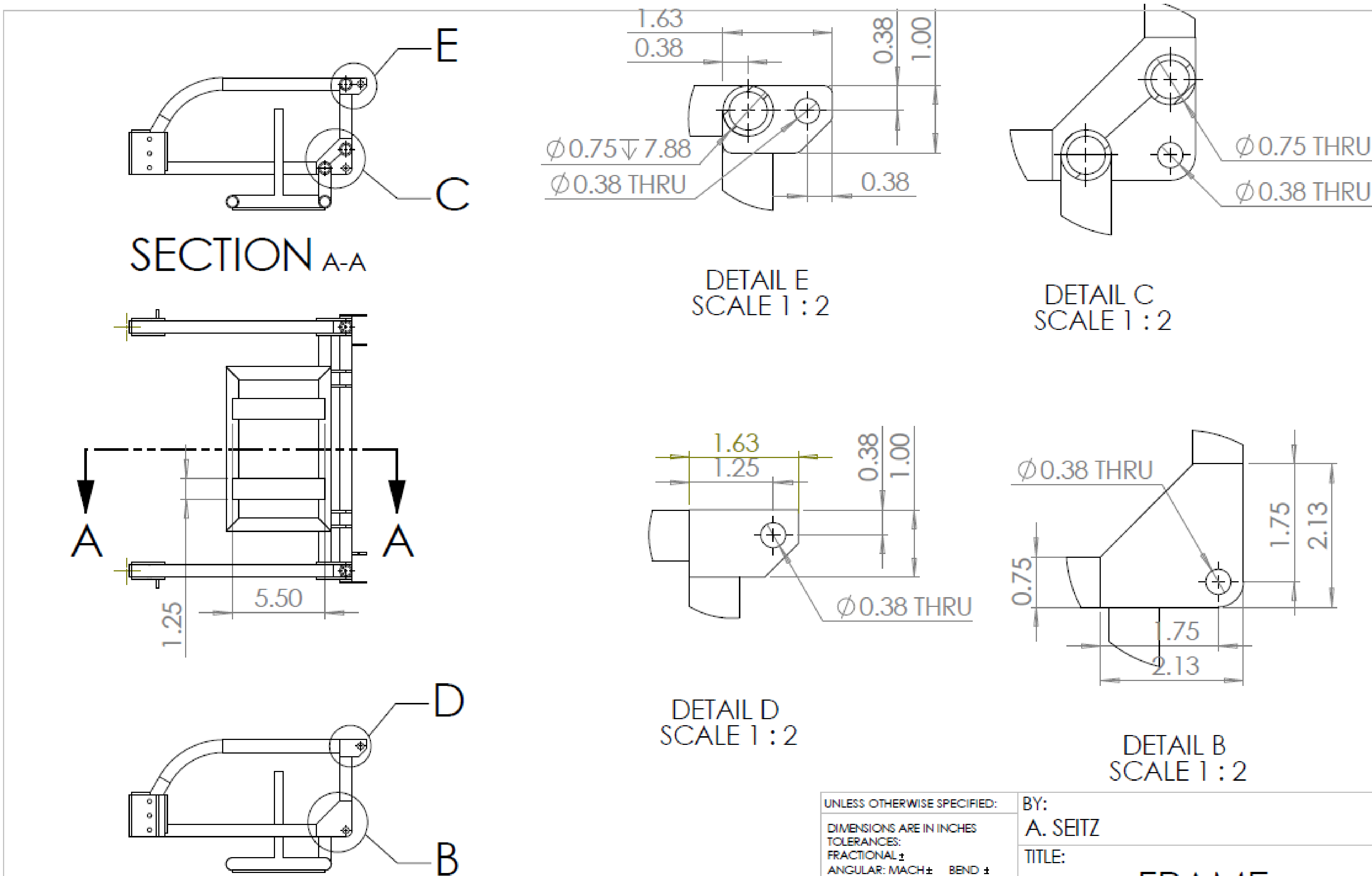
BY: A. SEITZ

TITLE: FRAME

SIZE: A | DWG. NO. 010 | REV G

SCALE: 1:8 | WEIGHT: | SHEET 2 OF 4

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: MILD STEEL

FINISH: BLUE POWDER COAT

DO NOT SCALE DRAWING

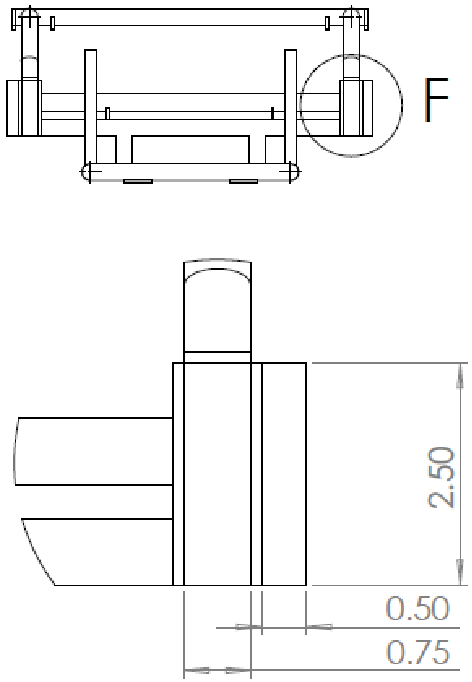
BY: A. SEITZ

TITLE: FRAME

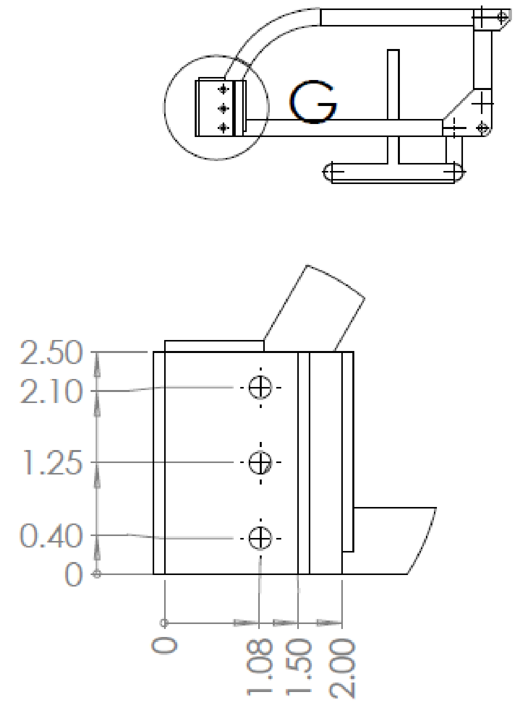
SIZE	DWG. NO.	REV
A	010	G

SCALE: 1:8 | WEIGHT: | SHEET 3 OF 4

5 4 3 2 1



DETAIL F
SCALE 1 : 2



DETAIL G
SCALE 1 : 2

SolidWorks Student Edition for Academic Use Only

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
MILD STEEL

FINISH
BLUE POWDER COAT

DO NOT SCALE DRAWING

BY:
A. SEITZ

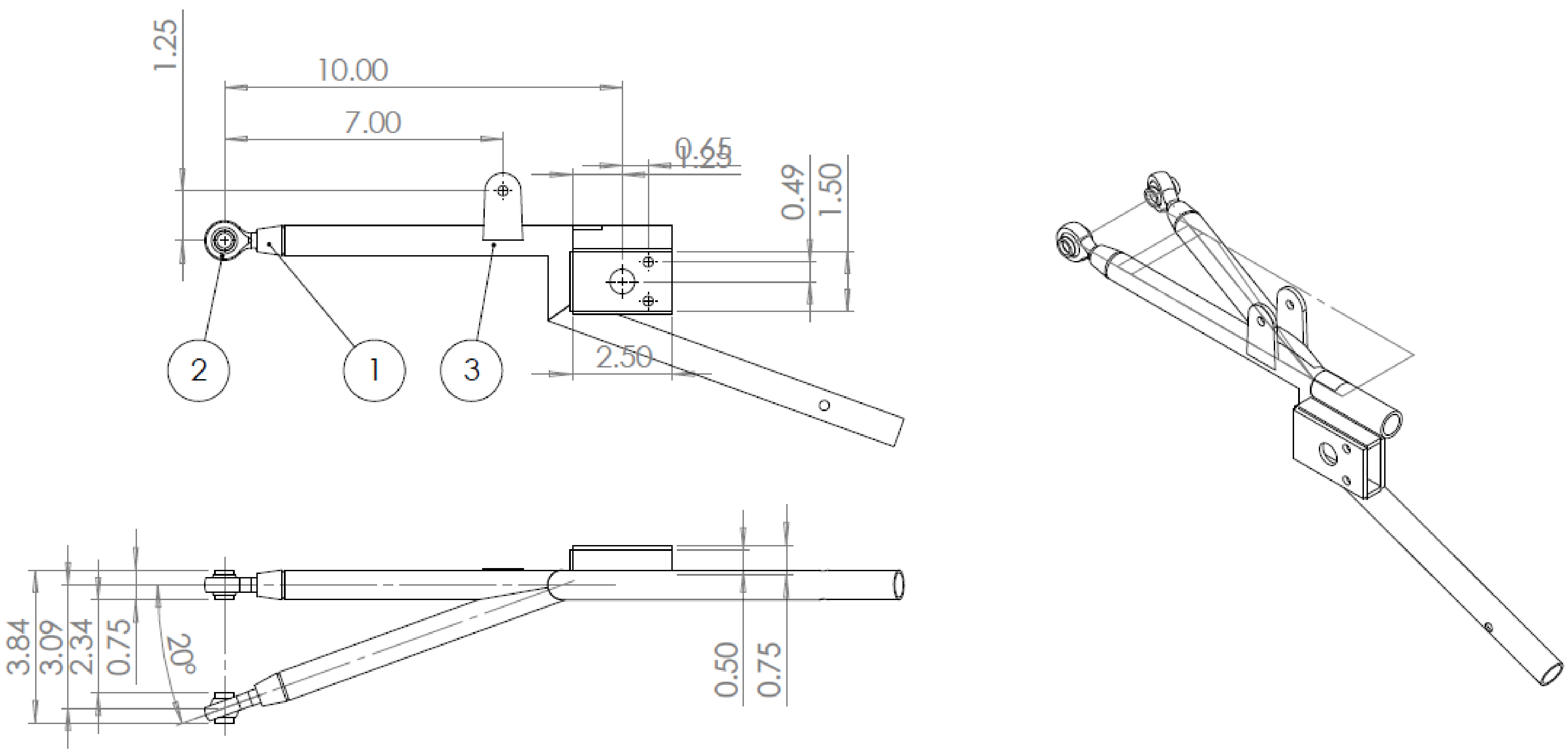
TITLE:
FRAME

SIZE A | DWG. NO. 010 | REV G

SCALE: 1:8 | WEIGHT: | SHEET 4 OF 4

5 4 3 2 1

ITEM NO.	PartNo	DESCRIPTION	QTY.
1	MCMASTER - 94640A115	THREADED WELD NUT	2
2	MCMASTER - 59915k274	3/8 THREADED ROD END	2
3	021	TRAILING ARM - LEFT	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL ASSEMBLY

FINISH N/A

DO NOT SCALE DRAWING

BY: A. SEITZ

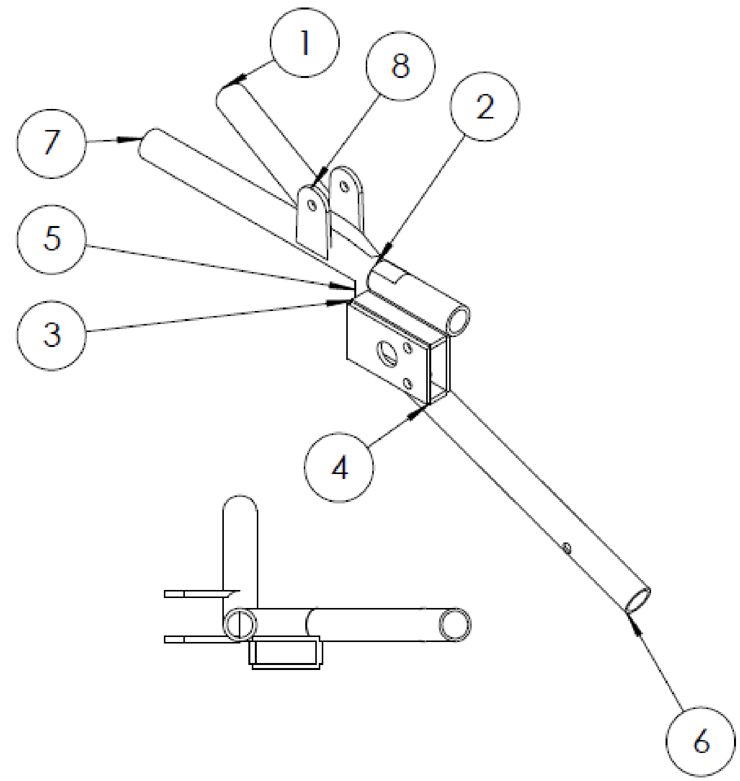
TITLE: ASSEMBLY - LEFT TRAILING ARM

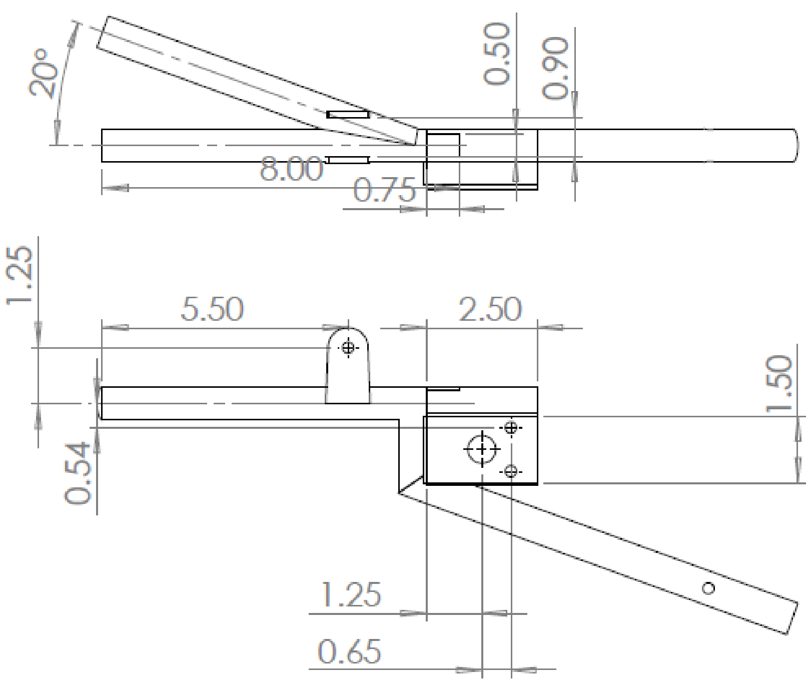
SIZE A | DWG. NO. 020 | REV F

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	TUBE, ROUND, .75 OD x .09	7.45
2	1		
3	1		
4	1		
5	1	TUBE, ROUND, .75 OD x .07	2.01
6	1	TUBE, ROUND, .75 OD x .07	9.26
7	1	TUBE, ROUND, .75 OD x .09	8
8	1	SHOCK MOUNTING TAB 0.125 IN	





PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: MILD STEEL

FINISH: POWDER COAT

DO NOT SCALE DRAWING

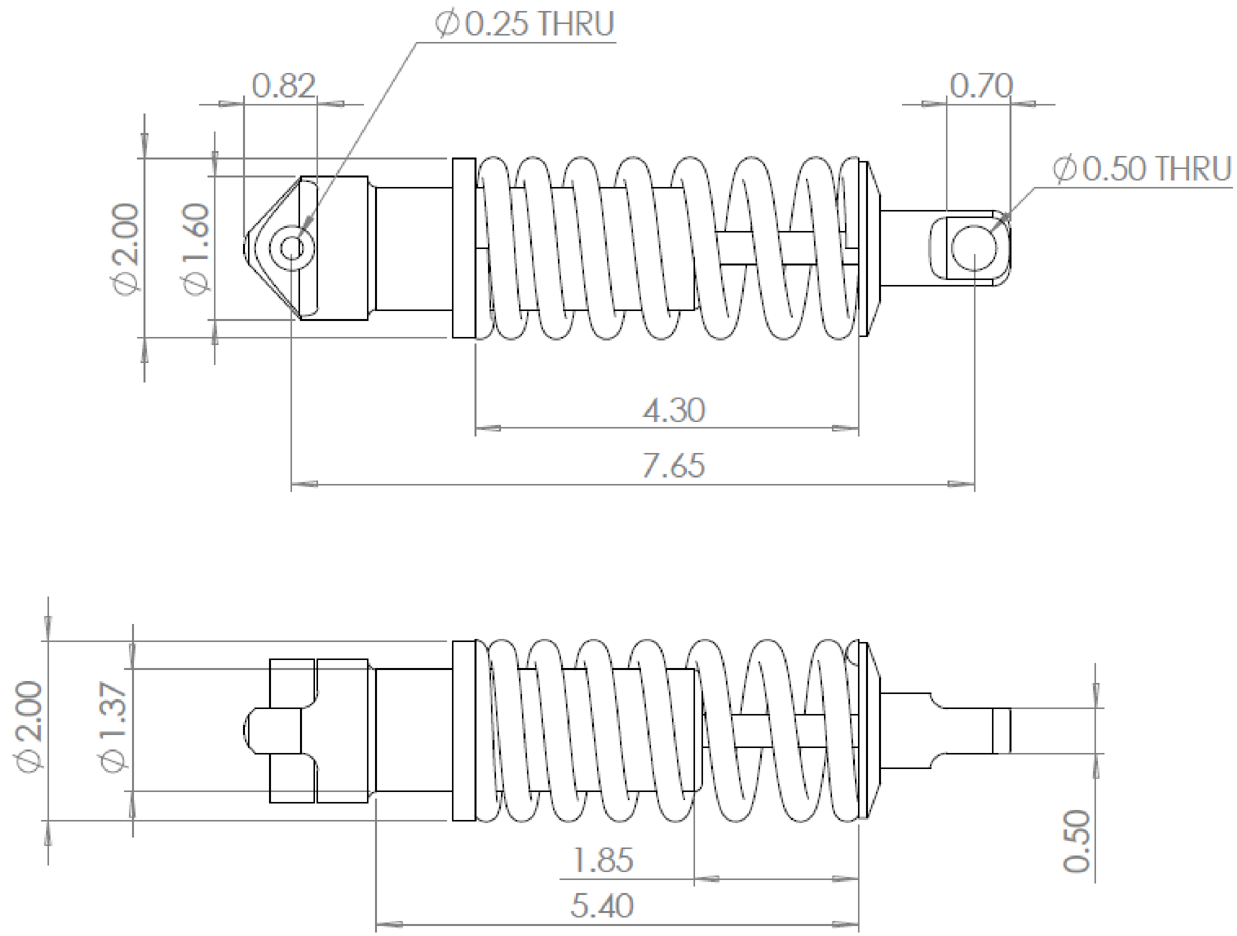
BY: A. SEITZ

TITLE: TRAILING ARM - LEFT

SIZE: A | DWG. NO. 021 | REV: F

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

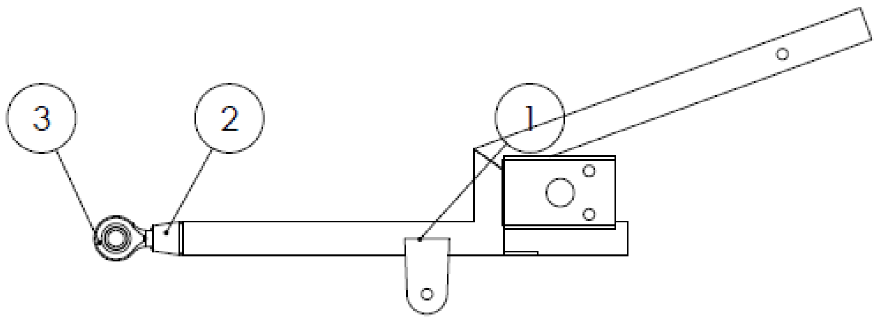


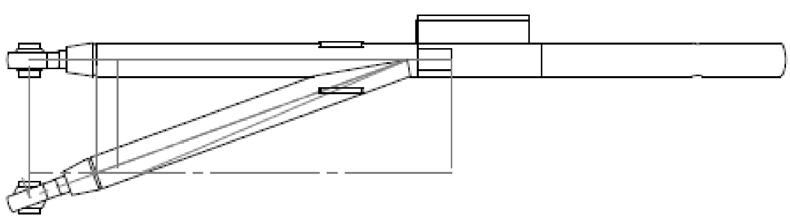
UNLESS OTHERWISE SPECIFIED:	BY: A. SEITZ
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: ROMIC D - COILOVER
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL ASSEMBLY	SIZE A / DWG. NO. 103 / REV N/A
FINISH N/A	
DO NOT SCALE DRAWING	SCALE: 1:2 / WEIGHT: / SHEET 1 OF 1

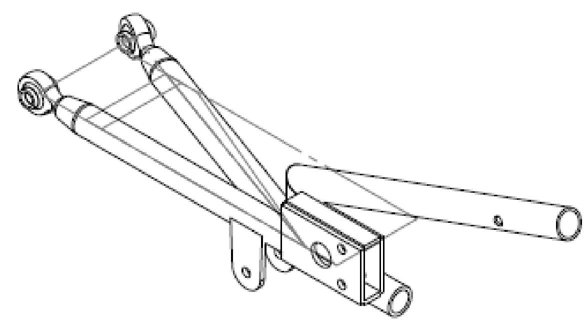
5 4 3 2 1

ITEM NO.	PartNo	DESCRIPTION	QTY.
1	031	TRAILING ARM - RIGHT	1
2	MCMASTER - 94640A115	THREADED WELD NUT	2
3	MCMASTER - 59915k274	3/8 THREADED ROD END	2

NOTE:
SEE ASSEMBLY - LEFT TRAILING ARM FOR DIMENSIONS



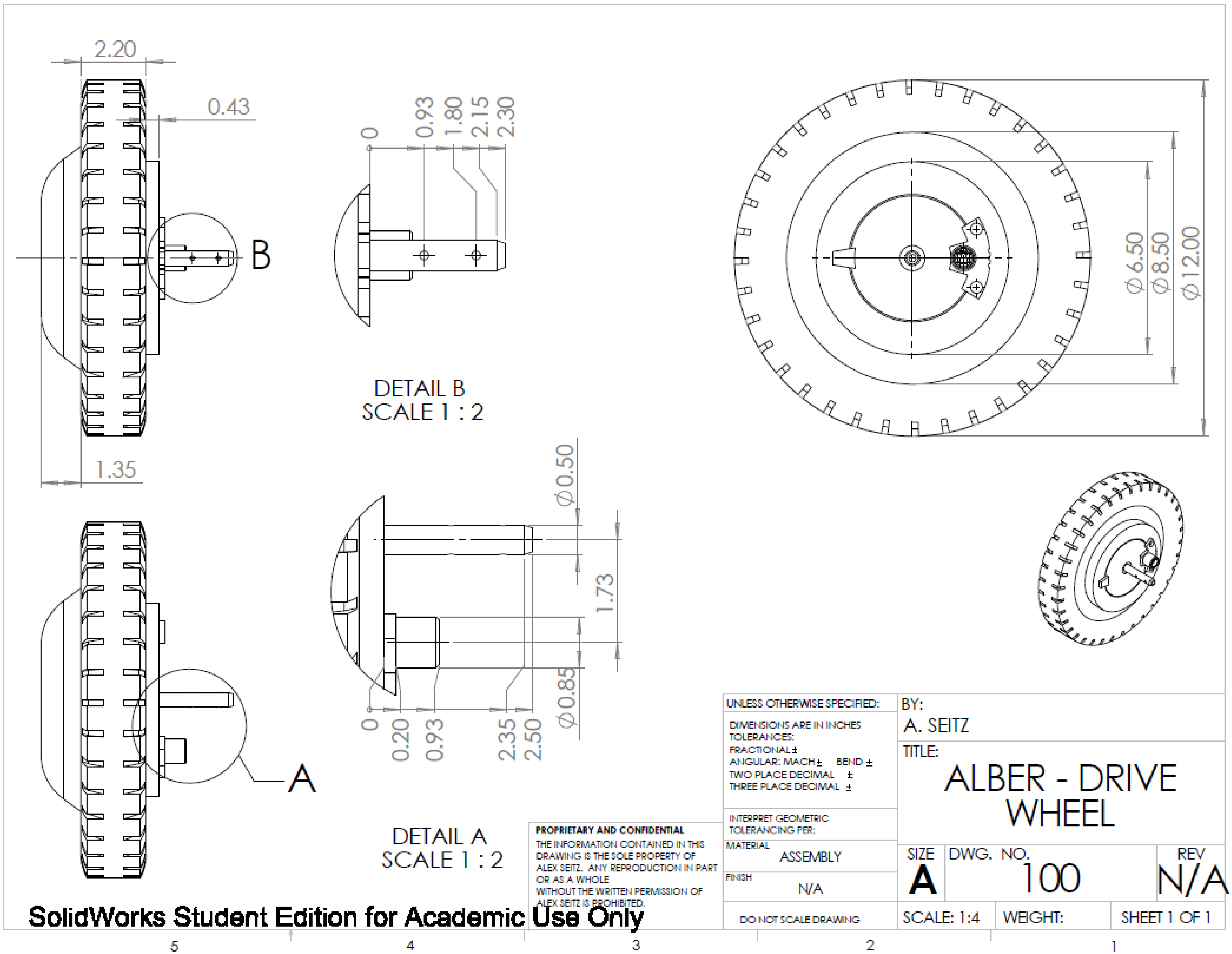


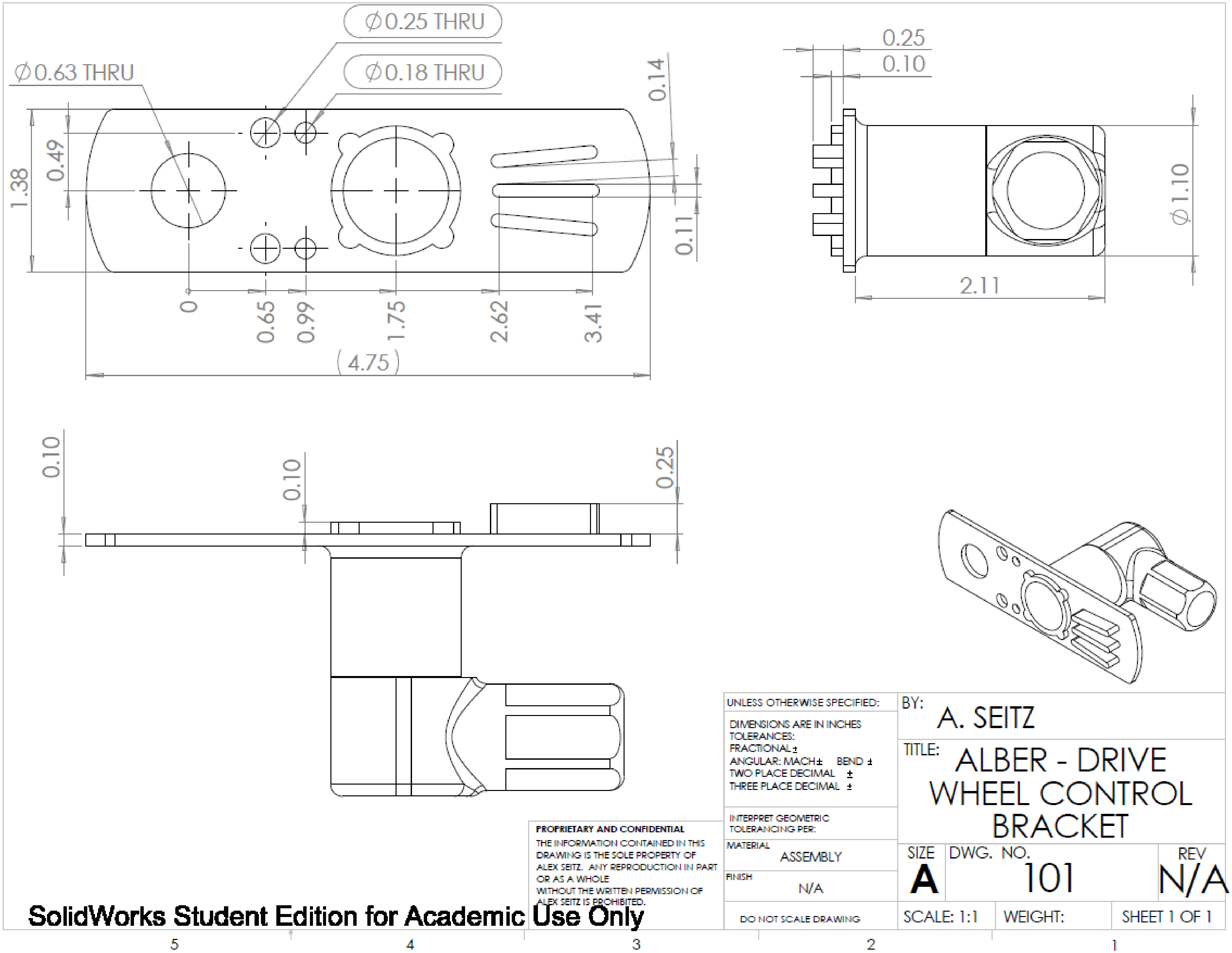


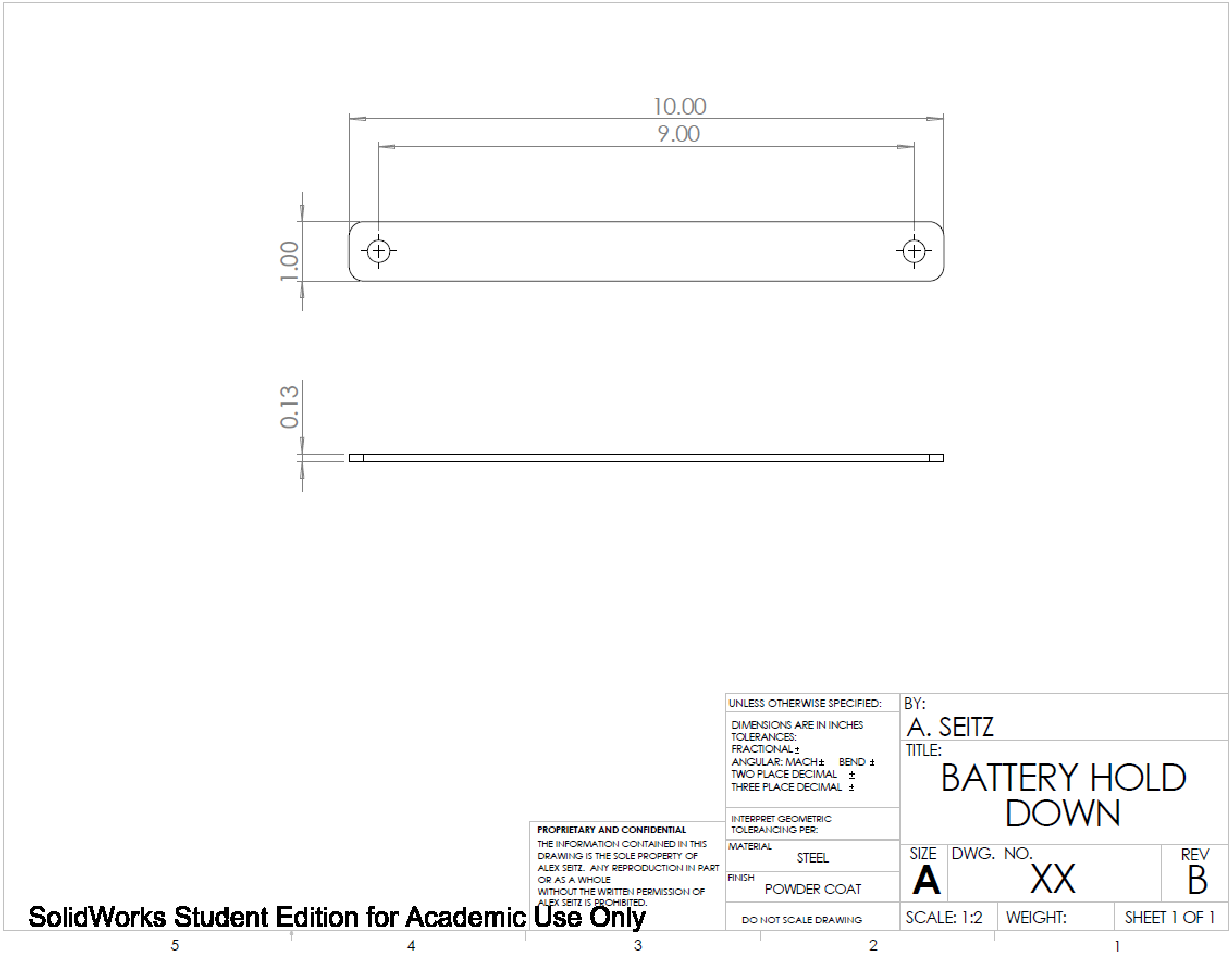
UNLESS OTHERWISE SPECIFIED:	BY: A. SEITZ
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	TITLE: ASSEMBLY - RIGHT TRAILING ARM
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL N/A	SIZE A · DWG. NO. 030 · REV G
FINISH ASSEMBLY	
DO NOT SCALE DRAWING	SCALE: 1:4 · WEIGHT: · SHEET 1 OF 1

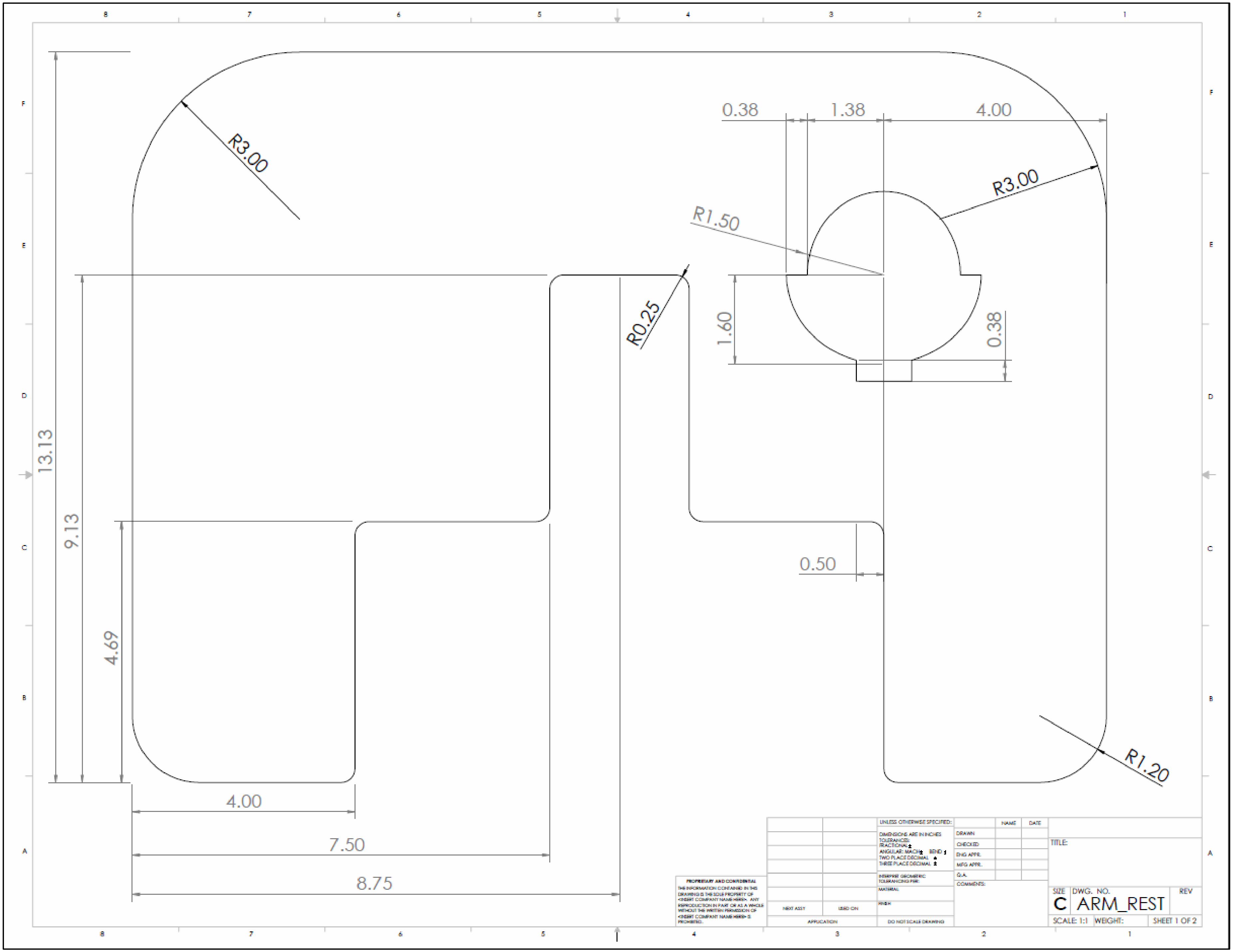
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.

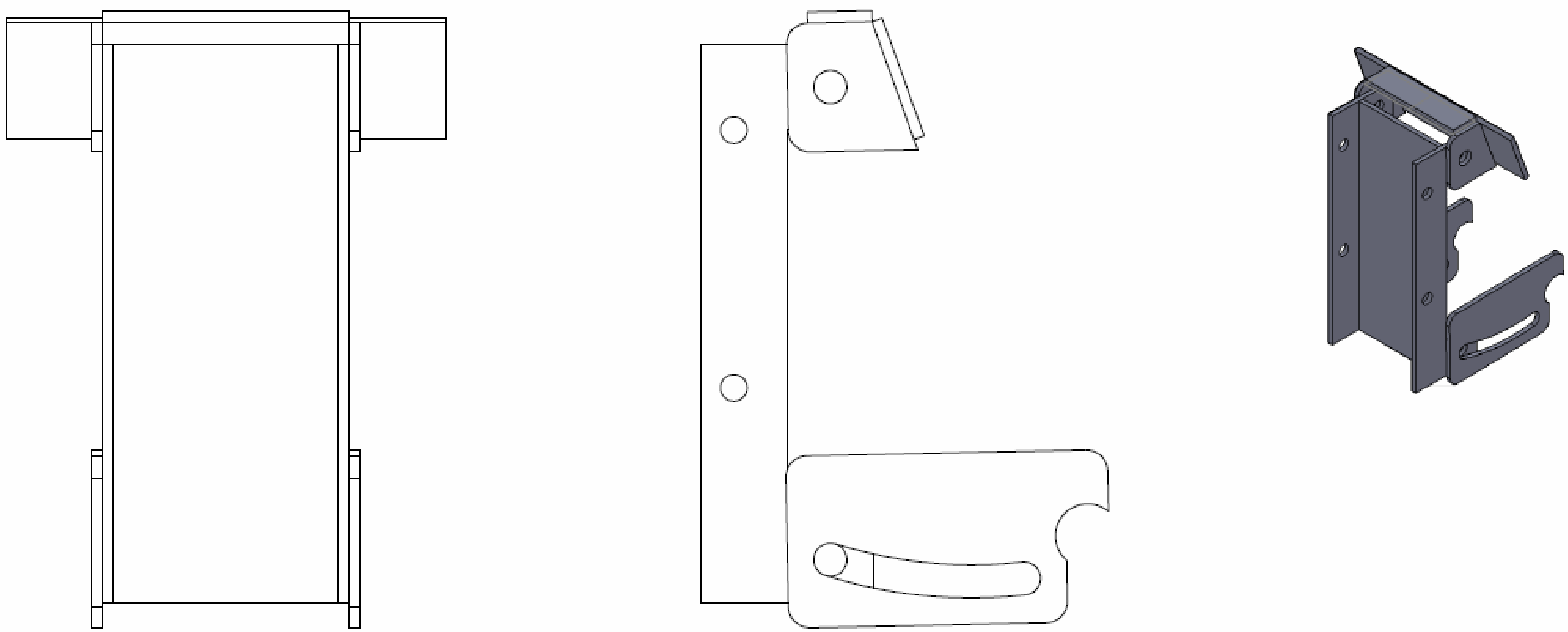
5 4 3 2 1

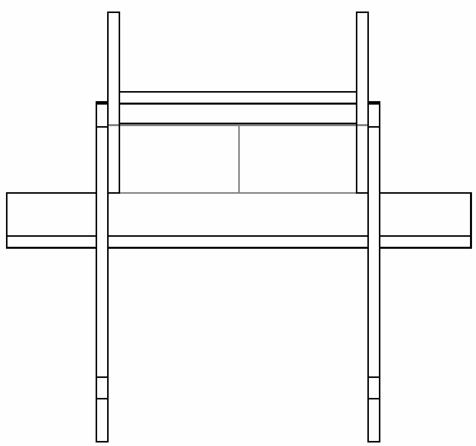

2.20
0.43
B
1.35
0
0.93
1.80
2.15
2.30
DETAIL B
SCALE 1 : 2
Ø6.50
Ø8.50
Ø12.00
Ø0.50
1.73
Ø0.85
0
0.20
0.93
2.35
2.50
A
DETAIL A
SCALE 1 : 2
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ASSEMBLY
FINISH
N/A
DO NOT SCALE DRAWING
BY:
A. SEITZ
TITLE:
ALBER - DRIVE WHEEL
SIZE
A
DWG. NO.
100
REV
N/A
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
SolidWorks Student Edition for Academic Use Only
5
4
3
2
1


⌀0.25 THRU
⌀0.18 THRU
⌀0.63 THRU
0.14
0.11
1.38
0.49
0
0.65
0.99
1.75
2.62
3.41
(4.75)
0.25
0.10
⌀1.10
2.11
0.10
0.10
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ASSEMBLY
FINISH N/A
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.
BY: A. SEITZ
TITLE: ALBER - DRIVE WHEEL CONTROL BRACKET
SIZE A
DWG. NO. 101
REV N/A
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
SolidWorks Student Edition for Academic Use Only
5
4
3
2
1


10.00
9.00
1.00
0.13
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
STEEL
FINISH
POWDER COAT
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ALEX SEITZ. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF ALEX SEITZ IS PROHIBITED.
BY:
A. SEITZ
TITLE:
BATTERY HOLD DOWN
SIZE
A
DWG. NO.
XX
REV
B
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
SolidWorks Student Edition for Academic Use Only
5
4
3
2
1


R3.00
0.38
1.38
4.00
R3.00
R1.50
R0.25
1.60
0.38
13.13
9.13
0.50
4.69
R1.20
4.00
7.50
8.75
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SIZE
DWG. NO.
REV
C
ARM_REST
SCALE: 1:1
WEIGHT:
SHEET 1 OF 2





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL STEEL

FINISH POWDER COAT

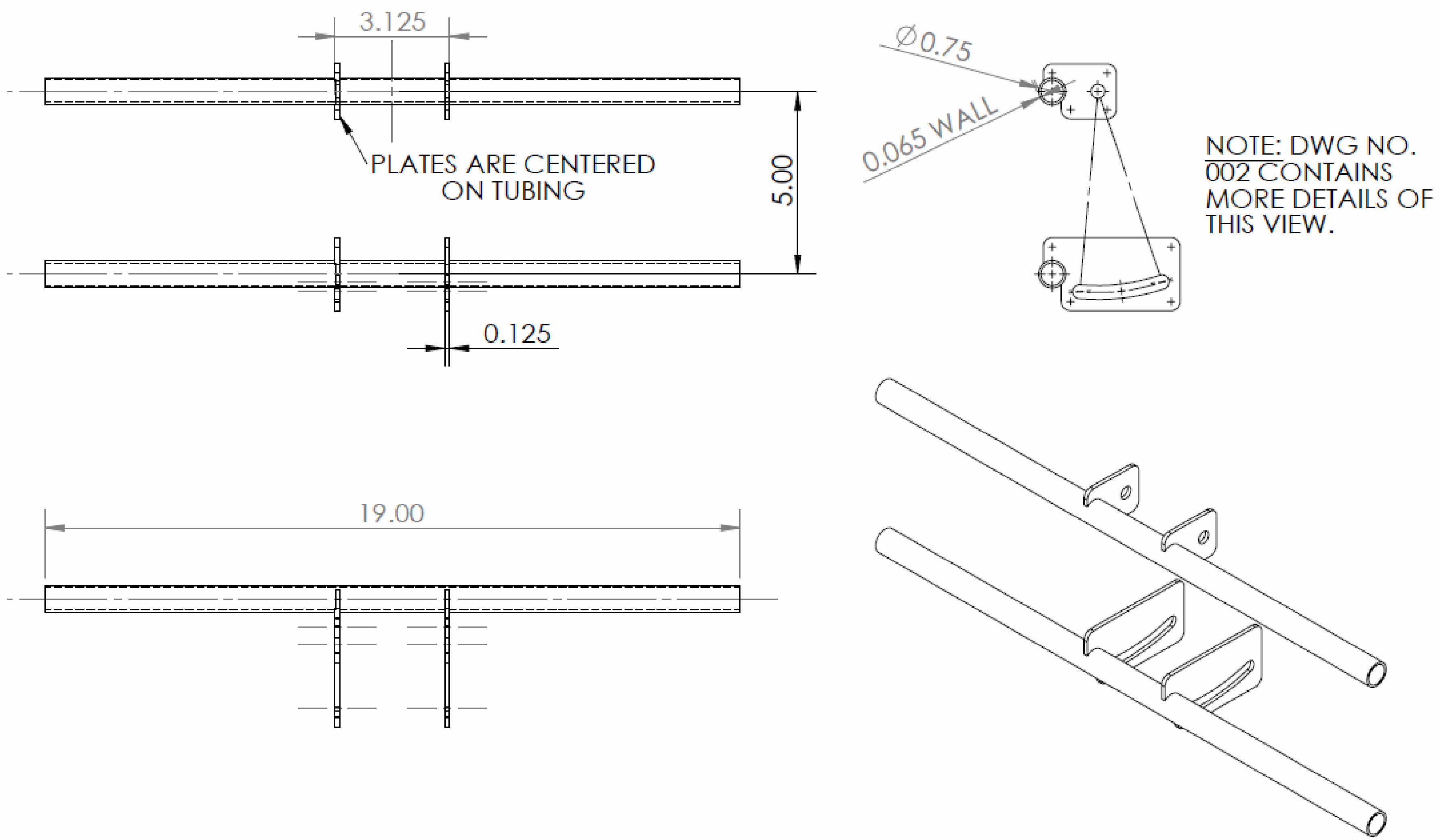
DO NOT SCALE DRAWING

BY: A. SEITZ

TITLE: CENTER ATTACHMENT

SIZE	DWG. NO.	REV
A	XX	B

SCALE: 1:2	WEIGHT:	SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	FW	5/27/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

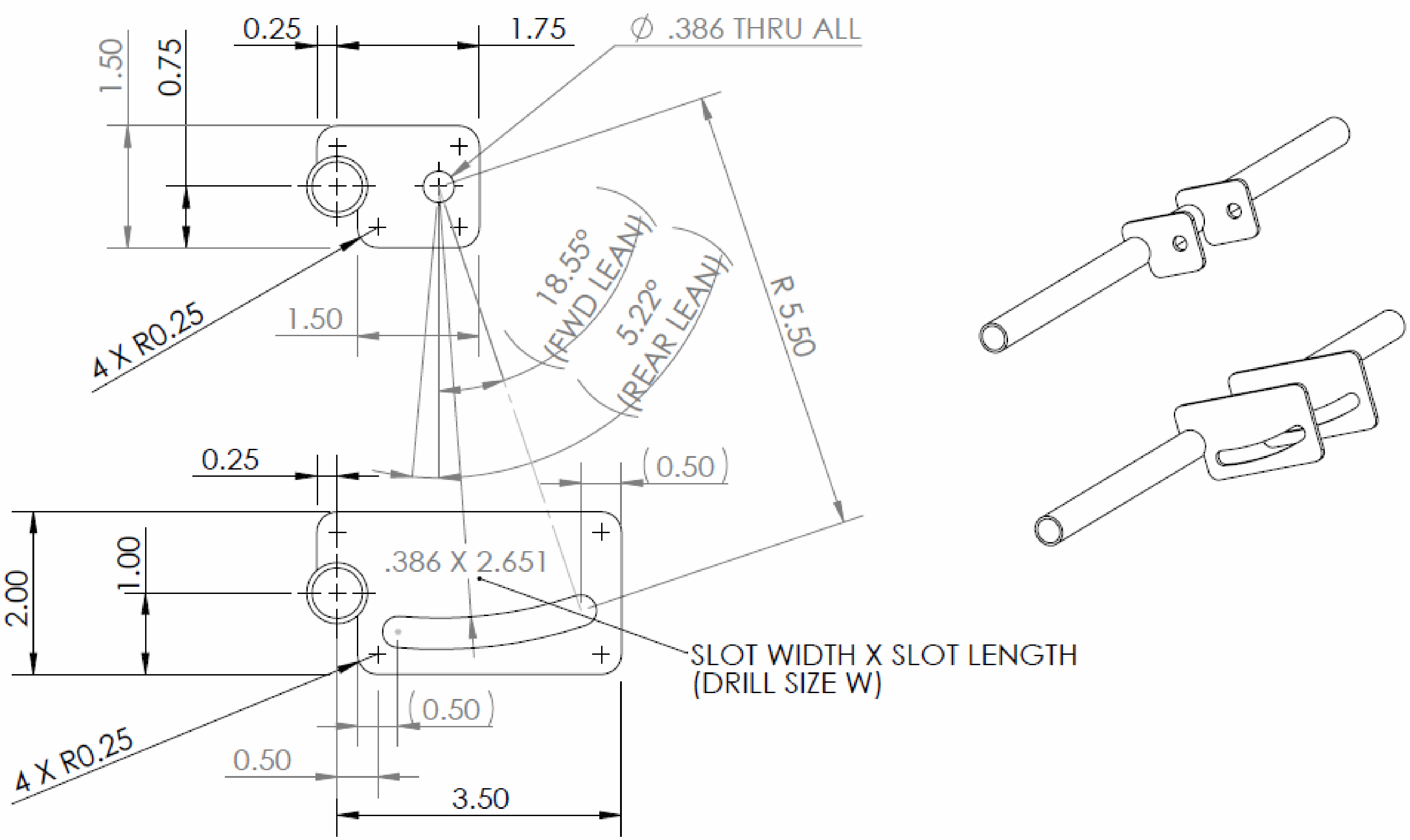
COMMENTS:

TITLE:

Tubing Part

SIZE A | DWG. NO. 001 | REV B

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 4

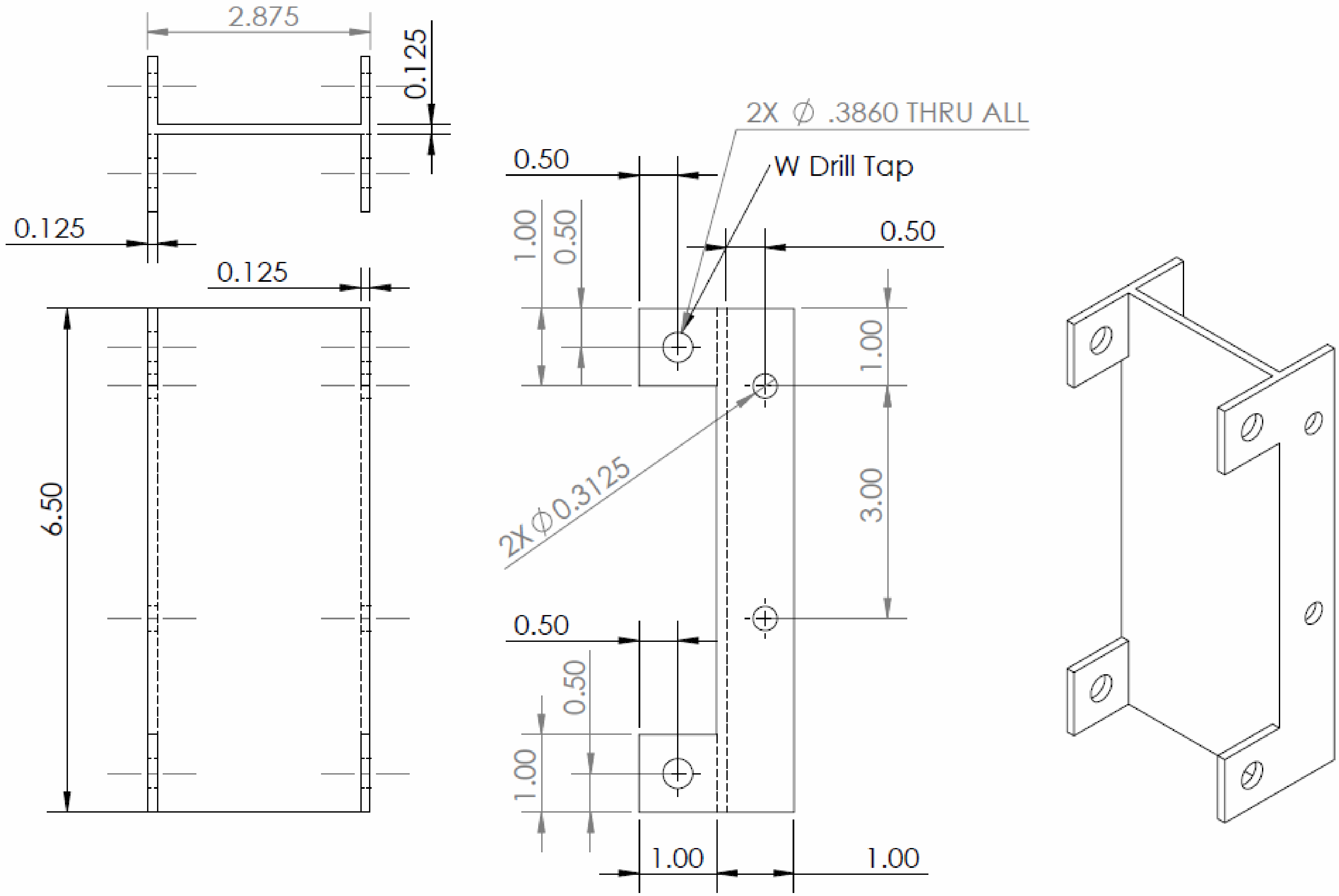


				NAME	DATE
		UNLESS OTHERWISE SPECIFIED:	DRAWN	FW	5/27/14
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Tubing Detailed

SIZE	DWG. NO.	REV
A	002	B
SCALE: 1:2	WEIGHT:	SHEET 2 OF 4



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	FW	5/27/14
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: Attachment Bracket

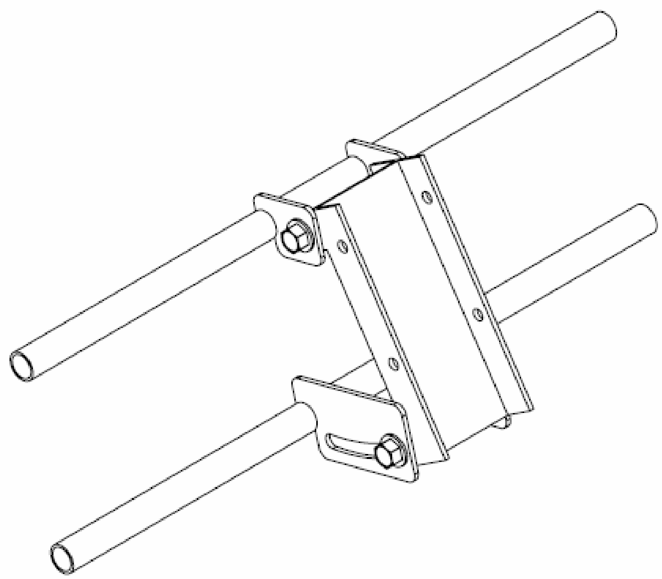
SIZE A | DWG. NO. 003 | REV B

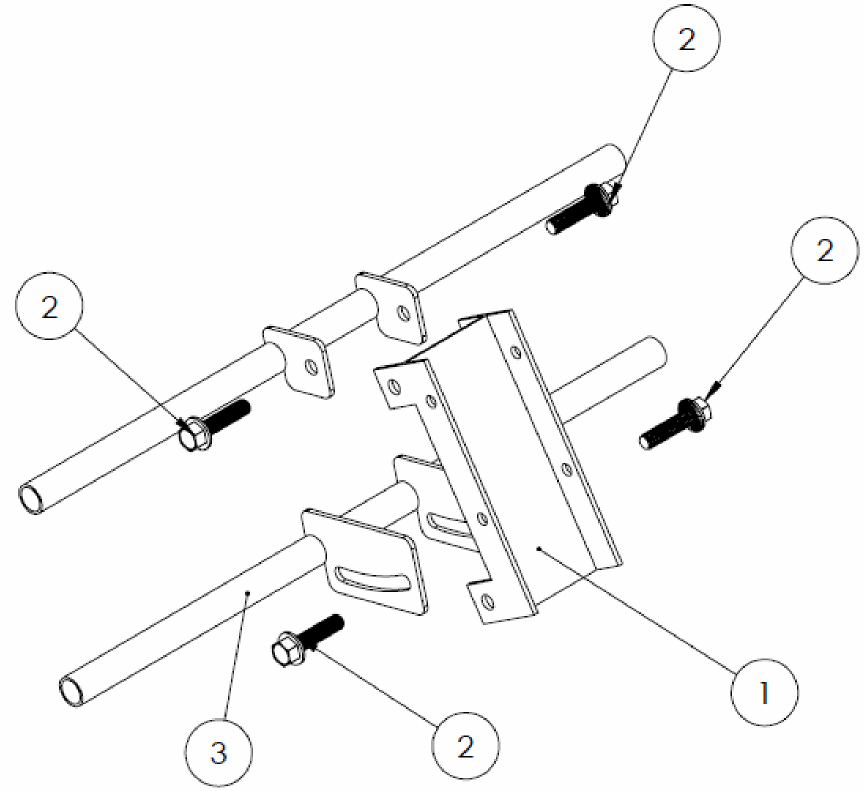
SCALE: 1:2 | WEIGHT: | SHEET 3 OF 4

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

ITEM NO.	PART NUMBER	QTY.
1	Attachment Bracket	1
2	92323A558	4
3	Tubing	1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN	FW	5/27/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

Assembly

SIZE **A** DWG. NO. 004 REV B

SCALE: 1:4 WEIGHT: SHEET 4 OF 4

APPENDIX D – LIST OF VENDORS, CONTACT INFORMATION, AND PRICING

Vendor	Item Description	Part Number	Price
Cambria Bicycle Outfitter (805) 543-1148 1422 Monterey St. San Luis Obispo, CA 93401 www.cambriabike.com slomgr@cambriabike.com	Romic D Shock 7.875” x 2.25”	100047449	$ 99.95
Caster City (800)-501-3808 8635 Bright Angel Way Las Vegas, NV, 89149 www.castercity.com sales@castercity.com	8” Pneumatic Wheel, Centered Hub, 1/2” Ball Bearings	SF8x3-BB12	$27.32
	8” Black Pneumatic Foam Filled Wheel with 1/2” ID Ball Bearings	SF8x3-FF	$58.20
Central Coast Powder Coating (805)-541-0404 3641 Sacramento Dr San Luis Obispo, CA 93401	Blue Powder Coat of the Frame		
	Black Powder Coat of two sets of springs		
Century Springs (213)-749-1466 222 E. 16th Street Los Angeles, CA 90015 www.centuryspring.com info@centuryspring.com	1.937” OD x 4.5” Compression Spring. 97 lbf/in	73002	$83.10
	1.687” OD x 3.5” Compression Spring. 42 lbf/in	72890	$38.14
Home Depot (805)-596-0857 1551 Froom Ranch Way San Luis Obispo, CA 93405	0.451 in 15/32 CAT BC Project Panel		$43.54

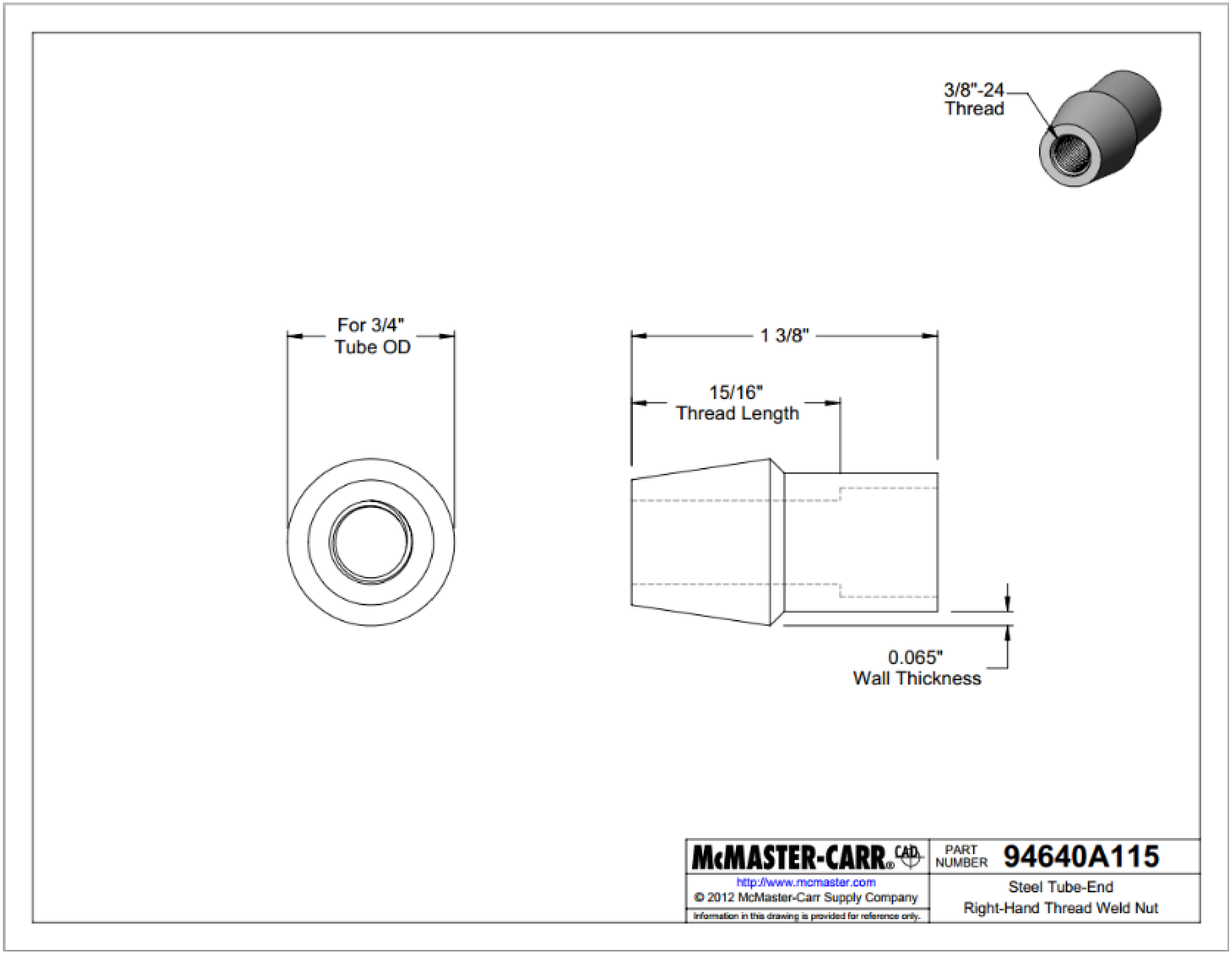
McCarthy Tank and Steel	Item Description	Part Number	Price
(805) 543-1760	1/8" x 2" Flat Bar		$ 5.51
313 South St	3/16" x 2" Flat Bar		$12.30
San Luis Obispo, CA 93401			

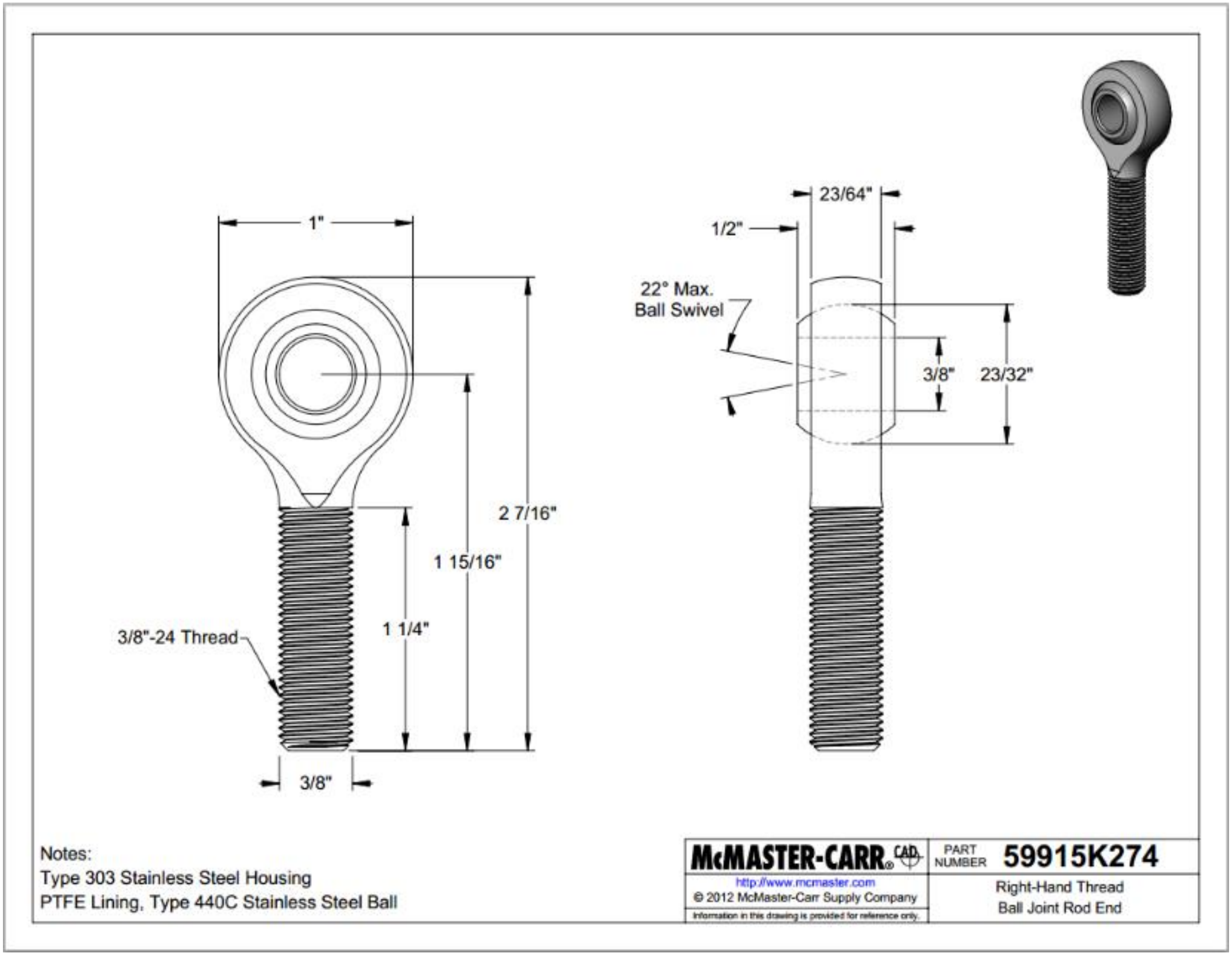
McMaster-Carr	Item Description	Part Number	Price
(562) 692-5911	Tube End Weld Nuts	94640A115	$ 5.04
9630 Norwalk Blvd.	Stainless Steel Ball Joint Rod Ends	59915K274	$ 17.14
Santa Fe Springs, CA 90670-2932			
www.mcmaster.com			
la.sales@mcmaster.com			

Monster Scooter Parts	Item Description	Part Number	Price
(800) 798-0325	8"x2" Foam-Filled Mobility Tire with Spirit Ribbed Tread (Primo)	T05-160	$22.99
www.monsterscooterparts.com	(Use for replacement for front caster tires)		

Precision Machine	Item Description	Part Number	Price
(805) 544-5694	3/4" ERW Steel Tubing 18'		$ 20.00
3681 Sacramento Dr. #2			
San Luis Obispo, CA 93401			
www.precisionmachine.us			
info@precisionmachine.us			

Speedy Metals	Item Description	Part Number	Price
(866)-938-6061	1/2" OD {A} x 0.370" ID {B} x .065" Wall {C} DOM Steel Tube-60"	dom.5x.065-60	$17.14
www.speedymetals.com	3/4" OD {A} x 0.606" ID {B} x .072" Wall {C} DOM Steel Tube-60"	dom.75x.072-60	$152.28
sales@speedymetals.com			


3/8"-24
Thread
For 3/4"
Tube OD
1 3/8"
15/16"
Thread Length
0.065"
Wall Thickness
McMASTER-CARR
CAD
PART NUMBER
94640A115
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Steel Tube-End
Right-Hand Thread Weld Nut


1"
2 7/16"
1 15/16"
1 1/4"
3/8"-24 Thread
3/8"
23/64"
1/2"
22° Max.
Ball Swivel
3/8"
23/32"
Notes:
Type 303 Stainless Steel Housing
PTFE Lining, Type 440C Stainless Steel Ball
McMASTER-CARR
CAD
PART NUMBER
59915K274
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Right-Hand Thread
Ball Joint Rod End

APPENDIX F – DETAILED SUPPORTING ANALYSIS

TEAM NATHAN | HAND CALCULATIONS: PROBLEM STATEMENT | 2/26/14 FRANKIE WIGGINS | ①

GIVEN: STANDING DANI™ SYSTEM W/ NATHAN COOPER AS DRIVER

UNIT SYSTEM: ENG MASS DEG PSIA F

K_s ≡ SPRING RATE = 300 #/IN

L_{ta} ≡ TRAILING ARM LENGTH = 12 IN

L_{ssa} ≡ SPRING-SHOCK ASSEMBLY LENGTH = 8 IN

Δx_{max} ≡ MAX ALLOWABLE SHOCK TRAVEL = 2.25 IN

ROMIC D SHOCKS

SAE 1018 HOT-ROLLED STEEL

FIND: (a) STATIC LOADING ANALYSIS (FACTOR OF SAFETY OF 5*)

(b) STRESS IN TRAILING ARM (AXIAL, BENDING, & PRINCIPAL)

(c) LONGITUDINAL & LATERAL ROLLOVER ANGLE

(d) NATURAL FREQUENCY OF SUSPENSION (~1-2 Hz GOAL)

OTHER ANALYSIS THAT WAS NOT DONE, BUT COULD HAVE BEEN...

STRESS IN MOUNTING TABS

FASTENER SHEAR STRESS

FATIGUE IN TRAILING ARM

FATIGUE IN FRONT STRUCTURE

FATIGUE IN MOUNTING TABS

FATIGUE IN FASTENERS

STRESS IN FRAME STRUCTURE (AXIAL, BENDING, & PRINCIPAL)

ASSUME: FRAME WEIGHT NEGLIGIBLE

MATERIAL (STEEL) IS DUCTILE

FRONT CASTER WEIGHT "

LINEAR SPRING (THIS MAY NOT BE APPROPRIATE FOR LARGE Δx)

TRAILING ARM IS A SINGLE TUBE

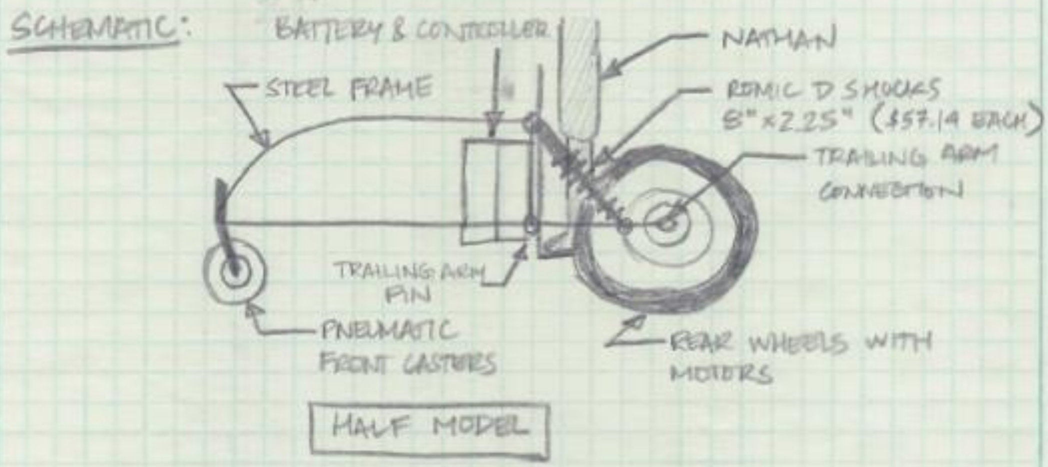
SHEAR & TORSION EFFECTS CONSIDERED NEGLIGIBLE

* F.S. OF 5 RECOMMENDED BY DR. MELLO TO ACCOUNT FOR IMPACT OF 2 FT DROP

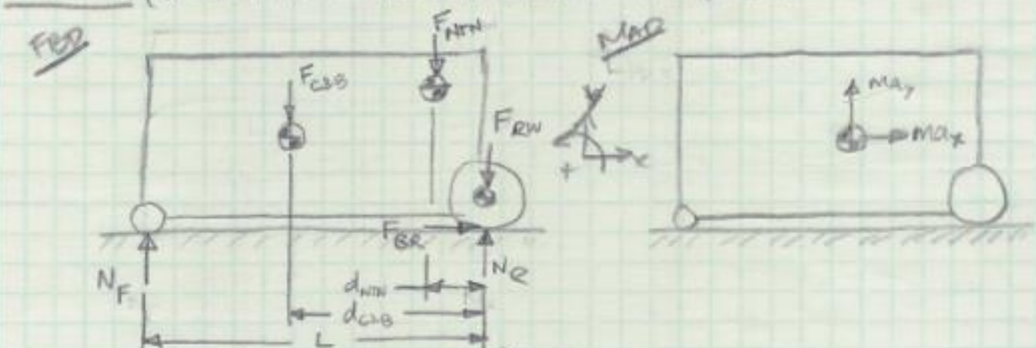
STATIC DEFLECTION

TEAM NATHAN | HAND CALCULATIONS: STATIC LOADING ANALYSIS (SLA) | 2/26/14 FRANKIE WIGGINS (2)

SCHEMATIC:



ANALYSIS: (1) REDRAWING THE SCHEMATIC AS AN FBD....



LOOKING AT THE SYSTEM @ REST...

$ma_x = ma_y = \emptyset$

$\Sigma F_x: \; 0 = F_{BR}$

$\Sigma F_y: \; 0 = (N_F + N_R) - (F_{C\&B} + F_{NTN} + F_{RW}) \quad (1)$

$\Sigma M_R: \; 0 = (F_{C\&B} d_{C\&B} + F_{NTN} d_{NTN}) - (N_F L) \quad (2)$

SOLVING FOR VARIABLES...

$F_{C\&B} \equiv$ WEIGHT OF CONTROLLER & BATTERY w/ F.S. OF 5 FOR ½ MODEL

$F_{NTN} \equiv$ " " NATHAN " " "

$F_{RW} \equiv$ " " REAR WHEEL ASS. " " "

$F_{C\&B} = (m_{C\&B}\, g)(½)(5)$

EACH FORCE CAN BE SOLVED FOR ACCORDINGLY...

$$\begin{bmatrix} F_{C\&B} \\ F_{NTN} \\ F_{RW} \end{bmatrix} = \frac{5}{2} g \begin{bmatrix} m_{C\&B} \\ m_{NTN} \\ m_{RW} \end{bmatrix}$$

KNOWING THAT...

$$\begin{bmatrix} m_{C\&B} \\ m_{NTN} \\ m_{RW} \end{bmatrix} = \begin{bmatrix} 9\ kg \\ 18\ kg \\ 11.2\ kg \end{bmatrix}$$

← GIVEN IN S.I. UNITS, CONVERT AFTER CALCS FOR FORCES

$$g = 9.81\ m/s^2$$

THEREFORE...

$$\begin{bmatrix} F_{C\&B} \\ F_{NTN} \\ F_{RW} \end{bmatrix} = \begin{bmatrix} 221\ N \\ 441\ N \\ 275\ N \end{bmatrix} \left(\frac{1\ lbf}{4.4482\ N} \right)$$

$$\begin{bmatrix} F_{C\&B} \\ F_{NTN} \\ F_{RW} \end{bmatrix} = \begin{bmatrix} 49.62 \\ 99.24 \\ 61.75 \end{bmatrix} [lbf] \qquad (3)$$

NOW WRITING DOWN DISTANCES...

$$\begin{bmatrix} d_{C\&B} \\ d_{NTN} \\ L \end{bmatrix} = \begin{bmatrix} \text{DIST. BETWEEN CG OF C\&B \& R.W. CENTER} \\ \text{" " " " NATHAN " "} \\ \text{" " F.W. CENTER " " "} \end{bmatrix}$$

FROM SOLIDWORKS DRAWINGS...

$$\begin{bmatrix} d_{C\&B} \\ d_{NTN} \\ L \end{bmatrix} = \begin{bmatrix} 13\ IN \\ 2\ IN \\ 25\ IN \end{bmatrix} \qquad (4)$$

↓

NOW SOLVING FOR N_F USING EQN(2)...

$$0 = \left[(49.62\ \text{LBF})(15\ \text{IN}) + (99.24\ \text{LBF})(2\ \text{IN})\right] - N_F(25\ \text{IN})$$

$$N_F = 37.712\ \text{LBF}$$

FINALLY SOLVING FOR N_R USING EQN(1)...

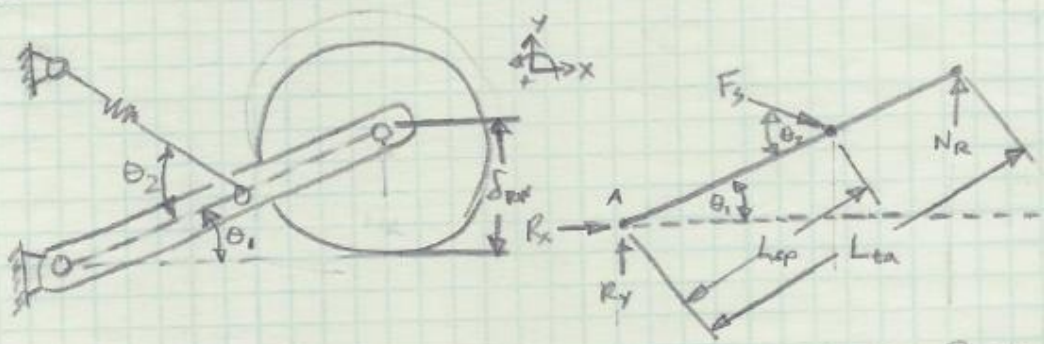
$$0 = \left[(37.712\#) + N_R\right] - \left[(49.62\#) + (99.24\#) + (61.75\#)\right]$$

$$\boxed{N_R = 172.90\ \text{LBF}} \qquad (5)$$

(2) NOW FINDING HOW MUCH REAR ASSEMBLY DEFLECTS UNDER STATIC LOADING...

DRAWING A NEW SCHEMATIC & FBD...

SCHEMATIC | FBD



AN M.A.D. COULD BE DRAWN SIMILAR TO FBD, ma_x & ma_y WOULD BOTH EQUAL ZERO B/C SYSTEM IS @ REST...

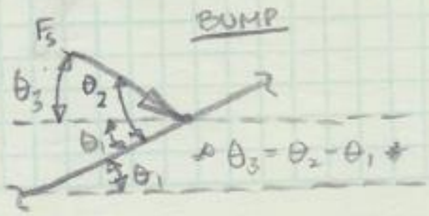
$$\Sigma M_A: 0 = N_R L_{ta}\cos\theta_1 - \left(F_{s,x} L_{sp}\sin\theta_1 + F_{s,y} L_{sp}\cos\theta_1\right) \qquad (6)$$

SOLVING FOR THE AMOUNT OF VERTICAL DEFLECTION OF THE REAR WHEEL...

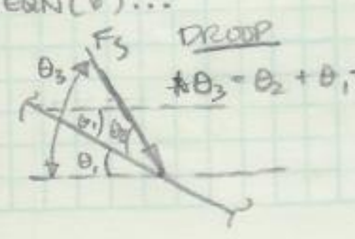
$$\delta_{RW} = L_{ta}\sin\theta_1 \qquad (7)$$

NOW SOLVING FOR THE UNKNOWNS IN EQN(6)...

BUMP



DROOP



SINCE THE WEIGHT OF THE SYSTEM WILL CAUSE A BUMP (DOWNWARD FORCE), THE DROOP EQN WILL BE IGNORED...

$\theta_3 = \theta_2 - \theta_1 \equiv$ DIRECTION OF F_3 WRT HORIZON (BUMP) (8)

~~$\theta_3 = \theta_2 + \theta_1$ (DROOP)~~

THEREFORE...

$F_{s,x} = F_s \cos|\theta_2 - \theta_1|$ (9)

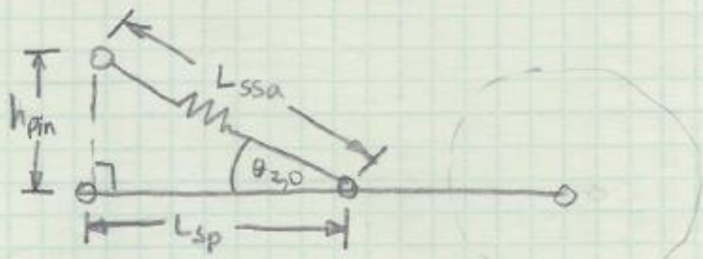
$F_{s,y} = F_s \sin|\theta_2 - \theta_1|$ (10)

ABSOLUTE VALUE BARS ACCOUNT FOR WHEN $\theta_1 > \theta_2$

NOW THE ONLY UNKNOWNS ARE θ_1, θ_2, F_s & L_{sp}. FIRST LOOKING @ L_{sp}...

$L_{sp} \equiv$ LENGTH OF TRAILING ARM UP TO SHOCK PIVOT

LOOKING @ THE GEOMETRY OF THE SPRING...



THE SYSTEM IS ADJUSTABLE SO THAT h_{pin} & L_{sp} COULD CHANGE, BUT L_{ssa} WILL REMAIN FIXED. THE GEOMETRIC RELATIONS ARE THEN...

$L_{ssa}^2 = h_{pin}^2 + L_{sp}^2$ (11)

$\sin\theta_{2,0} = \frac{h_{pin}}{L_{ssa}}$ (12)

IT SHOULD BE NOTED THAT...

$h_{pin} \equiv$ HEIGHT BETWEEN SHOCK & TRAILING ARM PINJOINTS

$h_{pin} < L_{ssa}$

$L_{sp} < L_{ssa}$

AT THIS POINT, A VALUE FOR h_{pin} OR L_{sp} MUST BE ASSUMED...

$h_{pin} = 4 \text{ IN} = 0.\overline{33} \text{ ft}$

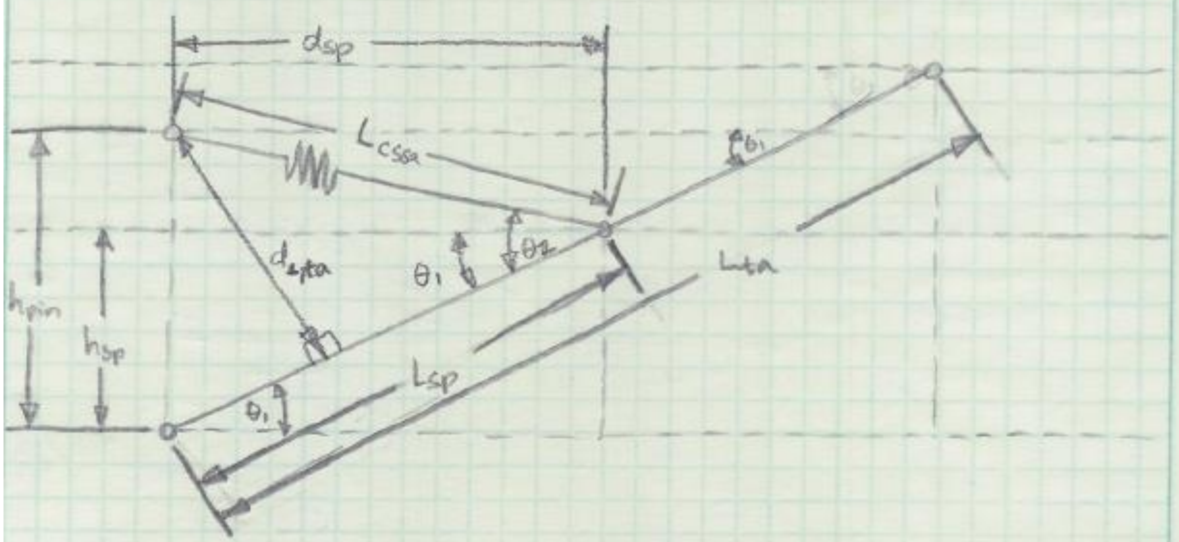
$\therefore L_{sp} = 6.93 \text{ IN} \approx 0.577 \text{ ft}$

$\theta_{20} \equiv$ INITIAL $\theta_2 = 30°$ ← (THIS WILL CHANGE)

NOW ONLY θ_1, θ_2, & F_s ARE UNKNOWN, SOLVING FOR F_s...

$$F_s = k_s \Delta x \qquad (12)$$

IN ORDER TO DETERMINE HOW MUCH Δx IS, NEED TO LOOK @ GEOMETRY OF DEFLECTED SYSTEM...



KNOWING THAT...

$$\Delta x = L_{ssa} - L_{cssa} \qquad (13)$$

$L_{csa} \equiv$ LENGTH OF COMPRESSED SPRING-SHOCK ASSEMBLY

NOW FINDING L_{cssa} USING THE FOLLOWING STEPS...

① DEFINE θ_1 AND USE AIA THEOREM

② " h_{pin}, L_{sp}, & L_{ta}

③ DEFINE h_{sp}

$$h_{sp} = L_{sp} \sin\theta_1 \qquad (14)$$

AT THIS POINT WE HAVE TWO MORE UNKNOWNS (L_{cssa} & θ_2) THAN EQUATIONS...

④ DEFINE d_{sp}

$$d_{sp} \equiv L_{sp} \cos \theta_1 \qquad (15)$$

⑤ CREATING AN EQN RELATING L_{cssa}, θ_1, θ_2 & d_{sp}...

$$d_{sp} = L_{cssa} \cos |\theta_2 - \theta_1| \qquad (16)$$

⑥ DEFINE DISTANCE $d_{\perp,ta}$

$$d_{\perp,ta} = h_{pin} \sin(90° - \theta_1) \qquad (17)$$

$d_{\perp,ta} \equiv$ PERPENDICULAR DISTANCE BTWN PIN & TRAILING ARM

⑦ RELATING $d_{\perp,ta}$, L_{cssa}, & θ_2...

$$\theta_2 = \sin^{-1}\left(\frac{d_{\perp,ta}}{L_{cssa}}\right) \qquad (18)$$

NOW THE NUMBER OF EQUATIONS MATCHES THE UNKNOWNS. AT THIS POINT THE EQUATIONS SHOULD BE SOLVED IN A PROGRAM LIKE ENGINEERING EQUATION SOLVER (EES).

THE MAIN RESULTS FROM THIS PROGRAM ARE LISTED BELOW. THE PROGRAM IS ATTACHED AT THE END.

$\delta_{rw,in}$ = 4.982 [IN]

$\delta_{rw,in,NOSF}$ = 0.9964 [IN] ← W/o SF

ΔX_{in} = 1.598 [IN]

θ_1 = 24.53°

θ_2 = 34.64°

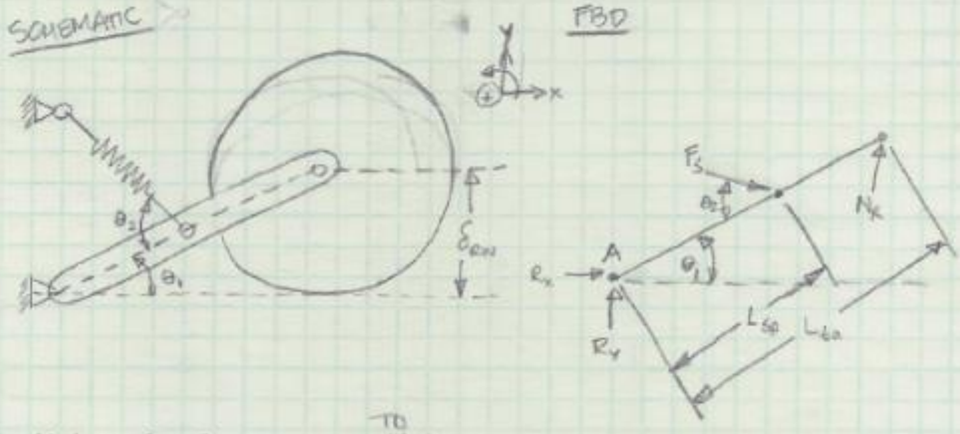
N_R = 172.9 [lbf]

TEAM NATHAN | HAND CALCULATIONS: STRESS IN TRAILING ARM (STA) | 2/24/14 FRANKIE WIGGINS | (8)

SCHEMATIC: FROM PART (2) OF HCs: SLA...

SCHEMATIC

FBD

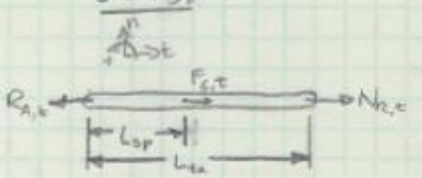


ANALYSIS: FIRST, WE NEED TO FIND THE COMPONENTS OF STRESS IN THE AXIAL & BENDING DIRECTIONS.

REDRAWING THE TRAILING ARM AS A SINGLE TUBE...

IN ORDER TO FIND THE AXIAL STRESS WE NEED TO DRAW SOME FBD's OF JUST THE AXIAL FORCES...

OVL FBD



$$\Sigma F_t = 0$$

$$0 = -R_{A,t} + F_{s,t} + N_{R,t}$$

$$R_{A,t} = F_{s,t} + N_{R,t} \qquad (19)$$

$$F_{s,t} = F_s \cos\theta_2 \qquad (20)$$

≡ TANGENTIAL COMPONENT OF SPRING FORCE

$$N_{R,t} = N_R \sin\theta_1 \qquad (21)$$

≡ TANGENTIAL COMP. OF NORMAL FORCE

GEOMETRY PROOF

NOTING THAT THIS HAS INTERMEDIATE FORCES, THE AXIAL DEFLECTION CAN BEST REPRESENTED AS...

$$\delta_a(x) = \int_0^{L_{sp}} \frac{P_1}{EA}\,dx + \int_{L_{sp}}^{L_{TA}} \frac{P_2}{EA}\,dx \quad \text{FOR } L_{sp} \le x \le L_{TA}$$

↓

$$\delta_a(x) = \frac{1}{EA}\left[\int_0^{L_{sp}} P_1\,dx + \int_{L_{sp}}^{L_{TA}} P_2\,dx\right] \quad \text{FOR } L_{sp} < x \leq L_{TA}$$

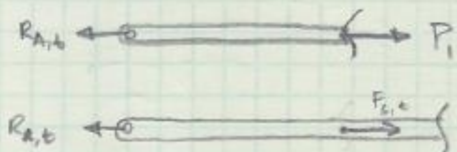
$$\delta_a(x) = \frac{1}{EA}\int_0^{L_{sp}} P_1\,dx \quad \text{FOR } 0 \leq x \leq L_{sp}$$

SOLVING THESE INTEGRALS...

$$\delta_a(L_{sp} \leq x \leq L_{TA}) = \frac{P_1 L_{sp} + P_2(L_{TA} - L_{sp})}{EA} \qquad (22)$$

$$\delta_a(0 \leq x \leq L_{sp}) = \frac{P_1 L_{sp}}{EA} \qquad (23)$$

NOW SOLVING FOR P_1 & P_2 USING FBD'S...



$$P_1 = F_{s,t} + N_{R,t} \qquad (24)$$

$$P_2 = N_{R,t} \qquad (25)$$

SOLVING FOR 'A', THE CROSS-SECTIONAL AREA OF THE TUBING...

$$A = \frac{\pi}{4}\left[d_t^2 - (d_t - 2t_t)^2\right] \qquad (26)$$

$d_t \equiv$ DIAMETER OF TUBING = 0.750 IN (27)

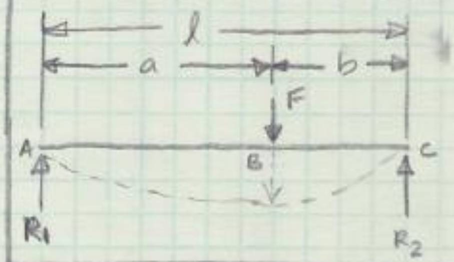
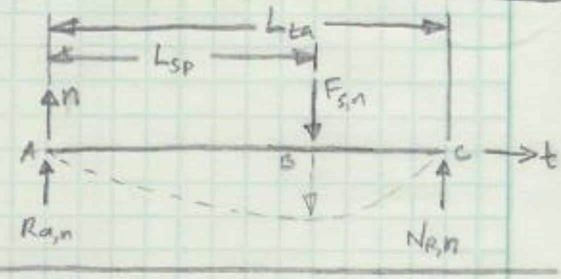
$t_t \equiv$ THICKNESS OF TUBING = 0.090 IN (28)

LOOKING IN SHIGLEY'S DESIGN TEXTBOOK, 9TH EDITION...

$E = 30.0E6$ PSI $\equiv$ MODULUS OF ELASTICITY (29)

NOW LOOKING @ THE BENDING STRESS IN THE TUBE. USING SHIGLEY'S TABLE A-9 (BEAM 6) AS A TEMPLATE FOR ANALYSIS...

REDRAWING TO BE MORE LIKE SHIGLEY'S DEF'N...

	SHIGLEY'S DEFN	TEAM NATHAN APPLICATION
SCHEMATIC		
MOMENT EQN'S	$M_{AB} = \frac{Fbx}{l}$ $M_{BC} = \frac{Fa(l-x)}{l}$	$M_{AB} = \frac{F_{s,n}(L_{ta}-L_{sp})x}{L_{ta}}$ (30) $M_{BC} = \frac{F_{s,n} L_{sp} (L_{ta}-x)}{L_{ta}}$ (31)
DEFLECTION EQN'S	$\delta_{AB} = \frac{Fbx}{6EIl}(x^2+b^2+l^2)$ $\delta_{BC} = \frac{Fa(l-x)}{6EIl}(x^2+a^2-2lx)$	$\delta_{AB} = \frac{F_{s,n}(L_{ta}-L_{sp})x}{6EIL_{ta}}\left[x^2+(L_{ta}-L_{sp})^2+L_{ta}^2\right]$ (32) $\delta_{BC} = \frac{F_{s,n} L_{sp}(L_{ta}-x)}{6EIL_{ta}}(x^2+L_{sp}^2-2L_{ta}x)$ (33)

NOW LOOKING AT THE UNKNOWNS IN EQN'S (30) – (33)...

$F_{s,n} \equiv$ NORMAL COMPONENT OF SPRING FORCE $= F_s \sin\theta_2$ (34)

$L_{ta} \equiv$ LENGTH OF TRAILING ARM (DEFINED IN HCs: S.L.A)

$L_{sp} \equiv$ LENGTH TO SHOCK PIVOT ON TRAILING ARM (DEFINED IN S.L.A.)

$X \equiv$ DISTANCE FROM TRAILING ARM PIVOT ON FRAME (VARIES) ← ALONG t-AXIS

$E \equiv$ SEE EQN (29)

$I \equiv$ MOMENT OF INERTIA ABOUT BENDING AXIS

USING ENGINEERINGTOOLBOX.COM FOR MOMENT OF INERTIA FOR TUBING...

$$I = \frac{\pi}{64}\left[d_t^4 - (d_t - 2t)^4\right] \quad (35)$$

NOW WRITING OUT THE EQN FOR BENDING STRESS IN THE TRAILING ARM...

$$\sigma_b = \frac{M_z c_n}{I_n} \quad (36)$$

SOLVING FOR UNKNOWNS IN EQN (36)...

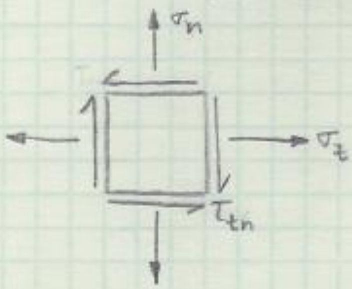
$$M_z = \begin{cases} M_{AB} & 0 \le x \le L_{sp} \\ M_{BC} & L_{sp} < x \le L_{ta} \end{cases} \quad (37)$$

$C_n = 0.5 d_t \equiv$ DISTANCE FROM AXIS TO MOMENT APPLICATION (GREATEST BENDING STRESS IS AT O.D.) (38)

$I_n = I$ (39)

NOW THAT BENDING AND AXIAL STRESS (↙ NEXT PAGE) HAVE BEEN SOLVED FOR, THE RESULTING PRINCIPAL STRESSES SHOULD BE CALCULATED TO DETERMINE THE WORST-CASE LOCATION...

DRAWING A STRESS BLOCK & USING MOHR CIRCLE CRITERIA...



$\sigma_t = \sigma_a$ ← (ACTUALLY SOLVED FOR ON NEXT PAGE - MISTAKE) (40)

$\sigma_n = \sigma_b$ (41)

$\tau_{tn} \cong 0$ (NEGLIGIBLE SHEAR STRESS) ← $\frac{L_{ta}}{d_t} > 10$ (42)

$\sigma_1, \sigma_2 \equiv$ PRINCIPAL STRESSES

$$\sigma_1 = \frac{\sigma_t + \sigma_n}{2} + \sqrt{\frac{(\sigma_t - \sigma_n)^2}{2} + (\tau_{tn})^2} \quad (43)$$

$$\sigma_2 = \frac{\sigma_t + \sigma_n}{2} - \sqrt{\left(\frac{\sigma_t - \sigma_n}{2}\right)^2 + (\tau_{tn})^2} \quad (44)$$

PLUGGING THESE EQUATIONS INTO EES (PROGRAM ATTACHED) AND LOOKING FOR THE MAXIMUM MAGNITUDES OF σ_1 & σ_2 FOR VALUES OF $0 \le x \le L_{ta}$. ALSO, LOOKING FOR THE FACTOR OF SAFETY INVOLVING YIELD FAILURE...

$\sigma_{MAX} = \frac{S_y}{n_{y,fs}} \equiv$ DUCTILE MATERIAL STRESS THEORY (SHIGLEY'S) (45)

$\sigma_{MAX} = MAX(|\sigma_1|, |\sigma_2|) \equiv$ MAXIMUM STRESS (46)

$S_y \equiv$ YIELD STRENGTH OF MATERIAL $= 32E3$ PSI (47)
← (TABLE A-20, SHIGLEY'S)

$n_{y,fs} \equiv$ YIELD FACTOR OF SAFETY

NOW SOLVING FOR AXIAL STRESS (ACCIDENTALLY SOLVED FOR AXIAL DEFLECTION ON PAGE 11 & 12)...

$$\sigma_a(x) = \begin{cases} P_1/A & 0 \le x \le L_{sp} \\ P_2/A & L_{sp} < x \le L_{ta} \end{cases} \quad (48)$$

AFTER MINIMIZING $n_{y,fs}$ IN EES FOR VALUES OF 'X', THE RESULTS WERE FOUND TO BE WHAT IS LISTED BELOW. THE PROGRAM IS ATTACHED.

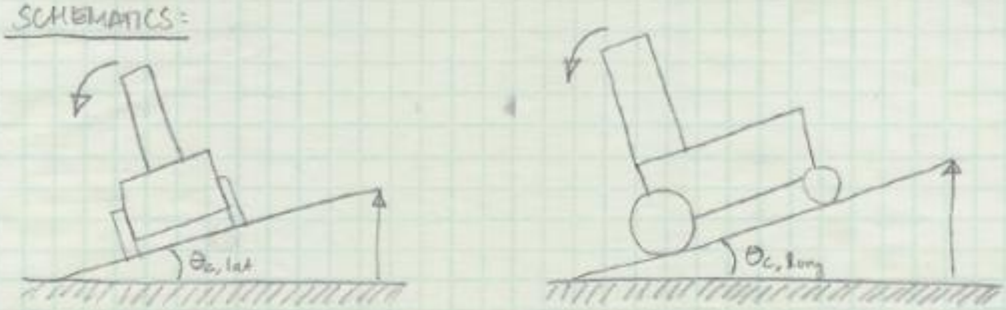
VARIABLE	UNITS	VALUE (SF=5)	VALUE2 (SF=3)	VALUE3 (SF=1)
$\delta_{a,in}$	IN	6.42E-4	3.852E-4	1.284E-4
$\delta_{b,in}$	IN	-3.01E-2	-1.905E-2	-6.578E-3
σ_t	PSI	384.7	156.3	19.86
σ_n	PSI	28,903	18,293	6318
σ_1	PSI	34,809	22,050	7622
σ_2	PSI	-5,522	-3600	-1284
$n_{y,fs}$	–	0.9193	1.451	4.198

*NOTICE THAT $n_{y,fs}$ IS LOWER THAN '1.2'. FOR THIS REASON, A FEW ITERATIONS WERE DONE WITH SF BEING LOWERED EACH TIME. THE RESULTS ARE SHOWN ABOVE.

[THE LOCATION WHERE THESE VALUES OCCURRED WAS AT X = 0.5774 FT, THE SPRING-SHOCK PIVOT LOCATION.]

HAND CALCULATIONS:
TEAM NATHAN — TILTOVER ANGLE ANALYSIS (RAA) — 4/12/14 WIGGINS (13)

SCHEMATICS:



ANALYSIS IS BASED ON WWW.SLIDESHARE.NET/HEBRONASHRAF/VEHICLE-ROLLOVER-ANALYSIS#

ANALYSIS: LOOKING @ SLIDE 29 OF 42, THE TILT TABLE TEST & RATIO...

TILT TABLE RATIO ≡ TTR
$TTR = \tan \theta_c$

BASED OFF OUR SPECIFICATIONS, WE DESIRE A TTR OF...

$TTR \geq 0.466$ ← CORRESPONDS TO AN ANGLE, θ_c, OF 25°

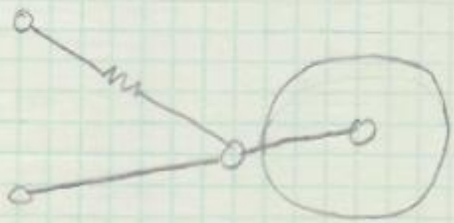
FROM WIKIPEDIA.ORG/TILT_TEST_(VEHICLE_SAFETY_TEST), UK DOUBLE-DECKER BUSES MUST SURVIVE AN ANGLE OF 28° IN THE TILT TEST.

[FOR EQUATIONS RELATED TO DYNAMIC ROLLOVER, SEE SLIDE 19 OF 42 OF THE SLIDESHARE PRESENTATION...]

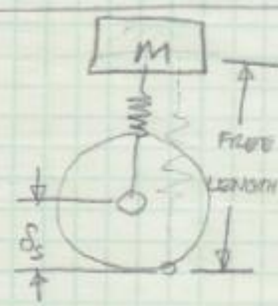
TEAM NATHAN | HAND CALCULATIONS: NATURAL FREQUENCY (NF) | 4/11/14 FRANKIE WIGGINS (14)

SCHEMATIC

ACTUAL



HOW WE WANT TO MODEL IT



KNOWING THAT THE NATURAL FREQUENCY CAN BE ESTIMATED BY... (MERLO)

$$\omega_n = \sqrt{\frac{g}{\delta_s}}, \quad g = 32.2\ ft/s^2$$

$\delta_s \equiv$ WHEEL STATIC DISPL. @ REST

$\delta_s = 0.9964$ IN ← PAGE (7)

SOLVING FOR $f_n = \omega_n / 2\pi$...

$$f_n = \sqrt{\frac{32.2\ ft/s^2}{(0.9964\ in)\left(\frac{1\ ft}{12\ in}\right)}} \cdot \frac{1}{2\pi}$$

$$\boxed{f_n = 3.13\ Hz}$$ ← A LITTLE STIFF, BUT THIS IS JUST AN APPROXIMATION

File:T:\Tube Technical Analysis2.EES 6/10/2014 3:27:52 PM Page 1
EES Ver. 9.442: #552: For use by Mech. Engin. Students and Faculty at Cal Poly

```
"Engineering Equation Solver (EES) Code"
"Analyzing Loading on the new Standing Dani(TM) Suspension"
"Team Nathan, teamnathan2014@gmail.com"
"Analyzed by Frankie Wiggins, 1/23/2014"
"Updated on 3/13/2014"

$UnitSystem ENG MASS DEG PSIA F
$TABSTOPS 0.25 0.5 0.75 1 1.25 in
$Complex Off

"************************"
"Functions"
"************************"
FUNCTION FindAxialStress(x)
$COMMON P_1,P_2,A,L_sp
	IF (x >= 0) and (x <= L_sp) THEN
		FindAxialStress := P_1/A
	ELSE
		FindAxialStress := P_2/A
	ENDIF
END

FUNCTION FindAxialDeflection(x)
$COMMON P_1,P_2,L_sp,L_ta,E,A
	IF (x >= 0) and (x <= L_sp) THEN
		FindAxialDeflection := P_1*L_sp/(E*A)
	ELSE
		FindAxialDeflection := (P_1*L_sp + P_2*(L_ta - L_sp))/(E*A)
	ENDIF
END

FUNCTION FindMomentZ(x)
$COMMON L_sp,F_s_n,L_ta
	IF (x >= 0) and (x <= L_sp) THEN
		FindMomentZ := F_s_n*(L_ta - L_sp)*x/L_ta
	ELSE
		FindMomentZ := F_s_n*L_sp*(L_ta - x)/L_ta
	ENDIF
END

FUNCTION FindBendDeflection(x)
$COMMON L_sp,M_z,L_ta,E,I
	IF (x >= 0) and (x <= L_sp) THEN
		FindBendDeflection := (M_z*(x^2 + (L_ta - L_sp)^2 + L_ta^2))/(6*E*I)
	ELSE
		FindBendDeflection := (M_z*(x^2 + L_sp^2 - 2*L_ta*x))/(6*E*I)
	ENDIF
END

"************************"
"Given"
"************************"
k_s = 300*12                    "lbf/ft"
L_ta = 12/12                    "ft"
L_ssa = 8/12                    "ft"
DELTAx_max = 2.25/12            "ft"
```

```

"*************************"
"System Statics"
"*************************"
0 = N_F + N_R - (F_C&B + F_NTN + F_RW)        "Sum of Forces Y"
0 = F_C&B*d_CB + F_NTN*d_NTN - (N_F*L)        "Sum of Moments about Rear Wheel Contact"

{SF = 5                                       "Loading Safety Factor"}
g = 9.81                                      "m/s^2"
NtoLBF = 1/4.44822162

F_C&B = m_C&B*(1/2)*SF*g*NtoLBF               "lbf"
F_NTN = m_NTN*(1/2)*SF*g*NtoLBF               "lbf"
F_RW = m_RW*(1/2)*SF*g*NtoLBF                 "lbf"

d_CB = 15/12                                  "ft"
d_NTN = 2/12                                  "ft"
L = 25/12                                     "ft"

m_C&B = 9                                     "kg"
m_NTN = 18                                    "kg"
m_RW = 11.2                                   "kg"

"*************************************"
"Rear Trailing Arm Statics"
"*************************************"
0 = N_R*L_ta*cos(theta_1) - (F_s_x*L_sp*sin(theta_1) + F_s_y*L_sp*cos(theta_1)) "lbf-ft"

delta_rw= L_ta*sin(theta_1)                   "ft, OBJECTIVE"
delta_rw_in = delta_rw*12                     "in"
delta_rw_in_NoSF = delta_rw_in/SF             "in"

F_s_x = F_s*cos(abs(theta_2-theta_1))         "lbf"
F_s_y = F_s*sin(abs(theta_2-theta_1))         "lbf"

L_ssa^2 = h_pin^2 + L_sp^2                    "ft"
{h_pin = 4/12                                 "ft"}

F_s = k_s*DELTAx                              "lbf"
DELTAx = L_ssa - L_cssa                       "ft"
DELTAx_in = DELTAx*12                         "in"

h_sp = L_sp*sin(theta_1)                      "ft"
d_sp = L_sp*cos(theta_1)                      "ft"
d_sp = L_cssa*cos(abs(theta_2-theta_1))       "ft"
d_p_ta = h_pin*sin(90-theta_1)                "ft"
sin(theta_2) = d_p_ta/L_cssa                  "deg"

LevRatio = delta_rw/DELTAx                 "Leverage Ratio"
"**********************************************"
"Rear Trailing Arm Stress Analysis"
"**********************************************"
{x = L_sp                                     "ft, OPTIMIZATION VARIABLE"}

R_a_t = F_s_t + N_R_t                         "lbf"
```

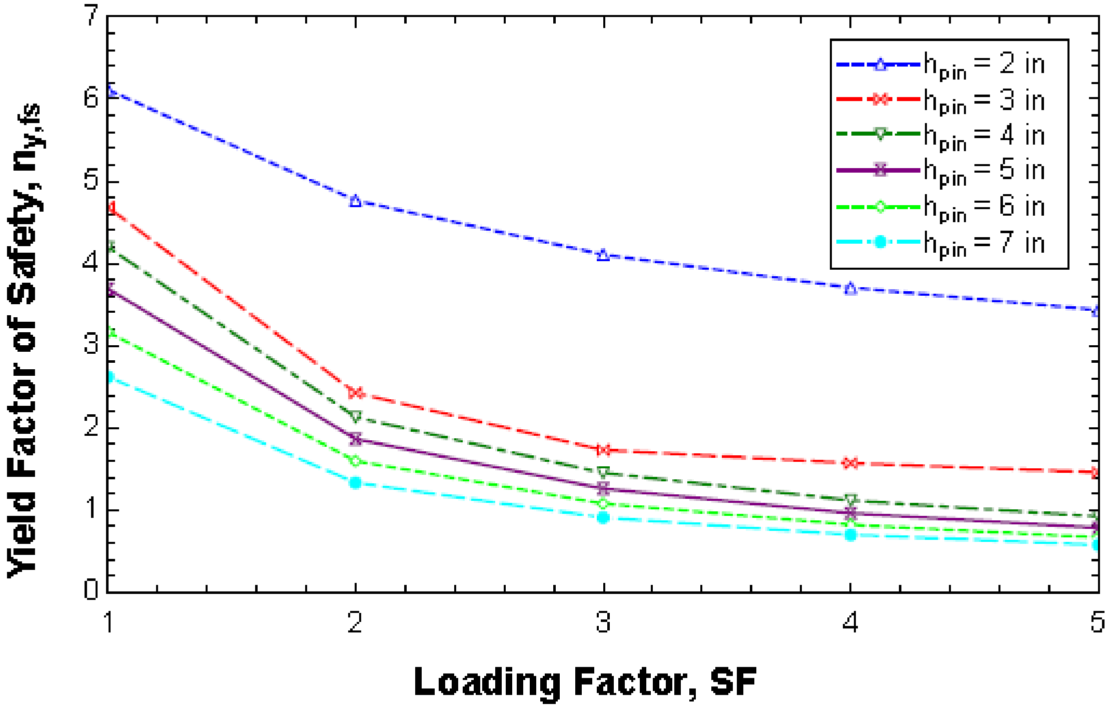
```
F_s_t = F_s*cos(theta_2)                              "lbf"
N_R_t = N_R*sin(theta_1)                              "lbf"

sigma_a_psf = FindAxialStress(x)                 "psf"
P_1 = R_a_t                                           "lbf"
P_2 = N_R_t                                           "lbf"
A = (pi/4)*(d_t^2 - (d_t - 2*t_t)^2)                  "ft^2"
d_t = 0.750/12                                             "ft"
t_t = 0.090/12                                        "ft"
E = 30E6*144                                          "psf"

sigma_b_psf = M_z*c_n/I_n                             "psf"
M_z = FindMomentZ(x)                                  "lbf*ft"
F_s_n = F_s*sin(theta_2)                              "lbf"
c_n = 0.5*d_t                                         "ft"
I_n = I                                               "ft^4"

sigma_t = sigma_a_psf/144                             "psi"
sigma_n = sigma_b_psf/144                             "psi"
RatioBtoA = sigma_n/sigma_t                           "Ratio of Bending to Axial Stress"
tau_tn = 0                                                 "psi"
sigma_1 = ((sigma_t + sigma_n)/2) + SQRT(((sigma_t - sigma_n)^2)/2 + tau_tn^2)        "psi"
sigma_2 = ((sigma_t + sigma_n)/2) - SQRT(((sigma_t - sigma_n)^2)/2 + tau_tn^2)        "psi"

n_y_fs = S_y/sigma_max
S_y = 32e3                                                 "psi"
sigma_max = max(abs(sigma_1),abs(sigma_2)) "psi"

"*********************************************"
"Rear Trailing Arm Deflection Analysis"
"*********************************************"
delta_a = FindAxialDeflection(x)                      "ft"
delta_a_in = delta_a*12                               "in"
delta_b = FindBendDeflection(x)                       "ft"
delta_b_in = delta_b*12                               "in"
I = (pi/64)*(d_t^4 - (d_t - 2*t_t)^4)                 "ft^4"

"________"
"Works Cited"
"________"
"Area Moment of Inertia.' Area Moment of Inertia. N.p., n.d. Web. 28 Jan. 2014."

"Budynas, Richard G., J. Keith. Nisbett, and Joseph Edward. Shigley. Shigley's Mechanical Engineering Design. New York:
McGraw-Hill, 2011. Print."
```

Parametric Table: Changing SF & h_pin, Minimizing n_y_fs with 'x'

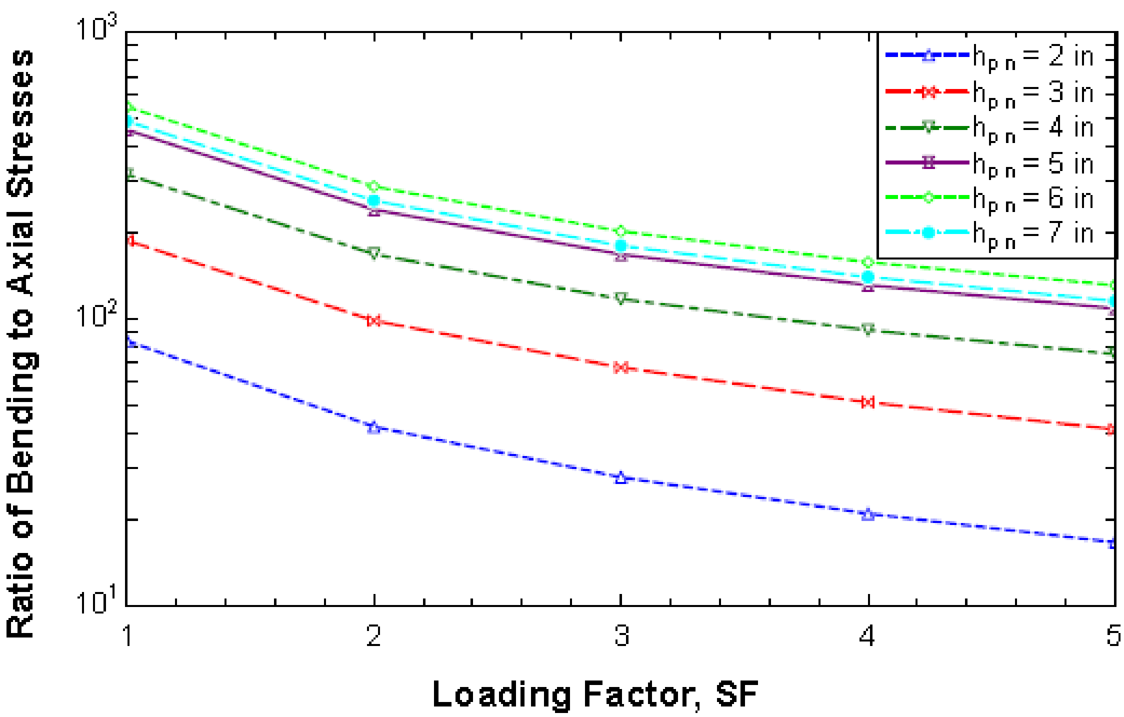
Table examines how changing the intial loading factor, SF, affects the results of the analysis. In the data table, the Yield FS was minimized for the condition using the distance along the trailing arm, 'x'.

	SF	h_{pin} [ft]	x [ft]	δ[illegible] [ft]	N_R [lbf]	RatioBtoA	LevRatio	σ_{max} [psi]	$n_{y,fs}$
Run 1	1	0.08333	0.6614	0.3216	34.58	19.69	11.85	1405	22.78
Run 2	2	0.08333	0.6614	0.4359	69.16	9.58	11.76	1835	17.44

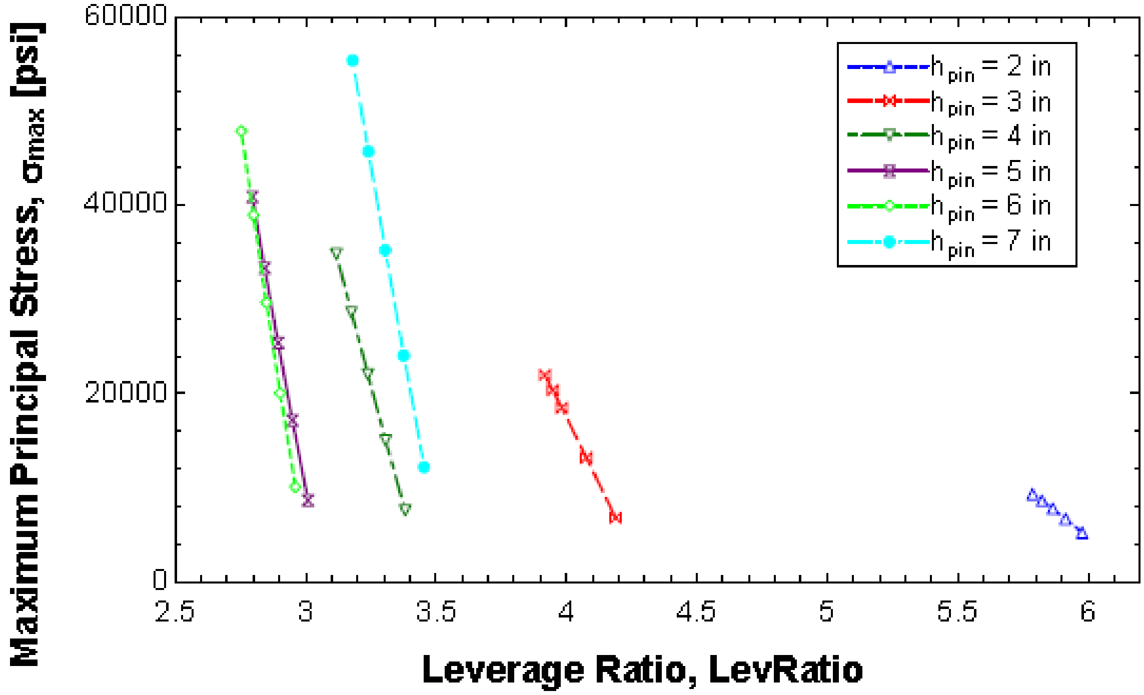
Shows how changing a given loading factor and distance betwen the shock and trailing arm pivots affects the Factor of Safety. Important when looking at when failure will occur (at what loading and at what pin height).



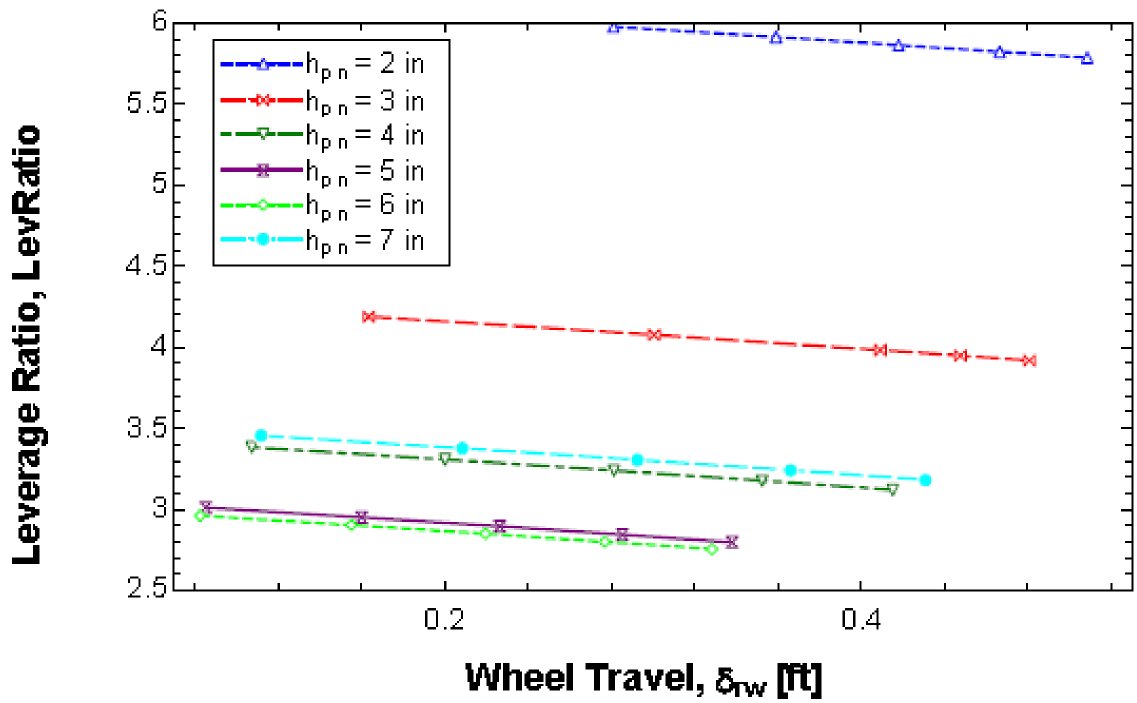
Shows how changing a given loading factor and distance betwen the shock and trailing arm pivots affects the Ratio of Bending to Axial Stresses. Important to look at when considering axial effects (they seem rather negligible for what is shown).



Shows how changing the Leverage Ratio and distance betwen the shock and trailing arm pivots affects the Maximum Stress. Important when considering what happens to the stress when the Leverage Ratio is increased



Shows how changing the Wheel Travel and distance betwen the shock and trailing arm pivots affects the Leverage Ratio. Important because this is a style of measuring shock performance.



SUSPENSION BEHAVIOR

After determining the behavior of the system through hand calculations, we chose to pursue a dynamic, computer model. This had seemed especially important initially considering our project dealt with suspension and dampening the effects of changing road surfaces. The analysis that we did was done entirely in MATLAB® and Simulink®. However, as we moved forward in design and time became more precious, we decided to move away from the model as a design tool. Our observations from earlier in the project are presented below.

TABLE 13. LIST OF CHANGES MADE TO KYLE'S ORIGINAL PROGRAM.

Change	Description
Variation Mode, X=3	*One vehicle parameter can be varied. For our project, we are most concerned with varying rear spring stiffness.*
Excitation Mode, E = 2	*Different excitation modes (a fancy way of saying road surface type) can be chosen. We looked at a sine wave, which is like a trail on Montana de Oro.*
Tire Stiffness, kkF1 & kkR2	*Since our tires feel solid to the touch, we chose high stiffness values that still produced realistic output values.*
Tire Damping, cF1 & cR1	*When any realistic damping effects of the tires were included in our model, the output produced unrealistic results. Therefore, we set damping to zero.*
Tire Mass, mm1 & mm2	*The front tire mass, mm1, was determined using caster weight. The rear tire mass, mm2, was determined using rear wheel weight.*
Suspension Stiffness, kkF2 & kkR2	*Similar to tire stiffness, the lack of a front spring meant we chose a high stiffness for the front. For the rear, we used the stock spring rate.*
Suspension Damping, ccF2, ccR2	*We assumed critical damping and then solved for the damping coefficient using the tire mass and suspension stiffness.*
Geometry Parameters	*The dimensions like overall length, greatest width, and height were determined from the prototype modeling in SolidWorks.*
Moment of Inertia in Roll & Pitch, $\boldsymbol{I_x}$ & $\boldsymbol{I_y}$	*The inertia of the system was estimated by treating the prototype like a rectangular prism with dimensions based off of the geometry parameters.*
Chassis Mass, mm3	*The mass of the chassis was determined by adding the weight of Nathan (the driver) to the weight of the controller & battery.*

The entire program – excluding our project-specific parameters – was provided by one of the members of our Senior Project class, Kyle Van Allen. Kyle has been a member of the Cal Poly's Society of Automotive Engineers Baja team and he developed the program for one of their race vehicles. The development of this model saved us time and for that we are very thankful (Van Allen & Gavrilovic, 2014). The significant changes that were made to the provided program are listed above in Table 13. The full MATLAB program can be found on the pages following the results. The Simulink model cannot be shown in this report with any detail due to the size and complexity of the sub-models.

The program output is shown on the next few pages. In Figure 74, the most interesting results are that the expected chassis displacement was 0.5 – 1 cm (very small). In Figure 75, it was expected that the rear mass would see greater displacement than the front mass given the existence of an actual rear spring-shock assembly. It was also interesting that the steady-state rear displacement led the excitation. Figure 76 shows that the contact forces are nearly equivalent in magnitude at about 22 pounds.

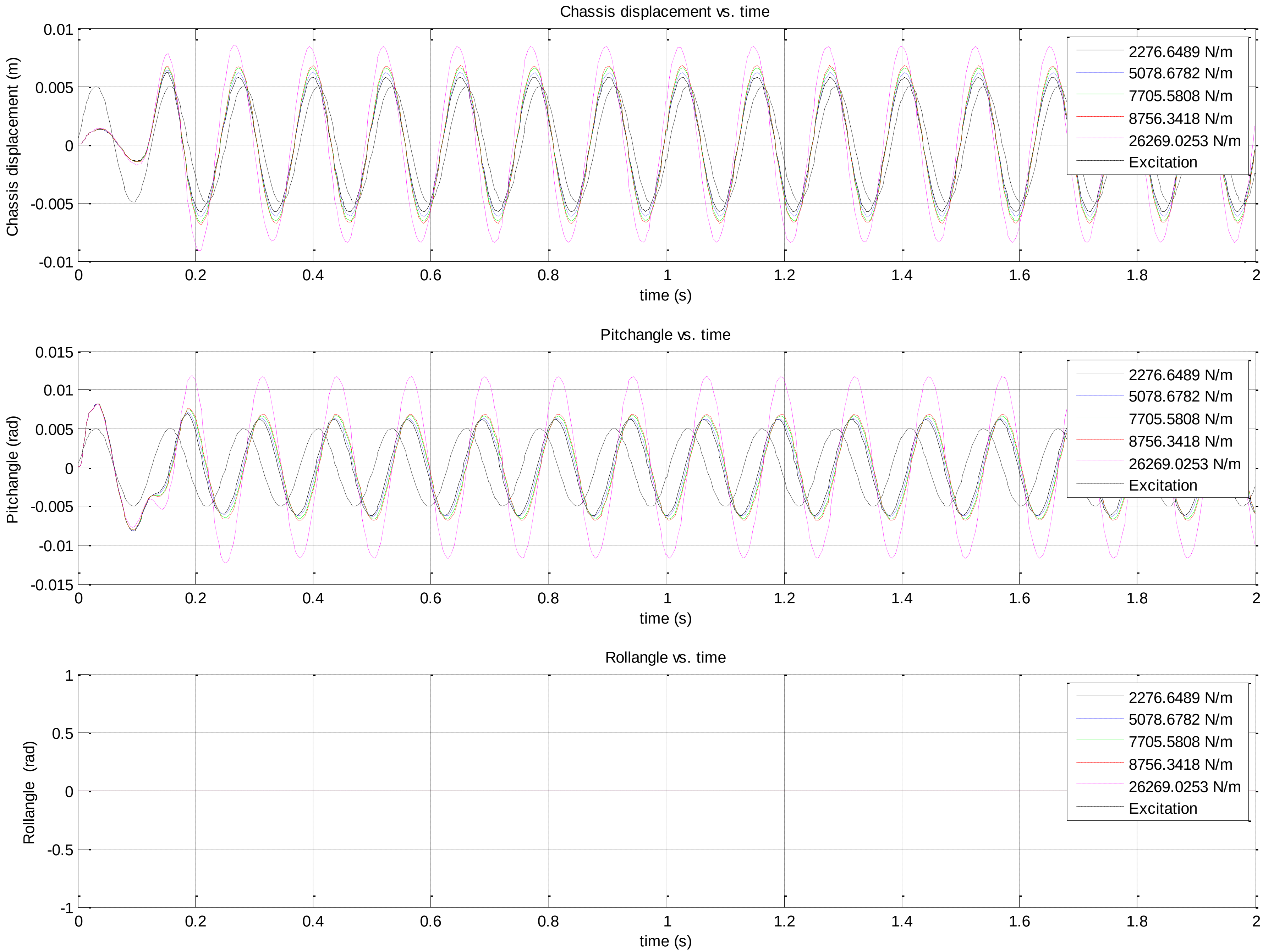


FIGURE 74. MATLAB SUSPENSION ANALYSIS OUTPUT: CHASSIS DISPLACEMENT, PITCHANGLE, AND ROLLANGLE VS. TIME.

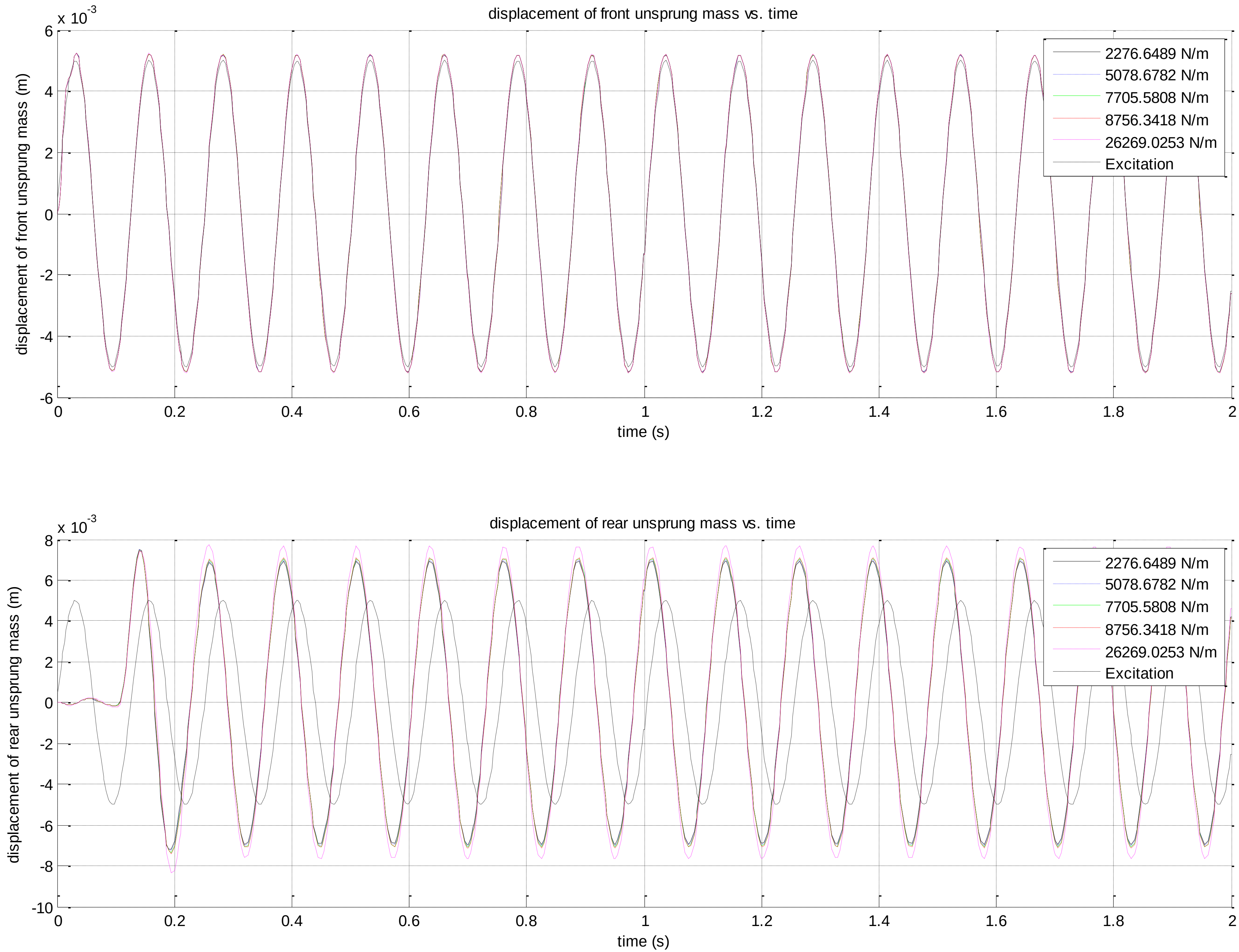
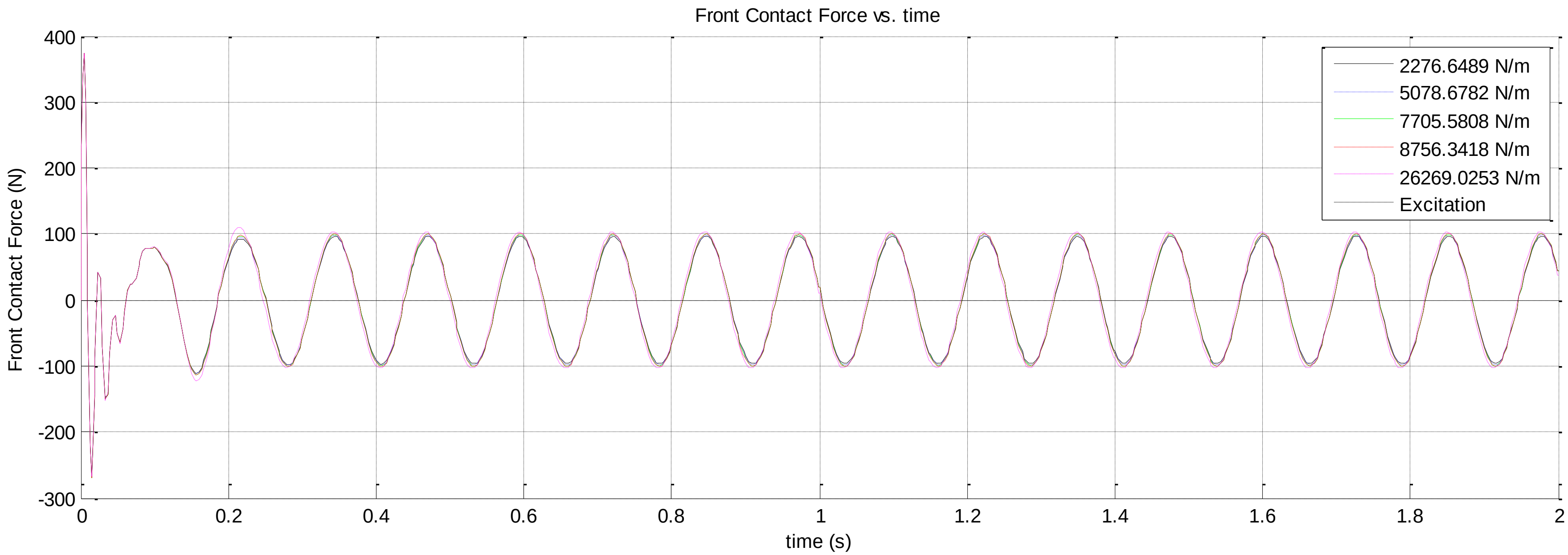


FIGURE 75. MATLAB SUSPENSION ANALYSIS OUTPUT: DISPLACEMENT OF FRONT & REAR UNSPRUNG MASSES VS. TIME.



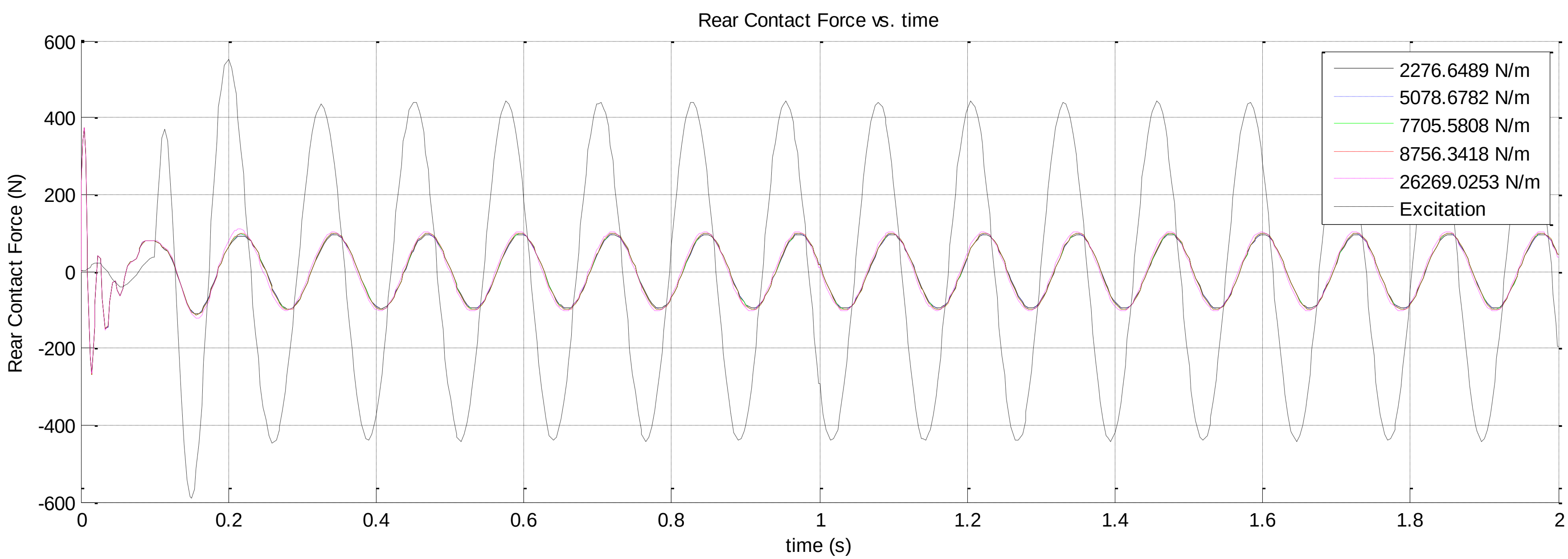


FIGURE 76. MATLAB SUSPENSION ANALYSIS OUTPUT: FRONT & REAR CONTACT FORCES VS. TIME.

```
% TEAM NATHAN modified code
close all
clear all
clc
%----VEHICLE HALF CAR SUPSENSION AND ROLL MODEL----%
%
% By: Kyle VanAllen (805-714-0007) and Nenad Gavrilovic
%
%  Description:
%
% 1. Select the desired variation mode (X) to create different plots (chassis
%    displacement, displacement of unsprung mass front and rear, movement of
%    pitchangle and roll angle)
%
% 2. Select road Excitation (E) mode and adjust the excitation parameters
%
% 3. Select Excitation for the Roll modell (R)
%
% 4. Adjust car parameters (type 5 different parameters where neccesary),
%    mass of tires, stiffnesses and damper coeffiecient has to me multplied.
%
% NOTE: ALL UNITS ARE IN SI-UNITS!

%% Conversion factors for Imperial units
inTOm = 0.0254;          % Conversion of inch to meters
lbfTOnewt = 4.44822162; % Conversion of lbf to Newtons
g = 9.81;                % Gravitational acceleration , m/s2
lbfTOkg = lbfTOnewt/g;  % Conversion of lbf to kg

%% Selecting Different Modes and Adjusting Vehicle Paramters

% select variation mode X:
% 1 = mass of chassis
% 2 = front spring stiffness
% 3 = rear spring stiffness
% 4 = damper value front
% 5 = damper value rear
% 6 = front tire pressure
% 7 = rear tire pressure
% 8 = front tire masses
% 9 = rear tire masses

X = 3;              % -- The only variation we really care about is the rear spring rate

%%-----------------Road Excitation---------------------------------%%

%--select Exitation mode E--%

% 1 = Only step function active
% 2 = only Sin1 excitation active
% 3 = only Sin2 excitation active
% 4 = only short time bump active
% 5 = Sin1 + Sin2 active
% 6 = Step + Sin1 active
% 7 = sin1 + bump active
% 8 = 1-8 active
% 9 = Random + Sin1 active
% 10 = pulse with sinwave function

E = 2;
```

```
%--Adjust Parameters of Excitation--%

f1 = 50;            % Frequency of sin1     (rad/sec) -- Assumed (Off-road is ~15 Hz)
A1 = 0.005;         % Amplitude of sin1     (m) -- Assumed (Off-road is ~0.01 m)

f2 = 15;            % Frequency of sin2     (rad/sec) -- Left with original settings
A2 = 0.01;          % Amplitude of sin2     (m) -- Left with original settings

Ab = 0.01;%0.125*inTOm;   % Height of bump  (m) -- thickness of one 1/8" piece of plywood

As = 0.01;%0.25*inTOm;    % Height of step  (m) -- thickness of two 1/8" pieces of
plywood

%--Activate Excitation for Rollmodel R--%
%
% 0 = off
% 1 = short time bump on the right side;
%

R = 0;              % -- We do not care about roll at this point


%%----------------------------------------------------------------%%

%-Adjust Simulation time-%

T = 2;             % Simulation Time         (sec)

%%-----------------Adjust Vehicle Parameters---------------------------------------------
----------------%%


%--Adjust Parameters of Front Tires--%

kkF1  = 6.5*[52.6e+3, 70e+3, 80e+3, 90e+3,100e+3];      % front tire stiffness/pressure
(N/m)
cF1   = 0;                                              % Damper coefficient of Front
Tire      (Ns/m)
mm1   = lbfTOkg*[4, 6, 8, 10, 12];                      % mass of front wheel (unsprung
mass)   (kg) -- castercity Model# 9SF8X3-S

%--Adjust Parameters of Rear Tires--%

kkR1  = 2*[52.6e+3, 70e+3, 80e+3, 90e+3,100e+3];        % rear tire stiffness/pressure
(N/m)
cR1   = 0;                                              % Damper coefficient of Rear Tire
(Ns/m)
mm2   = [10, 11, 11.2, 12, 13];                         % mass of rear wheel (unsprung
mass)    (kg) -- Alber Adventure Drivewheel = 11.2 kg


%--Adjust Spring and Damper Values in Front and Rear-%

kkF2= 2*[10.5e+3, 15.5e+3, 20.5e+3, 30.5e+3,40.5e+3];   % front spring stiffness
(N/m)
```

```
ccF2= 2*sqrt(mm1(3)*kkF2);                              % front damper coefficient
(Ns/m)

kkR2 = (lbfTOnewt/inTOm)*[26, 58, 88, 100, 300];        % rear spring stiffness
(N/m) -- www.centuryspring.com/Store/search_compression.php
ccR2 = 2*sqrt(mm2(3)*kkR2);                             % rear damper coefficient
(Ns/m) -- Assumed critically damped --> zeta = 1 = c/2*sqrt(k*m)


%--Solving for Inertia Parameters--%%
% Assumed a rectangular prism shape for the moment of inertia calculations.
width = [20.5,14.5];                                    % chassis width, width = [rear,
front]                            (in)
l_x = inTOm*27;                                         % effective wheelbase of vehicle
(along x-axis - roll)           (m)
w_y = inTOm*mean(width);                                % effective track width of
vehicle (along y-axis - pitch)        (m)
h_z = inTOm*17;                                         % effective height of vehicle
(along z-axis - turn)              (m)

%--Geometry parameters---%%

LF = inTOm*20;                                          % front distance (CG-front axle)
(m)
LR = inTOm*7;                                           % rear distance (CG-rear axle)
(m)

WLT = inTOm*mean(width);                                % left width (CG-left tires)
(m)
WRT = inTOm*mean(width);                                % right width (CG-right tires)
(m)

%--Chassis (Mass) Parameter--%%

mm3= 0.5*lbfTOkg*[20, 50, 60, 70, 80];                  % chassis mass (sprung mass)
(kg) mm3 = Half-Model*[No driver, 30lbf driver, 40, 50, 60]
Ix = mm3(3)*(h_z^2+w_y^2)/12;                           % moment of interia for roll
(kgm^2)
Iy = mm3(3)*(l_x^2+h_z^2)/12;                           % moment of interia for pitch
(kgm^2)

% ------------------------------------------------------------------------------------------
-----------------------%

%% Conditions of Excitation

% 1 = Only step function active;
% 2 = only Sin1 excitation active;
% 3 = only Sin2 excitation active;
% 4 = only short time bump active;
% 5 = Sin1 + Sin2 active;
% 6 = Step + Sin1 active
% 7 = sin1 + bump active
% 8 = all active;
% 9 = Random + Sin1 active
% 10 = pulse with sinwave function;

% Condition: Only step function active;
if E == 1
```

```
    SP =1;
    S1 =0;
    S2 =0;
    B = 0;
    RS = 0;
    PPS = 0;
end

% Condition: only Sin1 excitation active;
if E == 2
    SP = 0;
    S1 =1;
    S2 =0;
    B = 0;
    RS = 0;
    PPS = 0;
end

% Condition: only Sin2 excitation active;
if E == 3
    SP = 0;
    S1 =0;
    S2 =1;
    B = 0;
    RS = 0;
    PPS = 0;
end

% Condition: only short time bump active;
if E == 4
    SP = 0;
    S1 =0;
    S2 =0;
    B = 1;
    RS = 0;
    PPS = 0;
end

% Condition: Sin1 + Sin2 active;
if E == 5
    SP = 0;
    S1 =1;
    S2 =1;
    B = 0;
    RS = 0;
    PPS = 0;
end

% Condition: Step + Sin1 active
if E == 6
    SP = 1;
    S1 =1;
    S2 =0;
    B = 0;
    RS = 0;
    PPS = 0;
end

% Condition: sin1 + bump active
if E == 7
    SP = 0;
```

```
    S1 =1;
    S2 =0;
    B = 1;
    RS = 0;
    PPS = 0;
end

% Condition: 1-8 all active;
if E == 8
    SP = 1;
    S1 =1;
    S2 =1;
    B = 1;
    RS = 0;
    PPS = 0;
end

% Condition: Random + Sin1 active
if E == 9
    SP = 0;
    S1 = 0;
    S2 = 0;
    B = 0;
    RS = 1;
    PPS = 0;
end
% Pulse and sinwave
if E == 10
    SP = 0;
    S1 = 0;
    S2 = 0;
    B = 0;
    RS = 0;
    PPS= 1;
end


%% Running Loop
for i=1: 5              % Doing a for loop 5 times, loads parameters from the input
vector and creates plots
%% Loading Values from the input vector

% Loads different values from the input vector that and saves it in a
% constant which is used in the simulink model

% X = Changing in;
% 1 = mass of chassis;
% 2 = front spring stiffness;
% 3 = rear spring stiffness;
% 4 = damper value front;
% 5 = damper value rear;
% 6 = front tire pressure;
% 7 = rear tire pressure;
% 8 = changing front unsprung/tire mass

% Loads mass of chassis from the inputvector mm3 and saves current mass value in m3
if X==1
    m3 = mm3(i);
else
    m3 = mm3(3);
```

```
end

% Loads front spring stiffness from the inputvector kkF2 and saves current value in kF2
if X==2
   kF2 = kkF2(i);
else
   kF2 = kkF2(3);
end

% Loads front rear stiffness from the inputvector  kkR2 and saves current value in kR2
if X==3
   kR2 = kkR2(i);
else
   kR2 = kkR2(3);
end

% Loads front Damper Values from the inputvector  ccF2 and saves current value in cF2
if X==4
   cF2 = ccF2(i);
else
   cF2 = ccF2(3);
end

% Loads rear  Damper Values from the inputvector  ccR2 and saves current value in cR2
if X==5
   cR2 = ccR2(i);
else
   cR2 = ccR2(3);
end

% Loads front tire stiffness from the inputvector  kkF1 and saves current value in kF1
if X==6
   kF1 = kkF1(i);
else
   kF1 = kkF1(3);
end

% Loads Rear tire stiffness from the inputvector  kkR1 and saves current value in kR1
if X==7
   kR1 = kkR1(i);
else
   kR1 = kkR1(3);
end

% Loads Front tire masses from the inputvector  mm1 and saves current value in m1
if X==8
    m1 = mm1(i);
else
    m1 = mm1(3);
end

if X==9
    m2 = mm2(i);
else
    m2 = mm2(3);
end


%% Parameter Calculation for Roll model
```

```
%------------------Calculation of Paramters for the Roll modell (no adjustment needed)----
------------%%

kRT2 = ((kF2+kR2)/2);   % calculation right spring stiffness                 (N/m)
kLT2 = ((kF2+kR2)/2);   % calculation left spring stiffness                  (N/m)

cRT2 = ((cR2+cF2)/2);   % calculation right damper coefficient               (Ns/m)
cLT2 = ((cR2+cF2)/2);   % calculation left damper coefficient                (Ns/m)


kRT1 = ((kF1+kR1)/2);   % calculation right tire spring stiffness            (N/m)
kLT1 = ((kF1+kR1)/2);   % calculation left tire spring stiffness             (N/m)

cRT1 = ((cR1+cF1)/2);   % calculation right tire damper coefficient          (Ns/m)
cLT1 = ((cR1+cF1)/2);   % calculation left tire damper coefficient           (Ns/m)

m2lt = ((m1+m2)/2);     % calculation tire masses left                       (kg)
m2rt = ((m1+m2)/2);     % calculation tire masses right                      (kg)


%% Creating Plots

% Loading output data from the Simulink Model
[t,Z,P]=sim('Halfcarmodel_07_11_2013');

% Creating Vector with different line colors for the plots
C={'-k',':b','-g','--r','-.m'};


if X==1
%%  Plots with different chassis masses

% Plot Chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
```

```
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
         if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');

% Plot: Roll angle
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
```

```
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');
% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
legend(strcat(num2str(mm3(1)), ' kg'),strcat(num2str(mm3(2)), '
kg'),strcat(num2str(mm3(3)), ' kg'),strcat(num2str(mm3(4)), '
kg'),strcat(num2str(mm3(5)), ' kg'),'Excitation');


end


if X==2
%% Creating Plots with different front spring stiffnesses

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
```

```
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
 legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
        plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

%----- Roll model plots----%

figure(1)
```

```
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
legend(strcat(num2str(kkF2(1)/2), ' N/m'),strcat(num2str(kkF2(2)/2), '
N/m'),strcat(num2str(kkF2(3)/2), ' N/m'),strcat(num2str(kkF2(4)/2), '
N/m'),strcat(num2str(kkF2(5)/2), ' N/m'),'Excitation');

end


if X==3
%% Creating Plots with different rear spring stiffnesses

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
```

```
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
```

```
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');
%}

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
```

```
legend(strcat(num2str(kkR2(1)/2), ' N/m'),strcat(num2str(kkR2(2)/2), '
N/m'),strcat(num2str(kkR2(3)/2), ' N/m'),strcat(num2str(kkR2(4)/2), '
N/m'),strcat(num2str(kkR2(5)/2), ' N/m'),'Excitation');
end

if X==4
%%  Creating plots with different front damper values

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
         legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');
```

```
% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
        plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
```

```
          ylabel('Rear Contact Force (N)');
          title('Rear Contact Force vs. time');
                axis auto;
         grid on;
         if i==5
             plot(t,P(:,20),'--k');
         else
         end
legend(strcat(num2str(ccF2(1)/2), ' Ns/m'),strcat(num2str(ccF2(2)/2), '
Ns/m'),strcat(num2str(ccF2(3)/2), ' Ns/m'),strcat(num2str(ccF2(4)/2), '
Ns/m'),strcat(num2str(ccF2(5)/2), ' Ns/m'),'Excitation');
end

if X==5
%%  Creating plots with different rear damper values

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
         xlabel('time (s)');
         ylabel('Chassis displacement (m)');
         title('Chassis displacement vs. time');
         axis auto;
         grid on;
         if i==5
             plot(t,P(:,14),'--k');
         else
         end
          legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
        xlabel('time (s)');
         ylabel('Pitchangle (rad)');
         title('Pitchangle vs. time');
         axis auto;
         if i==5
             plot(t,P(:,14),'--k');
         else
         end
         grid on;
          legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
```

```
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
        plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

 % Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
         legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
```

```
         legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
         legend(strcat(num2str(ccR2(1)/2), ' Ns/m'),strcat(num2str(ccR2(2)/2), '
Ns/m'),strcat(num2str(ccR2(3)/2), ' Ns/m'),strcat(num2str(ccR2(4)/2), '
Ns/m'),strcat(num2str(ccR2(5)/2), ' Ns/m'),'Excitation');
end

if X==6
%%  Creating plots with different front tire stifnesses

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
           legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');
```

```
% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
```

```
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
         legend(strcat(num2str(kkF1(1)/2), ' N/m'),strcat(num2str(kkF1(2)/2), '
N/m'),strcat(num2str(kkF1(3)/2), ' N/m'),strcat(num2str(kkF1(4)/2), '
N/m'),strcat(num2str(kkF1(5)/2), ' N/m'),'Excitation');
end


if X==7
%%  Creating plots with different rear tire stifnesses

% Plot chassis displacement vs. time

figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
```

```
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
```

```
          legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
         legend(strcat(num2str(kkR1(1)/2), ' N/m'),strcat(num2str(kkR1(2)/2), '
N/m'),strcat(num2str(kkR1(3)/2), ' N/m'),strcat(num2str(kkR1(4)/2), '
N/m'),strcat(num2str(kkR1(5)/2), ' N/m'),'Excitation');
end

if X==8
%%  Creating plots with different front tire masses

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
     legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');
```

```
% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');


% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
```

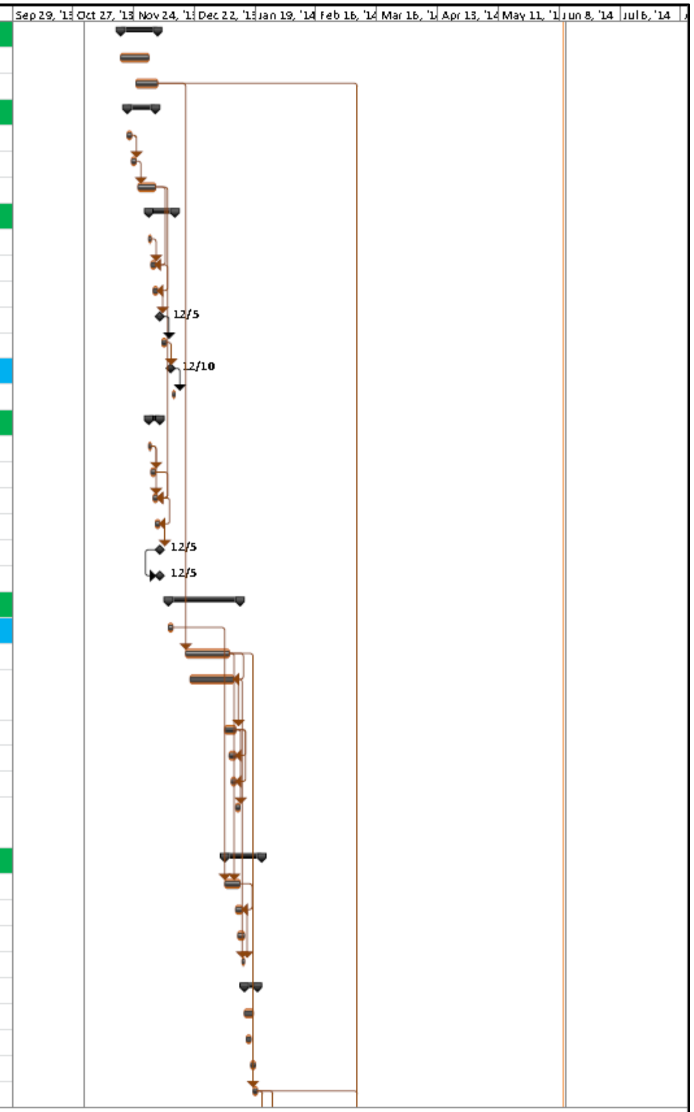
```
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
legend(strcat(num2str(mm1(1)/2), ' kg'),strcat(num2str(mm1(2)/2), '
kg'),strcat(num2str(mm1(3)/2), ' kg'),strcat(num2str(mm1(4)/2), '
kg'),strcat(num2str(mm1(5)/2), ' kg'),'Excitation');
end


if X==9
%%  Creating plots with different front tire masses

% Plot chassis displacement vs. time
figure(1)
subplot(3,1,1)
plot(t,P(:,13),C{i})    ;
     hold on
        xlabel('time (s)');
        ylabel('Chassis displacement (m)');
        title('Chassis displacement vs. time');
```

```
        axis auto;
        grid on;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
     legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: Pitchangle vs. Time
figure(1)
subplot(3,1,2)
 hold on
 plot(t,P(:,10),C{i});
       xlabel('time (s)');
        ylabel('Pitchangle (rad)');
        title('Pitchangle vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: displacement of front unsprung mass
figure(2)
subplot(2,1,1)
     hold on
     plot(t,P(:,1),C{i});
      xlabel('time (s)');
      ylabel('displacement of front unsprung mass (m)');
      title('displacement of front unsprung mass vs. time');
      axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: displacement of rear unsprung mass
figure(2)
subplot(2,1,2)
     hold on
       plot(t,P(:,4),C{i});
      xlabel('time (s)');
        ylabel('displacement of rear unsprung mass (m)');
         title('displacement of rear unsprung mass vs. time');
        axis auto;
        if i==5
            plot(t,P(:,14),'--k');
        else
        end
        grid on;
```

```
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: Rollangle vs. time
figure(1)
subplot(3,1,3)
     hold on
        plot(t,P(:,16),C{i});
         xlabel('time (s)');
         ylabel('Rollangle  (rad)');
         title('Rollangle vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: Front Tire Force
figure(3)
subplot(2,1,1)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Front Contact Force (N)');
         title('Front Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,18),'--k');
        else
        end
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');

% Plot: Rear Tire Force
figure(3)
subplot(2,1,2)
     hold on
        plot(t,P(:,19),C{i});
         xlabel('time (s)');
         ylabel('Rear Contact Force (N)');
         title('Rear Contact Force vs. time');
               axis auto;
        grid on;
        if i==5
            plot(t,P(:,20),'--k');
        else
        end
legend(strcat(num2str(mm2(1)/2), ' kg'),strcat(num2str(mm2(2)/2), '
kg'),strcat(num2str(mm2(3)/2), ' kg'),strcat(num2str(mm2(4)/2), '
kg'),strcat(num2str(mm2(5)/2), ' kg'),'Excitation');
end

end
```

APPENDIX G – GANTT CHART

ID	ℹ	% Complete	Task Name	Duration	Start	Finish
65	✓	100%	**Project Planning**	17 days	Mon 11/18/13	Wed 12/4/13
67	✓	100%	Rough Timeline for Project	13 days	Mon 11/18/13	Sat 11/30/13
66	✓	100%	Baseline Testing	10 days	Mon 11/25/13	Wed 12/4/13
48	✓	100%	**Concept Development**	13 days	Thu 11/21/13	Tue 12/3/13
50	✓	100%	Come up with Concepts	2 days	Thu 11/21/13	Fri 11/22/13
51	✓	100%	Develop Final Idea	2 days	Sat 11/23/13	Sun 11/24/13
49	✓	100%	Develop Final Concept Model (SolidWorks)	8 days	Tue 11/26/13	Tue 12/3/13
40	✓	100%	**Conceptual Design Review Presentation**	12 days	Sun 12/1/13	Thu 12/12/13
47	✓	100%	Outline Presentation	1 day	Sun 12/1/13	Sun 12/1/13
46	✓	100%	Finalize Details of Presentation	2 days	Mon 12/2/13	Tue 12/3/13
45	✓	100%	Rehearse Presentation	2 days	Tue 12/3/13	Wed 12/4/13
44	✓	100%	Give Presentation in Lab	0 days	Thu 12/5/13	Thu 12/5/13
43	✓	100%	Make any necessary changes to presentation	2 days	Sat 12/7/13	Sun 12/8/13
42	✓	100%	Give presentation to Coopers	0 days	Tue 12/10/13	Tue 12/10/13
41	✓	100%	Online reflection (after sponsor presentation)	1 day	Thu 12/12/13	Thu 12/12/13
52	✓	100%	**Conceptual Design Review Report**	5 days	Sun 12/1/13	Thu 12/5/13
58	✓	100%	Break Report into Sections	1 day	Sun 12/1/13	Sun 12/1/13
57	✓	100%	Update Project Proposal	2 days	Mon 12/2/13	Tue 12/3/13
54	✓	100%	Write Conceptual Design Report	2 days	Tue 12/3/13	Wed 12/4/13
56	✓	100%	Edit Conceptual Design Report	2 days	Wed 12/4/13	Thu 12/5/13
53	✓	100%	Send Final Report (.DOCX) to Professor Harding	0 days	Thu 12/5/13	Thu 12/5/13
55	✓	100%	Send Final Report (.PDF) to Coopers	0 days	Thu 12/5/13	Thu 12/5/13
68	✓	100%	**Final Research**	33 days	Tue 12/10/13	Sat 1/11/14
69	✓	100%	Obtain old wheels & take very detailed measurements of device	2 days	Tue 12/10/13	Wed 12/11/13
75	✓	100%	Expand on Ideas from Final Concept to Prep for Mfg Stage #1	20 days	Wed 12/18/13	Mon 1/6/14
74	✓	100%	Find parts for suspension (use as many off-the-shelf parts as possible, develop a database)	20 days	Fri 12/20/13	Wed 1/8/14
71	✓	100%	Research Materials	5 days	Sun 1/5/14	Thu 1/9/14
73	✓	100%	Talk with Dr. Mello about composites use	3 days	Tue 1/7/14	Thu 1/9/14
72	✓	100%	Talk with Rob Carter about Metallurgy	2 days	Wed 1/8/14	Thu 1/9/14
70	✓	100%	Choose/List out materials used with data sheets for any custom parts/frame	2 days	Fri 1/10/14	Sat 1/11/14
28	✓	100%	**Manufacturing Phase #1**	17 days	Sun 1/5/14	Tue 1/21/14
39	✓	100%	Update SolidWorks Model(s)	7 days	Sun 1/5/14	Sat 1/11/14
38	✓	100%	Create SolidWorks Drawings	3 days	Fri 1/10/14	Sun 1/12/14
37	✓	100%	Test Plan Development	3 days	Sat 1/11/14	Mon 1/13/14
36	✓	100%	Develop BOM	1 day	Mon 1/13/14	Mon 1/13/14
29	✓	100%	***Build Replica Frame***	6 days	Tue 1/14/14	Sun 1/19/14
30	✓	100%	Check out prices/buy stock materials	4 days	Tue 1/14/14	Fri 1/17/14
31	✓	100%	Check out/order shocks from bike shops in SLO	2 days	Wed 1/15/14	Thu 1/16/14
32	✓	100%	Prep Components of Frame (Mounting Tabs, etc.)	2 days	Fri 1/17/14	Sat 1/18/14
33	✓	100%	Notch & Weld components of Frame together	2 days	Sat 1/18/14	Sun 1/19/14

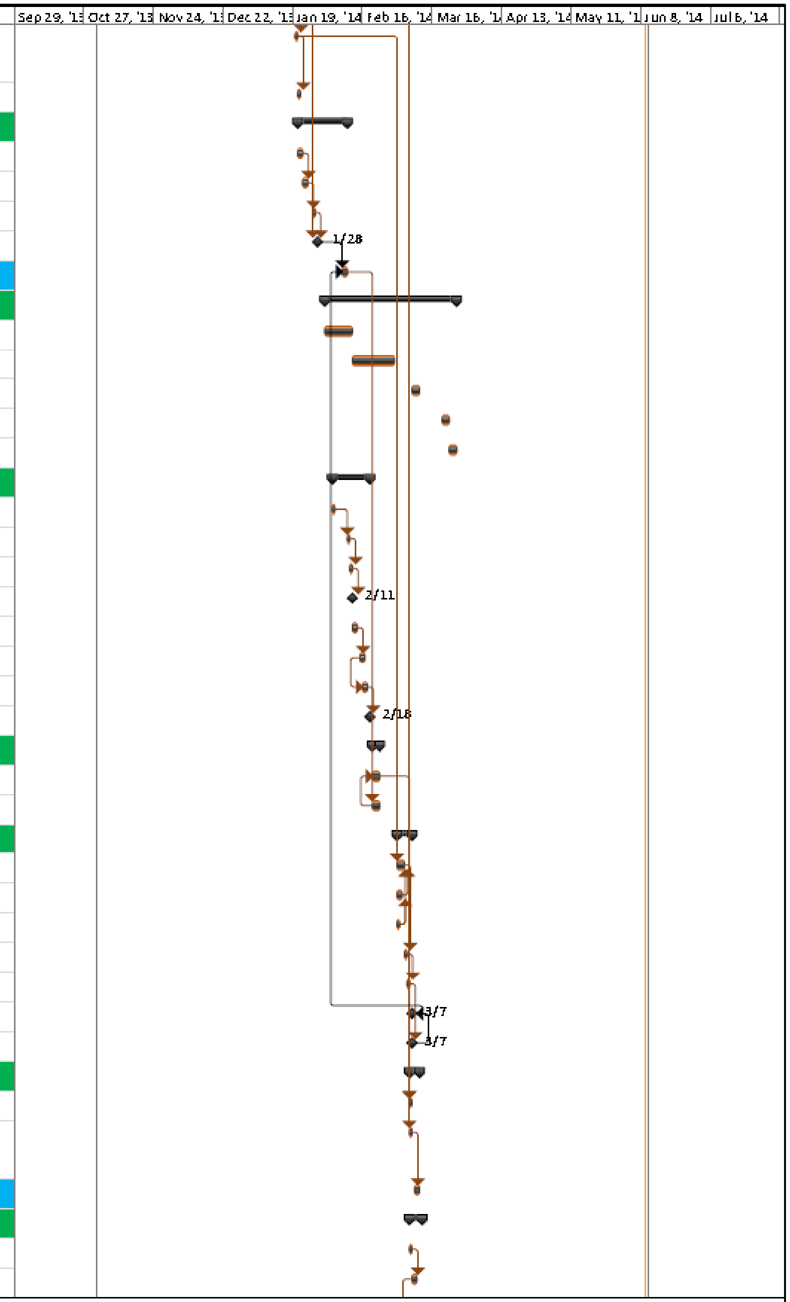


Project: Gantt Chart
Date: Tue 6/10/14

Legend: Task; Split; Milestone; Summary; Project Summary; External Tasks; External Milestone; Inactive Task; Inactive Milestone; Inactive Summary; Manual Task; Duration-only; Manual Summary Rollup; Manual Summary; Start-only; Finish-only; Deadline; Progress

Page 1

ID		% Complete	Task Name	Duration	Start	Finish
35	✓	100%	Make sure design avoids pinch points, avoids ball joints, & has plenty of strength	1 day	Mon 1/20/14	Mon 1/20/14
34	✓	100%	Order long-lead items	1 day	Tue 1/21/14	Tue 1/21/14
76	✓	100%	**Critical Design Review (CDR) Presentation**	**20 days**	**Tue 1/21/14**	**Sun 2/9/14**
81	✓	100%	Prepare outline	2 days	Tue 1/21/14	Wed 1/22/14
80	✓	100%	Finalize look of presentation	2 days	Thu 1/23/14	Fri 1/24/14
79	✓	100%	Rehearse for practice presentations	1 day	Mon 1/27/14	Mon 1/27/14
78	✓	100%	Practice Presentations	0 days	Tue 1/28/14	Tue 1/28/14
77	✓	100%	Presentation review with Coopers	2 days	Sat 2/8/14	Sun 2/9/14
59	✓	100%	**Technical Analysis**	**53 days**	**Sat 2/1/14**	**Tue 3/25/14**
60	✓	100%	Statics Analysis	11 days	Sat 2/1/14	Tue 2/11/14
61	✓	100%	MATLAB suspension analysis	17 days	Wed 2/12/14	Fri 2/28/14
62	✓	100%	Bending Analysis	3 days	Sat 3/8/14	Mon 3/10/14
63	✓	100%	Axial Thrust Loading & Bending in Rod Ends	3 days	Thu 3/20/14	Sat 3/22/14
64	✓	100%	Rollover Analysis (Hand Calculations)	3 days	Sun 3/23/14	Tue 3/25/14
91	✓	100%	**Ethics Memo & Presentation**	**15 days**	**Tue 2/4/14**	**Tue 2/18/14**
99	✓	100%	Choose topic for individual memo	1 day	Tue 2/4/14	Tue 2/4/14
98	✓	100%	Write individual memo	1 day	Mon 2/10/14	Mon 2/10/14
97	✓	100%	Edit individual memo	1 day	Tue 2/11/14	Tue 2/11/14
96	✓	100%	Submit individual ethics memo	0 days	Tue 2/11/14	Tue 2/11/14
95	✓	100%	Outline ethics team presentation	2 days	Wed 2/12/14	Thu 2/13/14
94	✓	100%	Finalize look of presentation	2 days	Sat 2/15/14	Sun 2/16/14
93	✓	100%	Rehearse presentation	2 days	Sun 2/16/14	Mon 2/17/14
92	✓	100%	Give team presentation	0 days	Tue 2/18/14	Tue 2/18/14
17	✓	100%	**Testing Prep**	**3 days**	**Thu 2/20/14**	**Sat 2/22/14**
18	✓	100%	Create mathematical models	3 days	Thu 2/20/14	Sat 2/22/14
19	✓	100%	Make changes to design before tests	3 days	Thu 2/20/14	Sat 2/22/14
20	✓	100%	**Critical Design Review (CDR) Report**	**6 days**	**Sun 3/2/14**	**Fri 3/7/14**
25	✓	100%	Write Report	3 days	Sun 3/2/14	Tue 3/4/14
26	✓	100%	Update concept design review report	2 days	Sun 3/2/14	Mon 3/3/14
27	✓	100%	Split up report sections	1 day	Sun 3/2/14	Sun 3/2/14
24	✓	100%	Edit report	1 day	Wed 3/5/14	Wed 3/5/14
23	✓	100%	Finalize report	1 day	Thu 3/6/14	Thu 3/6/14
21	✓	100%	Send report (.PDF) to Coopers	0 days	Fri 3/7/14	Fri 3/7/14
22	✓	100%	Send report (.DOCX) to Professor Harding	0 days	Fri 3/7/14	Fri 3/7/14
82	✓	100%	**Test Phase #1**	**4 days**	**Fri 3/7/14**	**Mon 3/10/14**
83	✓	100%	Test Prototype (w/o Standing Dani)	1 day	Fri 3/7/14	Fri 3/7/14
85	✓	100%	Compare test results to baseline test results (use statistical analysis, i.e. student-t test)	1 day	Fri 3/7/14	Fri 3/7/14
84	✓	100%	Meet with Coopers to review Aesthetics & Safety	2 days	Sun 3/9/14	Mon 3/10/14
86	✓	100%	**Manufacturing Test & Review Presentation**	**5 days**	**Fri 3/7/14**	**Tue 3/11/14**
90	✓	100%	Outline Presentation & Split up roles	1 day	Fri 3/7/14	Fri 3/7/14
89	✓	100%	Finalize details for presentation	2 days	Sat 3/8/14	Sun 3/9/14

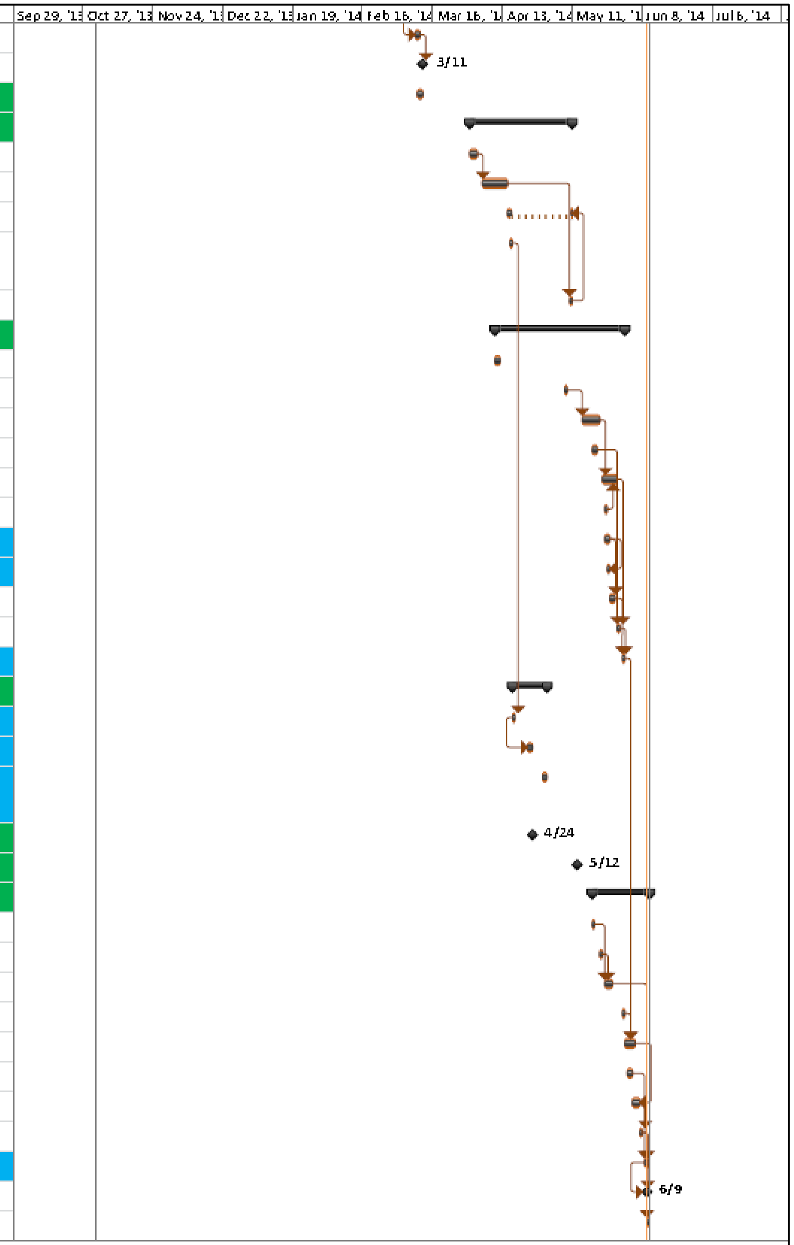


Project: Gantt Chart
Date: Tue 6/10/14

Task	Project Summary	Inactive Milestone	Manual Summary Rollup	Deadline			
Split	External Tasks	Inactive Summary	Manual Summary	Progress			
Milestone	External Milestone	Manual Task	Start-only				
Summary	Inactive Task	Duration-only	Finish-only				

Page 2

ID		% Complete	Task Name	Duration	Start	Finish
88	✓	100%	Rehearse presentation	2 days	Sun 3/9/14	Mon 3/10/14
87	✓	100%	Manufacturing test & review presentation	0 days	Tue 3/11/14	Tue 3/11/14
100	✓	100%	**Project Update Memo**	**2 days**	**Mon 3/10/14**	**Tue 3/11/14**
101	✓	100%	**Manufacturing Phase #2**	**41 days**	**Mon 3/31/14**	**Sat 5/10/14**
106	✓	100%	Make changes to design	3 days	Mon 3/31/14	Wed 4/2/14
105	✓	100%	Find any needed parts & manufacture new prototype design	10 days	Sat 4/5/14	Mon 4/14/14
104	✓	100%	Update SolidWorks parts, drawings, & BOM	2 days	Tue 4/15/14	Sat 5/10/14
102	✓	100%	Make sure design avoids pinch points, avoids ball joints, & has plenty of strength	1 day	Wed 4/16/14	Wed 4/16/14
103	✓	100%	Update technical analysis	1 day	Sat 5/10/14	Sat 5/10/14
109	✓	100%	**Senior Project Expo**	**52 days**	**Thu 4/10/14**	**Sat 5/31/14**
119	✓	100%	Send the Coopers a save-the-date	2 days	Thu 4/10/14	Fri 4/11/14
118	✓	100%	Split up roles for writing the poster	1 day	Thu 5/8/14	Thu 5/8/14
120	✓	100%	Write up poster contents	7 days	Thu 5/15/14	Wed 5/21/14
117	✓	100%	Sign up for the plotter	2 days	Mon 5/19/14	Tue 5/20/14
112	✓	100%	Edit Poster contents	6 days	Fri 5/23/14	Wed 5/28/14
114	✓	100%	Print out test of poster for review of looks/grammar	1 day	Sat 5/24/14	Sat 5/24/14
115	✓	100%	Set up a time for the Coopers to come by the booth	2 days	Sat 5/24/14	Sun 5/25/14
116	✓	100%	Make sure the Standing Dani will be charged	1 day	Sun 5/25/14	Sun 5/25/14
113	✓	100%	Get supplies for booth	2 days	Mon 5/26/14	Tue 5/27/14
111	✓	100%	Print out project poster	1 day	Thu 5/29/14	Thu 5/29/14
110	✓	100%	Present at Expo	1 day	Sat 5/31/14	Sat 5/31/14
13	✓	100%	**Test Phase #2**	**14 days**	**Thu 4/17/14**	**Wed 4/30/14**
16	✓	100%	Obtain Standing Dani for testing	1 day	Thu 4/17/14	Thu 4/17/14
15	✓	100%	Test prototype on actual standing dani	2 days	Wed 4/23/14	Thu 4/24/14
14	✓	100%	Meet with Coopers to review Aesthetics & Safety (Project Hardware & Assembly Demo)	2 days	Tue 4/29/14	Wed 4/30/14
107	✓	100%	**Senior Exit Exam**	**0 days**	**Thu 4/24/14**	**Thu 4/24/14**
108	✓	100%	**Senior Survey**	**0 days**	**Mon 5/12/14**	**Mon 5/12/14**
1	✓	100%	**Final Project Report**	**23 days**	**Mon 5/19/14**	**Tue 6/10/14**
12	✓	100%	Print & complete library form	1 day	Mon 5/19/14	Mon 5/19/14
11	✓	100%	Pay library fee	1 day	Thu 5/22/14	Thu 5/22/14
10	✓	100%	Sign & turn in library form	3 days	Sat 5/24/14	Mon 5/26/14
9	✓	100%	Split up roles for writing report	1 day	Sat 5/31/14	Sat 5/31/14
7	✓	100%	Write final report	4 days	Sun 6/1/14	Wed 6/4/14
8	✓	100%	Set up a time to deliver report	2 days	Mon 6/2/14	Tue 6/3/14
6	✓	100%	Edit final report	3 days	Wed 6/4/14	Fri 6/6/14
5	✓	100%	Print & bind final report	1 day	Sat 6/7/14	Sat 6/7/14
2	✓	100%	Deliver final bound copy of report to sponsor	2 days	Mon 6/9/14	Tue 6/10/14
4	✓	100%	Email PDF to Professor Harding	0 days	Mon 6/9/14	Mon 6/9/14
3	✓	100%	Upload final report to library (.PDF)	1 day	Tue 6/10/14	Tue 6/10/14



Project: Gantt Chart
Date: Tue 6/10/14

Task	Project Summary	Inactive Milestone	Manual Summary Rollup	Deadline	
Split	External Tasks	Inactive Summary	Manual Summary	Progress	
Milestone	External Milestone	Manual Task	Start-only		
Summary	Inactive Task	Duration-only	Finish-only		

Page 3

APPENDIX H – HELPFUL RESOURCES & POINTS OF CONTACT

CLIENT & SPONSOR

Nathan Cooper – Client and primary user of the product

Amy & Bob Cooper – Clients and parents of Nathan

Dr. Drew Davol – ME Department Chair, Sponsor representative

FIGURE 77. DR. DREW DAVOL.

SENIOR PROJECT STAFF

Professor Sarah Harding – Team Nathan Project Advisor, ME Professor

Dr. Jim Widmann – NSF Grant & VTC Enterprises Contact, ME Professor and Senior Project Staff Lead

Dr. Brian Self – NSF/RAPD Grant Contact & Adviser

FIGURE 78. PROFESSOR SARAH HARDING.

INDIVIDUALS INVOLVED WITH THIS AND PAST PROJECTS WITH THE CLIENT

George Leone – ME Department Technical Support

Brian Kreidle – Team Strider 2 (Preceding senior project with the Cooper family)

HELPFUL MEMBERS OF MECHANICAL ENGINEERING STAFF

Melinda Keller – ME Professor, Advisor on methods and scope of technical analysis

Dr. Joseph Mello – ME Professor, Advisor on methods of technical analysis

Dr. Peter Schuster – ME Professor, Advisor on methods and scope of Finite Element Analysis

FIGURE 79. GEORGE LEONE.

COMMUNITY SPONSORS

Cambria Bicycle Outfitters – Local bike shop that provided the spring-shock assembly at a significant discount

FIGURE 80. CENTRAL COAST POWDER COATING.

FIGURE 81. CAMBRIA BICYCLE OUTFITTERS.

Central Coast Powder Coaters – Local Powder Coater that powder coated our frame on a tight timeline

A-1 Mobility Scooters – Stan Manning & David Clarke both spent time with us to find the right wheelie bars for our frame and donated a set at no cost

ADDITIONAL RESOURCES

Kyle Van Allen – ME student in our Senior Project Class that provided us with suspension-modeling MATLAB code

Robert Kilbride – Point of contact for polycarbonate arm rest design & manufacture

Brian Kerns – Machinist for the polycarbonate arm rest

FIGURE 82. DAVID (L) & STAN (R) FROM A-1 MOBILITY.

Scott Kolofer – Frankie's roommate, helped with testing of the test rig

Chris Daley – Frankie's roommate, helped with testing of the test rig

Alec Bialek – CNC machinist & student shop technician at Mustang '60

Carter Wilson – CNC machinist-in-training at Mustang '60

FIGURE 85. ALEC BIALEK (LEFT) AND CARTER WILSON (RIGHT) WORKING ON THE CNC MACHINE.

FIGURE 84. CHRIS DALEY WITH THE TEST RIG.

FIGURE 83. SCOTT KOLOFER ON THE TEST RIG.

APPENDIX I – SUPPLEMENTARY TESTING INFORMATION

BASELINE DYNAMIC SUSPENSION TESTING GRAPHS

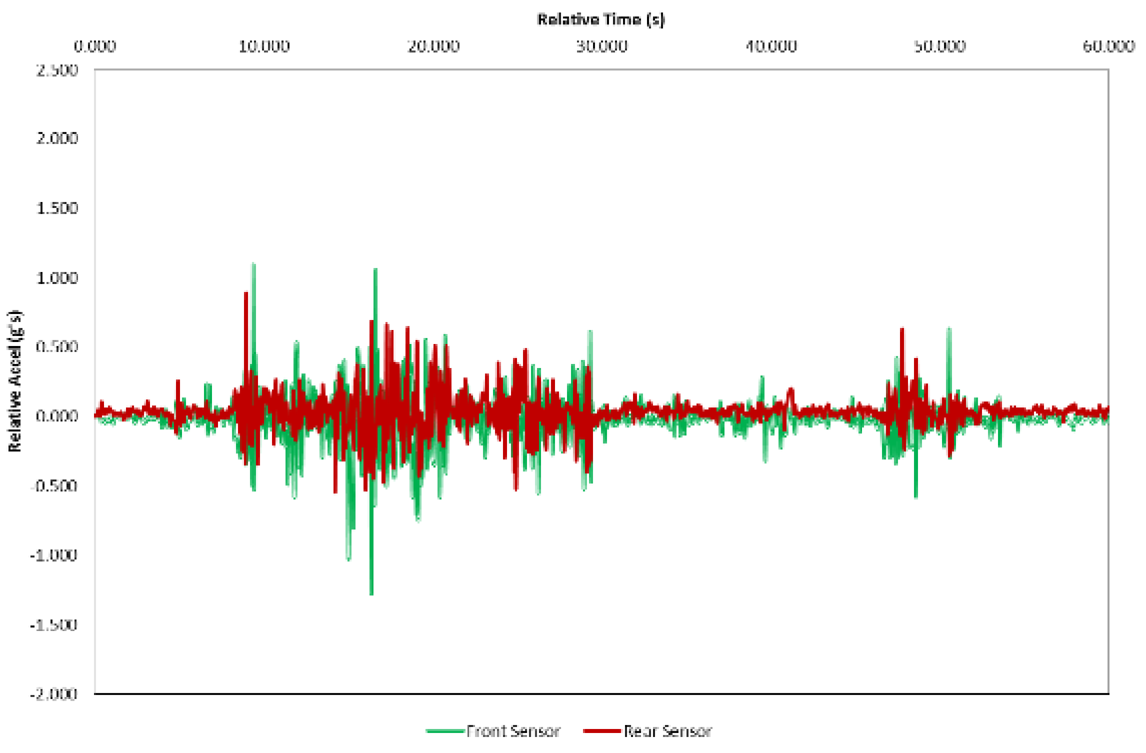


FIGURE 86. ACCELEROMETER OUTPUT FOR BASELINE DYNAMIC SUSPENSION TESTTRIAL 1.

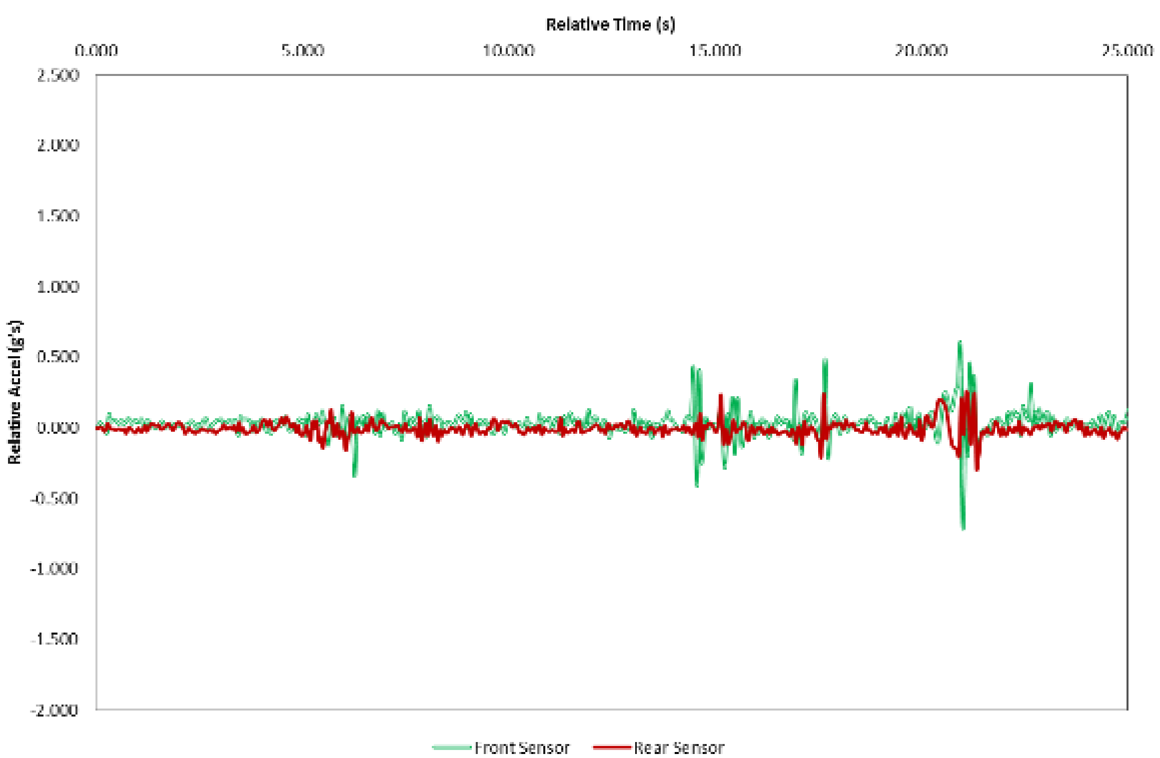


FIGURE 87. ACCELEROMETER OUTPUT FOR BASELINE DYNAMIC SUSPENSION TESTTRIAL 2.

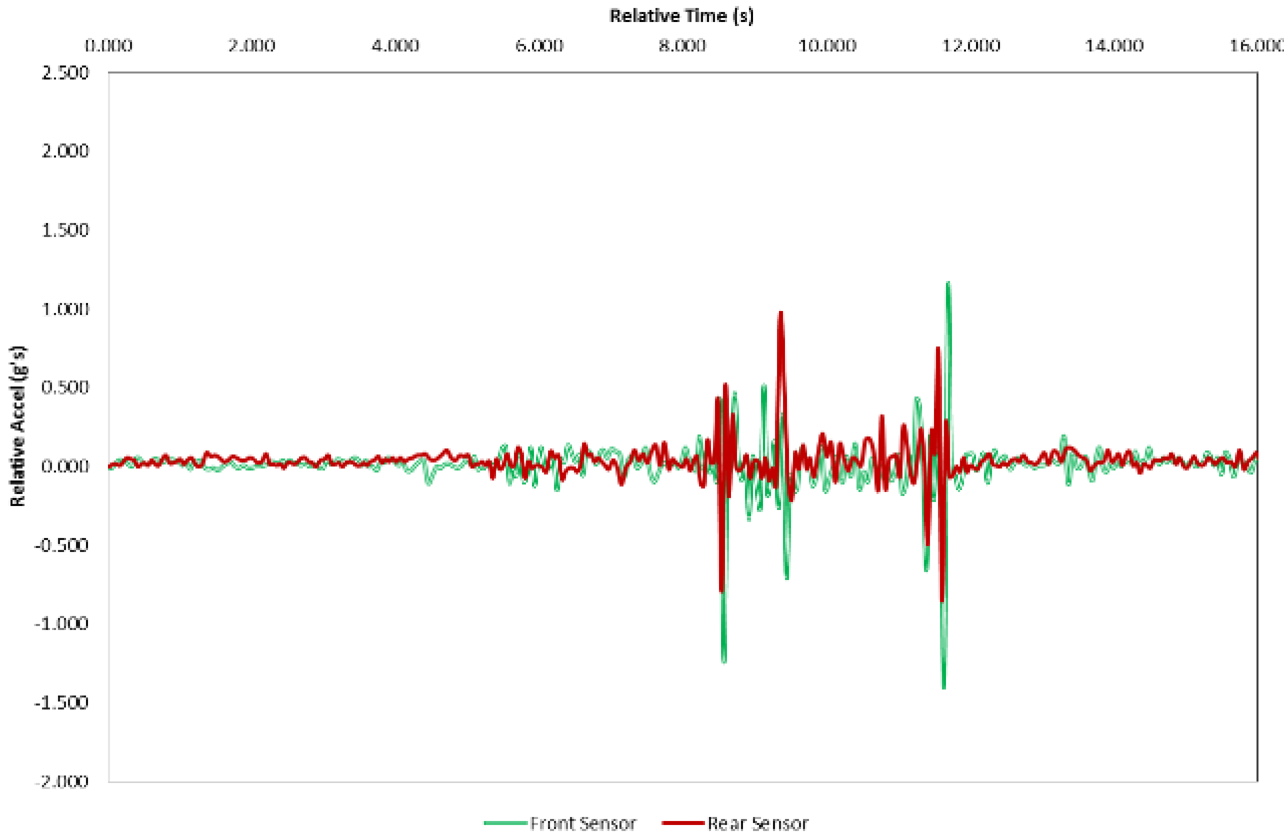


FIGURE 88. ACCELEROMETER OUTPUT FOR BASELINE DYNAMIC SUSPENSION TESTTRIAL 3.

Please note that each of the graphs are on different timescales, but have the same y-axis scale. Trial 1 (as indicated in Chapter 6: Design Verification Plan (Testing)) includes Nathan riding around as well as a bump test (between 45 and 55 seconds). Trial 4 has been omitted in this part of the report, but is shown as Figure 71 on page 57.

BASELINE DYNAMIC SUSPENSION TESTING SAMPLE DATA

RAW DATA

The raw data from the accelerometer comes in a form like what is seen below. It can be downloaded as a *.txt file or can act as a *.csv file. The data was truncated to save space in this report, but each line represents two collections from each sensor (one for each direction of acceleration). Each measurement had its own unique time. The units for the time measurements (t1,t2,t3,t4) are in milliseconds and the acceleration (x1,y1,x2,y2) measurements are in milli-g's. Below is the data from trial 4 shown in Figure 71.

X1,t1,Y1,t2,X2,t3,Y2,t4
x1offset=,0y1offset=,0x2offset=,0y2offset=,0
40967,784,40976,-112,40991,784,41000,-72
41026,784,41034,-120,41040,800,41050,-96
41075,800,41083,-112,41091,792,41099,-96
41124,808,41134,-112,41140,760,41148,-88
41174,792,41183,-112,41189,784,41198,-88
41223,816,41232,-112,41239,776,41247,-88
41273,832,41281,-104,41288,792,41296,-88…

The raw data was converted from the form shown on the previous page to the form below for easy graphing and analysis. The initial value for the variable ‘t1’ was set as the initial time (t = 0 s) and all the other times were adjusted accordingly. The accelerations were also zeroed by subtracting off the initial bias. In addition, all the times & accelerations were converted from milliseconds & milli-g’s to seconds & g’s, respectively. Furthermore, only the “X” accelerations were graphed as the “Y” accelerations did not see any change. In the actual testing environment, the “X” direction corresponded with the vertical movement (what we were concerned with). The small “Y” direction accelerations indicated that the tests took place at relatively constant horizontal speeds.

TABLE 14. MANIPULATED DATA FOR BASELINE TEST TRIAL 4 (TRUNCATED).

Front Sensor				Rear Sensor			
X-Dir Data		Y-Dir Data		X-Dir Data		Y-Dir Data	
Relative Time (s)	Relative Accel. (g's)	Relative Time (s)	Relative Accel. (g's)	Relative Time (s)	Relative Accel. (g's)	Relative Time (s)	Relative Accel. (g's)
t1	X1	t2	Y1	t3	X2	t4	Y2
0.000	**0.000**	0.009	0.000	**0.024**	**0.000**	0.033	0.000
0.059	**0.000**	0.067	-0.008	**0.073**	**0.016**	0.083	-0.024
0.108	**0.016**	0.116	0.000	**0.124**	**0.008**	0.132	-0.024
0.157	**0.024**	0.167	0.000	**0.173**	**-0.024**	0.181	-0.016
0.207	**0.008**	0.216	0.000	**0.222**	**0.000**	0.231	-0.016
0.256	**0.032**	0.265	0.000	**0.272**	**-0.008**	0.280	-0.016
0.306	**0.048**	0.314	0.008	**0.321**	**0.008**	0.329	-0.016
0.355	**0.032**	0.363	0.000	**0.370**	**0.016**	0.380	-0.024
0.404	**0.048**	0.412	0.000	**0.420**	**0.016**	0.429	-0.016
0.453	**0.040**	0.461	0.000	**0.470**	**0.008**	0.478	-0.024
0.502	**0.040**	0.512	-0.008	**0.519**	**0.016**	0.528	-0.016
0.552	**0.032**	0.561	-0.008	**0.568**	**0.016**	0.577	-0.024
0.601	**0.032**	0.610	0.000	**0.618**	**-0.024**	0.626	-0.016
0.651	**0.016**	0.659	0.000	**0.667**	**-0.032**	0.676	-0.016
0.700	**0.040**	0.708	0.000	**0.716**	**-0.024**	0.726	-0.016
0.749	**0.048**	0.757	0.000	**0.766**	**0.000**	0.775	-0.024
0.798	**0.056**	0.807	0.000	**0.816**	**0.000**	0.824	-0.016
0.848	**0.056**	0.857	0.000	**0.865**	**0.008**	0.874	-0.016
0.897	**0.040**	0.906	0.000	**0.914**	**-0.008**	0.923	-0.016
0.946	**0.048**	0.955	0.000	**0.964**	**-0.016**	0.972	-0.016
0.996	**0.048**	1.004	-0.008	**1.013**	**0.000**	1.023	-0.016
1.045	**0.032**	1.053	-0.008	**1.063**	**-0.008**	1.072	-0.024
1.094	**0.048**	1.103	-0.008	**1.113**	**0.016**	1.121	-0.024
1.143	**0.040**	1.152	0.008	**1.162**	**0.008**	1.170	-0.016
1.193	**0.064**	1.202	0.000	**1.211**	**-0.016**	1.220	-0.016
1.242	**0.072**	1.251	0.008	**1.260**	**-0.024**	1.269	-0.016
1.291	**0.064**	1.300	0.000	**1.310**	**0.024**	1.319	-0.016
1.341	**0.048**	1.349	0.000	**1.360**	**-0.024**	1.369	-0.016
1.390	**0.032**	1.398	-0.008	**1.409**	**0.016**	1.418	-0.024
1.439	**0.056**	1.448	0.000	**1.459**	**0.000**	1.467	-0.016

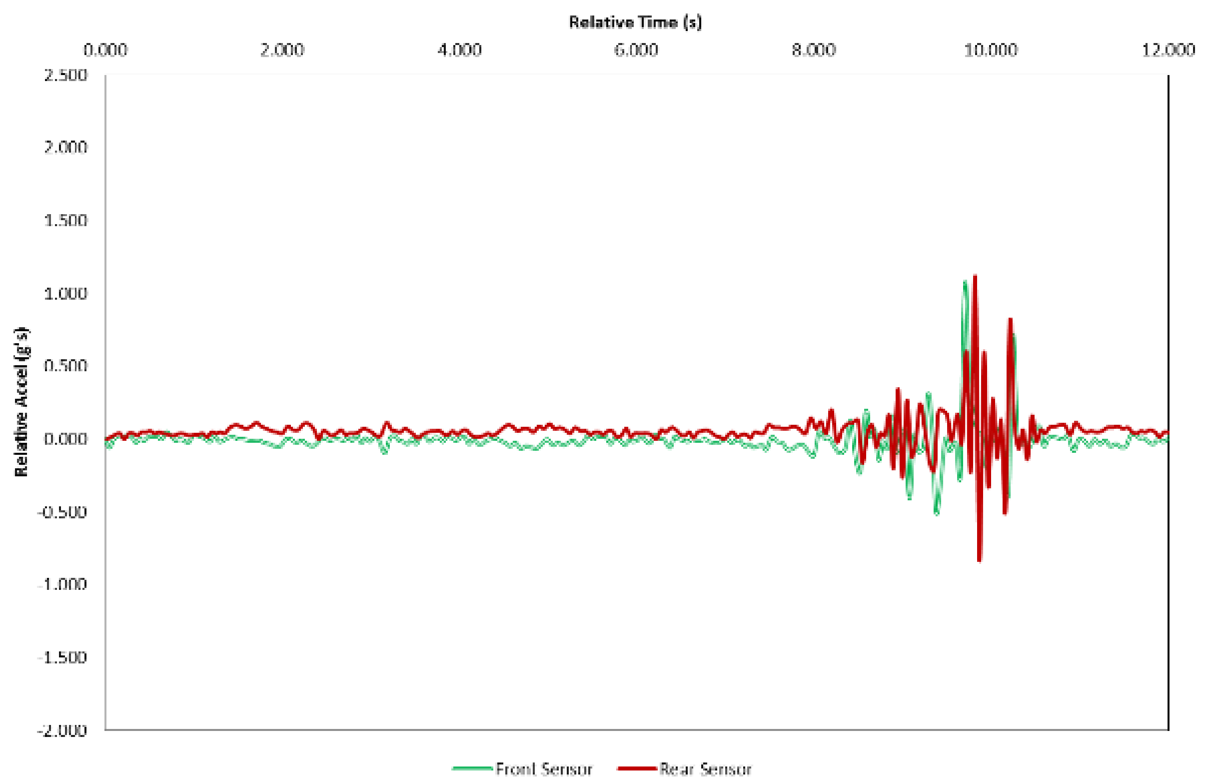


Figure 89. Accelerometer Output for Test Rig Trial 1.

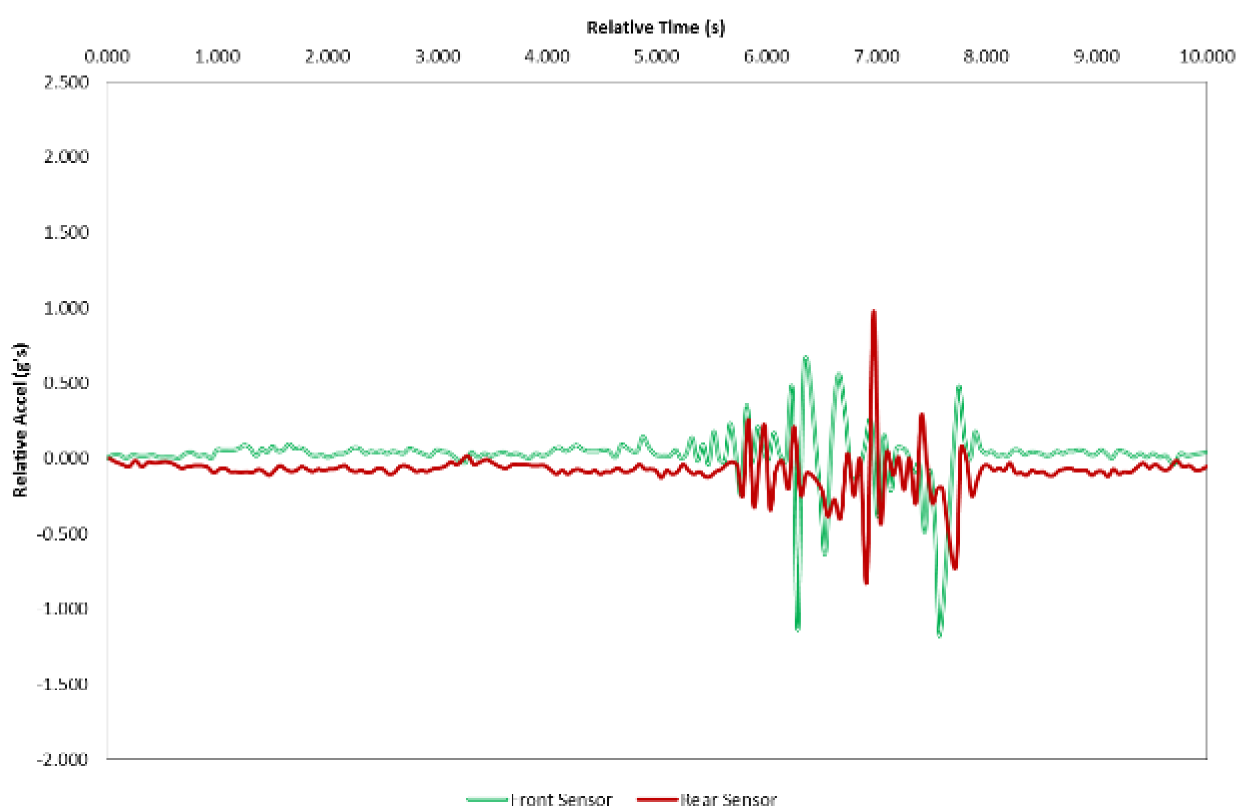


Figure 90. Accelerometer Output for Test Rig Trial 2.

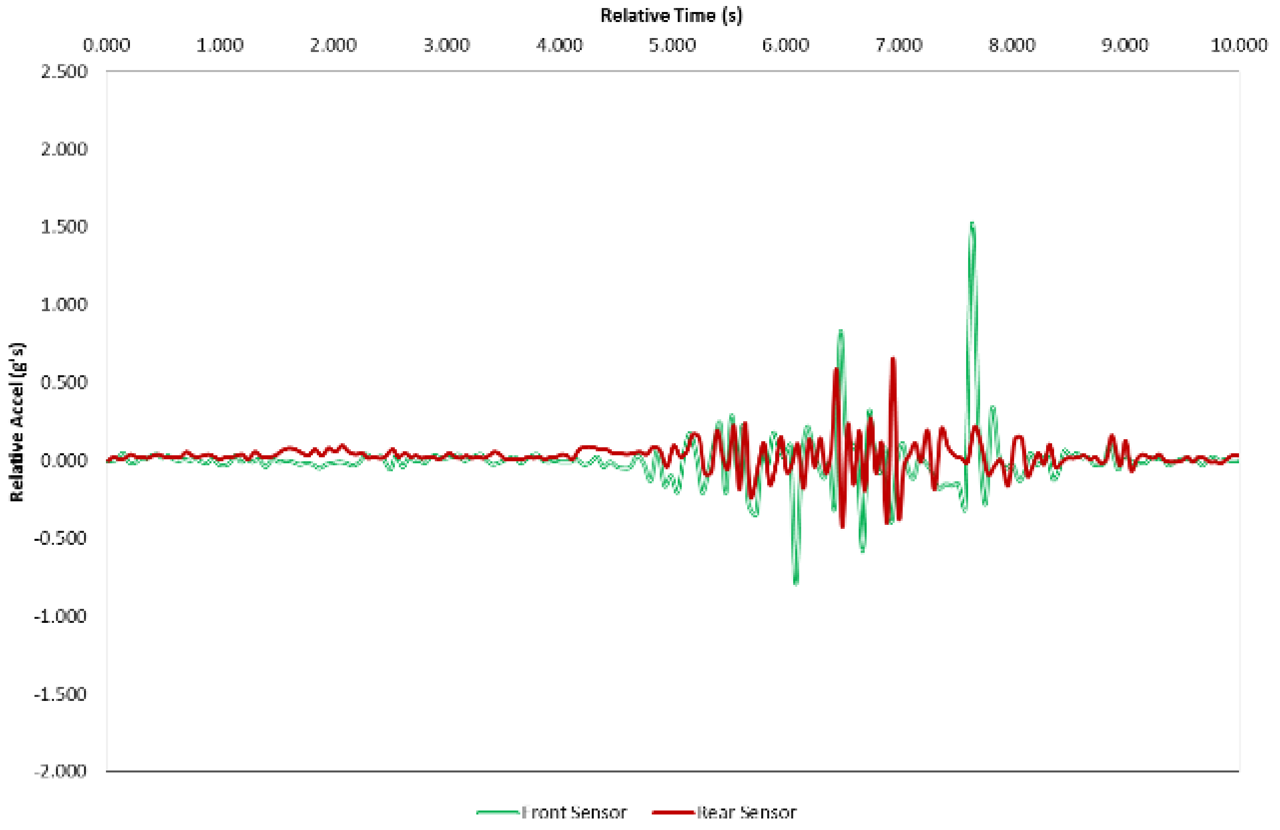


FIGURE 91. ACCELEROMETER OUTPUT FOR TEST RIG TRIAL 3.

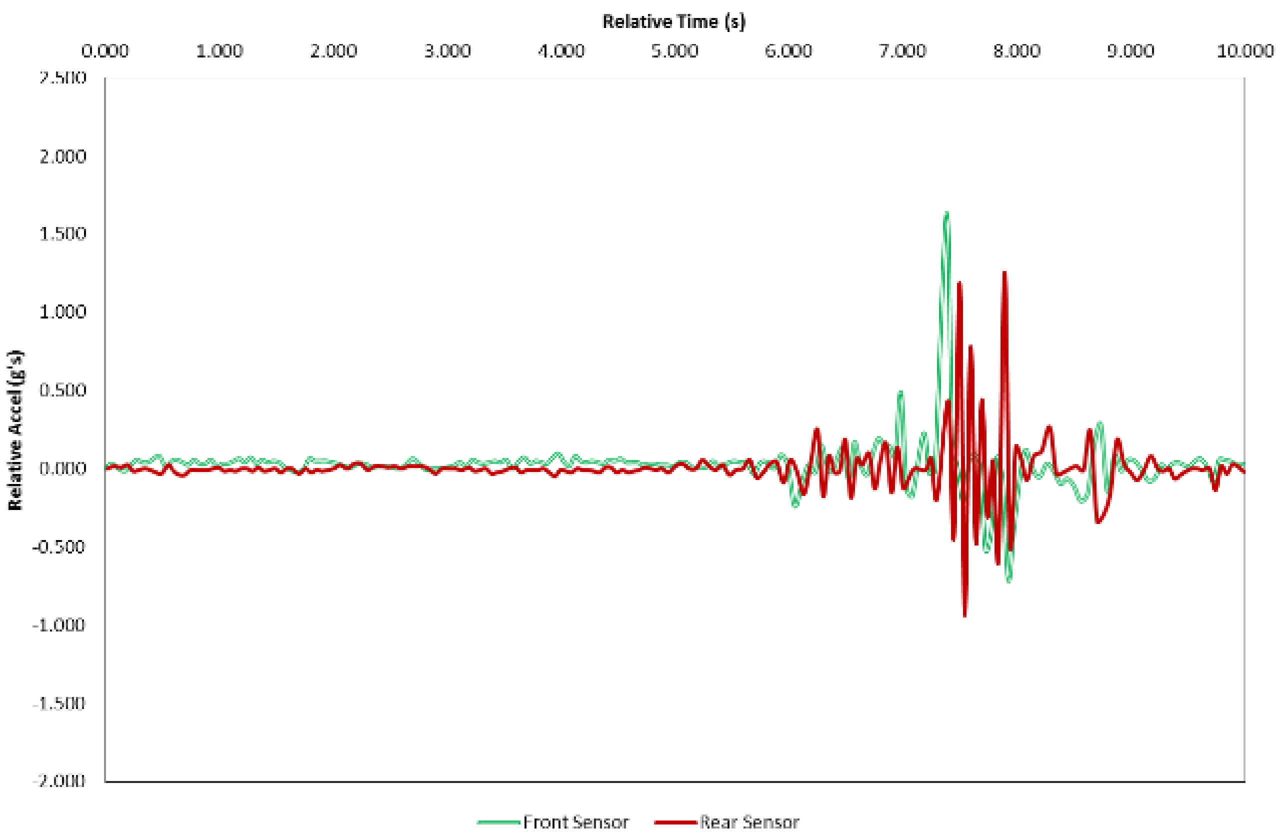


FIGURE 92. ACCELEROMETER OUTPUT FOR TEST RIG TRIAL 4.

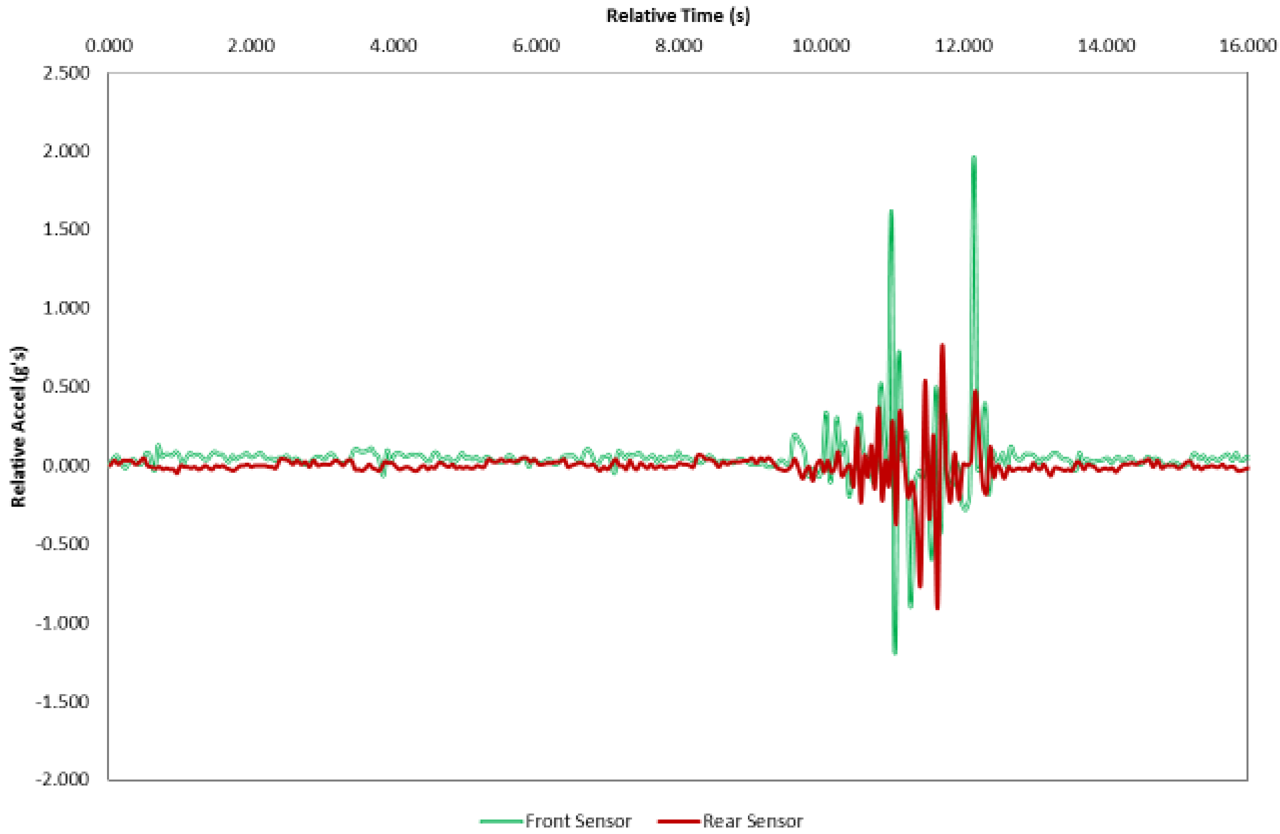


FIGURE 93. ACCELEROMETER OUTPUT FOR TEST RIG TRIAL 5.

Please note that each of the graphs are on different timescales, but have the same y-axis scale. Trial 6 has been omitted in this part of the report, but is shown as Figure 72 on page 60.

TEST RIG DYNAMIC SUSPENSION TESTING SAMPLE DATA

RAW DATA

The raw data from the accelerometer was collected in the same manner as described for baseline testing. Below is sample data from trial 6 shown in Figure 72.

```
t1,X1,t2,Y1,t3,X2,t4,Y2
x1offset=,0y1offset=,0x2offset=,0y2offset=,0
25149,792,25158,-40,25164,808,25174,-24
25199,832,25207,-32,25214,816,25223,-40
25248,824,25257,-32,25264,816,25273,-40
25298,864,25307,-48,25313,816,25322,-40
25348,840,25357,-40,25372,840,25381,-16
25407,824,25416,-40,25432,856,25441,-16…
```

MANIPULATED DATA

The raw data from the accelerometer was manipulated in the same manner as described for baseline testing. Below is sample data from trial 6 shown in Figure 72. In the actual testing environment, the “X” direction corresponded with the vertical movement (what we were concerned with). The small “Y” direction accelerations indicated that the tests took place at relatively constant horizontal speeds.

TABLE 15. MANIPULATED DATA FOR TEST RIG TRIAL 6 (TRUNCATED).

Front Sensor				Rear Sensor			
X-Dir Data		Y-Dir Data		X-Dir Data		Y-Dir Data	
Relative Time (s)	Relative Accel (g's)	Relative Time (s)	Relative Accel (g's)	Relative Time (s)	Relative Accel (g's)	Relative Time (s)	Relative Accel (g's)
t1	X1	t2	Y1	t3	X2	t4	Y2
0.000	**0.000**	0.009	0.000	**0.015**	**0.000**	0.025	0.000
0.050	**0.040**	0.058	0.008	**0.065**	**0.008**	0.074	-0.016
0.099	**0.032**	0.108	0.008	**0.115**	**0.008**	0.124	-0.016
0.149	**0.072**	0.158	-0.008	**0.164**	**0.008**	0.173	-0.016
0.199	**0.048**	0.208	0.000	**0.223**	**0.032**	0.232	0.008
0.258	**0.032**	0.267	0.000	**0.283**	**0.048**	0.292	0.008
0.328	**-0.040**	0.337	0.000	**0.352**	**0.072**	0.360	0.008
0.397	**0.016**	0.405	0.000	**0.421**	**0.088**	0.430	0.008
0.457	**0.080**	0.465	0.000	**0.480**	**0.048**	0.489	0.008
0.516	**0.048**	0.525	0.000	**0.540**	**0.016**	0.549	0.000
0.575	**0.032**	0.585	0.000	**0.599**	**0.032**	0.608	0.008
0.635	**0.016**	0.644	0.000	**0.658**	**0.016**	0.668	0.000
0.694	**0.032**	0.703	0.008	**0.718**	**0.024**	0.727	0.000
0.754	**0.024**	0.763	0.000	**0.777**	**0.040**	0.786	0.008
0.814	**0.016**	0.822	-0.008	**0.837**	**0.056**	0.845	0.016
0.873	**0.032**	0.882	0.000	**0.896**	**0.048**	0.904	0.008
0.933	**0.024**	0.941	0.008	**0.955**	**0.024**	0.964	0.008
0.992	**0.024**	1.001	0.000	**1.015**	**0.064**	1.023	0.008

MATLAB CODE FOR FILTERING DATA

After observing the data output in excel, we started to pursue filtering of the data. However, we decided to not pursue the code further because it seemed to overcomplicate our results. The code is provided along with its output as an example.

```
% Team Nathan Testing Data Filter from Excel File
% Created by Frankie Wiggins
% Created on 6/10/14
% Updated on 6/11/14

%% Retrieval of Excel Data
% Code help from at http://www.mathworks.com/help/matlab/ref/xlsread.html
% NOTE: Make sure the Excel File is in the same directory as this MATLAB
% file.

% TRTrial_i represents Test Rig data for Trial 'i' (i = 1,2,3,4,5,6)
TRTrial_1 = xlsread('All Testing Data','TRTrial1M');

%% Smoothing of Data
% Moving Average Filter
% Smoothing signals http://www.mathworks.com/help/signal/examples/signal-smoothing.html
```

```
% Number of samples (N) = number of rows in matrix
% N = size(TRTrial_1,1); % **THIS DIDN'T WORK VERY WELL**
N = 2;

% Filter Front & Rear Sensor Data
coeffMATrial_1 = ones(1, N)/N;
Avg_TRTrial_1 = [(filter(coeffMATrial_1,1,TRTrial_1(:,2))),...
                 (filter(coeffMATrial_1,1,TRTrial_1(:,6)))];

%% Plotting of Data
% Graph Labels
XLABEL = 'Time (sec)';
YLABEL = 'Acceleration (g''s)';
SENSOR = cellstr(['Front Sensor';'Rear Sensor ']);
LEGEND = cellstr(['Unfiltered Response';'Filtered Response  ']);
TRIAL_NAME = cellstr(['Trial 1';'Trial 2';'Trial 3';'Trial 4';'Trial 5';'Trial 6']);
t_min = 0   ; % Start Time for all graphs
t_max = 16  ; % End Time for all graphs
a_neg_max = -1.2; % Max (-) Acceleration
a_pos_max = 1.8 ; % Max (+) Acceleration
AXIS_LIMITS = [t_min t_max a_neg_max a_pos_max];

% FILTERED AND/OR UNFILTERED, TWO PLOTS
% What would you like to plot?
% 0 - Unfiltered AND Filtered
% 1 - Unfiltered ONLY
% 2 - Filtered ONLY
What2Plot = 0;

% For Loop - Plots Front & Rear Sensor Input
for i = 1:2
    % Set indices for plotting (i = given, j = time col, k = accel col)
    if i == 1
        j = 1;
    elseif i == 2
        j = 5;
    else
        disp('ERROR IN FOR LOOP')
    end
    k = j + 1;

    % Other Plotting code
    subplot(2,1,i)
    if What2Plot == 0
        plot(TRTrial_1(:,j),[TRTrial_1(:,k),Avg_TRTrial_1(:,i)])
        legend('Unfiltered Response','Filtered Response')
      elseif What2Plot == 1
        plot(TRTrial_1(:,j),TRTrial_1(:,k))
        legend(LEGEND(1))
      elseif What2Plot == 2
        plot(TRTrial_1(:,j),Avg_TRTrial_1(:,i))
        legend(LEGEND(2))
      else
        disp('ERROR in IF PLOT LOOP (WITHIN FOR LOOP)')
    end
    title(strcat(TRIAL_NAME(1),'-',SENSOR(i)))
    xlabel(XLABEL)
    ylabel(YLABEL)
    axis(AXIS_LIMITS
end
```

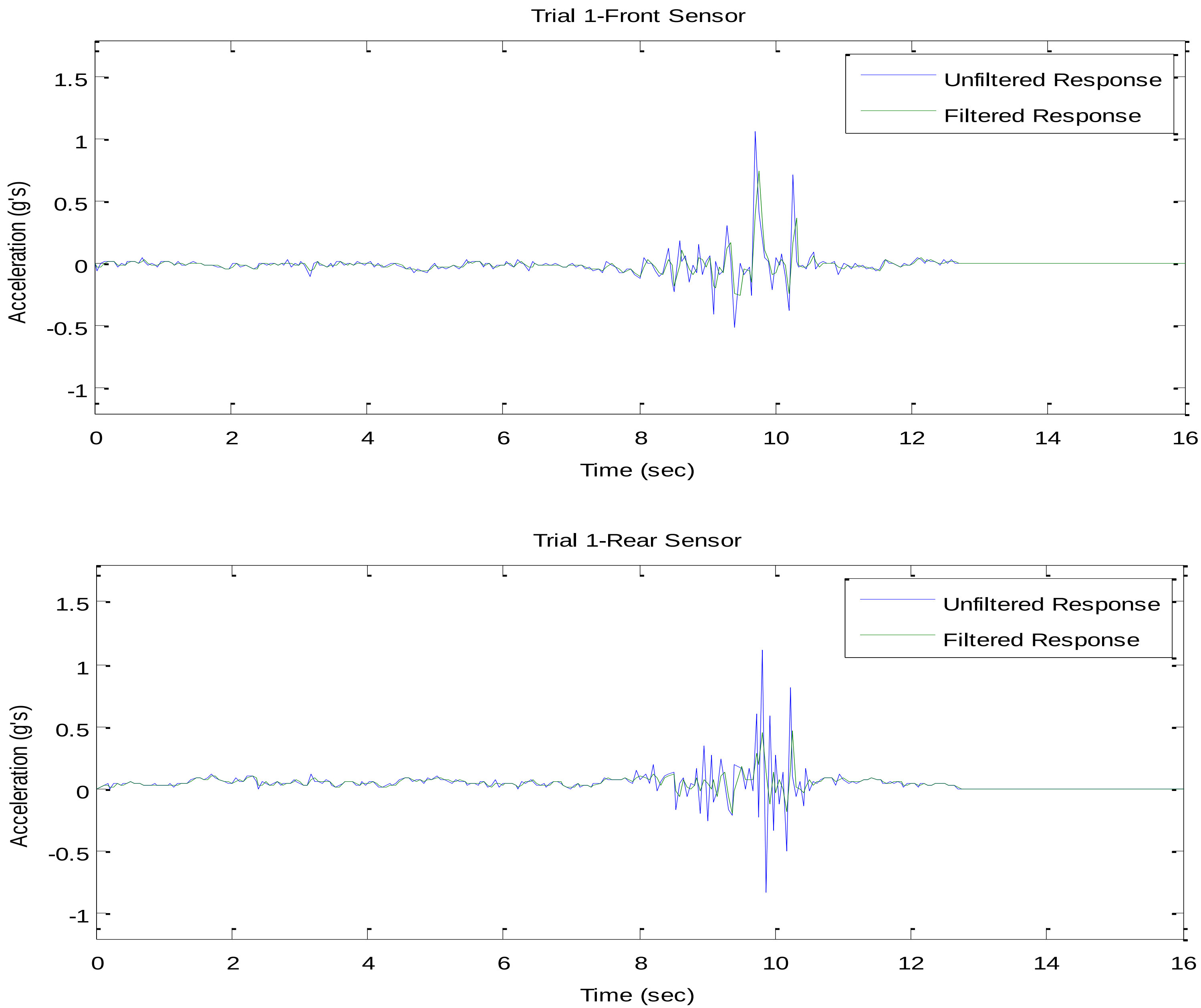
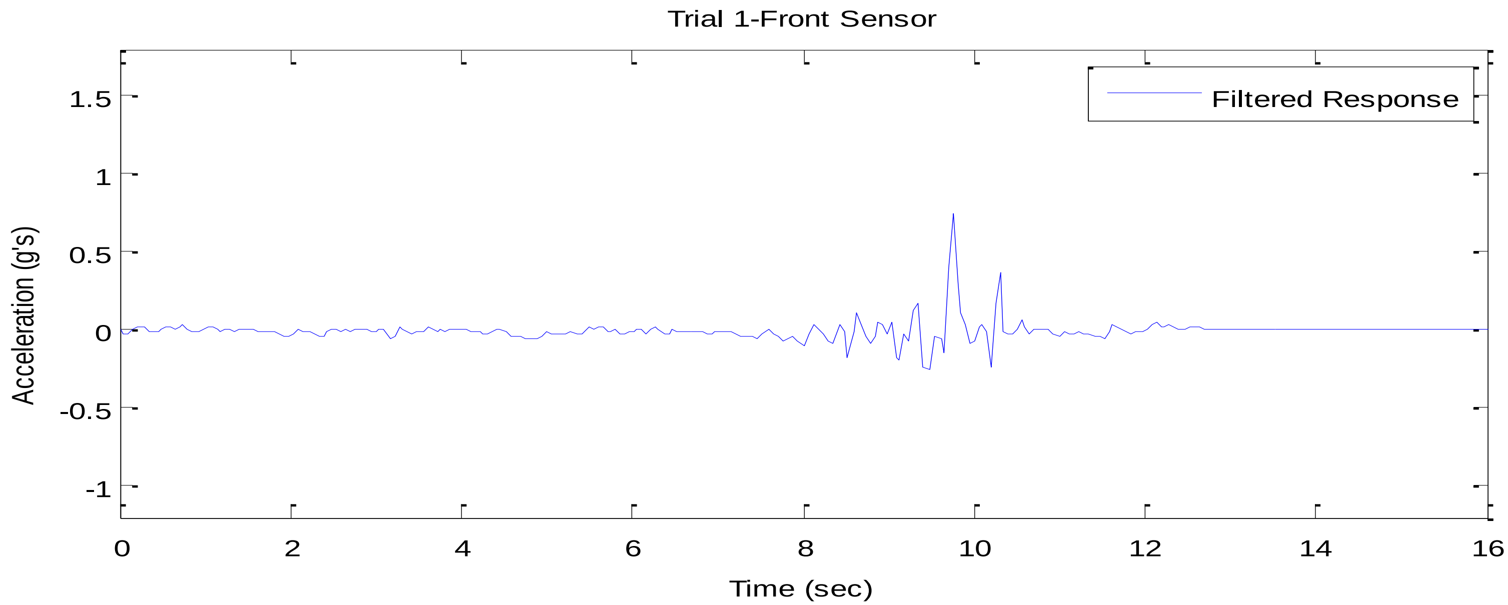


FIGURE 94. UNFILTERED AND FILTERED MATLAB RESPONSE FOR FRONT & REAR SENSORS (BASELINE TEST TRIAL 1).



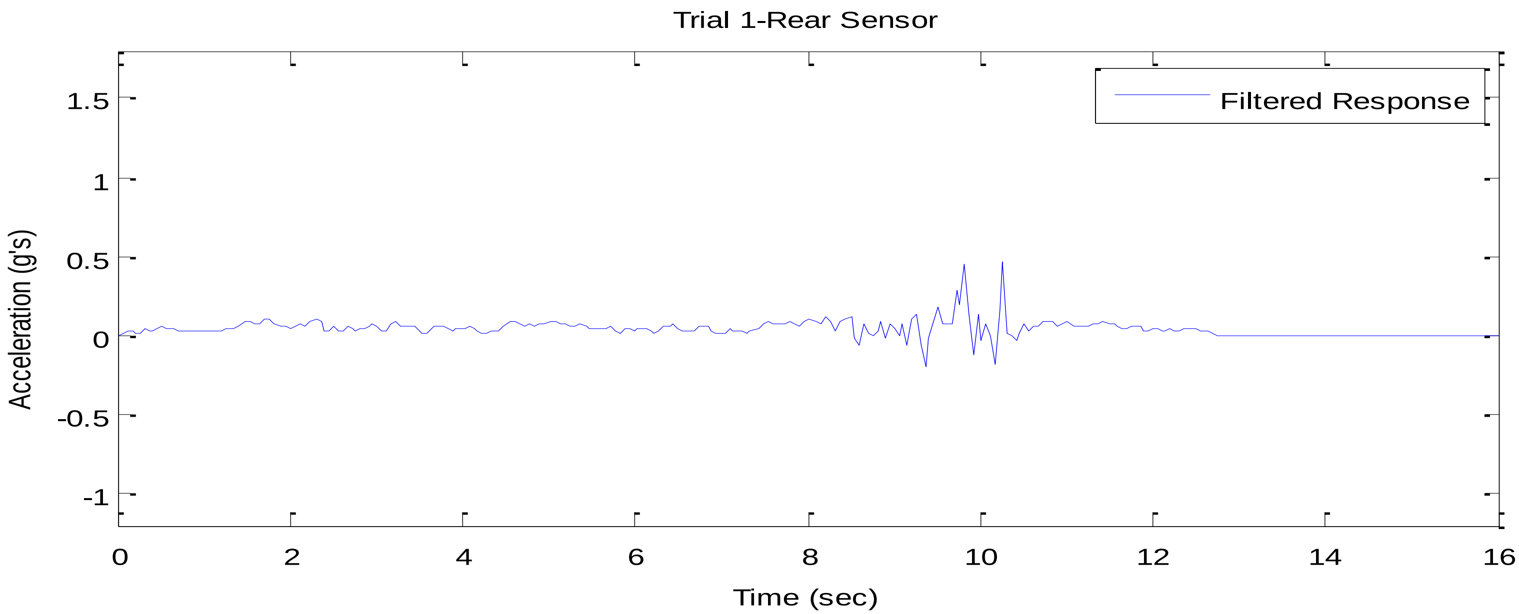


FIGURE 95. FILTERED MATLAB RESPONSE FOR FRONT & REAR SENSORS (BASELINE TEST TRIAL 1).