The REV Project - SAE Team

University of Western Australia

THE UNIVERSITY OF
WESTERN AUSTRALIA

Analysis and Evaluation of the SAE Space Frame Chassis for Modification

Submitted by: Robert Powers

Student Number: 20565313

Supervisor: Kamy Chang

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I. Synopsis

This paper briefly examines the history, development, and current events of the Rev Project Team. More specifically the paper examines the progress of the SAE group within the REV Project Team and the development of a fully electric SAE motorsport vehicle. With the idea of making the SAE motorsport car competition worthy in the future, this examination leads us to the need for evaluating the current chassis used by the REV-SAE Team. This paper will briefly examine SAE rules and regulations that need to be considered in the chassis design for competition vehicles. The paper will then examine the development of the space frame chassis along with basic principles surrounding favorable chassis design. It will examine the effect of total mass, roll centers, center of gravity, and chassis stiffness on the performance of racecars. Through examination of these factors and SAE rules, I will propose an alternative design for modification to the chassis. Ultimately evaluation of possible alternatives will show that modification to the current chassis is impractical and counterproductive. Research and general trends in the racecar arena will show that the SAE team should pursue producing a carbon-fiber monocoque chassis if the team wants to be competitive in the future.

II. Table of Contents

III. Background

The REV Project was begun in 2004 by students and professors with the goal of designing and producing a renewable energy vehicle. The group explores possibilities and promotes innovation in renewable energy vehicles whilst holding the importance of the field for the future of the automotive industry. The REV Project team completed its first renewable energy vehicle, the Hyundai Getz, which was licensed and tested in 2008, but the car continues to be evaluated and modified. The REV project group currently has three more cars in different stages of design. A new Lotus Elise is in the process of being converted to an electric vehicle and should be road worthy in the coming months. A BMW X5 is being examined for assisted driving capabilities and completion is pending a solution to mounting a servos. The SAE Motorsport team is in the process of designing a fully electric run motorsport car using a recycled space frame chassis from the UWA SAE Motorsport team. Various aspects of design for all four vehicles are broken up among the students for independent research while collaborating to achieve the overall functionality of the cars.

My vehicle, the SAE racecar, is expected to be fully functioning by the end of the current semester in November of 2009. The goal is simply to have moving electric vehicle by the end of the semester while realizing the long-term goal of making the car competition worthy. The original proposal was to drive the SAE car on electric hub motors providing a lightweight design that required no inboard motor producing a torque on the chassis. The design and time constraints on the car made this design possibility unreasonable. The design required for the available hub motors was inefficient and provided minimal start-up torque for the vehicle. Consequently, this design was abandoned in favor of two in board motors that were more available and provided the necessary torque and gear ratio for the drive. The team also saw the space frame chassis sandblasted, the tyres sealed, the brake fluid drained, and the handling tuned in order to make the vehicle drivable.

For the current semester, the goal of the SAE team was to produce an electric vehicle that was simply drivable. However, the long-term goal of the team was to consider producing a racecar that could be competition worthy in the hybrid division of the SAE competition. The recycled chassis provided to the REV Project-SAE Team is relatively long and bulky compared to typical SAE competition racecars. In order to even consider making the SAE car competition worthy, the chassis had to be evaluated for possible modifications. For the purpose of minimizing design costs, I was assigned with the task of determining how to improve the performance of the available chassis by simple modifications to existing members, namely shortening the back end of the chassis. In order to take on this task, I was forced to examine the function and principles of the chassis and the characteristics that define favorable chassis design as well as SAE rules and regulations regarding the chassis.

IV. Examining the Chassis – Literature Review

A. SAE Rules and Regulations

The most important part of making the SAE car competition worthy initially is to make sure that the chassis complies with the SAE Rules and Regulations. For the sake of this paper, I examined the SAE Rules and Regulations from 2008. The chassis met the basic requirements that the vehicle be an open-wheeled and open-cockpit car without any opening into the driver compartment other than the cockpit between the front of the car and the roll bar main hoop (SAE 2008).

The vehicle is required to have a wheelbase of *1525 mm* with four wheels that cannot be in a straight line. The smaller track, either front or rear, must at least be *75%* of the length of the larger track (SAE 2008). This requirement of the car is met with a wheelbase of *1805 mm* in the current chassis and the track ratio of 89%. Provisions were made not to change this parameter significantly in redesign to keep a legal wheelbase with the modifications.

The vehicle must have significant ground clearance to avoid touching the ground in any area other than the tyres. The minimum allowable ground clearance is *25.4 mm* for all points on the vehicle body while the driver is in the vehicle (SAE 2008). Although the car was not fully loaded, an approximation of this parameter was met for the vehicle with an actual minimum ground clearance of *50 mm*. Provisions should be made to lower the height of the vehicle body in order to improve aerodynamics of the car, possibly adding body work to the car that uses the aerodynamics to hug the vehicle to the track. However, the lowest point on the vehicle was a joint of the suspension spring arm, which would be acceptable on a smooth racing track but should be carefully heeded on any other surface.

The chassis was examined to ensure that structural members, specifically the roll hoops (front and main), complied with the SAE rules and regulations. Figure 1 shown below provided by the *2008 Formula SAE Rules* was used to examine this compliance.

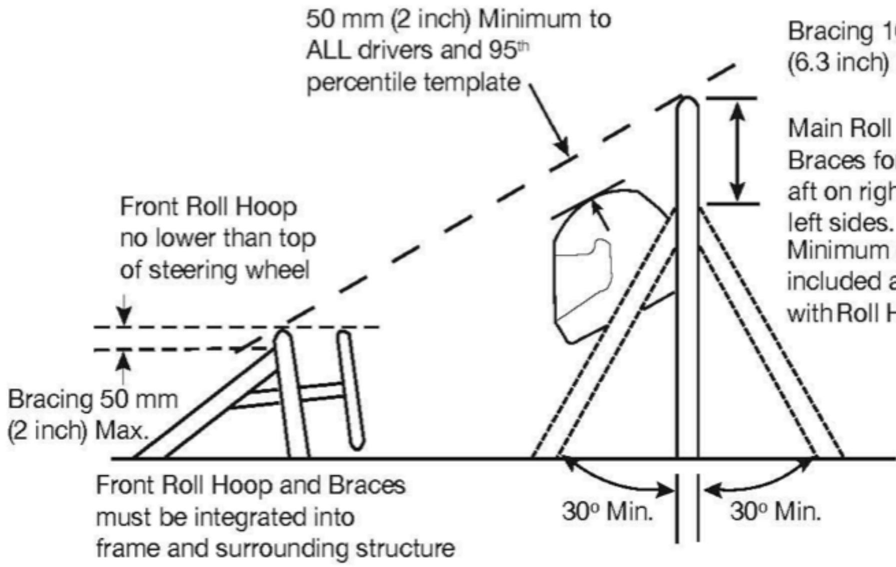

Figure 1: Roll Hoop Requirements

Four main parameters for the roll hoops shown in Figure 1 were examined on the actual REV-SAE chassis. The front bracing was measured at 54 *mm*, which was slightly above the maximum allowable offset of *50 mm* from the top of the front roll hoop. Although the error is relatively insignificant, allowance from SAE Formula Motorsport should be sought out before competing. The rear bracing was measured at *13.0 cm* in compliance with the maximum allowable offset of *16.0 cm* from the top of the main roll hoop (SAE 2008). The head clearance was measured for a driver of *178 cm* height, which would allow for a driver of average height, and provided a clearance height of *40 mm*. This parameter was not in compliance with the minimum required clearance of *50 mm*. The location of the driver seat would have to be moved toward the rear of the car and tilted backward in order to allow for sufficient clearance. For the purpose of this evaluation, only a rudimentary method was used to evaluate the head clearance. Before competition analysis should be completed in accordance with the current SAE suggested "95th Percentile Male Template Dimensions" two-dimensional analysis of the head clearance. The bracing angles for the main roll hoop were measured behind the main hoop at 35°, which was in compliance with the minimum required angle of *30*° from the vertical (SAE 2008). This angle was an important consideration in examining redesign as well.

The vehicle must be equipped with a main hoop made of a single uncut piece of tubing extending from the lowest frame member on one side of the chassis up, over, and down to the lowest frame member on the other side of the chassis. These requirements hold for the front roll hoop also, and the front hoop must be no lower than the top of the steering wheel in any possible position (SAE 2008). These parameters on the REV-SAE chassis were seen to be in compliance with the *2008 Formula SAE Rules* as seen in Figure 2 of the picture below.

Figure 2: REV-SAE chassis roll hoops

The side impact structure was also examined to gauge compliance with the SAE rules. The chassis was examined for compliance with three required parameters displayed in Figure 3 below.

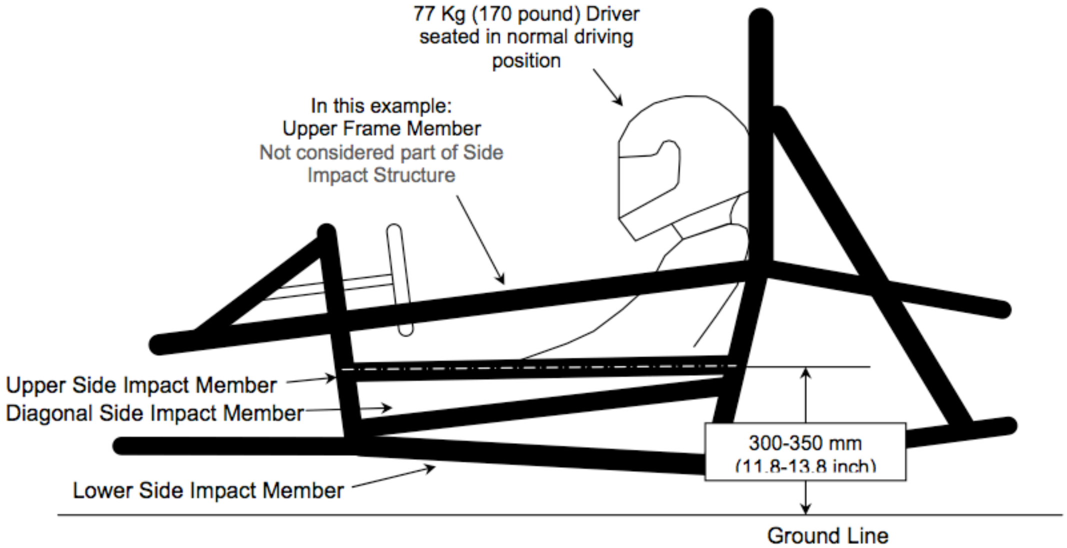

Figure 3: Side Impact Structure Requirements

2008 Formula SAE Rules require that the upper side impact member be placed between *300 mm* and *350 mm* above the ground line of the car with a *77 Kg* driver seated in the vehicle. This parameter was met by the REV-SAE chassis with an actual upper side impact member height of *336 mm*. The lower side impact member attaches the bottom of the front roll hoop to the bottom of the main roll hoop as required. The diagonal side impact frame member connects the lower side impact member to the upper side impact member forward of the main hoop and rearward of the front hoop as required by the rules (SAE 2008). After examining the current state of the REV-SAE motorsport car chassis for compliance with SAE rules and regulations, the second stage of redesign was to examine the development, purpose, and principles of the space frame chassis.

B. The Development of the Space Frame Chassis

Colin Chapman, the famous designer of Lotus race and sports cars, described an automobile chassis as “a big bracket that holds everything else in place”. A racecar chassis is the structure of the vehicle. Properties like its mass, material composition, stiffness, shape, and strength all have effects on the performance of the car. The idea of the chassis is to serve as a frame that connects the rest of the parts of the car. This being said, the correct development for designing a racecar chassis would be to would be to determine the position of all other parts of the vehicle first then to design the frame to accommodate all the mounting points. Therefore, a well-designed chassis is theoretically designed last (Aird 1997). In actuality, it should be the last major item to go on the drawing board as a way of connecting the mounting brackets in the most advantageous manner and resisting the loads in the simplest manner (Costin & Phipps).

The REV-SAE motorsport car currently uses a modified space frame chassis. According to Forbes Aird in *Race Car Chassis: Design and Construction,* the space frame chassis developed from its predecessor the four tube chassis. It is designed so that all structural members resist loads in either compression or tension (Aird 1997). By definition, a space frame is a structure in which all joints could be flexible without the chassis losing any of its stiffness (Costin & Phipps). The tubing of the frame is much stronger in compression and tension than in bending, so it is favorable that the members never experience bending. Because of the rigid design of a space frame chassis, less material is needed to provide a frame with equivalent stiffness, and the frame is lighter. However, space frames are not ideal for making modifications or additions to the design (Aird 1997). The primary function and criterion for design of the space frame chassis is torsional rigidity. The lightest, simplest, stiffest, and cheapest space frame chassis that could hypothetically be designed would be a rectangular box with all six faces triangulated by a diagonals running from one corner through the center of the face to the other corner (Costin & Phipps), as seen in Figure 4 (Cushing).

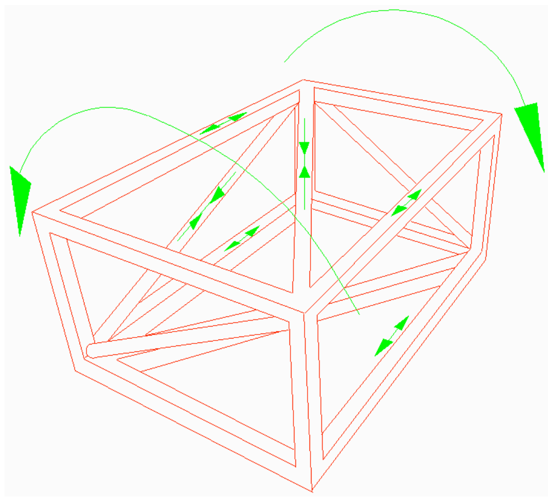

Figure 4: Ideal space frame displaying loads

However, this design is impractical for racecar design due to the necessity of the cockpit opening and localizing the effects other components of the vehicle, so the car is split into bays, preferably two but often three or four (Costin & Phipps). Design of the chassis actually begins by identifying the location of the various loads on the car and then identifying a series of lines to connect these forces. The material used is then determined by the magnitude of these loads. In design, it is important to recognize that chassis stiffness is likely the most important criteria, but it is not the only criteria examined for design. Compromise in design must be made to accommodate for aerodynamics, the location of parts, weight, and other factors (Costin & Phipps). The importance of these design considerations is discussed in the following sections.

C. Favorable Chassis Design Considerations

i. The effect of change in mass

Possibly the most obvious of properties affecting racecar performance is the mass of the car. The motor in any vehicle can provide a certain torque to the drive shaft or wheels of the car. This torque is then transferred from the axis of the wheel to provide a lateral friction force from the wheels F_{wheels} against the road surface that then accelerates the car. This acceleration A_{car} is inversely related to the mass of the car m_{car} by Newton's second law as follows:

$$A_{car} = F_{wheels} / m_{car}$$

Thus, it is important in design to determine the least amount of material that is required to provide enough stiffness to car because extra mass has a detrimental effect on performance of the car. The measure of this value is known as the specific stiffness (Brinkworth et al.).

ii. Torsional Loads in Cornering

The chassis of a racecar experiences a torsional load whenever the car is cornering. This load arises to due to the inertial forces from the car being accelerated in a different direction (Aird 1997). The lateral acceleration $A_{Lateral}$ causes a load transfer LT that increases the load on the outside tyres and decreases the load on the inside tyres (Deakin et al). This load transfer is related to the mass supported by the relevant axle m_{car}, the height of the center of gravity h_{CG}, and the track width w_T by the following equation:

$$LT = m_{car} A_{Lateral} h_{CG} / w_T$$

This relation is significant in the vehicle tyres' ability to produce a lateral force to accelerate the vehicle because the lateral force applied is dependent on the vertical load on the tyre. The relation between the vertical load on a tyre and the max lateral force produced for a typical SAE tyre can be seen in Figure 5 (Deakin et al).

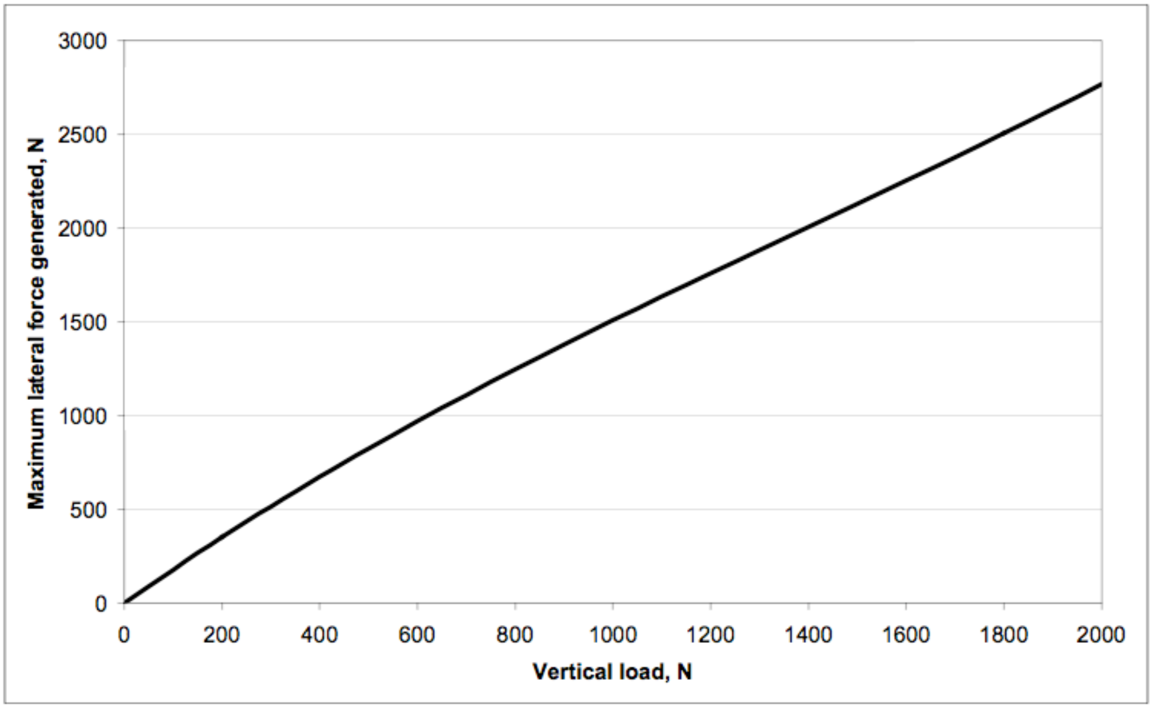

Figure 5: Non-linear behaviour of a typical Formula SAE tyre

As seen by the behaviour of the tyres in Figure 5, the combined lateral force of the tyres will be greatest when the load is transferred equally between the tyres (Deakin et al).

iii. Importance of Stiffness in racecar design

The roll stiffness varies in the front and rear wheels in order to prevent a phenomenon known as under steering (Aird 1997). Under steering occurs when a car has too little grip at the front (Deakin et al). However, the roll stiffness will tend to equalize when cornering if the chassis is springy, so the chassis stiffness is important to prevent the roll stiffness in each from equalizing (Aird 1997). Adjusting the level of grip to the tyres is known as tuning the handling the balance, and a car can be considered balanced when the front and rear axles produce a force to provide the same lateral acceleration (Deakin et al). A stiff chassis makes it easier for the designer to obtain this balanced acceleration.

iv. The Effect of Stiffness on Handling

The chassis stiffness is important because it affects the ability to tune the suspension to have the desired effect on handling. The relation of stiffness to handling can be examined by an idealized model of a chassis presented by Andrew Deakin et al. in their article ‘The Effect of Chassis Stiffness on Race Car Handling Balance’. The model displayed in Figure 6 idealizes the chassis as a pair of masses m_f and m_r in the front and rear of the vehicle respectively connected by a torsional spring with stiffness K_{ch} that is representative of the chassis stiffness. The suspension at the front and rear of the car are represented roll stiffness of K_{rollf} and K_{rollr} .

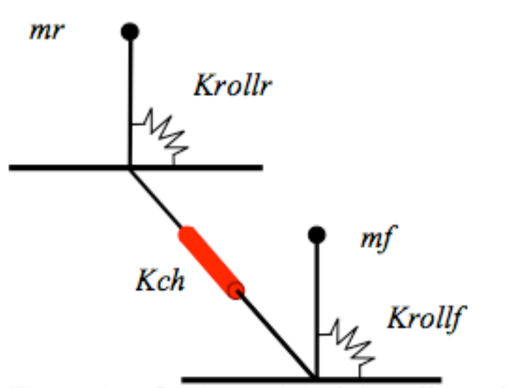

Figure 6: Idealized chassis for analyzing stiffness

Using this model, the angles of roll for the front and rear suspension ϕ_1 and ϕ_2 and the angle of twist of the chassis ϕ_3 can be related to the front and rear moments due to the lateral acceleration of the masses M_f and M_r . These relations are as follows:

$$M_f = K_{rollf} \ \phi_1 - K_{ch} \ \phi_3$$

$$M_r = K_{rollr} \ \phi_2 + K_{ch} \ \phi_3$$

$$\phi_1 + \phi_3 = \phi_2$$

By examining these equations we can understand the importance of chassis stiffness. We must first understand that the desired effect of racecar design is to be able to control the roll angles ϕ_1 and ϕ_2 in order to control the lateral load transfer (discussed in the sections above) on the tyres and produce the most desirable handling effect while cornering in a vehicle. These angles will be significantly different. Examining the first equation individually, it can be seen that ϕ_1 and ϕ_3 are both dependent variables that rely on the moment M_f produced by the masses. However, if the chassis stiffness K_{ch} is increased its magnitude dominates the angle of twist and the term can theoretically be considered constant. Consequently, the angle of twist of the front suspension ϕ_1 can be controlled simply by modifying the roll stiffness K_{rollf} , a process more commonly known as tuning. This same principle applies for the rear roll angle. Nevertheless, this is only an idealized model of a chassis and the loading does not actually occur as simply as shown. The deflection of the chassis is not uniform throughout the car, and most of the twisting usually occurs around the cockpit (Aird 1997).

v. Center of Gravity and Roll Centers

It was discussed above in a simplified model how the stiffness affects the load transfer of a vehicle while cornering. The load transfer, however, is also affected by an important relationship between the center of gravity of the vehicle and the roll centers of the suspension systems. When a car is cornering, it can be imagined to have a point (actually an axis in three dimensions) about which it is rolling (Aird 1997). This axis is theoretically the same axis shown in the Figure 6 model containing the torsional chassis spring. The direct relation of the center of gravity was also seen in the equation for load transfer examined above:

$$LT = m_{car}\, A_{Lateral}\, h_{CG} / w_T$$

It has been attempted throughout the years to produce a car without any roll, and theoretically if the roll centers at both ends of the vehicle were the same height as the center of gravity, this would be possible. But a high roll center presents many drawbacks, so roll centers in racecars are often located much closer to the ground than the center of gravity (Aird 1997). Nonetheless, lowering the center of gravity in a chassis is an important consideration for improving the handling of a vehicle. The center of gravity is also important in considering the lateral stability, rollover propensity, and overall performance of the vehicle, although in practice it is actually very difficult to obtain an accurate measurement of the vehicle center of gravity (Bagaria 1998). The horizontal location of the center of gravity is significant for loading the wheels. A center of gravity that is located in the center of the mountings for all four wheels will load them equally (Aird 1997). This parameter is considered more closely in determining the location of the loads that are placed in the chassis, and it is also the reason a chassis is usually designed to be completely symmetric across the vertical plane through the middle.

D. Measuring torsional stiffness of a chassis

The theoretical and physical measurement methods for obtaining a torsional stiffness of a racecar chassis can actually be very similar in practice. If one were to estimate the torsional stiffness through finite element analysis of a computer model of a vehicle, the loads experienced by a car in torsion could be modeled by placing loads F equal and opposite at the position of the suspension mounts a distance d from the axis of rotation. Recording the displacements at these mounting locations Y_1 and Y_2 will give the angle of twist ϕ of the chassis by the following equation (Brinkworth et al):

$$\phi = tan^{-1}[(Y_1 + Y_2) / d]$$

The stiffness of the chassis K_{ch} can then be determined as follows:

$$K_{ch} = F\, d / \phi$$

This equation is of little importance in determining performance, however, because as was said before, any chassis can be made stiffer by adding more material (Aird 1997). Thus, the desired value, the specific stiffness $K_{ch,sp}$, is found by dividing by the mass m of the chassis resulting in stiffness to weight ratio:

$$K_{ch,sp} = F\, d / (\phi\, m)$$

Which has units of *Nm/°Kg* and is the best measure of chassis performance (Brinkworth et al). Physically a similar method can used to test the actual stiffness of the chassis. The torsional loads can be simulated by rigidly securing one end of the chassis and attaching a rigid bar across the front of the chassis near the location of the suspension mounts. Heavy weights can then be attached at both ends of the bar with different magnitudes, the difference in the weights simulating the total load transfer. The angle of twist is then measured and the stiffness related by the same equations as above.

V. Alternative Design

A. Examining geometry and design possibilities

In determining a possible alternative design, it was important to understand the development of the space frame chassis and the principles surrounding favorable chassis design. It was also important to consider cost, time, and relative performance as well. Due to limited costs and labor availability, I was set with the task of examining the chassis for simple modifications that could improve performance without requiring a great deal of manufacturing time. Originally, the REV-SAE car was set to be equipped with wheel hub motors that would make the rear bay of the chassis an unnecessary extension. The bay was the original location of the rear transmission when the car was a petroleum car. The bay can be seen in blue in Figure 7 at the back of the car.

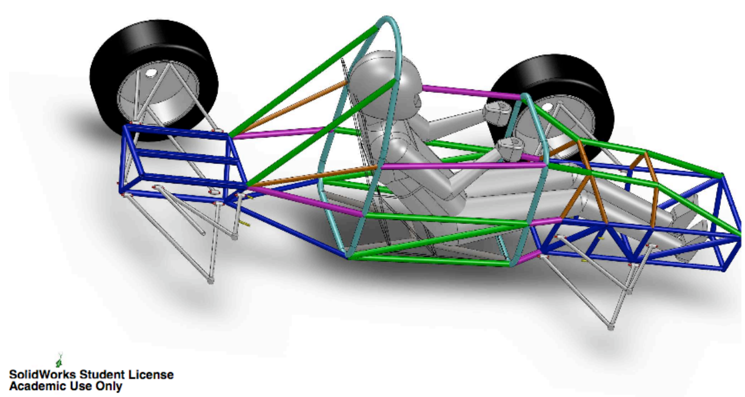

Figure 7: Rev-SAE chassis rear bay

Although the REV-SAE team finally decided to use an inboard motor for this semester making the rear bay necessary, for future development it will be considered that wheel hub motors will be used. Consequently, modification to the chassis should involve completely removing the rear bay and modifying the back of the main bay to accommodate new suspension mountings. Ideally the rear suspension mountings would be moved up as close to the main roll bar as possible and batteries could be loaded in cages built onto the side of the cockpit bay thus moving up the center of gravity. Unfortunately the maximum length that can be taken off the chassis is *28.0 cm* due the SAE required wheelbase of *152.5 cm*. This length can be seen in Figure 8.

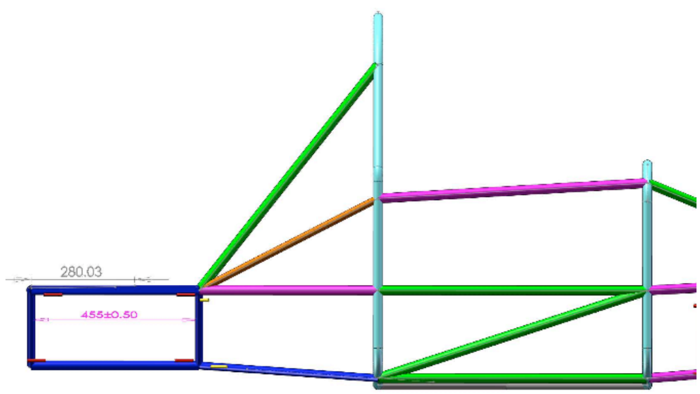

Figure 8: Length that chassis can be shortened

With this constraint in consideration, it was still deemed favorable to remove the rear bay. This made it necessary to modify the back of the main bay to accommodate the extra length while still properly triangulating the beams to load in tension or compression. A schematic of a potential design possibility can be seen in Figure 9.

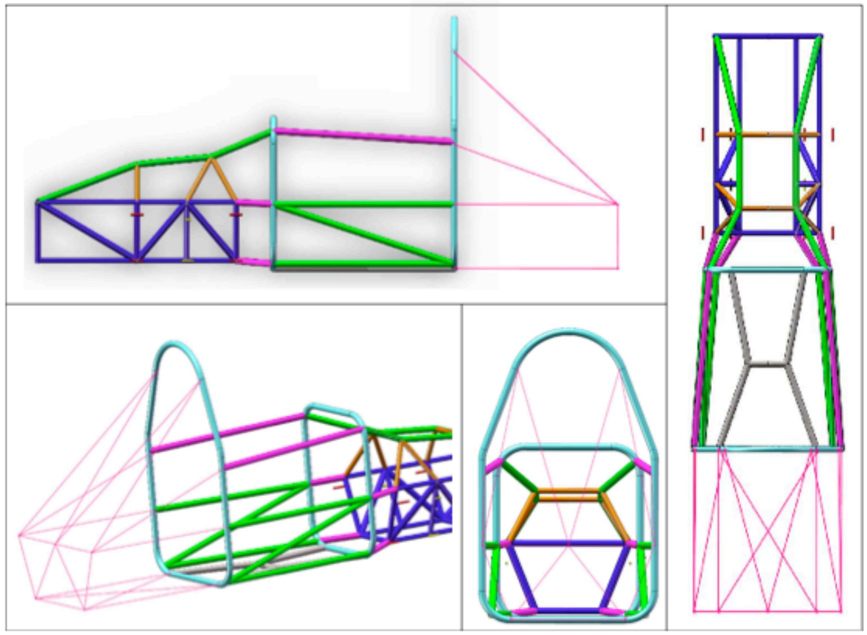

Figure 9: Modified chassis schematic

This model would effectively shorten the chassis and decrease some of the excess mass caused by the rear bay while still triangulating the loads to remain stiff. The design would also leave sufficient room in the rear for the placement of the batteries.

B. Effects of Redesign

Shortening the length of the vehicle would significantly increase the stiffness of the chassis. This change in stiffness could not be measured because physical testing would require the redesign to already have been built along with a huge testing rig, and displacement calculations through finite element analysis were outside the realm of my abilities in terms of the appropriate software. Nonetheless, the effect can be seen by examining the simple torsional twist on a typical pipe tube. A pipe under a torsion force *T* with polar moment of inertia J, modulus of elasticity G, and length L is related to the angle of twist θ as follows (Leckie 2009):

$$\theta = T\,L\,/\,G\,J$$

Simply by examining this direct relation, we can see that by shortening the length L of the bar by *.28 m* of the total *1.80 m* length (lengths corresponding to the redesigned chassis) would provide a *15.6 %* increase in stiffness of the bar. This same principle applies to the stiffness of the chassis with respect to its length, although the percentage increase would not be exact because the chassis does not have a uniform stiffness throughout the frame (Aird 1997).

Decreasing the mass of the chassis through modification, as discussed earlier in this paper, will increase the acceleration produced by the motors. But although the relation is direct, the acceleration will not increase linearly as would be predicted by Newton's second law because the lateral force produced by the tyres is also dependent on the vertical loads on the tyres. Still, the performance of the vehicle will be improved by modifying the chassis to decrease the total mass.

C. Analysis of design alternative

According to Forbes Aird in his book *Race Car Chassis: Design and Construction*: "Space frames also have their drawbacks. They involve a lot of tricky welding and will not tolerate thoughtless additions or modifications". Michael Costin and David Phipps in their book *Racing and Sports Car Chassis Design* write: "Furthermore, even after completing a satisfactory chassis frame for any given car, the designer must be not afraid to alter the whole conception because of some minor change required in suspension or other components”. At the beginning of the semester I was set with the task of analyzing the current chassis and recommending a redesign scheme. However after researching the principles of designing a space frame chassis, my recommendation would be not to make any modifications at all. Redesigning the chassis would demand huge amounts of shop time, which currently do not seem to be available for the REV-SAE team. It would also demand a significant amount of tricky welding, which if performed incorrectly would sacrifice the structural integrity of the entire chassis. Modifying the chassis would also require designing a completely new suspension system that would require more time and money.

This brings up another argument against modifying the chassis. In racecar design, the chassis is to be seen as “means to an ends” (Costin & Phipps). Therefore a suspension system in a racecar should never be designed in order to fit onto the chassis. Rather if proper design practices are to be followed, the desired suspension system of the vehicle should be designed first and foremost followed by the chassis. In examining the effects modifications would have on the structural rigidity and mass of the vehicle, it is apparent that modifying the chassis would improve the performance if done correctly. However, this is not to say that it would improve the vehicle enough to be worthy of competition in SAE motorsport racing as a hybrid vehicle. The general trend in SAE motorsport is the shift to the composite carbon-fibre monocoque chassis which is lighter and more rigid than its predecessor, the space frame chassis. The space frame is simply an outdated model in the competitive arena, especially considering the heavy steel tubing space frame of REV-SAE team. In order to produce a competition worthy vehicle, I would propose for the future that the REV-SAE scrap the existing chassis completely rather than modifying it and pursue the production of a carbon-fibre composite monocoque chassis, or at least a chassis which is built after the design of the rest of the vehicle.

VI. Discussion and Conclusion

I was assigned to the REV-SAE team at the beginning of the semester with the task of examining the current chassis for redesign. Upon researching the possibility, I would strongly discourage the future REV-SAE team from making any attempt at redesigning the current chassis. The constraint presented by the SAE required wheel base makes any modification have a limited effect on improving the actual performance of the car. At the same time, any modifications would require extensive shop time with tricky welding. The chassis should be completely redesigned, but the REV-SAE team currently does not have the technical knowledge or resources to complete this task. In order to make a vehicle that is competition worthy, I would suggest that the REV-SAE team partner with the UWA Motorsport team to make the possibility of a competition electric vehicle a reality. The UWA motorsport team has put in huge amounts of research and resources specifically into developing the structures of their cars, the chassis and the suspension systems. It would benefit the REV-SAE team to learn form their experience. The REV-SAE team would also require more organization, better delegation, and more funding to complete the ultimate goal of competing in SAE Formula Motorsport.

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VIII. Definitions

Main Hoop - A roll bar located alongside or just behind the driver's torso.

Front Hoop - A roll bar located above the driver's legs, in proximity to the steering wheel.

Roll Hoops – Both the Front Hoop and the Main Hoop are classified as "Roll Hoops"

Frame Member - A minimum representative single piece of uncut, continuous tubing.

Frame - The "Frame" is the fabricated structural assembly that supports all functional vehicle systems. This assembly may be a single welded structure, multiple welded structures or a combination of composite and welded structures.

Primary Structure – The Primary Structure is comprised of the following Frame components: 1) Main Hoop, 2) Front Hoop, 3) Roll Hoop Braces, 4) Side Impact Structure, 5) Front Bulkhead, 6) Front Bulkhead Support System and 7) all Frame Members, guides and supports that transfer load from the Driver's Restraint System into items 1 through 6.

Major Structure of the Frame – The portion of the Frame that lies within the envelope defined by the Primary Structure. The upper portion of the Main Hoop and the Main Hoop braces are not included in defining this envelope.

**Provided by 2008 SAE Rules*