Design of a UWA Electric Racecar

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Abstract

The University of Western Australia (UWA) Motorsport Team has been developing performance racecars for the Formula SAE competition since 2001. In this time the team has won numerous awards and is well regarded internationally for their innovative designs.

In 2009 the UWA Formula Renewable Energy Vehicle (REV) Student Project began developing a second series of competition-specific racecars to meet the growth of technology into electric propulsion vehicles.

The Formula SAE opportunity enriches student experiences for more than 500 university teams internationally, a challenge that kick-starts their mastery of professional engineering skills.

Design decisions are inclined on the availability of industrial sponsorship and yields some of the freshest applications of electric propulsion technology in Australia.

Resources gathered for use in this work are varied but most notably, the availability of past UWA-designed racecars of both combustion and electric propulsion will be the basis of which this work is unique and novel.

Letter of Transmittal

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Foreword

Every racecar is a complex system of physical components competing for space and performance improvements. The comprehensive design of this type of machine will take the form of an iterative process drawn from the previously designed racecar.

> *The outcome of this work is to review the 2013 Campaign to identify undesirable performance, and updating unsuccessful designs with the specific focus on being able to source and manufacture for the Design of a UWA Electric Racecar.*

The author of this work, through participation as the Project Manager and Design Director of UWA Formula REV and as an experienced mechanic on UWA Motorsport, will cover a range of common and not-so-common racecar engineering designs through extensive literature review of state of the art prototypes, and form the groundwork for future UWA-designed racecar campaigns.

Design decisions involving the propulsion system are influenced by sponsored technology and for intellectual property reasons, some of them will not be discussed in this work.

In addition to this, UWA Formula REV is sponsored by businesses and industry, many offering in-kind services. Many designs will be influenced by the availability of these services in lieu of performance benefits, and the author will be very clear where this is the case.

The racecar detailed will form the intermediate concept of the team, with the intention to be entered into the Formula SAE-Australasia competition in December 2014, and then be entered into the 2015 Formula Student Germany and Formula Hybrid US competitions. The rules for each competition and each competition-specific technical inspection are related, but where there are differences they will be discussed.

Context of the 2014-2015 Campaign

In an effort to minimise confusion, this work will refer to *'2014 Prototype – Stage I'* as the *'2014 Prototype'.* Below is the stage progression as planned for the entire 2014-2015 Campaign:

2014 Prototype – Stage I

Prototype ready to drive by end of June 2014 for the purposes of propulsion testing and driver training. This stage will also be used for demonstration purposes, as demonstration is inherently pivotal to on-going sponsorship and recruitment success. This will feature a driven locked beam-axle rear, and steering and suspension components from the 2013 Prototype. The front wheels will not have propulsion assemblies at this stage.

2014 Prototype – Stage II

Prototype ready for Formula SAE-Australasia Competition in December 2014. Should feature front in-wheel propulsion and in-board rear propulsion. Prototype will be fully rules compliant and complete with body-work.

Graphic 1: Society of Automotive Engineers International

2015 Prototype – Stage III

Prototype with major refinements depending on performance at Stage II, prepared for the purposes of Formula Student Electric in Germany 2015. Possible features may include basic aerodynamics, composite chassis construction and suspension adjustments.

Graphic 2: Formula Student Germany

2015 Prototype – Stage IV

Prototype prepared for Formula Hybrid US 2015. It is likely that this stage will only feature a back-end change to accommodate a 300cc turbocharged bio-diesel generator and feature less accumulator cells. Additionally, the rear propulsion assemblies may have to be shifted from in-board to in-wheel.

Graphic 3: Formula Hybrid

Objectives

The success of this work is evaluated as:

- Reviewing the 2013 Campaign in order to identify the capacity of the 2014-2015 Campaign to execute the design detailed within
- Identifying manufacturing issues of the 2013 Prototype through comprehensive review
    - Serviceability and adaptability are major factors in reliability and performance tuning at the expense of increased weight. This would include implementing design criteria such as designing low-cost spares, standardising fasteners/bearings and utilising non-permanent mounting methods.
    - Weight saving is encouraged but is secondary to reliability, as all current points-based simulators would agree that the points benefit of any amount of weight-saved performance increase pales in comparison to scoring zero points for failing to complete an event.

- Commencing a design within the resource limitations of the 2014-2015 Campaign
- Designing a rules compliant chassis structure
  - The chassis will be the most difficult component to update during testing; therefore the chassis should be designed rules compliant from the beginning. This design includes considerations for accumulator placement, which are collaterally included within this work.
- Determining a reliable in-wheel assembly system
  - Based on official Formula SAE and Formula Student results, roughly 66% of teams do not finish the endurance event, the most points-significant event in the competition. (Events.imeche.org 2013; Fsae.com 2013). At Formula SAE-A 2013 it was observed that, save for UWA Motorsport's suspension failure, every single 'did not finish' (DNF) result was caused by a propulsion system failure of some manner.
- Commencing the design of a system ready for testing by the end of June 2013
  - A major recommendation by successful teams at Formula SAE-A is to test and refine the concept as a priority, and therefore having a prototype ready early is highly advantageous.

Execution

- Complete the 2013 Prototype for competition in December 2013
- Review the 2013 Prototype during January and February 2014
- Consolidate resources for the 2014 Campaign during January and February 2014
- Commence design of the 2014 Prototype throughout February 2014
- Handover design tasks to Design Managers for review and completion throughout Stage I of the 2014-2015 Campaign

Review of the State of the Art

In the Design of a UWA Electric Racecar, the author seeks to determine the most desirable performance achievable within the limits of the 2014-2015 Campaign resources.

The method to this was set out by first defining an appreciation of the task. Resources used have included student literature, engineering design manuals, carefully reviewed online sources and primary account observation. Directly related areas of research include the Formula SAE, Formula One and the emerging Formula E(lectric).

The 2013 Prototype is also commonly referred to in this work. It and its designs are considered for all intents as directly related literature.

Graphic 4: The completed 2013 Prototype at the competition in Werribee, Victoria.

Electric Formula SAE

Primary account observation was able to be conducted on a number of UWA-designed racecars and some present at the Formula SAE-A Competition 2013, in particular the RMIT and Swinburne electric vehicles as the three teams worked closely together in the week leading up to the competition.

A common observation among the vehicles experienced was ‘simple and reliable designs, with excessive allowance in the timeframe for testing’. There were some conflicting interpretations on successful electric vehicle design with none of the three teams claiming to be maturely experienced in the technology such as high voltage compared with high current, one/two/four electric motor configuration, accumulator capacity and chassis construction.

Interestingly, the UWA Formula REV 2013 Prototype was the lightest of the three electric vehicles on the day of the competition (275kg), despite the other two vehicles featuring carbon fibre monocoque construction (RMIT 280kg, Swinburne 320kg). The 2013 Prototype featured an accumulator capacity (6.56kWh) between the RMIT (4.44kWh) and Swinburne (undisclosed, but much greater).

Graphic 5: The 2013 Prototype being prepared for the tilt-test: an element of the technical inspection.

It is still uncertain why the RMIT vehicle weighed more, as it featured smaller 10” wheels from which one would expect a profound decrease in vehicle mass.

Torque Vectoring and Regenerative Braking

Another common agreement among Australian Formula SAE teams is that the implementation of high-level electric vehicle-specific features such as torque vectoring and regenerative braking violates the mindset of designing for simplicity and reliability. These two features, although proven to be highly effective even on smooth surfaces, are not discussed in this work but mentioned for completeness. (Ward 2013; Howard 2013)

Chassis Construction

An example of interesting expected design-performance correlation is the widespread acceptance of carbon fibre monocoque as the highest performing chassis construction. Recently there have been notable successes of non-carbon fibre monocoque construction such as electric team Stuttgart Greenteam’s 2010 steel spaceframe (truss), and TU Delft Racing’s aluminium 2012 monocoque. The latter has been recognised as the lightest electric Formula SAE vehicle, and placed international First Place Electric, however is considered an extreme example of the technology.
(GreenTeam Uni Stuttgart 2013; Formula Student Team Delft 2013)

Observed from data collected by Anderson (2012) at the Formula Student 2012 competition, there was an emergence of alternative constructions with good weight outcomes; however engine size also should be considered.

This suggests that there are alternate constructions that can achieve greater performance than carbon fibre monocoque, perhaps due to recent evolvements in manufacturing processes, or perhaps that there are more significant factors in effect above a certain level of chassis performance.

Compact Electric Propulsion

Similar and relevant areas of electric propulsion development are bespoke electric vehicle conversions, and electric remote controlled (RC) hobbies including helicopters, cars and boats.

With the rise of these home-engineering projects being revealed through internet communities such as Rcgroups.com (n.d.) and Forums.aeva.asn.au (n.d.), there are more and more technologies being publicly attempted and it would be prudent to review some of the outcomes and empirical data – in conjunction with the methods used to produce them. These sources are by no-means guaranteed to be strictly procedural, comprehensive or technical, however they can often provide indications of the limitations of the hardware without having to purchase or reproduce them.

In the case of this work, the selection of commercially available compact electric motors (especially those new to the market) were greatly simplified by the availability of internet discussions and videos which, once carefully reviewed, indicated early the build quality, reliability, performance and drive control problems that could be expected. Whilst not strictly literature, these sources proved themselves to be duly useful when reviewed methodically.

From these sources, using hobby RC motors for propulsion applications has been accomplished with some success, with performance compared to that exhibited by the 2013 Prototype. Cooling is confirmed as a major issue and the reliability of various electric motors can be predicted by visual assessment of their build quality prior to use. Very few of the electric motors discussed by the communities have been identified as of unusable quality or prone to catastrophic malfunction within manufacturer-specified use.

Judging by the review by Hooper in (2011), commercial interest in compact electric propulsion technology is still hesitantly incipient. Reliability, performance, weight and cost are commonly at compromise, and including the informal internet communities mentioned above, there are very few reliable sources for validating this emerging hardware. Due to this, compact electric propulsion is considered an area of research gap.

In the 20-30kW range, small motors relevant for in-wheel applications are split between extremely high powered hobby and RC motors, and precision and purpose-developed motors only available through close collaboration with the manufacturer such as AMK Motors. AMK Motors sponsors a number of successful European teams, working with them to develop an application-specific motor. Reliable literature is hard to locate as the former has only internet communities as discussed above and the latter tends to be well guarded for business reasons.

Accumulators

Accumulator cell chemistry will be discussed with reference to load testing performed by (Hooper 2007; 2008) in the Accumulator design section.

Controversial design criteria

Rear Wheel Drive or Four Wheel Drive

A significant component in the decision to pursue four wheel propulsion is the fact that UWA Motorsport are already highly proficient (Pearson 2009) in two wheel propulsion and thus dedicating another entire team's-worth of research into this area raises nothing novel.

10" or 13" wheels?

Most common wheel sizes in Formula SAE are 10” and 13” (Anderson 2012; Kasprzak and Gentz 2006). A fundamental area of racecar design is the selection of wheel size, with the 13” size being the most common and the 10” size recently increasing in popularity. This push towards 10” wheels has risen from observations such as increased tyre temperature, lower unsprung assembly mass and lower rotational inertia resulting in a higher torque output and acceleration.

Advantages towards 13” tyres include high-speed stability, packaging space within the wheels and a larger selection of tyre makes and compounds. These advantages however are becoming less significant due to the increase in the use of aerodynamic devices compensating for high-speed stability, and the use of exotic suspension systems that avoid traditional problems with in-wheel packaging.

This design will make use of the team’s existing 13” wheels, and the author agrees that the increase in packaging space is a very important feature of 13” wheels with in-wheel propulsion.

In-Wheel or not?

As principles of performance four-wheel-electric propulsion are developing the emergence of new propulsion configurations is of particular interest. The locations of motors in four-wheel electric propulsion vehicles have some effect on the yaw inertia and location of the yaw axis of the vehicle.

Karlsruhe Institute of Technology Electric Racing feature inboard front motors driving the front wheels through constant-velocity (CV) joints. This is a particular marvel as CV joints with angular offset suitable for Formula SAE vehicles are difficult to source. This configuration however would greatly reduce yaw inertia and shift the yaw axis rearwards.

Formula Student Team Delft (as one example from many) has used the inboard rear motors configuration once again decreasing yaw inertia and this time shifting the yaw axis forward.

In-board propulsion has the advantages of lower wheel assembly mass as well, as detailed below. The answer to this perhaps distils from how simple each transmission can be made (inboard compared to in-wheel).

Wheel Assembly Mass

A commonly debated argument with in-wheel propulsion systems is the overdamped dynamic response of significantly heavier wheel assemblies. Two examples other than propulsion where excessive wheel assembly mass is relevant occur in kinetic energy recovery systems (KERS) and in vehicles featuring larger-than-standard tyre sizes.

In the former the KERS can weigh up to 25kg and are placed inside the rear wheels and are considered as an effective addition to the vehicle (Racecar-engineering.com 2011; Flybridsystems.com n.d.) and in the latter, larger tyre sizes (of both width and diameter) are generally selected to improve vehicle stability in high speed steady state vehicle conditions. This would suggest that stability and dynamic response are perhaps inversely proportional and a compromise could be met for a given performance target.

The author does not claim to know the solution to this controversy, but it is supposed that through these two relevant examples there are methods that exist to manage excessive wheel assembly masses. This is to say that within reason and within the scope of this work, the increase in mass should not be fatal to the performance of the assembly.

Accumulators

Although not exactly an area of controversy, the feature of removable accumulators is one of which the author has mixed views. Some advantages include, interchangeable energy between race events, components are easily accessible for servicing, the accumulators can be charged elsewhere whilst the vehicle is being serviced, the vehicle can be re-energised quickly for continuity during testing and training, and the energy stored is only required to complete one event resulting in lower battery mass. This is especially important as competition programs place an endurance event in the morning and then another in the afternoon of the final day, which does not give vehicles featuring non-removable accumulators the time to charge fully for the second event.

However, the feature also includes some general disadvantages, increased complexity and weight in extra mounting hardware, requires an ‘accumulator hand cart’ to be designed, and some teams are unable to purchase a set of spare batteries, which can sometimes be the most expensive area of the vehicle.

Part One:
Review of the 2013 Campaign

Since the formation of the team in 2009, Formula REV has experienced difficulties in raising a strong managerial, technical and logistical focus within the team. This section is a list of recommendations based on the findings of the author throughout his involvement with Formula SAE. A number of elements that are commonly identified as strong influences on a Formula SAE team's capability are detailed below.

Presence within the student community

A strong presence within the university’s student body promotes professional and practical engineering, which directly affects recruitment and retention, as well as support from academics and university administration. In a time where students must stand out in order to appeal to potential employers, well run and well represented Formula SAE projects are go-to resume building experiences for proactive students.

In some cases, automotive and aerospace engineering companies will directly select top students from Formula SAE programs for their prior experience and for having demonstrated intrinsic motivation through their participation (Spinelli 2014; Crash.net n.d.; Porter 2013).

Particularly common in European university teams, team sponsors make practicum placements or industrial projects available to the students. In this type of exchange, students receive an opportunity to connect and impress a potential employer, and the Formula SAE team benefits from some sponsored technology or research conducted during the placement. The author of this work is one of few examples of this kind of arrangement in Australian Formula SAE.

In addition to serving as an express connection with industry, nearly every Formula SAE program will facilitate academic course work for students. These can vary in size usually between six months and two (sometimes three) years. Academic course work is important for the program because it generates research interest and technological development in that field. It is also important to students who are motivated to do the extra work in order to fulfil their engineering appetite. Occasionally, notable work will bring recognition to the team and university, and these small successes can add up to a reputation for innovation and applied engineering within international Formula SAE teams.

Graphic 6: UWA Motorsport and UWA Formula REV on display among the student community.

Formula SAE teams are well connected with other universities and some large companies, and from a marketing perspective can be a source of impressive advertising potential. Many teams feature on covers and banners of university and industrial promotional material.

Finally, Formula SAE provides a social and cultural aspect to studying engineering with similar dynamics to a student club, and a strong purpose within the field of study of engineering. Especially for young students, simply realising the existence of a Formula SAE opportunity serves to provide an outlet for their education and unites them with like-minded and proactive students.

Conversely, the experience is not desired by every student, and each individual will have varying reservations for commitment to perform this extra work. Promoting the experience to the student community merely introduces the idea that there are employability and academic benefits for those fortunate enough to have time to contribute.

Access to experienced Formula SAE members

Access to experienced Formula SAE members exists in different forms. At the highest level, it involves members on the team having experienced one or two competitions; at the lowest level, trawling the internet-forums for discussions between teams; and at some level in-between, visiting another local team's workshop for advice.

Experienced Formula SAE participants tend to have a particularly accurate interpretation of the rules. Having seen other teams' vehicles fail or marginally pass technical inspection serves as a continually present reminder to take the rules seriously and understand the intent of the rules during design.

Additionally, these members have experienced first-hand and researched the relationships between design and performance for their relevant areas. This helps to cull a large number of solutions to a few well considered ones with a lesser amount of effort. It is important that design decisions are well considered for the purposes of the design and cost events (static competition events) where judges assess the justifications for deciding on certain design solutions.

An experienced member can do this through frequent exposure to state of the art designs internationally, recognising elegant solutions and those that have potential from those that are inefficient.

Another practicality of consultation with experienced members is their familiarity with both common and exotic manufacturing techniques. Manufacturability is the most limiting factor to design and therefore the ability to dismiss intensive or impossible designs is highly desirable prior to commencing the manufacture.

Graphic 7: UWA Formula REV achieved 3rd Place Electric Vehicle

Presence within local industry for technical and logistical support

A good relationship with industry can open up many otherwise impractical design options. Most obvious advantages are manufacturing facilities and specialist manufacturing technology, experience and access to specialised materials, and research regarding technological developments.

Not-so-obvious advantages also include access to software for data acquisition, modelling or simulation; as well as testing facilities such as engine dynamometers, wind tunnels, testing tracks and such like.

Time management and project focus

Every Formula SAE project is large and detailed. It is the duty of the students to organise and manage themselves and the resources they have available to them.

The management of people is an essential skill for the team to be able to function effectively and accomplish tasks to an acceptable quality by the due date. In addition to people, the management of resources such as materials, equipment, money and transport are all a part of day-to-day operations. These resources are likened to pieces of a puzzle where they are required to fit together in order to form a solution.

The new design calls for a distinctive team structure in order for workflow and accountability to be transparent. The restructure is loosely derived from the structure of that of UWA Motorsport and concepts mentioned by Pearson (2009). While there are some parallel functions to those of UWA Motorsport, the UWA Formula REV structure focuses on the design of the vehicle and two additional figures managing all of the logistical requirements for the design.

Business Team Manager:

- Responsible for managing sponsorships, academic and Faculty relations, co-ordination with other student clubs and all promotional matters.
- In the unlikely event that it is required, the Business Team manager has ultimate project authority.
- Facilitates recruitment and initiation of members into the team.

Project Director:

- Responsible for leading the design and layout of the vehicle. Design Managers should seek endorsement from the Director for all design implementations.
- Ensures that each component/assembly will perform as designed, and that all necessary integration hardware such as brackets, fasteners and bearings are accounted for.

Safety and Utilities Manager:

- Responsible for tools, machines, space and materials.
- Meets with other representatives of the workspace (such as UWA Motorsport and Facilities Management) to routinely resolve the use of the space.
- Organises safety training for members when required.
- Preferably also has the duty of managing software and computers for the team.

Design Managers:

- There are three to four Design Managers responsible for a major area of design each, which may include several related components or assemblies. The scopes of these areas are usually near that of a thesis project.
- Design Managers co-ordinate 1-2 students allocated to them in order to complete the design area.
- Also responsible for organising testing events, including when testing the car.

The task of developing a racecar should not be taken lightly, so care must be taken to pace and spread out the workload over the resources and over the time that is available. It is often that students will either leave tasks to the last minute and burn themselves out, or start out taking on too much workload and eventually exhaust themselves.

One way of managing this problem is through a combination of the early establishment of long-term project goals, and the routine identification of short-term project goals. The 2014-2015 Campaign has been split into four short-term project goals known as ‘stages’ in an effort to maintain the momentum of enthusiasm on the team by providing, at each interval, a tangible reward of a drivable racecar.

The final and least obvious element to Formula SAE project time management is the coping with delays, problems and unexpected failures. These events can degrade the performance of the team in the short-term while resources are expended in order to rectify the situation, and they can degrade the performance of the team in the long-term by distracting members from the original project goals set out if the situation drags out for too long.

It is important that there are efforts in place to deal with these events in a timely manner, and this can be helped by a strong and clear management structure, motivation within the team, and conservative workload.

There are many frameworks that promote effective project management. Such frameworks are listed below:

- SMART objectives; Specific, Measurable, Achievable, Relevant, Timelined
- Risk matrices
- Work Breakdown Structures
- Stakeholder management charts (stakeholders in this case referring to sponsors and administrative bodies such as the Faculty)
- Project Charter or Mission Statement.

Conclusion

The 2011, 2012 and 2013 teams, although unclear as to exactly why, had not focused on these aspects of the project. This had caused them to repeatedly miss due dates, re-do existing work and get stuck on incoming problems.

Throughout this work there has been great progress on beginning to implement some of the methods discussed above. At the time of writing the project has seen an increase in contributing members, indicated interests of students nominating thesis preferences for the project (from representatives of other student clubs), and a refreshed support from sponsors and from the Faculty of Engineering Computing and Mathematics.

Following this has also inspired a new co-operative spirit between the two Formula SAE teams at UWA.

Graphic 8: The current Project Director of UWA Formula REV (left) and Project Manager of UWA Motorsport (right) working together.

Part Two:

Design of the 2014 Prototype

(Including technical review of the 2013 Prototype)

The 2013 Prototype was designed during 2011 and 2012, prior to completion in 2013. The team had little experience with Formula SAE and had limited workshop resources and manufacturing experience. For the first time, all of the available thesis literature has been reviewed to understand design decisions and their effect on the vehicle performance.

The design, construction and completion were respectively performed by three different teams of students. This discontinuity caused many design elements to be simply ‘inherited’ from the prior teams, and therefore great effort was required upon each handover to understand and master the concepts developed. This caused large delays along the Prototype’s development, and a number of less-than-optimal design solutions due to the proneness of misunderstandings.

Following from Part One, a new design methodology has been adopted by the 2014-2015 Campaign drawing upon lessons learned from completing the 2013 Prototype in combination with a firm understanding of each competition-specific set of rules.

Accumulator Design

Introduction

Accumulator is a general term for energy storage, which includes both batteries and capacitors. Batteries are common for Formula SAE vehicles due to their specific energy, and capacitors are more common in the Formula Hybrid competition due to their specific power as the accumulators have to efficiently handle being electrically supplied by an internal combustion engine.

The accumulator cells used in 2013 and 2014 are high in both specific energy and specific power (relatively) as the propulsion system has high ampacity (amperage capacity) requirements. This, and in confirmation with the specifications sheet, affirms that the cells are suitable for use in a hybrid-configured vehicle.

The perceived cost of not using the existing 640 cells was also a factor in resolving this design.

An intermediary accumulator was originally considered as an addition to the primary accumulators, made up of capacitors as capacitors' low internal resistance lends them well to regenerative braking systems. The project is no longer considering regenerative braking.

The following considerations went in to the power system when determining its configuration:

Low voltage high current configuration:	High voltage low current configuration:
• Small voltage drop over discharge	• Large voltage drop over discharge
• Components are readily available and less expensive	• Components are specialty devices and are more expensive
• Safer due to reduced risk of arcing	• Dangerous due to risk of arcing
• Requires larger and heavier conductors	• Requires high-voltage rated insulation
• Conductors can be manufactured	• High-voltage components must be purchased
• Conductors have more surface area for cooling	• High-voltage components require intensive cooling due to small package devices
• Failure is easily identifiable	• Failure is not always evident
• Conductors suffering minor failure are inexpensive to replace	• High-voltage devices suffering minor failure are expensive to replace
• Over-current conditions can be avoided through the appropriate use of fuses	• High-voltage control is more intricate
• Motors operate at a higher temperature	• Motors operate cooler

The low voltage high current configuration was selected due to safety and cost reasons. Additionally, majority of low-cost compact electric motors and speed controllers that appealed to this application operate at or below 72V. Therefore (and due to cell configurations) it has been decided that the tractive system will operate at either 64V or 72V.

The 2013 vehicle features two non-removable accumulators alongside the driver in the driver's cell, and separated from the driver by a sheet steel firewall. The cells are contained within an enclosure constructed of Bakelite. The chemistry selected by the team in 2011 was LiFePO4, in the K2 26650P form factor (Hooper 2008; Conquilla and Speidel 2013).

Due to the design and placement of these, there were a number of undesirable outcomes such as:

- Packaging of the driver
- Poorly integrated chassis design
- Difficult access and servicing of cells/fuses
- No account for heat dissipation
- Cells were not adequately mechanically secure

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Graphic 9: The 2013 Prototype accumulator featuring permanent construction

Two accumulators is a preferred number as opposed to one or three, as one accumulator would inherently occupy a large inflexible volume; and since every accumulator requires two contactors, a system with any more than two accumulators would contain a difficult number of contactors to manage.

There are also a variety of form factors for cells such as cylindrical, flat and ‘brick’ forms. The Renewable Energy Vehicle Project at UWA has access and experience with the cylindrical and brick type cells. Typically brick and flat cells are simpler to package due to their tessellating geometry.

However as the team already had a large amount of K2 26650P cells (cylindrical) a solution was reached that would package groups of cells into a brick configuration for ease of packaging. These will be mounted together in a non-permanent arrangement, as the previous arrangement was permanent and caused a number of troubles with servicing and access.

Additionally flat and brick cells have a tendency to swell, enough to mechanically displace cells and fixtures around them. Cylindrical cells will tend to burst at the cap which is likely to cause less damage to surrounding cells.

As for the cells themselves, Hooper (2007; 2008) has performed tests of discharge rates, charge rates, heat generation, voltage stability over time, total capacity and specific energy, and compares them to their manufacturer specified ratings in addition to a variety of similar cells, documented at his business Zero Emissions Vehicles Australia (ZEVA).

Functional requirements

There are many explicit rules that affect the design and construction of the accumulators. Some of the most specific rules are quoted below from the 2014 Formula SAE Rules (2013, p. 91-92).

> *EV3.3.2 Every accumulator container must contain at least one fuse and at least two accumulator isolation relays...*
> *EV3.3.7 Contacting / interconnecting the single cells by soldering in the high current path is prohibited*
> *EV3.4.5 The accumulator container must be built of mechanically robust material.*
> *EV3.4.6 The container material must be fire resistant according to UL94-V0, FAR25 or equivalent.*

General performance:

- Weight and Distribution – May have affects on handling of the vehicle (for example: overall mass, yaw inertia, yaw axis, rollover stability, roll inertia, roll dynamics, pitch dynamics et cetera.)
- Electrical Isolation (contactors) – Must be vibration and ingress resistant
- Physical Isolation (firewall) – There must be a mechanical barrier from the driver
- Volumetric and Packaging – May be difficult to package and package among other components
- Mechanically robust construction – There are mechanical load cases specified within the rules but additionally, designs should ensure that torsional and bending loads have no adverse effects on the operation of the accumulators such as compromising contact or stressing connections within the accumulator.

Electrical load cases:

- Energy Capacity (endurance) – Must be able to supply energy for a complete endurance race
- Maximum Power Capacity (discharge) – Must be able to deliver enough power without overheating
- Continuous Power Capacity – Should be able to handle continuous conservative driving
- Chemical Efficiency – Must have a usable operating temperature range and be able to remain stable during and after short periods of a mildly higher temperature. Additionally, some cell constructions have a tendency to physically swell under high electrical loading which can cause mechanical failure of the accumulator.

Energy and power capacity:

Indicative research was conducted to determine the energy storage requirements of the accumulators. This is a factor of the anticipated average power output and time taken to complete the endurance event. There is no safety factor included as to do so would incur large costs, large weight increase and additional design. The team is also considering that they may remove some of this capacity after testing if conservative driving technique is increased.

As a performance measure, in the event that for whatever reason there has been an unexpectedly high power usage, the driver will receive an indication from the vehicle instrumentation to drive conservatively to finish the event without concern for lap times. This is because it is undeniably beneficial to finish the event and score from slow lap times than to score zero points from a DNF result.

Average power output is converged from a number of sources to be 19kW, as summarised by Henson (2014) in his progress report about the new accumulator design. From this and a presumed time of 22 minutes, also converged by Henson, Olsson (2012) and Events.imeche.org (2013) the resultant requirement is 7kWh capacity.

The endurance curve for this configuration is estimated by:

$$\text{Capacity (kWh)} = \text{Time (Hours)} \times P_{ave}\text{(kW)}$$

This estimation tells us the amount of total endurance (in units of hours) given the average power output.

Features to update

The permanent non-removable construction of the 2013 Prototype's accumulators produced problems for access and servicing. In addition, the cells were not well mechanically secured. The conductive bus plates were not manufactured to a professional standard, and on speculation would not be able to handle the current draw.

Polycarbonate was selected as the firewall construction material as certain compositions (Makrolon and Lexan) are UL94-V0 fire resistant. They also exhibit excellent toughness and workability. (Lexan Polycarbonate Technical Data Sheet n.d.; Polycarbonate Fabrication Guide – Makrolon n.d.)

The original concept utilised laser-cut machining in order to produce the two-dimensional profile. Laser-cutting was considered due to its process speed and the quantity which was intended to be manufactured.

Through an email received from Mulford Plastics it was deemed that the laser-cutting process was less desirable to computer-numerical-controlled (CNC) routing of the polycarbonate sheet. (Polycarbonate for laser cutting 2014)

It is understood that CNC routing is only slightly slower however is a common process for sign-making and therefore possibly an easier process to perform.

Laser-cut prototypes were used to ensure secure fitting of the cells in the proposed arrangement. Cut-outs of 0.1mm incrementally varying nominal fit were produced to obtain optimal dimensioned manufacturing drawings.

Graphic 10: The laser-cut design mocked up in wood before being approved for manufacture.

Conductive bus plates will be constructed out of milled anodized aluminium in order to ensure their safety and reliability. Connections will be made using conductor bars manufactured in the same method and bolted with positive-locking nuts. Electrical connections will be completed solely by conductor contact and not through the bolts.

Aluminium was selected since for the same ampacity, it features less weight but more section area requirement than copper.

The design has been handed over by thesis student Andrew Henson, who will develop the mounting hardware, electrical connections and enclosure for the accumulators.

Chassis Manufacture

Introduction

The chassis forms the structure of the vehicle, contains the driver, and locates nearly every major component. It is the largest part of the vehicle and has a significant influence of the overall weight and weight distribution through its construction and geometry.

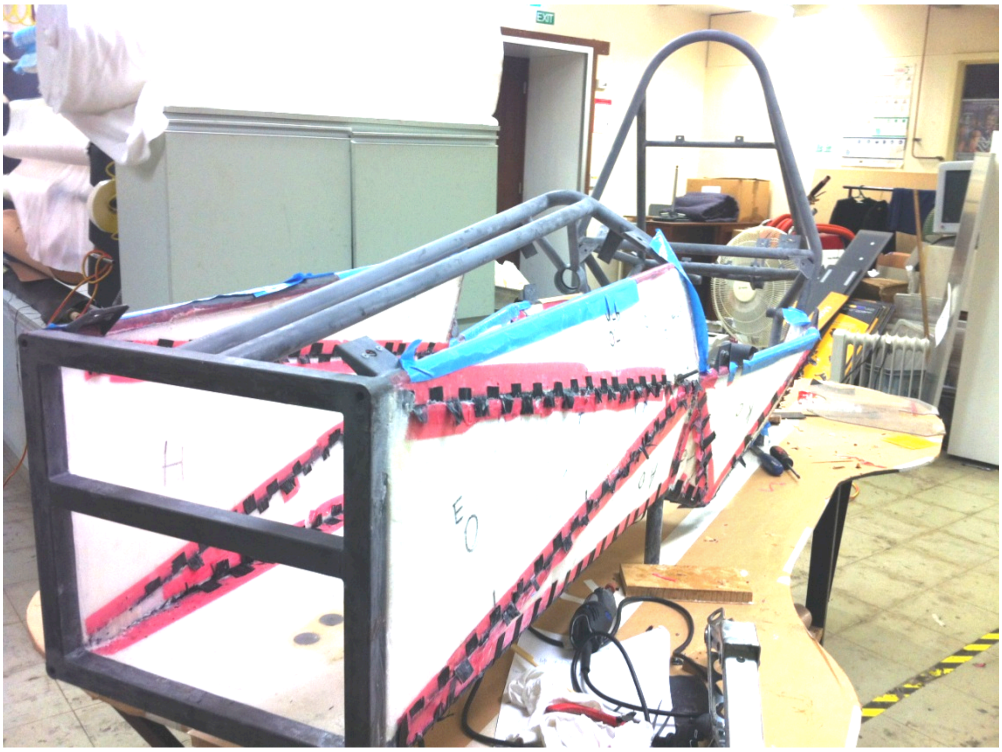
Electric vehicles have different packaging problems when compared to their more understood internal combustion vehicle counterparts. Immediately obvious is the lack of an engine and in in-wheel cases the lack of a transmission or drivetrain. Additionally the placement of electrical components *can* be more flexible due to the transmission of power through cables; however electrical firewall regulations can make certain cable routes inefficient.

There are a number of different types of chassis manufacturing methods outlined below in order of general performance:

- Mild Steel Spaceframe (standard rules compliant)
- Chromoly Steel Spaceframe
- Aluminium Spaceframe
- Titanium Spaceframe
- Carbon Fibre Tube Spaceframe
- Fibreglass Monocoque
- Aluminium Monocoque
- Carbon Fibre Monocoque
    - Hybrid constructions (even more exotic combinations of the above)

Graphic 11: The UWA Formula REV 2013 Prototype stripped of all sensitive components for welding. The vehicle features mild steel spaceframe construction. Note the locations for the two accumulators, either side of the driver.

Graphic 12: The UWA Motorsport 2011 Prototype featuring carbon fibre monocoque construction.



Graphic 13: The UWA Motorsport 2013 Prototype featuring hybrid carbon sandwich panel and spaceframe. This photo was taken prior to applying the carbon fibre skin.

Manufacturing Difficulty

In correlation with general performance, manufacturing difficulty also increases. For example, the design process for monocoque constructions is highly detailed, with such specifications as the fibre grade, resin grade, weave direction, core materials and number of plies; which in addition may vary along the chassis. When compared to a spaceframe construction, they often can be as simple as specifying two or three tube sizes and the welding process.

Further to this, monocoque constructions require a mould process which can limit the geometries achievable.

Other difficulties in design for manufacture include aluminium or titanium welding operations, as they require special processes, and there are also specific requirements stated in the rules such as certification and aging of welds. It may also be difficult to weld in hard to reach places, and this issue must be avoided in the design or addressed in the manufacturing process.

Any non-steel construction must also undergo equivalency testing which is both time consuming and expensive.

Cost

Material costs can be significant without sponsorship support, especially for titanium and carbon fibre. Certain processes may also be expensive or rare such as titanium welding, or forming of monocoque shapes.

Another cost which is less obvious is the team's time and labour required to notch tubes for a spaceframe or lay inserts and core for a monocoque. In the example of a bespoke steel spaceframe, chromoly steel is notoriously difficult to cut and grind, so it would be advisable to pursue a mild steel construction.

Functional Requirements

The chassis design is complicated by rules requirements, suspension layout and driver ergonomics in that order of importance. Excerpts from the 2014 Formula SAE Rules (2013, p. 26-27) below outline the primary considerations of the construction of a standard (baseline) chassis.

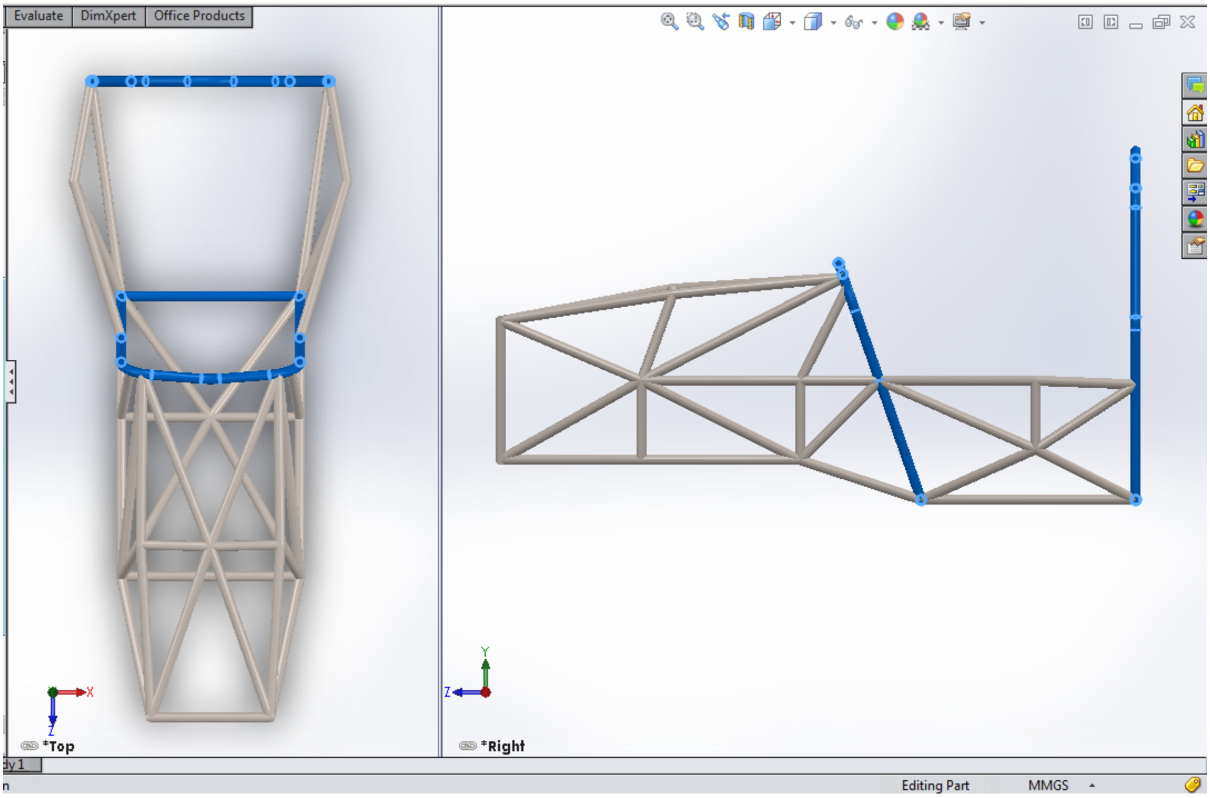
> *T3.3 Definitions*
> *The following definitions apply throughout the Rules document:*
> - *Main Hoop – A roll bar located alongside or just behind the driver's torso.*
> - *Front Hoop – A roll bar located above the driver's legs, in proximity to the steering wheel.*
> - *Roll Hoops – Both the Front Hoop and the Main Hoop are classified as "Roll Hoops"*
> - *Roll Hoop Bracing Supports – The structure from the lower end of the Roll Hoop Bracing back to the Roll Hoop(s).*
>
> *...*

- *Front Bulkhead – A planar structure that defines the forward plane of the Major Structure of the Frame and functions to provide protection for the driver's feet.*

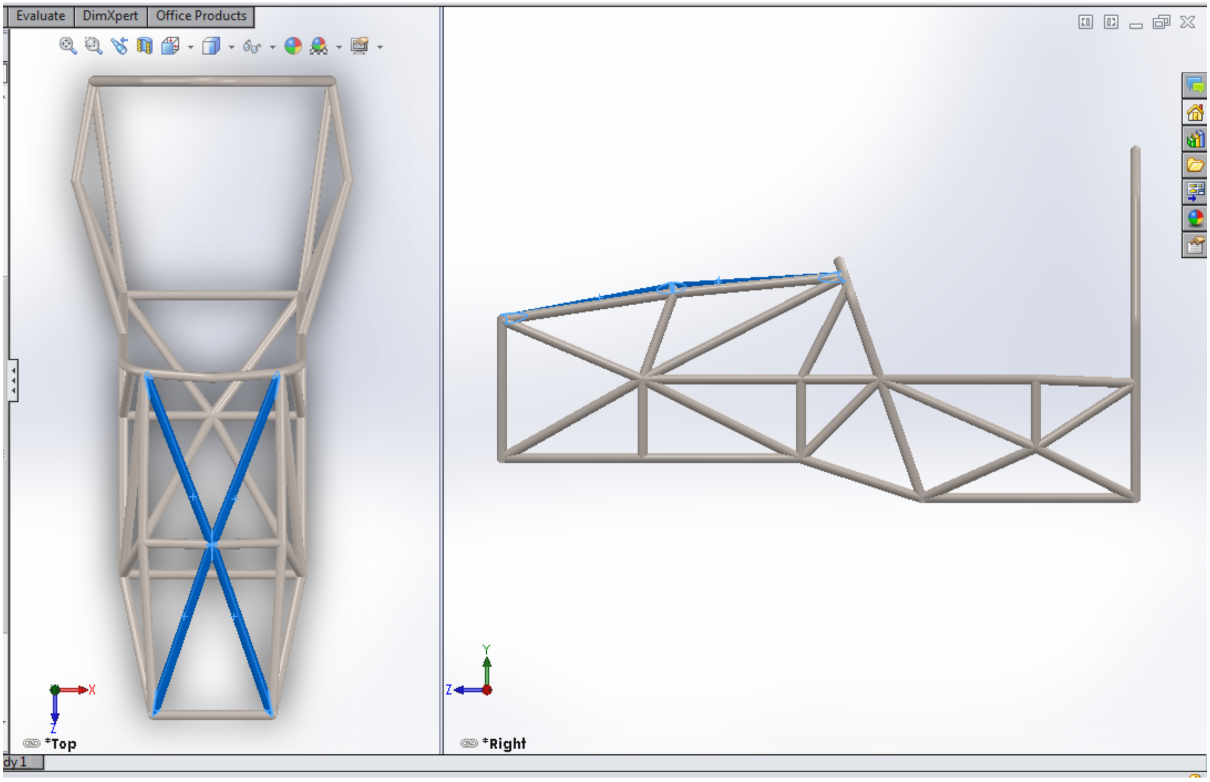
...

- *Side Impact Zone – The area of the side of the car extending from the top of the floor to 350 mm (13.8 inches) above the ground and from the Front Hoop back to the Main Hoop.*

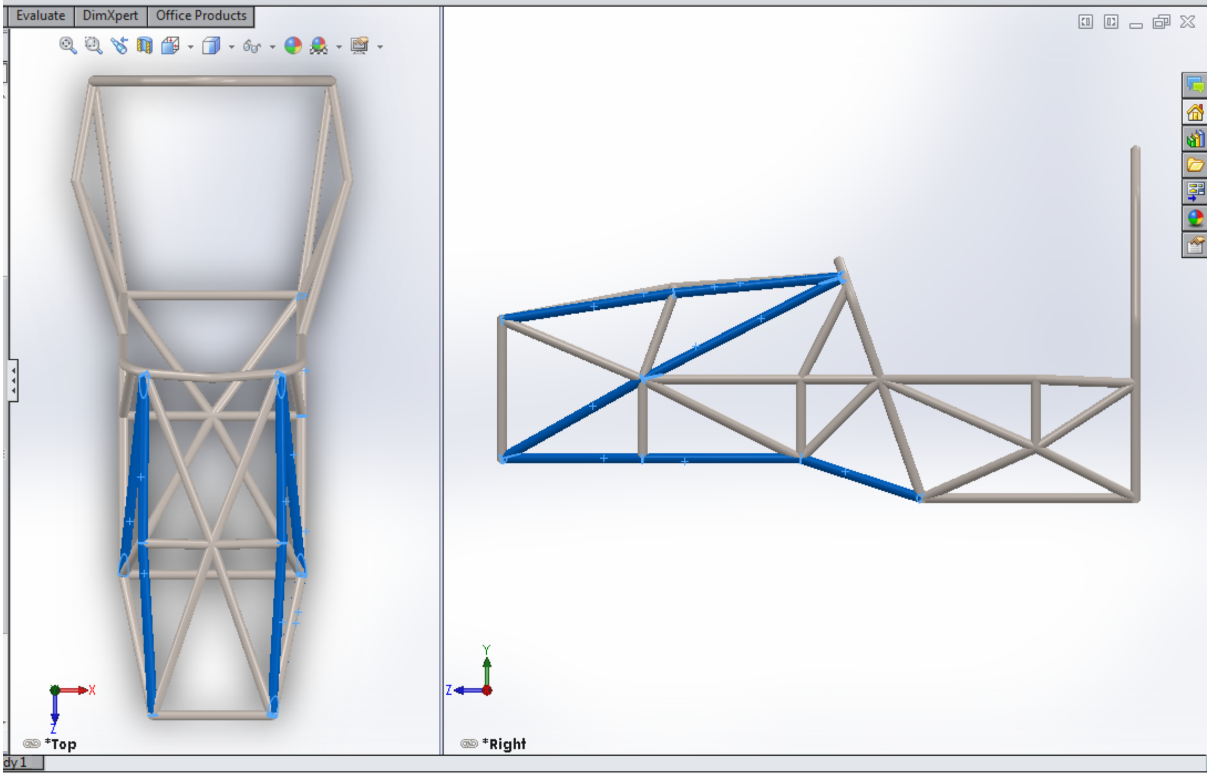
Node-to-node triangulation – An arrangement of frame members projected onto a plane, where a co-planar load applied in any direction, at any node, results in only tensile or compressive forces in the frame members. This is also what is meant by "properly triangulated"



Graphic 14: Front and rear roll hoops highlighted



Graphic 15: Front roll hoop bracing highlighted



Graphic 16: Front bulkhead support highlighted

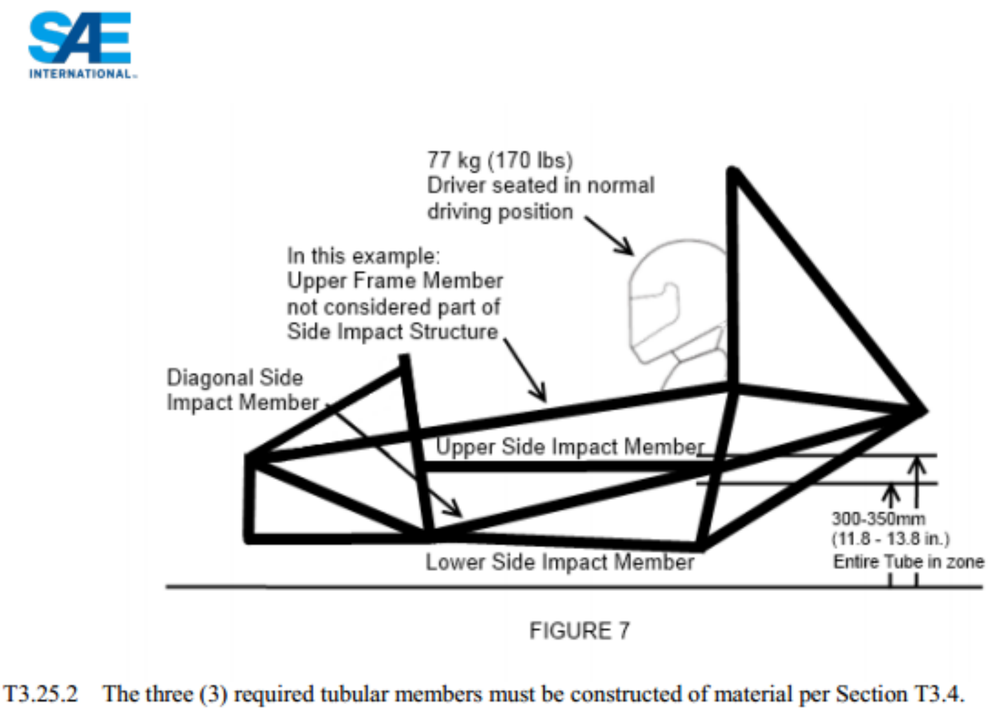
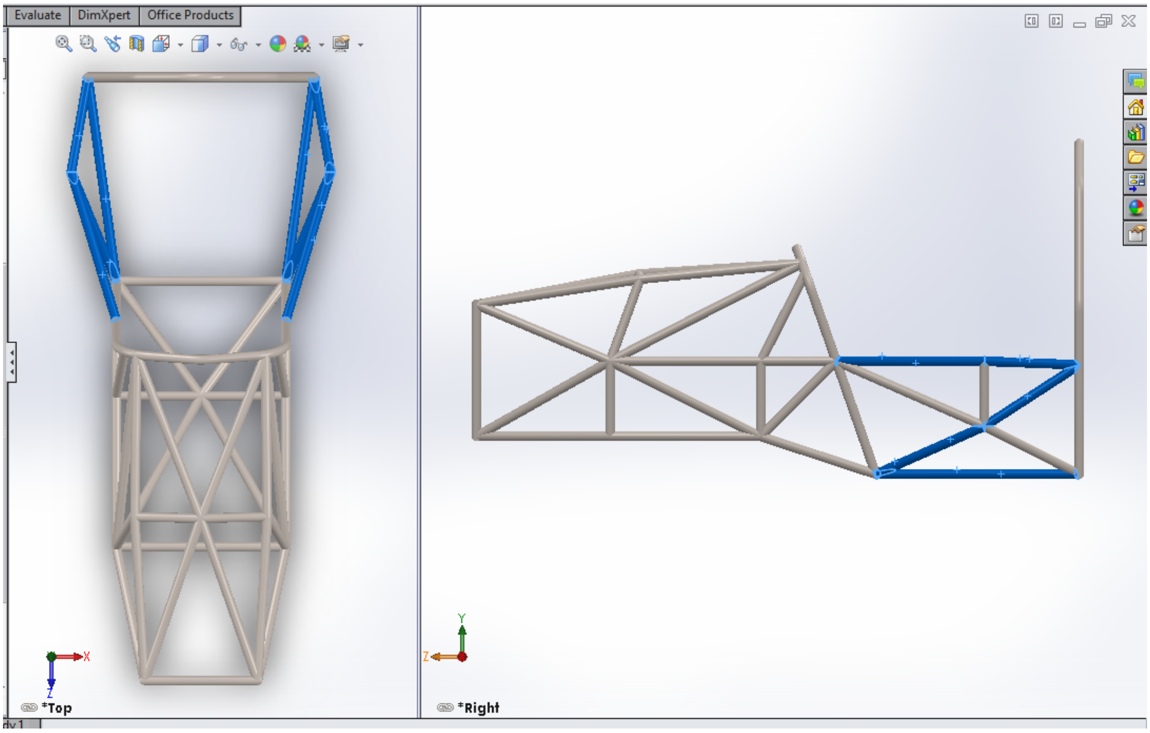


FIGURE 7

T3.25.2 The three (3) required tubular members must be constructed of material per Section T3.4.

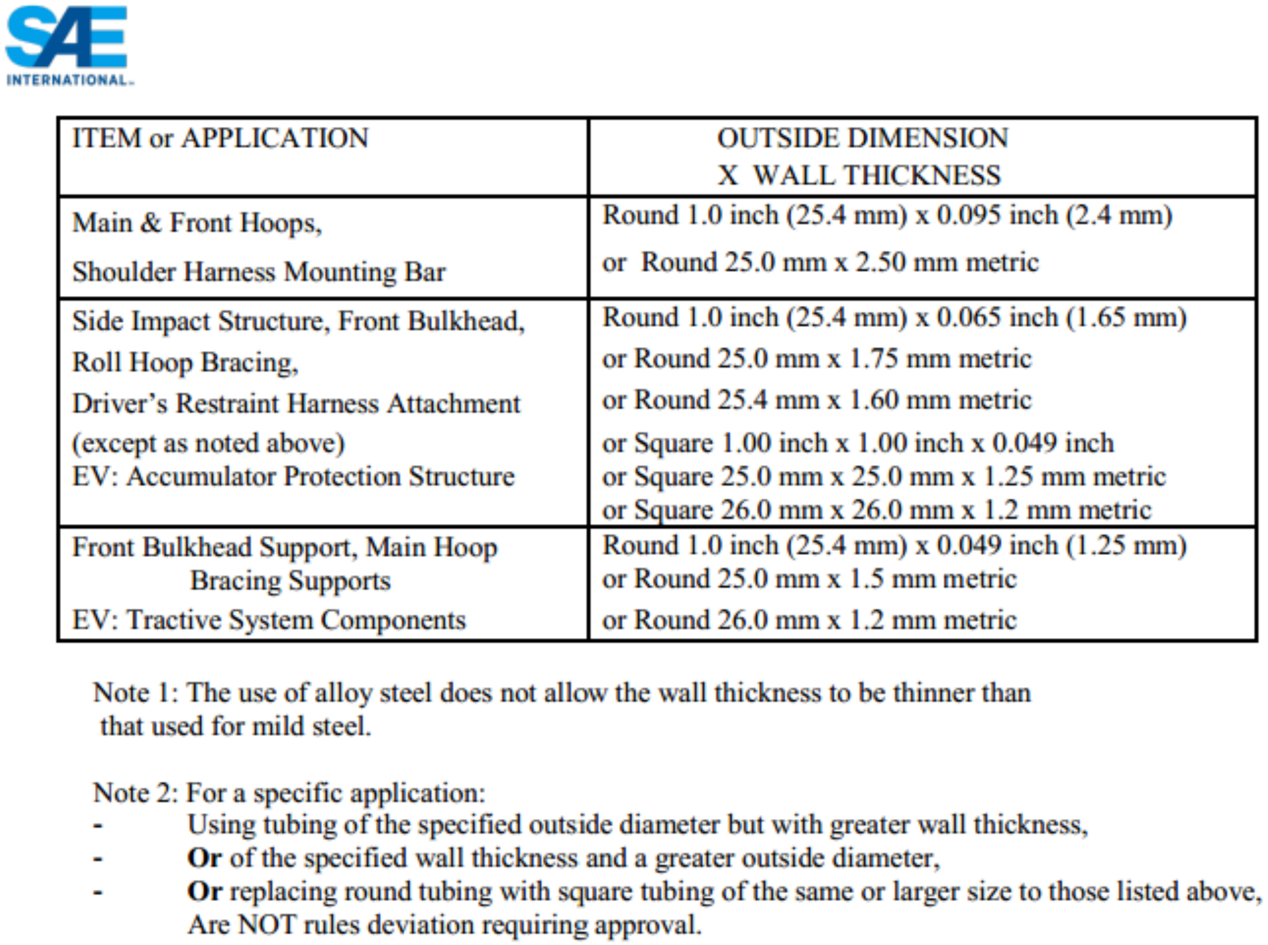
Graphic 17: (2014 Formula SAE Rules 2013, p. 40)



Graphic 18: Side impact structure highlighted

2014 Formula SAE Rules (2013, p. 27):

> *T3.4 Minimum Material Requirements*
>
> *T3.4.1 Baseline Steel Material*
>
> *The Primary Structure of the car must be constructed of: Either: Round, mild or alloy, steel tubing (minimum 0.1% carbon) of the minimum dimensions specified in the following table, Or: Approved alternatives per Rules T3.4, T3.5, T3.6 and T3.7.*



ITEM or APPLICATION	OUTSIDE DIMENSION X WALL THICKNESS
Main & Front Hoops, Shoulder Harness Mounting Bar	Round 1.0 inch (25.4 mm) x 0.095 inch (2.4 mm) or Round 25.0 mm x 2.50 mm metric
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment (except as noted above) EV: Accumulator Protection Structure	Round 1.0 inch (25.4 mm) x 0.065 inch (1.65 mm) or Round 25.0 mm x 1.75 mm metric or Round 25.4 mm x 1.60 mm metric or Square 1.00 inch x 1.00 inch x 0.049 inch or Square 25.0 mm x 25.0 mm x 1.25 mm metric or Square 26.0 mm x 26.0 mm x 1.2 mm metric
Front Bulkhead Support, Main Hoop Bracing Supports EV: Tractive System Components	Round 1.0 inch (25.4 mm) x 0.049 inch (1.25 mm) or Round 25.0 mm x 1.5 mm metric or Round 26.0 mm x 1.2 mm metric

Note 1: The use of alloy steel does not allow the wall thickness to be thinner than that used for mild steel.

Note 2: For a specific application:

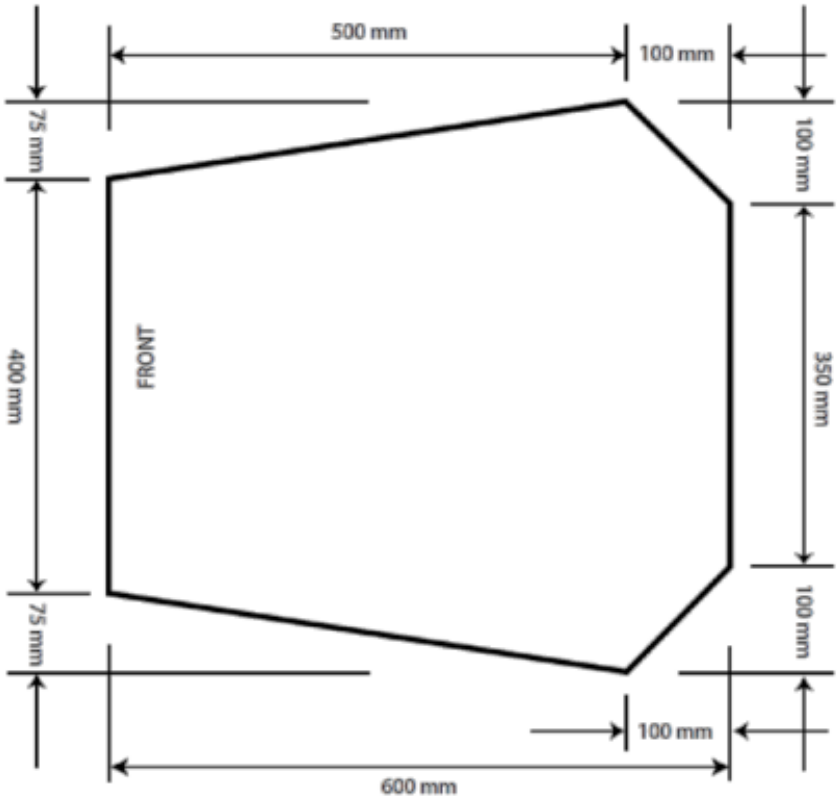
- Using tubing of the specified outside diameter but with greater wall thickness,
- **Or** of the specified wall thickness and a greater outside diameter,
- **Or** replacing round tubing with square tubing of the same or larger size to those listed above,

Are NOT rules deviation requiring approval.

Graphic 19: (2014 Formula SAE Rules 2013, p. 27)

T4.1 Cockpit Opening

T4.1.1 In order to ensure that the opening giving access to the cockpit is of adequate size, a template shown in Figure 8 will be inserted into the cockpit opening. It will be held horizontally and inserted vertically until it has passed below the top bar of the Side Impact Structure (or until it is 350 mm (13.8 inches) above the ground for monocoque cars). No fore and aft translation of the template will be permitted during insertion

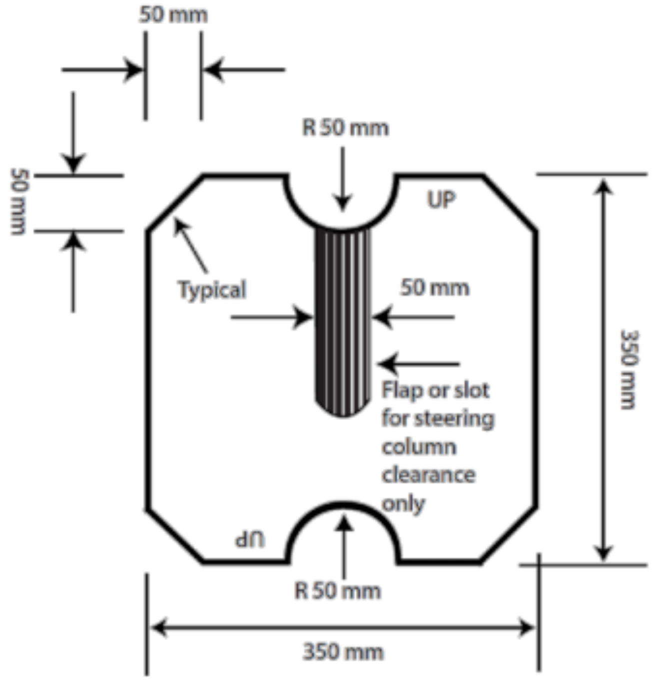


Graphic 20: (2014 Formula SAE Rules 2013, p. 46)

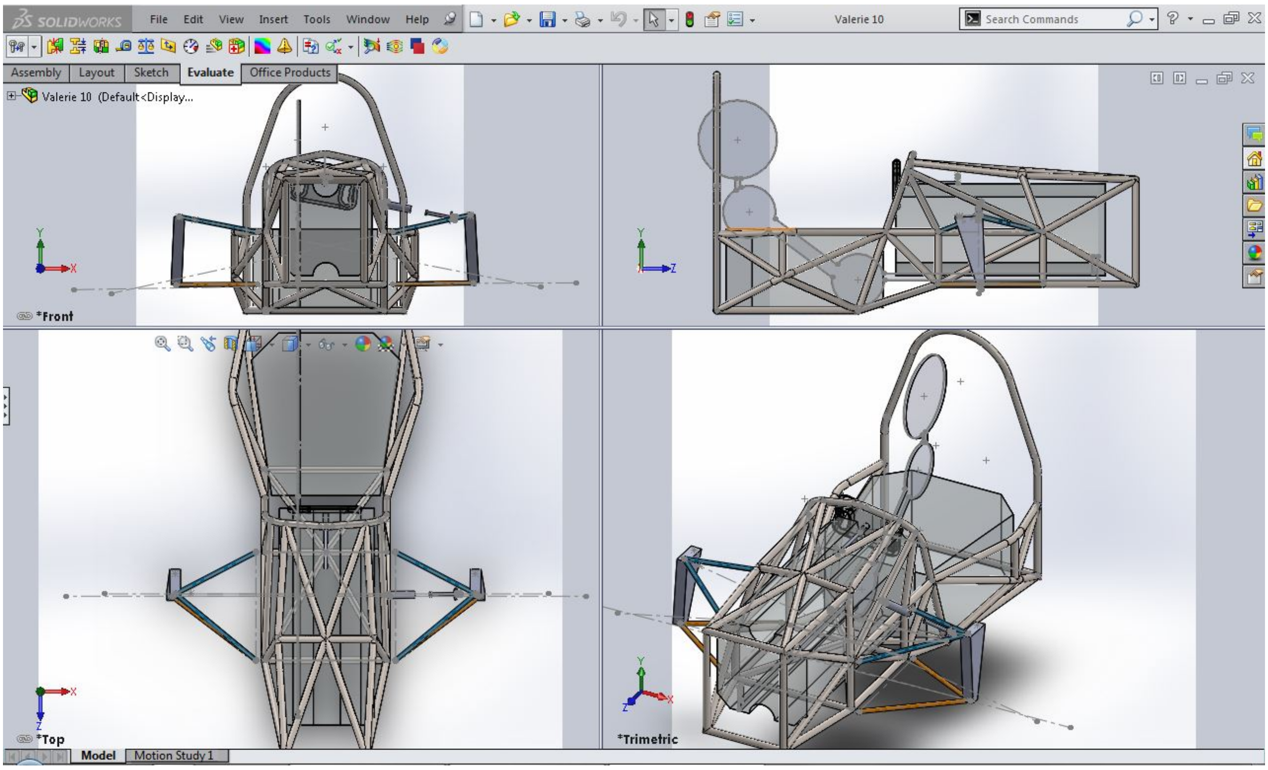
T4.2 Cockpit Internal Cross Section:

T4.2.1 A free vertical cross section, which allows the template shown in Figure 9 to be passed horizontally through the cockpit to a point 100 mm (4 inches) rearwards of the face of the rearmost pedal when in the inoperative position, must be maintained over its entire length. If the pedals are adjustable, they will be put in their most forward position.

Note: Cables, wires, hoses, tubes, etc. must not impede the passage of the templates required by T4.1.1 and T4.2.



Graphic 21: (2014 Formula SAE Rules 2013, p. 47)

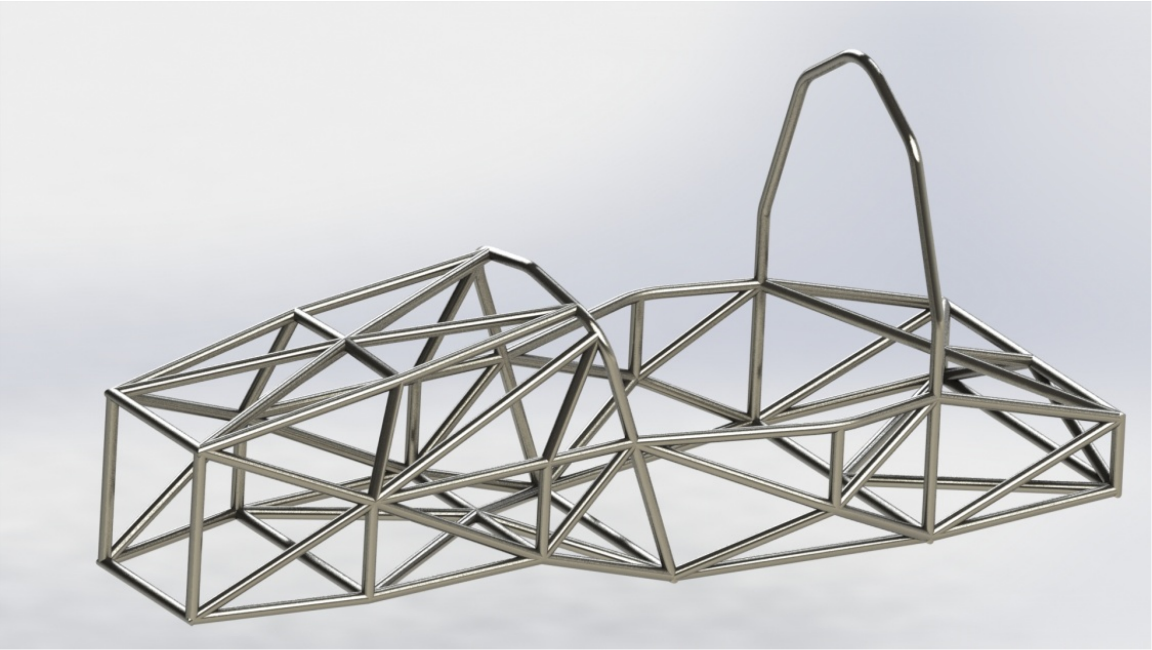


Graphic 22: The templates inserted into the assembly to check for interference.

Features to keep

Mild steel construction: Materials sourced with relative ease (and sponsorship), and compared with chromoly alloys is easier and cheaper to cut, notch and weld. The use of mild steel over chromoly alloy means that metal inert gas welding is a more suitable process, as otherwise tungsten inert gas welding would need to be used and is considered a much slower and more sensitive process.

Mild steel construction also does not necessarily require normalisation of the chassis. This in turn makes frame adjustments simpler. On a number of vehicles examined it was found that the ability to modify mounting hardware would have allowed for trivial solutions, however vehicles featuring chromoly alloy or carbon fibre construction were forced to use alternative less elegant methods such as cable ties or epoxy-resin.



Graphic 23: The concept render for the 2014 Prototype with the Rear Bolt-On featured.

Graphic 24: Commencement of the chassis manufacture.

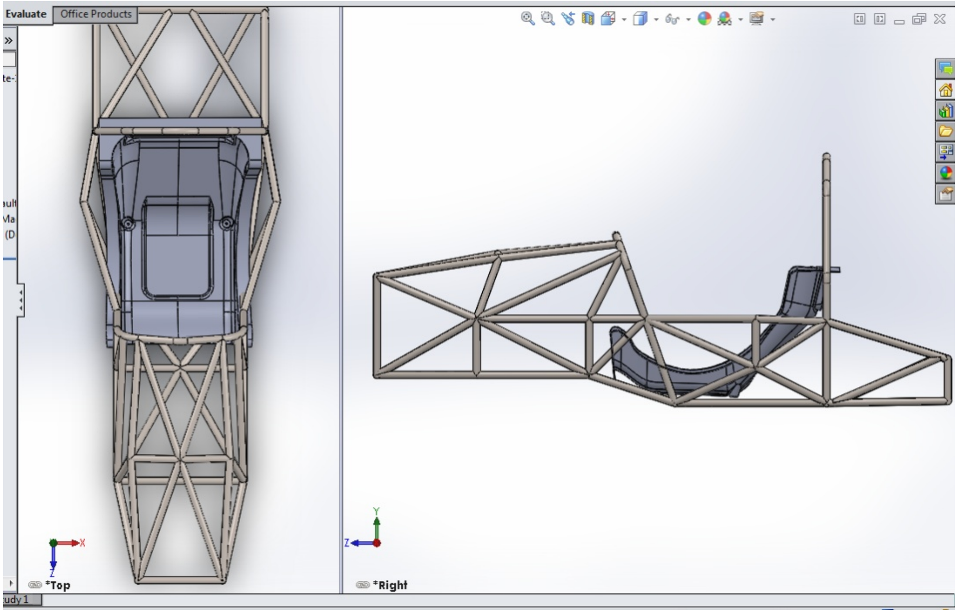
Features to update

Initially the chassis had mechanical issues that were worked through by the 2013 team in order to reach competition, and these issues were noted for the design of the following chassis.

- Whilst weight-saving is not a priority, the estimated weight of the chassis was 58kg, considered excessive. The new chassis weighs a projected 26kg, including the rear bolt-on assembly.
- A combination of square and round tube was used for no apparent benefit, and whilst not illegal, did complicate manufacture.
- Tubing that featured bolted connections such as for the accumulators and suspension had no mechanism (such as a welded tube insert) to avoid crushing the tube when the bolt is tightened or loaded during operation.
- The construction of the chassis was based on an incomplete design and resulted in a warped and non-symmetrical final component.
- The chassis was not node-to-node triangulated, and the two inspection templates did not fit. Extensive restructure of the chassis had to be performed.
- Ergonomics were not considered in the design and it was noticed that seat position, steering wheel placement and elbow room should have been considered. Chassis members and accumulator firewall in the driver bay would contact the driver in multiple places during driving.
- The chassis design largely limited placement of suspension hardpoints and steering, as well areas of unintentional contacting near the limits of travel of each system. Some considerations into these limits of travel and some flexibility (adjustability) in the design of the suspension hardpoints were recommended for the following design.

Ergonomics

A number of methods were used to confirm ergonomic factors. Using photographs of international Formula SAE vehicles that were reputed for being ergonomic, the chassis was checked for compatibility.



Graphic 25: Ergonomics check performed with a reputable seat, SolidWorks part file made available by Formula Seven (n.d.). The fit of this seat within the assembly is indicative that the chassis structure is compatible with an ergonomic driving position.

Graphic 26: Photograph transplant technique: Photograph is taken with a known dimension and transplanted into the assembly for reference. Pictured is the chassis design being evaluated with reference to the UWA Motorsport 2008 Prototype.

Rear Bolt-On Assembly

Introduction

The rear bolt-on assembly is a structure on the rear that traditionally allows packaging of power and drivetrain components, whilst accounting for access and serviceability of the systems it packages. It is known by many other names as well such as the bracket-for-everything, rear bulkhead, rear frame, differential carrier, and engine bay plate, depending on its function on the design of other vehicles. Sometimes it is not removable and so is considered part of the chassis.

Since the 2013 chassis extends to the rear it is not considered to have a rear bulkhead. The integrated rear frame caused numerous major packaging conflicts during the construction and preparation of the vehicle, with the rear suspension, rear chassis triangulation structure, GLV control, HV distribution and charging, rear propulsion controllers, rear firewall, high voltage disconnect, brake light and jacking bar sharing the volume.

The cause of this was poor accumulator placement and poor GLV and HV layout. There was no plan for this area in the 2013 chassis' original design, and as such there is no literature available to determine a legitimate reason that this solution should be attempted again.

Functional Requirements:

The primary role of the rear bolt-on assembly is to allow for low difficulty modifications of the rear drive system packaging. It also supports a number of other systems:

- Rear suspension
- Rear roll hoop bracing
- Rear chassis triangulation structure
- Rear firewall
- High voltage disconnect
- Jacking bar
- Brake light

In addition, the two mounting minimum requirements for this system are:

- Non-welded roll hoop braces must use minimum 8mm Metric Grade 8.8 bolts.
- Mounting plates welded to roll hoop braces must be at least 2mm thick steel. (2014 Formula SAE Rules 2013)

Graphic 27: The UWA Motorsport 2003 rear bulkhead was the first of its kind throughout the international competition. This vehicle was awarded the prestigious Carroll Smith Design Award for innovation in packaging.

Advantages

The use of a rear bolt-on assembly allows for swift transition between the 2014-2015 Campaign stages as detailed in the Introduction. Specifically, it allows the design of a beam axle rear to be developed for completion of

Stage I without commitment to the beam axle suspension configuration for the Formula SAE-Australasia competition.

The fact that the Stage I rear bolt-on assembly will not be required to pass technical inspection allows for flexibility in the design, and saves some cost for manufacturing as an intermediate solution.

This simplifies the facilitation of testing and driver training in the short term. It is intended that the beam axle rear will make use of components from the 2013 Prototype in order to produce a functional vehicle exerting the least resources.

The rules for competition require a minimum wheelbase of 1525mm, however the vehicle’s suspension setup can be adjusted through the non-permanent nature of the rear bolt-on assembly. This ensures that the vehicle complies with technical inspection requirements, and also allows for an increased wheelbase if it is found that during testing it is required.

The final advantage to featuring a non-permanent rear bolt-on assembly is the ease of transition to Formula Hybrid 2015 in Stage IV. The addition of a turbocharged bio-diesel generator would most certainly cause mounting hassles, and the necessary engine components such as air intake, exhaust and radiators would have difficulty packaging well in a pre-designed frame.

The modularity of the rear is intended so that during Stage IV the entire rear bolt-on assembly can be designed around the generator and components before being mounted to the hardpoints on the existing chassis.

The chassis and rear bolt-on assembly are expected for completion before June 2014.

In-Wheel Propulsion Assembly

Introduction

The in-wheel propulsion assembly is the prominently unique element of the UWA Formula REV 2014 Prototype, developed through the technological support of a sponsor and as an iteration of the 2013 Prototype's in-wheel assembly.

At its current stage, the assembly consists of two water-cooled brushless DC motors coupled by a zero-gear ratio transmission, wheel mount and brake system. The assembly is expected to weigh approximately 16kg.

A major finding from the 2013 Prototype was that brushless DC electric motors exhibit their lowest efficiency at low rotations, with a discontinuity of zero efficiency at zero rotations (ZEZRot). This effectively means that short circuit current occurs when the output is stalled causing one set of coils to heat up considerably until either the driver's torque request is ceased or a rotor magnet passes a coil.

From the design of the 2013 Prototype in-wheel assembly (Hooper, 2011) and in conjunction with evidence from the 2013 Prototype testing, it was clear that the power output of the Turnigy CA 120-70 motors used was as expected, except for the period of time when the vehicle is beginning to move from rest where the motors generate significant heat.

A traditional solution to this problem among the electric vehicle internet community such as Forums.aeva.asn.au (n.d.) is to largely over-specify the power output of the motor. A consideration in doing this is that larger motors can handle larger current surges in order to produce the torque required to accelerate the vehicle from rest. The excess power capacity of the motor is rarely made use of, as the power usage of the vehicle declines as the vehicle speed increases.

Designs observed by the RMIT and Swinburne vehicles featured motors capable of producing 100kW of power even though they were only providing 60kW and 85kW respectively through their controllers.

However as a primary requirement of the compact propulsion system is to fit within a 13” wheel there were (at the time design started) limited options accessible to the team. Late in the design the team discovered the availability of some competition electric boat motors from TP Power at a rated power output of 26kW at 72V, with responsive customer support and a very small form factor.

Prior to this discovery, UWA Formula REV alumni Graham Lionnet presented a concept to use a centrifugal clutch from an off road motorcycle in order to avoid the ZEZRot condition and allow the motor to only output power in the preferred band of rotations.

Clutches examined had power uses in the range of ~35kW, and are of low cost to source and replace regularly. Although the concept was set aside due to the sponsored transmission technology, small clutch units are still valid for investigation in following campaigns.

The sponsored transmission concept was provided under confidentiality through sponsorship of the team in addition to monetary support in order to develop and implement the transmission.

The purpose of this section is to propose an in-wheel assembly concept to implement the transmission that will be effective and reliable for this campaign.

Functional requirements

The first priority of the system design is reliable operation of the system. This means:

1. That the propulsion effectively and reliably transmits torque to the tyre contact patch, and,
2. That the assembly should transmit all loads between the tyre and the suspension without failure taking into account extreme conditions.

In order to predict the reliability of the system, factors are addressed such as whether the design is common, whether the components used are reputable or well documented specifications, whether the design can be checked and serviced regularly, the number of moving components present, and the number of functions each component performs.

The last factor is a modified incarnation of the common “number of moving components” assessment, as it is common among Formula SAE is to reduce the number of components in a system by increasing the number of functions the replacement component has to perform. This however implies more stresses are present within the given component which can lead to complicated analysis and design mistakes. Therefore some measure between “number of moving components” and “number of functions” may be a more encompassing representation of reliability.

This concept could be expanded in future work after further investigation of its validity within this work.

The second priority is stiffness of the assembly, as compliance can cause premature failure due to either fatigue or the deflection of components causing the assembly to unfasten. A common design practice mentioned among Formula SAE teams is that in general, a design that minimises compliance will experience stresses well below the yield stress.
(Colley 2013, Eos.info n.d.)

Mass within the wheel assembly is considered a major detriment to the handling and tractive response of the tyre contact patch and the road surface. The increase in mass causes the suspension assembly to work harder in order to maintain the tyre's rolling conformity with the road.

Additionally, in the case of both the 2013 and 2014-2015 Prototypes where each wheel assembly is intended to be identically configured, each unit of mass present within the wheel assembly adds four units of mass to the overall mass of the vehicle.

Another effect of wheel assembly mass is the increase in yaw inertia of the vehicle. Yaw inertia increases by a factor of the square of the distance of the mass from the axis of rotation. As the wheel assemblies are often the furthest components from the vehicle yaw axis, the yaw inertia decreases considerably for mass reductions in the wheel assembly.

This represents an area of significant weight-savings and performance benefit; however no mass reduction in the assembly will be pursued until the first two priority functional requirements have been met.

Propulsion load cases:

Propulsion load cases address situations where the vehicle is accelerating or braking. During acceleration the torque is transmitted from the in-wheel transmission output to the tyre contact patch. During braking conditions the torque is transmitted from the tyre contact patch to the brake calliper.

To simplify the analysis, the reaction loads are assumed to be fixed at the point where the suspension wishbones attach. These loads are then useful in order to optimise the wishbone design in future work.

Dynamic load cases:

Dynamic load cases address situations where the wheels may be undergoing large unusual loads and are categorised into two motions: bump and lateral.

Bump motions represent the wheel travelling over a bump or recess at speed, and also account for vertical forces when the vehicle corners. When two wheels on the same side experience bump the condition is called (not to be confused with rollover).

Lateral motions represent the wheel forces which produce a moment about the tyre contact patch when viewed from the circumference of the tyre (i.e. from the front, rear or top views). Examples of these are caused by cornering, sliding, steering input and excessive camber.

As examined by Lionnet (2013) the 20mm dia. steel shaft is able to support the relevant bending and torsional forces. However, there was noticeable bending compliance observed during testing and at the competition.

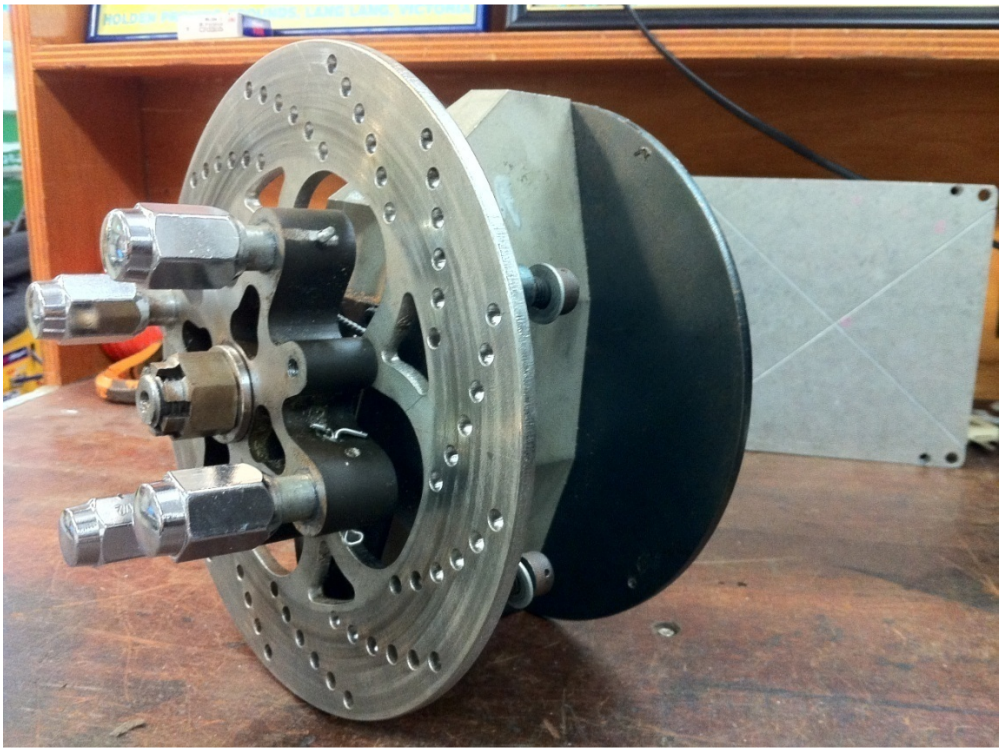
Features to update

The 2013 Prototype wheel assembly made extensive use of sponsorship from the School of Physics Workshop who supported the team with electro-discharge machining (EDM or wire-cutting) facilities free of charge. The wheel assembly consisted of components listed below.

- 13" wheel rim
    - Selected for packaging space

Graphic 28:Tyre, wheel and wheel centre

- EDM aluminium upright
    - Material was easy to source and machine, and relatively lightweight for the function
    - Suspension hardpoints were tapped directly to the aluminium without some sort of thread relief such as a helicoil. Some threads failed after repeated adjustment of the assembly.
    - Suspension bolts tightened directly into aluminium without adequate stress relief such as a steel washer. This prevented bolts from being preloaded enough due to the aluminium deforming before torque was reached.



Graphic 29: Upright assembly from 2013 Prototype

- Laser-cut steel brackets
    - Allowed adjustment of critical points of the upright
    - Use of material was far from conservative
    - Plates were not stiff enough in bending, causing transmission gear tooth slip, tooth slap, backlash and presumably incorrect involute contact angle.

Graphic 30: Laser cut brake mount plate

- Turned 4140 steel drive shaft with DIN spline and M16 castellated nut
    - The original design in 2012 featured a mild steel shaft, four square keyed slots and an M6 bolt with no positive locking mechanism. The soft steel and square keys deformed causing the bolt to loosen and the hub to partially fall off the car, bending the brake rotor and jamming the assembly.
    - The updated design addressed these issues; however the shaft was not very stiff in bending resulting in major camber and toe compliance issues under load variation.

Graphic 31: Driveshaft

Graphic 32: EDM machined hub

- EDM 4140 Steel Hub with DIN spline
    - Component was heavy and not entirely necessary. The hub performed a redundant function to the wheel centre.
    - High stress area between shaft and hub interface in all modes, i.e. torsion, bending, shear, axial; due to immediate change in cross section, and reduced cross section due to splines.

- Mild steel pinion and pinion shaft
    - Pinion shaft was too thin as examined by Lionnet (2013), and one failure occurred at the location where a circlip groove had been machined. No circlip groove should be placed on the torque side of a shaft.

- Mild steel machined drive gear
    - Component was heavy despite weight-saving efforts by Hooper (2011).
    - Due to the gear's size and location it would contact wishbones at the limits of travel of both the steering and suspension mechanisms.

Graphic 33: Large drive gear

Propulsion assembly load case

Calculations yielded the following load cases for the new propulsion system:

- TP100 Brushless Motor
- Unspecified speed controller
- 13” wheels
- Vehicle expected mass: 220kg
- Maximum power output: 85kW
- System voltage: 64V or 72V
- Maximum current: 1328A or 1180A
- Motor torque at power limitation: 41.65Nm
- Output maximum torque per wheel: 166.6Nm
- Transmission reduction: 4:1
- Vehicle maximum speed: 117.6km/h

Future work

An area of future work resides in optimisation of the in-wheel assembly. Optimisation software by Altair called Optistruct has been a successful design tool for UWA Motorsport, and there are a number of top-ranking international teams that have used the Optistruct software to develop extremely light high performance components. (Ranking Amongst the Top... 2013; Reducing Weight and Max... n.d.)

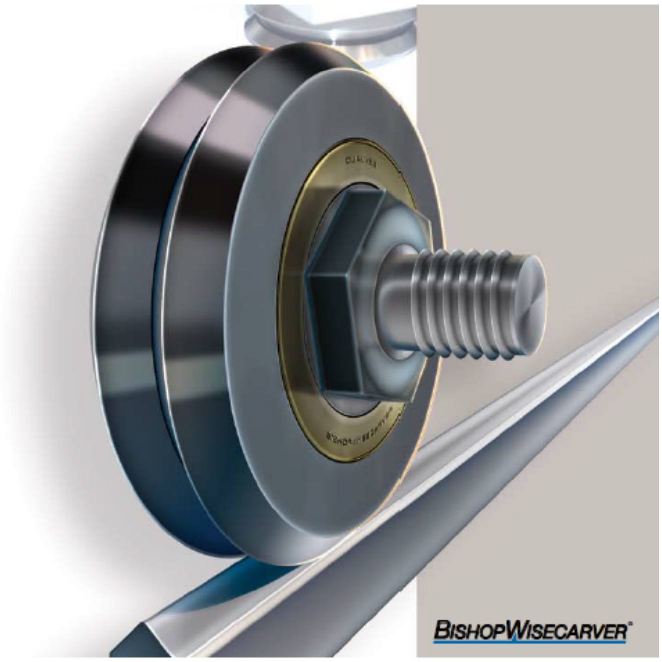
Under similar review of Optistruct analysis for wheel applications (Coons, et al 2007; Yadav, et al n.d.), it can be observed that the stresses decrease radially on the wheel centre, and also decrease towards the extremes of the upright component.

Due to this, high amounts of material are required on the upright component, whereas low amounts of material are required on the wheel centre. Examination of the load path of the typical wheel centre, driveshaft to upright configuration would suggest that the diameter of the driveshaft is the most influential factor on the stress.

A suggestion for further work is to examine omitting the wheel centre, driveshaft and upright components altogether and redirecting the load through the rim of the wheel directly to the wishbones. This would be considered a “centreless wheel” which has already been executed to some success by another Formula SAE team, Amberg-Weiden.

The proposed concept would save weight by omitting these components and gain a more optimised assembly, at the expense of major manufacturing complexity. There currently are problems with simply using a large ball or needle roller bearing for this function, as the angular velocity of the wheel during operation would well exceed the bearing rated angular velocity.

Another consideration is to make use of a rail and vee-bearing such as the one depicted below. The wheel rim would feature a circular rail, whilst an inner rim would mount four to six vee-style bearings. Special consideration should be made into preload adjustment on the vee bearings. This particular system (DualVee) has been confirmed by the manufacturer to be unsuitable for the speeds involved, however a prototype could be developed and assessed in future.



Graphic 34: Example DualVee bearing and rail system for illustration purposes only. (DualVee Components Technical Specifications 2007)

A major factor in the inclination towards a centreless wheel concept is that the packaging space available in-wheel is not currently enough to package both the transmission and an axle. This means that the transmission would have to be located outside the wheel which would cause high bending stresses and consequently more material in order to reduce this stress.

The proposed concept would drive the wheel rim as an internal gear, which would mean that there would be no requirement for the transmission and wheel to be located concentrically, which greatly simplifies the design with regard to clearances throughout the entire range of motion of the suspension and steering mechanisms.

There currently exist concepts developed by the author for in-wheel assemblies that exceed the scope of this work. For completeness however, the centreless wheel and a traditional upright are compared below.

The intention is that either design would be manufactured by EDM as this is a sponsored service to the UWA Formula REV team.

Centreless wheel (EDM)	**Three-piece spoked upright** (EDM)
1.Higher rotational inertia	1.Lower rotational inertia
2.No wheel centre mass	2.Wheel centre mass
3.Higher spindle mass	3.Lower spindle mass
4.Odd bearing sizes	4.Standard bearing sizes
5.High bending stiffness	5.Low bending stiffness
6.Susceptible to dirt	6.Dirt ingress protected
7.Bearing preload difficult	7.Bearing preload trivial
8.Largely increased packaging space	8.Packaging space limited
9.Increased airflow	9.Airflow restricted by wheel centre
10.Floating rotor is necessary, possible better heat sinking	10.Floating rotor optional
11.Extremely unreliable concept for retaining wheels	11.Reliable and well studied concept
12.Induced squish compliance leads to uneven wishbone loading	12.Wishbones loaded more evenly
13.Higher torque/braking stiffness	13.Lower torque/braking stiffness

Lastly, it is noted that an update to 2014 Formula SAE Rules (2013, p. 88) details the following rule, which could be used to advantage as a load-bearing structure in addition to mandated function.

> *EV2.1.2 Motors must be contained within a structural casing where the thickness is at least 3.0 mm (0.120 inch). ...*

Conclusion

Through the technical review of the 2013 Prototype a large number of improvements were compiled for the design of the 2014-2015 Prototype.

The identification of an easy-to-manufacture polycarbonate structure and the decision to feature removable accumulators has led to the design of a stronger, more secure and serviceable cell configuration that allows a more integrated chassis layout and addresses the problems raised during the 2013 Campaign.

Maintaining the ease of manufacture of mild steel spaceframe construction and the modularity of featuring a rear bolt-on assembly in addition to the shifting of the accumulators externally to the frame has led to a much more ergonomic chassis design, and significantly lighter than the 2013 Prototype chassis. Rules have specifically been addressed in order to ensure the vehicle passes technical inspection.

It is somewhat disappointing to note that the full design of the in-wheel assembly was not completed in this work due to the increase in complexity throughout the progress. However, significant groundwork has been compiled in order to develop a well-considered design from the concepts raised with this work.

Following this work, an accumulator concept has commenced detailed design and prototyping, both the chassis solution and rear bolt-on assembly have begun manufacture, and the preliminary designs for an in-wheel propulsion system have progressed to produce two concepts for further investigation. It is anticipated that the developments within this work will form a foundation upon which future UWA-designed racecars will be able to begin from.

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