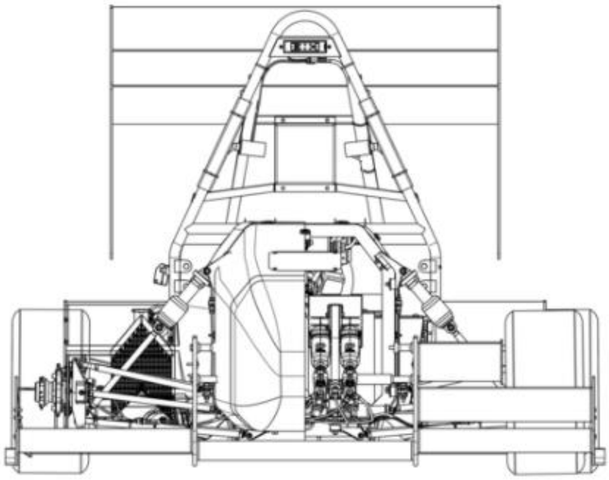
Technical Feasibility Study: Front Suspension



Name: Tom McGuinness
Supervisor: Daniel Corren
Assessor: Edward Chappell
Wordcount: 2189

1 Summary

This report looks at the technical feasibility of a variety of concepts for the front suspension design in order to provide the TBRe 2022 car the best chance at winning the most possible points at Formula Student UK 2022. Concepts were designed with the goal of offering high quality performance on track, then analysed iteratively through a variety of methods until the preferred concept, an outboard pushrod double wishbone design, is settled upon.

Table of Contents

Table of Figures

List of Tables

List of Equations

$$\Delta W = \frac{m\omega^2 rh}{t} \tag{1}$$

$$\theta = \frac{m\omega^2 r(a_F d + a_r c)}{l\left(\frac{K_F t^2}{2} + \frac{K_R t^2}{2} - \frac{W}{l}(a_F d + a_R c)\right)} \tag{2}$$

Nomenclature

Symbol/Abbreviation/Acronym	Definition
TBRe	Team Bath Racing Electric
CAD	Computer Aided Design
FEA	Finite Element Analysis
I	Moment of Inertia
m	Mass
r	Radius
K_e	Rotational Kinetic Energy
ω	Angular Velocity
W	Weight
ΔW	Load Transfer
h	Centre of Mass Height
t	Track Width
θ	Body Roll Angle
a_F	Difference between centre of mass and front roll centre height
a_R	Difference between centre of mass and rear roll centre height
c	Longitudinal distance from front of wheelbase to centre of mass
d	Longitudinal distance from centre of mass to rear of wheelbase
K_F	Front Effective Stiffness
K_R	Rear Effective Stiffness
l	Wheelbase Length

2 Introduction

Formula Student is a prestigious educational engineering competition with university students across the world competing to produce cars that will win the most points at its various events.

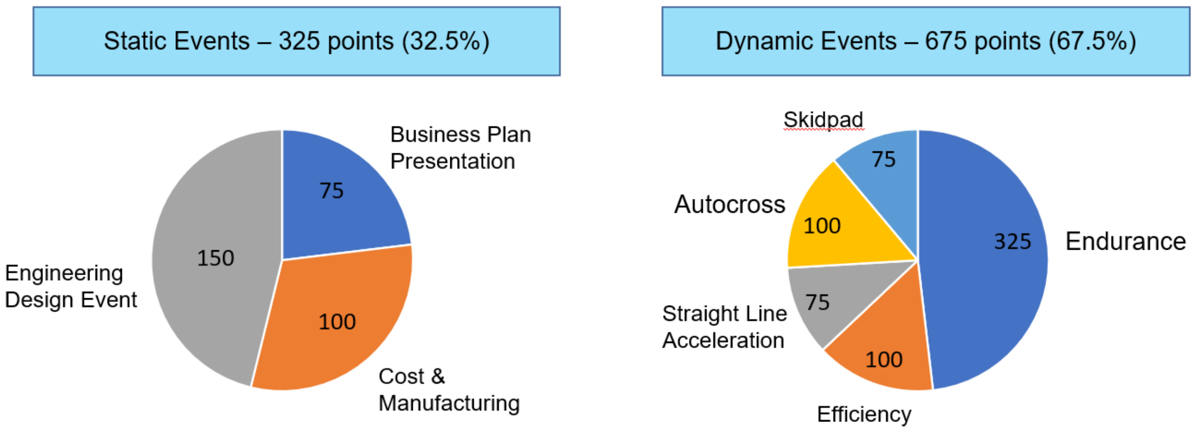


Figure 1: Points available at Formula Student competition

The University of Bath's electric vehicle entry into this competition is designed by 4 sub-teams: aerodynamics & cooling, chassis, powertrain and vehicle dynamics. This report will focus on the design of the front suspension as a part of the vehicle dynamics package.

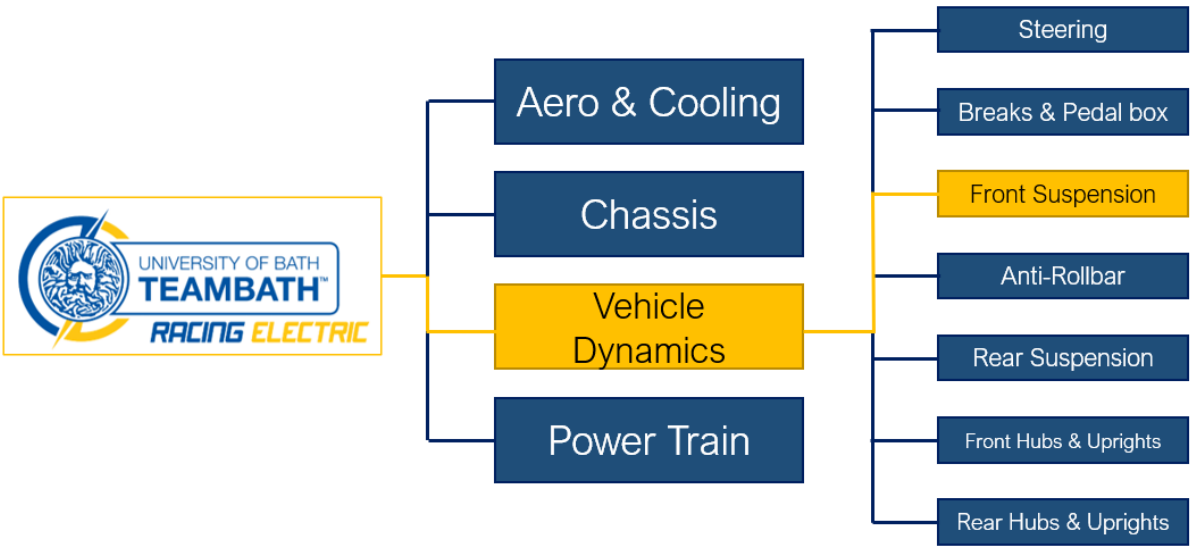


Figure 2: TBRe team breakdown

2.1 Team Aims

For the wider team's design to function harmoniously, overarching goals are set that impact every design decision. This prevents isolated subsystems from creating designs that conflict with other areas of the car. The key aims for this year's car and reasoning are shown below in *Table 1*.

Driver safety	Ensuring the driver risk is minimalised is paramount as no gain in performance should warrant putting a driver at risk of injury.

Reliability	Competing in all the dynamic events regardless of performance already puts our car at a great advantage as many teams, including the previous TBRe car, fail pass scrutineering for many of the events.
Handling	Roughly 60% of points are earned in the corners during the dynamic events, so a car that handles well is more likely to earn more points than a car that focuses its efforts elsewhere i.e. straight-line acceleration [*Appendix A*].
Adjustability	There is no general perfect set up for every possible track layout and condition, therefore designing adjustability into the system will allow for optimisation in the testing phase of development.

Table 1: Key aims for the 2022 Formula Student entry

2.2 COVID-19 Considerations

The team is taking all necessary precautions to minimise risk to the people and project, including a fulltime work from home schedule preventing any access to on campus resources such as labs and build rooms. Further assessment of the risk can be found in the risk register in *section 6.2.2*.

3 Design Considerations

3.1 Market Research

In order to design a vehicle that best completes the relevant requirements of the project customers, their needs must be analysed and ranked in terms of priority. The key customers are laid out below in *Table 2*.

Table 2: Project customers

Formula Student – high priority
Formula Student's rules and regulations must be followed diligently when assessing every design decision as any failure to comply with the rulebook will disqualify our design and cause us to fail all our stakeholders and customers.
TBRe Design Team – medium priority
The package that the vehicle dynamics team provide should work to integrate with all other sub teams in order to produce a consistent car and therefore perform well at competition.
Industry Sponsors & University of Bath – low priority
The bodies that fund this project should be considered when progressing with the design process, however, they fall much lower in priority. Their needs are met, on the whole, if the higher priority customers' needs are met.

3.2 Existing Concepts

3.2.1 Within Formula student

Formula Student's focus on education and many team's removal of inherited designs from previous years teams makes for reduced diversity and complexity of existing products within the competition. Most teams focus their efforts on extracting the maximum performance out of a wishbone setup using a simple pushrod design to provide the stiffness needed (example in *Figure 3*).

Figure 3: Example of a Formula Student car with double wishbone front suspension [11]

3.2.2 Previous teams

One of the most relevant market products is the previous year's vehicle and although the team will not use any designs that other students have produced, a focus is placed on not making similar mistakes in terms of holistic design approach and analysis. The vehicle wide parameters for last years vehicles are used in initial calculations and data gathering (e.g. *Appendix E* uses previous data to estimate tyre load variations).

3.3 Sub-system: Front Suspension

The primary function of a suspension system is to connect the wheel to the vehicle body and provide improved handling characteristics. It achieves this through limiting tyre load variation, controlling the body pitch and roll and maintaining contact of all four tyres with the road. *Figure 4* shows a simple example of how energy is stored in the springs when a vehicle is cornering. Since the team are designing from scratch, not iterating on a previous design, the feasibility of a first time reliable front suspension is the focal point of this assessment.

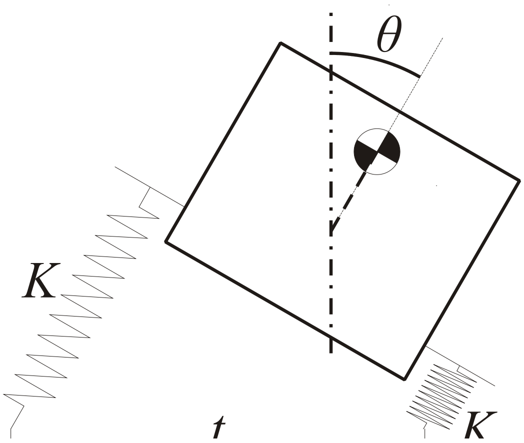


Figure 4: Diagram of a vehicle cornering (t = track width, K = spring stiffness)

3.4 Dependencies

Since the suspension is connecting feature from the tyre to the body of the vehicle, it has a range of dependencies both within the vehicle dynamics sub-team, as well as with the wider TBRe team. The nature of dependencies and the relevant sub-teams are show below in *Table 3*

Table 3: Front suspension dependencies

Internal/ external	Subsystem	Decision	Dependency (Precursory /Dependency /Compromise)	Description
E	Chassis	Wishbone mounting location	C	Where the wishbones are anchored onto the body of the vehicle
I	Front Hubs &Uprights	Wishbone mounting location	P	Where the wishbones are anchored onto the uprights
I	Front Hubs &Uprights	Hub size and layout	C	If the wishbones will interfere with the hubs in max steer situations
I	Rear Suspension	Suspension setup	C	Deciding consistent roll stiffnesses, roll centre heights etc
I	Anti-Roll bar	Suspension setup	C	Deciding consistent roll stiffnesses
E	Drivetrain	Drive shaft	D	Allowing for potential front driveshafts or in-hub motor setups
I	Steering	Tie rod locations	C	Providing room for tie rods around wishbone travel
E	Aerodynamics	Packaging constraints	P	Deciding usable locations for aerodynamic surfaces
E	Aerodynamics	Wishbone aerodynamic impact	P	Designing aerodynamic impact of wishbones and springs.
E/I	General	Centre of mass height	D	Adjusting suspension setup based on centre of mass height of the vehicle

3.5 Sub-System Requirements

A product design specification is created to track all design requirements through the development process as well as remain accountable to other teams' requirements. The front system PDS is available in *Appendix B*

4 Concept Generation

4.1 What defines a good suspension concept?

The aim of a suspension system within a racing context should focus on a few key points. These criteria form the basis for assessment of any system that is considered:

-Maintaining contact between the tyre and the road

-Control of the body pitch and roll

-Limit tyre load variations

Extracting the maximum traction from the tyres will providing a stable platform for the aerodynamic package to perform at its best, and will be the focus of all following designs. These considerations lead into detailed aspects of suspension, such as camber and toe meaning that any suspension concepts should have the ability to control various aspects of the tyre's geometry.

4.2 Discarded Concepts

Some concepts inherently suit the racing environment better than others. Therefore, some designs are ruled out to allow for more efficient use of time by focusing on more applicable designs. The discarded concepts are shown below in *Table 4*:

Discarded Concept	Justification
Leaf Spring	Requires mounting points far in front of the axle which is unfeasible at the front of the vehicle.
McPherson Strutt	Packaging constraints and the lack of control over design aspects such as camber gain makes it inferior to wishbone designs
Trailing arm	Reduced control over camber, complex to implement at the front of the vehicle compared to wishbone setup.

Table 4: Discarded concepts

4.3 Effective stiffness at the wheel

Figure 5 outlines the two potential methods of outlining initial values for effective stiffness at the wheel and roll stiffness.

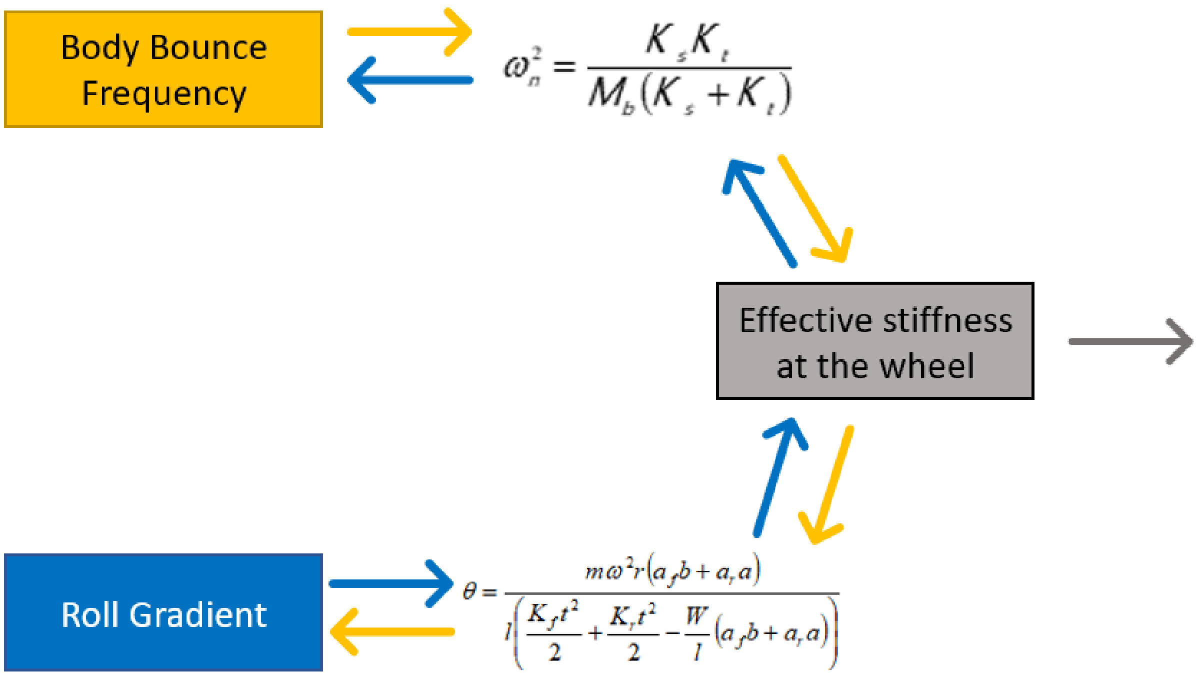


Figure 5: Physical analysis design flow

For this feasibility report, analysis started with body bounce natural frequencies recommended in textbooks [1] [2]. An example calculation shown in *Appendix E* shows how the initial estimations for a range of effective stiffness at the wheel (25N/mm to 70N/mm) are achieved, depending on the requirements from the aerodynamics package and other factors. These values then give corresponding roll gradients of 1.14 deg/g and 0.41 deg/g. A sensitivity analysis of body bounce natural frequency is shown below in *Figure 6*. The calculated roll gradients are greater than the recommended ranges suggesting that an anti-roll bar may be feasible. For further detail, see the anti-roll bar feasibility section of this report.

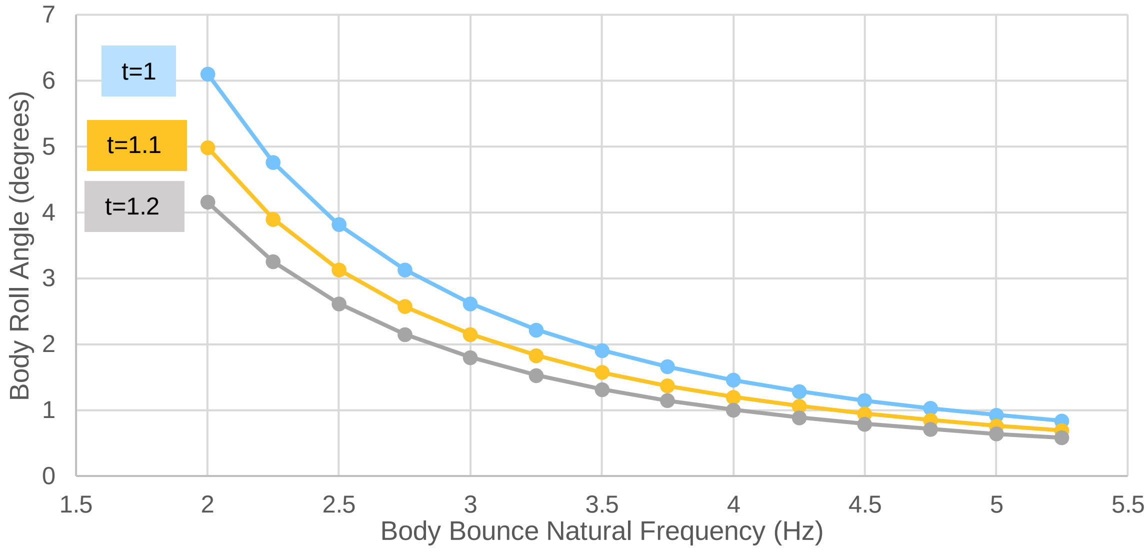
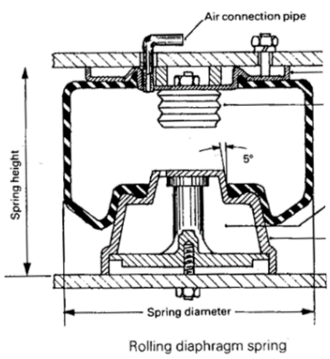


Figure 6: Body roll angle against ride frequency in a cornering situation (t = trackwidth in meters)

4.4 Springs

The methods of providing this spring rate can be broken down in to two main sections, coil springs and torsion bars. These are discussed below in *Table 5.*

Table 5: Spring variants

Coil Springs	 *Figure 7: 'Coilover' component example [8]*	Coil springs are the most common solution to suspension used in formula student. The nature of the coil allows for efficient packaging if the damper is placed inside the spring, saving space by removing the need for a rocker/an extra mount on a rocker. As the spring compresses, its spring stiffness can change depending on its design, allowing for more complex responses to inputs from the road. This complex characteristic along with its wide variety of makes and models due to its simplicity, make a coil spring an effective and flexible component [3].
Torsion Springs	 *Figure 8: Torsion bar pushrod and rocker setup [10]*	Torsion springs are a bar of metal that are twisted to store energy, in the same way a coil spring is compressed. The bars are incredibly space efficient so are valuable when packaging internally and can be made extremely light. If a damper is used alongside the torsion bar then the packaging gains are nullified as a damper would need to be added through a rocker, taking up space.
Other	 *Figure 9: Air spring bag suspension example - rolling diaphragm spring [12]*	There have been many innovations in the commercial car industry that have yet to see widespread application in racing. Developments such as gas springs and airbag springs should not be ruled out of the design process, but are less likely to be implemented into the final design due to overcomplexity or underperformance compared to torsion and coil springs.

4.5 Dampers

The tyres on a formula student car can only provide approximately 2% damping, so dampers or 'shock absorbers' are added to the suspension system [4]. Each damper must damp all aspects of the body movement including but not limited to: heave, pitch and roll of the sprung mass. While there is no perfect answer for a damping coefficient, a general guide is 0.5-0.7 and in line with the team's aim of adjustability, a testing focused approach will help the final design, utilise the most effective value for a given scenario. The more common types of dampers are:

Table 6: Types of commonly available dampers [5]

Type	Pros	Cons
Monotube	-Larger capacity so can be more compact -Better heat dissipation -No issues with orientation -Oil is separated from gas	-Struggles at longer strokes -Ride tends to be stiffer -Higher friction within the design
Twin Tube	-Easier to achieve longer stroke -Friction can be negated	-Smaller capacity -Instillation angles restricted
Monotube with compression piston	-Lower gas pressure can be used -Oil is separated from gas	-Longer body -Higher friction within design.

There are alternatives to these simple damper setups such as magnetorheological and electronically actuated dampers that are potentially viable but take away from the reliability and add to complexity to the vehicle. These are therefore considered more niche solutions [6].

4.6 Geometry

The most widely used and effective form of suspension in open wheeled high downforce settings is a double wishbone design due to its flexibility and range of parameters it can control. All following analysis will be based around a solution through a double wishbone setup.

4.6.1 Roll centres

The roll centre target location will play a large role in deciding the geometry of the front wishbones as it has a large impact on the handling characteristics. The roll axis height tends to be proportional to the weight distribution and centre of mass height along the car as the roll moment is tied to the mass location and has a large impact on handling. At the front of the car the mass over the axle tends to be lower due to fewer powertrain components being located towards the nose as well as the driver being seated further back.

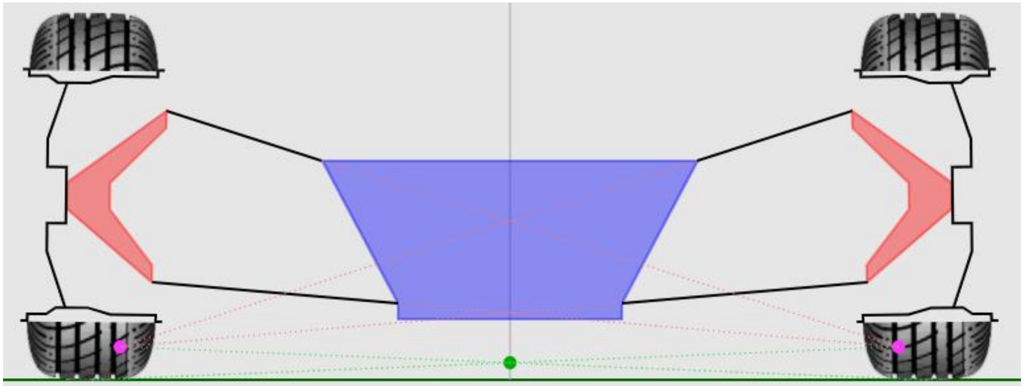


Figure 10: Diagram showing roll centre location based off instantaneous centres and wishbone geometry [7]

4.6.2 Camber gain

Wishbone geometry can also affect how the camber of the tyre changes as the vehicle undergoes body roll during cornering but also in breaking and accelerating. This impact can be reduced through the angle of the wishbones as well as their length. These values will differ from front to rear as the front of the car has a much narrower chassis and therefore requires longer control arms. However, the principles are still the same and are covered in depth within the rear suspension feasibility report.

4.6.3 Anti-geometry

The effects of dive on an aerodynamic race car are twofold. Firstly, the load transfer is analysed as with any other situation, to maximise the tractive force the tyres can provide and therefore help improving braking characteristics. Secondly, the undertray of the vehicle as well as front wing can be affected dramatically by the pitching and squatting of the vehicle. This impact can be altered by designing the wishbone geometries at certain angles and moving the pitch centre to the same location as the centre of mass or through heave dampers. Further analysis can be seen in the rear suspension feasibility report.

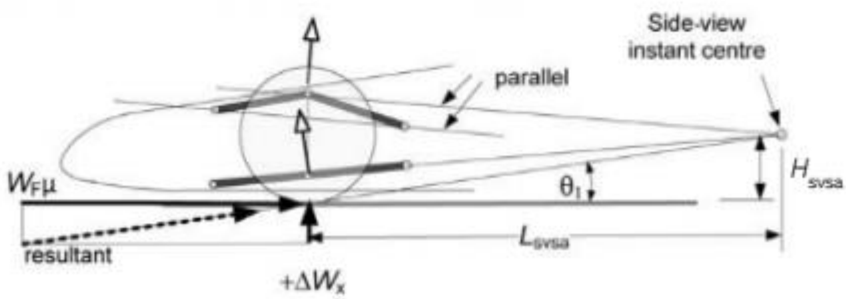


Figure 11: Example of 100% anti-dive geometry with pitch centre located at centre of mass [2]

4.6.4 Impact on steer

Bump steer, the change of toe when the suspension undergoes bump or droop, can drastically impact handleability of a car if not designed for. While it is nearly impossible to completely remove all bump steer for all turning angles and all suspension loads, it can be reduced to a manageable level. This burden lies mainly on steering concept design but does compromise with wishbone geometry and so should be considered in any design. This concept is covered in further detail in the steering feasibility section of this report.

4.7 Concepts

Concepts generation is focused around the mounting of the push or pull rod at the front as packaging constraints are a large factor. All designs can undergo geometry adjustment depending on target roll and pitch centre changes and will be adjustable in the final design via shims.

A list of symbols used in the concept generation phase are shown below in *Table 7*

Table 7: List of symbols

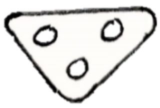
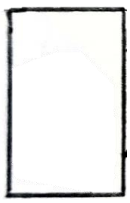
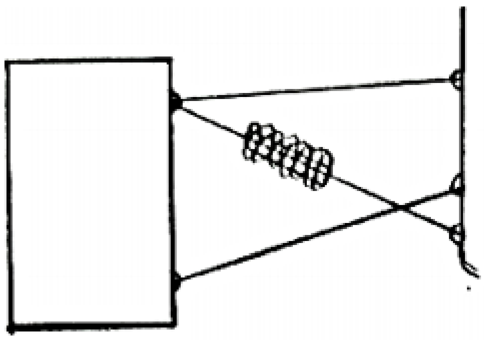
	Rocker – translate directions of movement
	Mounting point
	Torsion Bar
	Joint with 2 degrees of freedom
	Damper
	Coilover
	Wheel upright

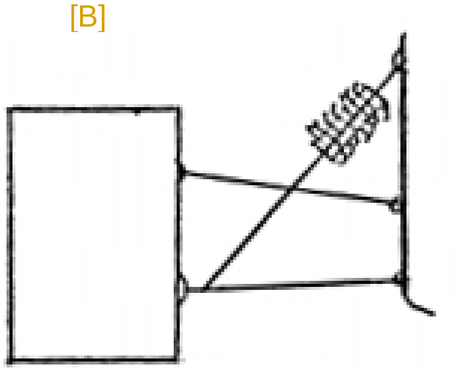
Table 8: Concept generation (concepts labelled A through I)

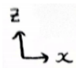
Outboard push and pullrod

[A]



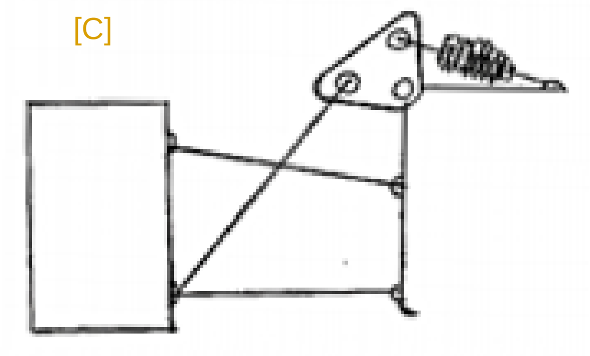
[B]



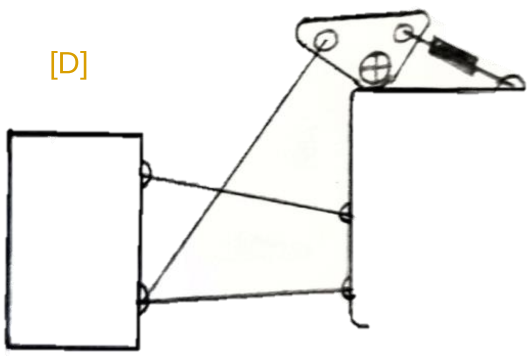


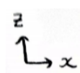
Inboard pushrod with torsion and coil spring variants

[C]



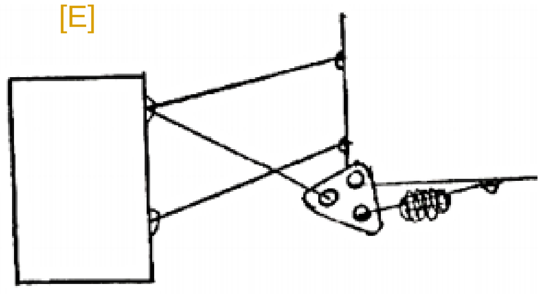
[D]



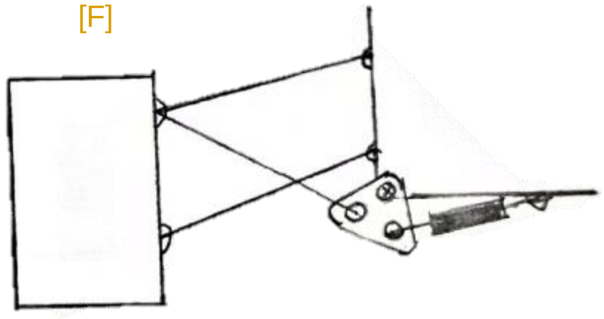


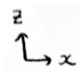
Inboard pullrod with torsion and coil spring variants

[E]

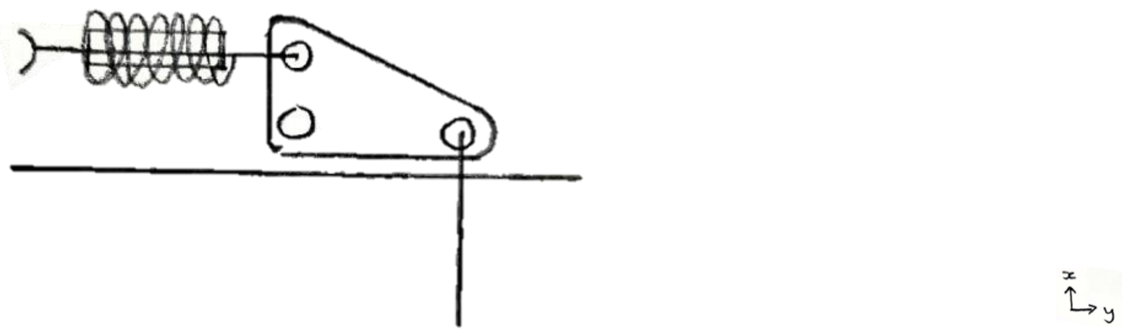


[F]



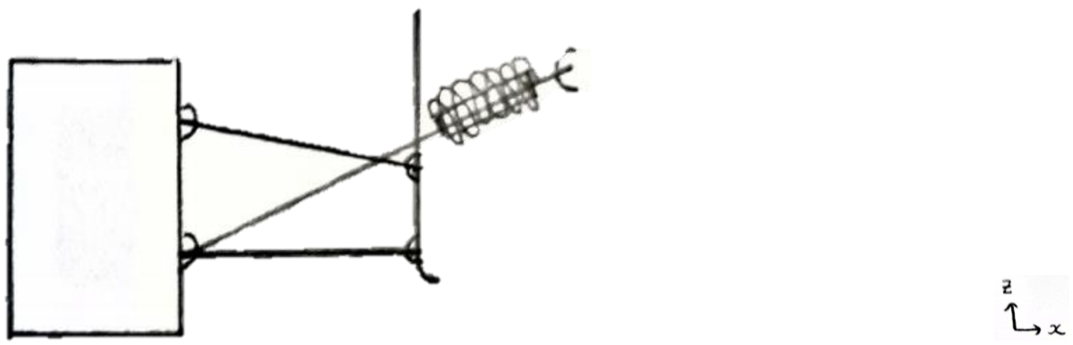


Orientation example of alternative rocker setup (parallel to wheelbase)



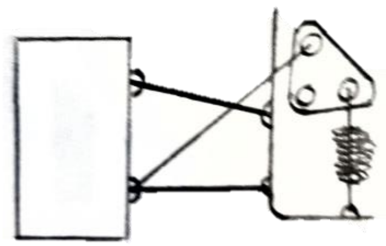
Internal pushrod design without rocker

[G]

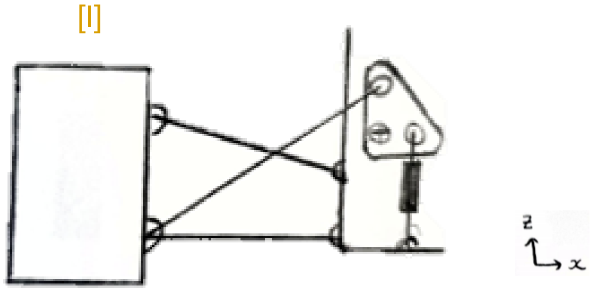


Internal pushrod design with rocker

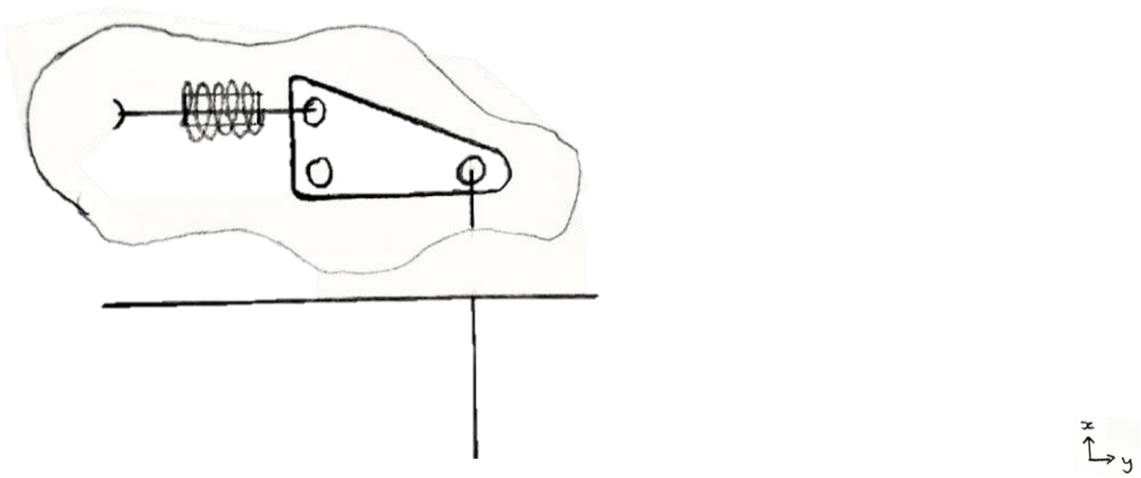
[H]



[I]



Internal push or pull rod design with rocker parallel to wheelbase



5 Preffered concept

The decision process started with the core team aims described in section 2.1. using pairwise analysis [*Appendix C*] the core aims as well as other key design paramters are weighted against eachother. The outcome of that weighting is shown below in *Figure 12*.

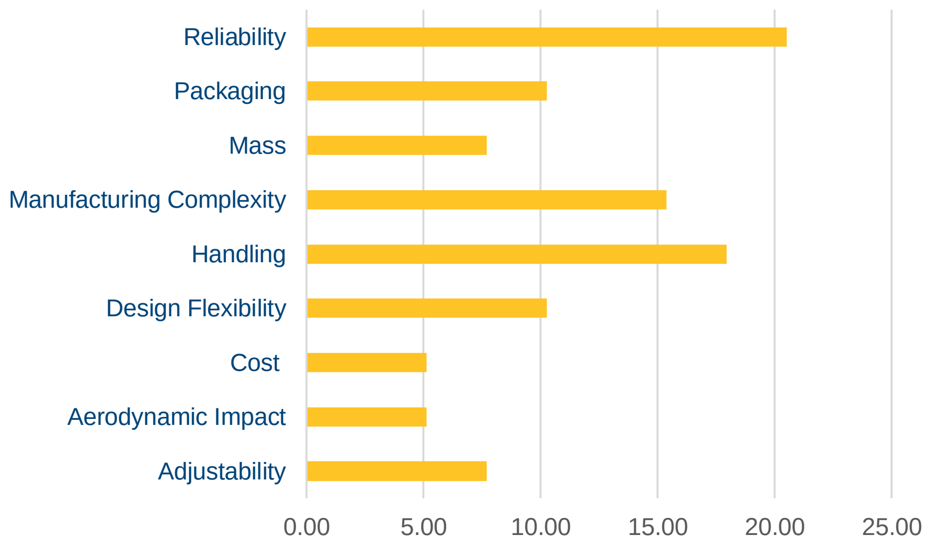


Figure 12: Pairwise weighting of decision criteria

From this a full Pugh Matrix [*Appendix D*] is formed in order to analyse the best solution moving forward. Due to its size, a breakdown of the decision making is seggregated into internal, inboard and outboard designs. For all analysis the baseline conept [A] is an outboard pushrod concept using coilover springs.

Design Criteria	Criteria Weighting	Inboard				Outboard
		Concept [C]	Concept [E]	Concept [D]	Concept [F]	Concept [A] (baseline)
Adjustability	7.69	0	0	1	1	0
Aerodynamic Impact	5.13	-2	-2	-1	-1	0
Cost	5.13	-1	-1	0	0	0
Design Flexibility	10.26	0	-2	-1	-1	0
Handling	17.95	-1	1	-1	1	0
Manufacturability	15.38	-2	-2	-2	-2	0
Mass	7.69	-1	-1	0	0	0
Packaging	10.26	-2	-2	-2	-2	0
Reliability	20.51	-1	-1	-1	-1	0
	Net Score	-112.821	-97.436	-97.4359	-61.538	0
	Rank	8	5	5	4	1
	Move Forward?	No	No	No	No	Yes

Figure 13: Inboard Pugh Matrix

Figure 13 shows the comparison of the baseline concept to the inboard designs. The increased number of parts hinders the reliablilty and ease of manufacture of the concepts which makes it much less preferable to the baseline simple outboard pushrod design. The pull rod concepts will have improved handling due to a lower centre of mass as most working components are placed lower within the vehicle.

Design Criteria	Criteria Weighting	Inboard (internal)			Outboard
		Concept [G]	Concept [H]	Concept [I]	Concept [A] (baseline)
Adjustability	7.69	0	0	0	0
Aerodynamic Impact	5.13	2	1	1	0
Cost	5.13	-1	-2	-2	0
Design Flexibility	10.26	0	-1	-1	0
Handling	17.95	0	0	0	0
Manufacturability	15.38	-1	-2	-2	0
Mass	7.69	-1	-2	-1	0
Packaging	10.26	-2	-2	-2	0
Reliability	20.51	0	-1	-1	0
	Net Score	-38.4615	-102.564	-112.821	0
	Rank	3	7	8	1
	Move Forward?	No	No	No	Yes

Figure 14: Inboard (internal) Pugh Matrix

In *Figure 14* the analysis is continued with the internal designs. These suffer heavily due to the issues with packaging constraints as other subsystems such as pedal boxing and steering are all competing for space in a small section of chassis. The fact that all of the components are internal boosts aerodynamic performance, however, these gains are marginal as shown by the weighting.

Design Criteria	Criteria Weighting	Outboard Concept [B]	Outboard Concept [A] (baseline)
Adjustability	7.69	0	0
Aerodynamic Impact	5.13	-1	0
Cost	5.13	-1	0
Design Flexibility	10.26	0	0
Handling	17.95	1	0
Manufacturability	15.38	0	0
Mass	7.69	-2	0
Packaging	10.26	0	0
Reliability	20.51	0	0
	Net Score	-7.692308	0
	Rank	2	1
	Move Forward?	No	Yes

Figure 15: Outboard Pugh Matrix

Finally, *Figure 15* shows the comparison between outboard push and pull rods, with the more effective being the push rod design. The large benefit of push rod over pull rod is that the upper wishbone can be made much lighter as it is sharing the load far better with the push rod.

6 Discussion

6.1 Preferred design

This led to the final concept of a more simple outboard push rod design using coilover springs. Despite the design having some key trade-offs, a combination of discussion between vehicle dynamics and other subsystems along side the Pugh Matrix concluded that, for exmple, the extra weight of the coilover compared to the lightweight torsion bar alternative was not worth the extra design complexity and therefore potential lack of reliability. This design suits the key user benefits as well as the team aims laid out in *section 2.1* ,however, it is not perfect. An outline of some of the strengths and weaknesses that need to be considered moving forward are below in *Table 9.*

Table 9: Strengths and weaknesses of preferred design

Strengths	
Simplicity	Fewest moving parts as well as simple mounting setup
Affordability	Short wishbones and few parts brings costs down
Reliability	Lack of moving parts means there is less chance of error in lifetime analysis

Design flexability	Easy to relocate mounting points around changes to dependencies such as chassis geometry
Weaknesses	
Aerodynamic impacts	Coilover being exposed created turbulent air downstream
Coilover size restrticted	The coilover is restricted in size by the nature of the geometry and length of push rod
Mass	The system has a high centre of mass height as well as utilising coilovers which weigh more than their torsion bar damper alternatives

6.2 Project Planning

6.2.1 Gantt Chart

The upcoming stage gates do not leave room for error and as such, a detailed Gantt chart has been created by the team in order to give suitable time for each design task. This tool consists of the whole team's work plans so everyone can plan around each other's time allocations effectively. This can be seen in *Figure 16*

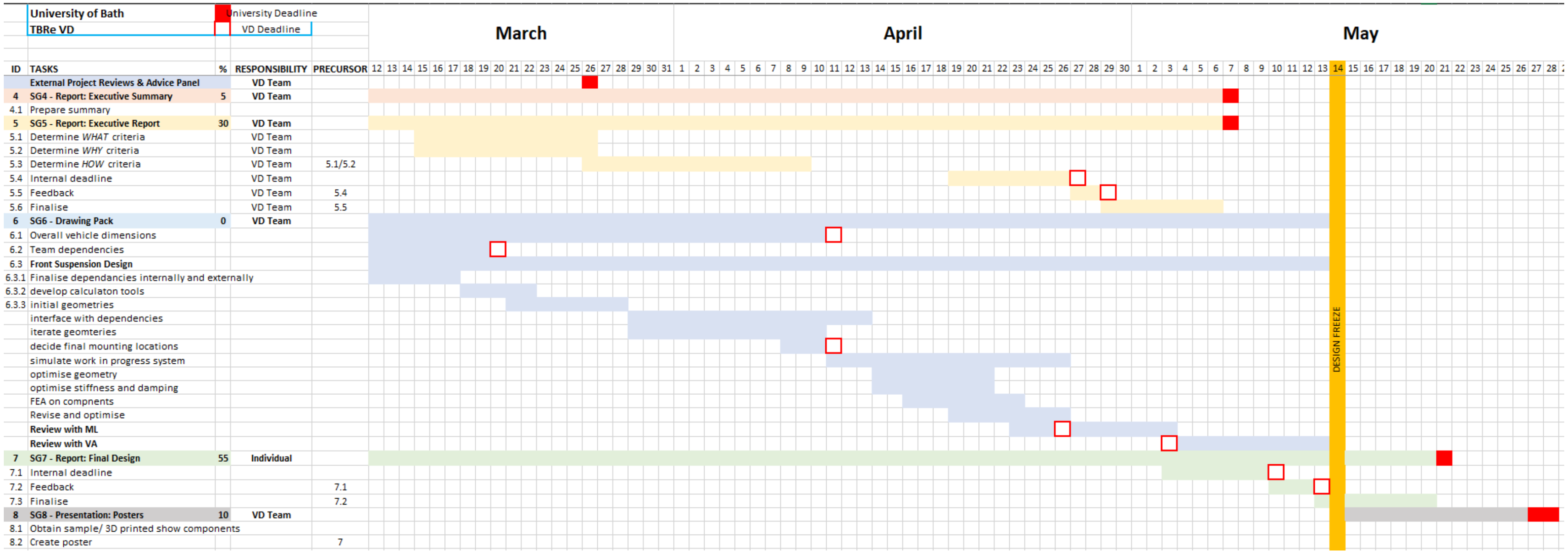


Figure 16: Project Gantt chart

6.2.2 Risk Register

The complexity of the design task and integrating each individual solution leaves the project with many potential risks. In order to best understand and manage them, both sub-systems and the wider team have created a risk register including potential issues with technical design aspects, but also wider personal issues. By effectively utilising and iterating on this document, the more important risks can be mitigated effectively. An example can be seen below in *Figure 17* as well as in *Figure 18.*

Front Suspension													
5.1	Integration	TM	12/03/2021	Powertrain decision change on drive method (in hub vs inboard)	FSUS, FWA, BR,ST	3	4	12	Regular integration meetings and early design freeze	1	4	Open	12/03/2021
5.2	Integration	TM	12/03/2021	Conflict with packaging within in-hubs/ uprights	FSUS, FWA, BR,ST	2	3	6	Simultaneous design process so there is transparency in the design process	1	3	Open	12/03/2021
5.3	Technical	TM	13/03/2021	Incorrect estimation of complex loading conditions	RSUS, RWA, BR,FSUS	1	5	5	High safety factor on critical parts, detailed FEA and range of other analysis methods	1	5	Open	12/03/2021
5.4	Integration	TM	14/03/2021	Chassis mounting points not flexible	FSUS,ARB, ST,RSUS	3	3	9	Find flexibilities in other regions to adapt to constraints	2	6	Open	12/03/2021
5.5	Integration	TM	12/03/2021	Conflict in priorities with chassis design team	FWA ,FSUS, ST	3	2	6	Regular CAD review	2	4	Open	12/03/2021
5.6	Technical	TM	12/03/2021	Lack of data from previous suspension performance	FSUS	5	3	15	Use of wide range of simulation methods, litrature and performance tests before competition	3	9	Open	12/03/2021
5.7	Testing	TM	12/03/2021	Car does not perform/handle as simulated/predicted	RSUS, ARB, BR,ST, FWA,FSUS	4	3	12	Design lots of adjustabiliy into the car so changes can be made easily at testing	3	9	Open	12/03/2021
4.2	Integration	TM	12/03/2021	Issues with too much bump steer	FSUS,ST,FWA	3	3	9	Constant communication with steering lead alongside simulation and testing	2	6	Open	12/03/2021
4.3	Competition	TM	12/03/2021	Front suspension does not pass scrutineering	FSUS,FWA	3	5	15	Constantly check models and simulations to make sure tests are passed as well as rigorous testing	2	10	Open	12/03/2021
4.4	Technical	TM	12/03/2021	Tolerance stacking reduces front suspension effectiveness	FSUS,FWA	2	4	8	ensure a complete tolerance stacking analysis is completed	1	4	Open	12/03/2021

Consequence		Score				
	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
		Probability				

	High Risk
	Medium Risk
	Risk
	Low Risk

Probability	
1	Very Unlikely
2	Unlikely
3	Slightly Possible
4	Likely
5	Very Likely

Consequences	
1	Very Insignificant
2	Insignificant
3	Slightly Significant
4	Significant
5	Very Significant

Figure 17: Risk register (front suspension)

Risk Identification					Risk Assessment				Risk Treatment				
Risk No.	Risk Type	Risk Owner	Date Raised	Risk Description	Affected Parties	Probability	Severity	Score	Mitigating Action	Mitigated Probability	Mitigated Score	Status	Last Updated
Full Team													
1.1	Technical		15/02/2021	Design does not meet the FS rules and regulations	TBRe22	3	5	15	Ensure full team understanding of rules concerning subteams	1	5	Open	15/02/2021
1.2	Organisational		15/02/2021	Deadlines are missed (both internal and external)	TBRe22	2	4	8	Continual Gantt chart review and time planning	1	4	Open	15/02/2021
1.3	Organisational		15/02/2021	Sudden design change from another sub-team	TBRe22	3	4	12	Continue routine integration meetings between subteam leads Enforce design freeze dates	2	8	Open	15/02/2021
1.4	Organisational		15/02/2021	Team comunication breakdown or miscommunication	TBRe22	3	3	9	Regular team meetings and social discussions	2	6	Open	15/02/2021
1.5	Project		15/02/2021	Team member falls ill (Covid-19 or other)	VD	4	2	8	Abide by Government regulation	3	6	Open	15/02/2021
1.6	Technical		15/02/2021	Design is over-budget	TBRe22	2	4	8	Regular cost review of intended designs	2	8	Open	15/02/2021
1.7	Technical		15/02/2021	Over-complex design leading to manufacturing issue	TBRe22	2	4	8	Virtual slow builds	2	8	Open	15/02/2021
1.8	Technical		15/02/2021	Poor understanding of research and content, leading to a poor design	TBRe22	2	4	8	Ensure team read and review appropriete literature	1	4	Open	15/02/2021
1.9	Technical		15/02/2021	Lack of data from previous years, leading to lack of improvement	TBRe22	5	3	15	Organise CAD access for full team Aim for test data to aid future years	3	9	Open	15/02/2021
1.10	Organisational		15/02/2021	Team member productivity reduces due to "cabin fever"	VD	3	3	9	Social activities in line with Government guidelines	2	6	Open	15/02/2021
1.11	Technical		15/02/2021	A team member's computer fails, leading to a stop in the design process	TBRe22	2	4	8	Ensure all files virtually backed up to allow access from any computer	2	8	Open	15/02/2021
1.12	Organisational		15/02/2021	A team member fails to contribute to the group	VD	2	4	8	Aim to sort the issue internally, work with supervisor if persistance	1	4	Open	15/02/2021

Consequence	Score				
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5
	Probability				

	High Risk
	Medium Risk
	Risk
	Low Risk

Probability	
1	Very Unlikely
2	Unlikely
3	Slightly Possible
4	Likely
5	Very Likely

Consequences	
1	Very Insignificant
2	Insignificant
3	Slightly Significant
4	Significant
5	Very Significant

Figure 18: Risk register (whole team)

6.3 Limitations and Reflection

Due to the severe time constraints this feasibility report faced, not everything was able to be covered in as much breadth or depth as possibly is optimal. Given the chance, there would be a much larger focus on the physical analysis during the concept generation, with aspects such as material selection brought to light, as well as changes to track width as the vehicle undergoes bump and droop.

7 Conclusion

A variety of feasible solutions have been produced, each with their own strengths and weaknesses, and the current preferred solution, an outboard pushrod design, has been justified. At this stage of the design the concept remains preferred and not final in order to remain flexible and not railroad the team into any one situation. The complexity of the solution is a reflection of the context in which the project exists, in that this is a 'rebuild year' for TBRe after the failure of recent vehicles in their competitions as well as the exceptional nature of the circumstances in which this project takes place due to COVID-19.

8 References

[1] M. &. Miliken, Race Car Vehicle Dynamics, Warrendale,Pa: Society of Automotive Engineers, 1995.

[2] D. Seward, Race Car Design, Red Globe Press.

[3] “Linear vs Progressive Rate Suspension Springs,” Hyperco, 15 April 2015. [Online]. Available: https://www.hypercoils.com/tech-tips/linear-vs-progressive-rate-suspension-springs/. [Accessed 11 March 2021].

[4] J. Kasprzak, “Understanding your Dampers: A guide from Jim Kasprzak”.

[5] “Differences/Benefits of a Monotube & Twintube Shock Absorber, Also Info on Inverted,” Club RSX, 2 July 2014. [Online]. Available: https://www.clubrsx.com/threads/differences-benefits-of-a-monotube-twintube-shock-absorber-also-info-on-inverted.1021346/. [Accessed 11 March 2021].

[6] “What are the different types of shock absorbers, their pros and their cons,” Automanana, [Online]. Available: https://automanana.com/different-types-shock-absorbers-pros-cons/. [Accessed 11 March 2021].

[7] “VSusp,” [Online]. Available: https://www.vsusp.com/#0.8%26project_name%3Adefault%20values%26trim%7Bbody_roll_angle%3A0%7Cfront.left_bump%3A0%7Crear.left_bump%3A0%7Cfront.right_bump%3A0%7Crear.right_bump%3A0%7D%26front%7Bframe.susp_type%3A0%7Cframe.bottom_y%3A9200%7Cframe.center_to_up. [Accessed 12 March 2021].

[8] Trunology, [Online]. Available: https://www.turnology.com/features/coil-springs-selecting-right-suspension-ride/#:~:text=In%20a%20road%20racing%20scenario,selling%20points%20for%20coil%20springs.. [Accessed 11 March 2021].

[9] Hangar 111, [Online]. Available: https://www.hangar111.com/shop/lotus-elise-s2-suspension-a-steering/199-elise-s2-parts-bilstein-replacement-spring-damper-assy-rear.html. [Accessed 11 March 2021].

[10] “Torsion bar,” Formula 1 Dictionary, [Online]. Available: http://www.formula1-dictionary.net/torsion_bar.html. [Accessed 11 March 2021].

[1 “Formula Student Germany – the Most Advanced Student Competition in the World!,” SIEMENS, [Online]. Available: https://blogs.sw.siemens.com/academic/formula-

[11] student-germany-the-most-advanced-student-competition-in-the-world/. [Accessed 11 March 2021].

[12] "Fluid Suspension (Automobile)," When-What-How, [Online]. Available: https://what-when-how.com/automobile/fluid-suspension-automobile/. [Accessed 12 March 2021].

9 Appendix

Appendix A

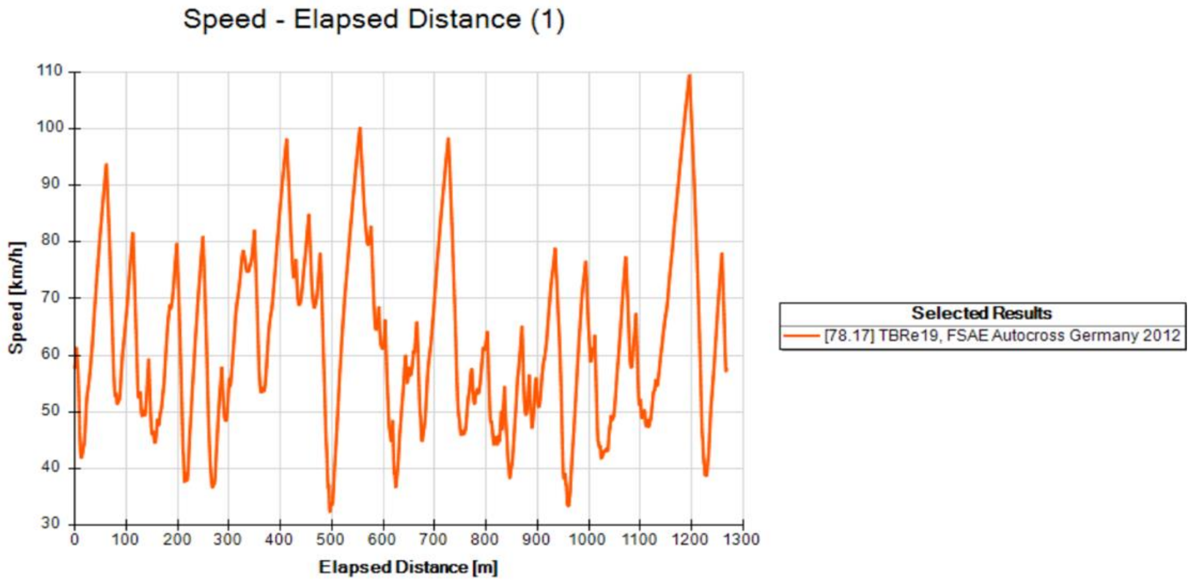
Points breakdown

Events	Points
Static Events	325
Business Plan	75
Cost & Manufacturing	100
Engineering Design	150
Dynamic Events	675
Skid Pad	75
Finish w/o DNF/DQ	3.5
Points due to Cornering (100%)	71.5
SLA	75
Finish w/o DNF/DQ	3.5
Points due to SLA (100%)	71.5
Autocross	100
Finish w/o DNF/DQ	4.5
Points due to Cornering (est. 80%)	76.4
Points due to SLA (est. 20%)	19.1
Endurance	325
Finish w/o DNF/DQ	25
Points due to Cornering (est. 80%)	240
Points due to SLA (est. 20%)	60
Efficiency	100

Total Points	1000
Total Dynamic Event Points	675
Total Dynamic Event Points from driving (exc. Points for finishing)	638.5

Total Points due to Cornering	387.9
Total Points due to SLA	150.6
Total Points due to Efficiency	100

% Points due to Cornering (Dynamic)	57.47
% Points due to SLA (Dynamic)	22.31
% Points due to Efficiency (Dynamic)	15.66



[B]

Appendix B

#	requirement	target	source	must/ wish	Verification
			Rules		
1.1	Minimum suspension bump travel	**>50 (min)**	FSR2020 - T 2.3.1	**m**	Testing simulation
1.2	Minimum suspension jounce travel (Assumes FR=RR)	**>25 (min)**	FSR2020 - T 2.3.1	**m**	Testing simulation
1.3	Ride height/ground	**>30 (min)**	FSR2020 - T 2.3.2	**m**	Testing simulation

	clearance (static - with driver)				
	Only minimal openings around front suspension and steering system components	-	FSR2020 - T 2.2.1	m	CAD views Testing
1.4	Suspension mounting must be visible	-	FSR2020 - T 2.3.3	m	CAD views Testing
Performance					
2.1	Roll Gradient	**0.25-1 deg/g**	Race Car Vehicle Dynamics	**w**	Testing simulation
2.2	Ride Frequency	**2-5Hz (0.2-0.4Hz lower than rear)**	Race Car Vehicle Dynamics + [4]	**w**	Testing simulation
2.3	Anti-Dive strength	**20-30%**	Race Car Design	**w**	Testing simulation
2.4	Unsprung mass	**Minimise**	Vehicle Dynamics notes (J.Darling)	**w**	Testing simulation
2.5	Static Camber	**0 to -3 Degrees**	Race Car Design	**w**	Testing simulation
2.6	Toe Static	**0 to -3 Degrees ()**	Race Car Design	**w**	Testing simulation
2.7	Camber Gain	**Negative (≈1 deg/g)**	Based on 2.5 and maximum cornering accelerations	**m**	Testing simulation
2.8	Roll Centre Height	**≈400mm from ground**	TBRe20	**w**	Testing simulation
2.9	Effective stiffness at the wheel	**20-70 N/mm**	Calculations based on 2.2 &2.1	**w**	Testing simulation
3	Centre of gravity of components	**Minimize**	Vehicle Dynamics notes (J.Darling)	**w**	Testing simulation
Reliability					

3.2	Minimum reliability	**survive through FSUK22 event**	-	**w**	Testing simulation
3.3	Long term testing and reliability	**survive 1500km use**	Based on information provided by power train team	**w**	Testing simulation
3.4	Perform in all conditions	**No change in performance from -5 to 35 degrees/ wet or dry**	Team aim based on stakeholder and customer analysis	**m**	Testing simulation

Appendix C

	Item being analysed TITLE									
	Adjustability	Aerodynamic Impact	Cost		Design Flexibility	Handling	Manufacturing Complexity	Mass	Packaging	Reliability
Adjustability		0	0	0	0	1	1	1	1	1
Aerodynamic Impact	0		1	0	0	0	0	0	0	0
Cost	1	1		0	1	1	1	1	1	1
	1	1	1		1	1	1	1	1	1
Design Flexibility	1	0	0	0		1	1	0	0	1
Handling	0	0	0	0	0		0	0	0	1
Manufacturing Complexity	0	0	0	0	0	1		0	0	1
Mass	0	0	0	0	1	1	1		1	1
Packaging	0	0	0	0	1	1	1	0		1
Reliability	0	0	0	0	0	0	0	0	0	
Total	3	2	2	0	4	7	6	3	4	8
Weighting	7.69	5.13	5.13	0.00	10.26	17.95	15.38	7.69	10.26	20.51

Appendix D

		Outboard	Inboard				Inboard (internal)			Outboard
Design Criteria	**Criteria Weighting**	Concept [B]	Concept [C]	Concept [E]	Concept [D]	Concept [F]	Concept [G]	Concept [H]	Concept [I]	Concept [A] (baseline)
Adjustability	7.69	0	0	0	1	1	0	0	0	0
Aerodynamic Impact	5.13	-1	-2	-2	-1	-1	2	1	1	0
Cost	5.13	0	-1	-1	0	0	-1	-2	-2	0
Design Flexibility	10.26	-1	0	-2	-1	-1	0	-1	-1	0
Handling	17.95	1	-1	1	-1	1	0	0	0	0
Manufacturability	15.38	-1	-2	-2	-2	-2	-1	-2	-2	0
Mass	7.69	0	-1	-1	0	0	-1	-2	-1	0
Packaging	10.26	0	-2	-2	-2	-2	-2	-2	-2	0
Reliability	20.51	0	-1	-1	-1	-1	0	-1	-1	0
	Net Score	-12.82051	-112.821	-97.436	-97.4359	-61.538	-38.4615	-102.564	-112.821	0
	Rank	2	8	5	5	4	3	7	8	1
	Move Forward?	No	No	No	No	No	No	No	No	Yes

Appendix E

	Value
Wheelbase (l)	1.525
Distance from CoG to front axle (c)	0.7625
Distance from CoG to rear axle (d)	0.7625
Vehicle and Driver Mass (m)	275.5
Vehicle Forward Velocity (V)	12.00
Turn Radius	9.125

Outputs	**Value**
Front Left Corner (FL_V)	**675.7**
Front Right Corner (FR_V)	**675.7**
Rear Left Corner (RL_V)	**675.7**
Rear Right Corner (RR_V)	**675.7**

Further Inputs	**Value**
Track width (t)	1.25
Height of CoG (h)	0.3
Front roll centre height (h_F)	0.045
Rear roll centre height (h_R)	0.055
Front Sus. Spring Stiffness (K_{sf})	20
Rear Sus. Spring Stiffness (K_{sr})	20
Front lever ratio (λ_f)	1
Rear lever ratio (λ_r)	1

body bounce wn	2
*2*pi	**12.56637061**
springs in parallel	**1.09E+04**

Height of CoG above front roll centre (a_F)	**0.255**
Height of CoG above rear roll centre(a_R)	**0.245**
Effective spring stiffness at front wheels (K_f)	**10.88**

Effective spring stiffness at rear wheels (K_r)	10.88
Body Roll Angle (θ)	0.067
Body Roll Angle (θ)	3.82

Load Transfer due to Springs	452.76
Load Transfer due to Linkages	78.26
Load Transfer due to CoG Lateral Shift	2.85
Total Load Transfer across Front (ΔW_f)	533.87
Load Transfer due to Springs	452.76
Load Transfer due to Linkages	95.65
Load Transfer due to CoG Lateral Shift	2.74
Total Load Transfer across Rear (ΔW_r)	551.15

Front Inner	141.79
Front Outer	1209.54
Rear Inner	124.51
Rear Outer	1226.82

Formula:

Equations Used

(1) $W_{FL_v/FRV} = \frac{mg}{2} \cdot \frac{d}{l}$ (2) $W_{RL_v/RRV} = \frac{mg}{2} \cdot \frac{c}{l}$ (3) $W_{FL_L/FRL} = \frac{mV^2}{2R} \cdot \frac{d}{l}$ (4) $W_{RL_L/RRL} = \frac{mV^2}{2R} \cdot \frac{c}{l}$

Equations Used

(5) $a_f = h - h_f$ (6) $a_r = h - h_r$ (7) $K_f = \frac{K_{sf}}{{\lambda_f}^2}$ (8) $K_r = \frac{K_{sr}}{{\lambda_r}^2}$ (9) $\theta = \frac{m\omega^2 r\,(a_F d + a_R c)}{l\left(\frac{K_F t^2}{2} + \frac{K_R t^2}{2} - \frac{W}{l}\,(a_F d + a_R c)\right)}$

(11) $$\Delta W_r = \frac{K_r t}{2}\theta + m\omega^2 r \frac{c}{l}\frac{h_r}{t} + a_r \theta \frac{W}{t}\left(\frac{c}{c+d}\right)$$

(10) $$W_f = \frac{K_f t}{2}\theta + m\omega^2 r \frac{d}{l}\frac{h_f}{t} + a_f \theta \frac{W}{t}\left(\frac{d}{c+d}\right)$$