MRacing: Improve Low Speed Cornering
Design Report

ME 450 - Fall 2020
Section 3
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Sponsor
MRacing Formula SAE

Executive Summary

Our sponsor, MRacing Formula SAE Team, is a student team at the University of Michigan that designs and builds a race car every year. The team has competed in the Formula SAE competitions and placed high among the competitors. Coming off of a fourth place finish in 2019, MRacing is looking to improve the performance of the current vehicle to guarantee a higher place finish in future competitions. In particular, MRacing is interested in improving the vehicle's low speed performance. Our team was asked to develop a solution that fulfills this purpose.

Our team analyzed past competition results of MRacing and consulted with our project stakeholder, Harvey Bell, to set the requirements and specifications for this project. To achieve our sponsor's goal of improving place finish at competitions, our solution must improve overall points finished at competition and comply with competition rules. To ensure optimal vehicle performance during the events at competition, our solution must be reliable through regular testing and be drivable for drivers to produce consistent results. Due to the Covid-19 situations, our solution must integrate with the current chassis of the MRacing vehicle, be manufacturable using limited team resources, and fit within the associated budget. Specifications were set for each requirement to target a third place finish at Michigan International Speedway in order to ensure an improved overall place finish at future competitions.

With our requirements and specifications, a functional decomposition of our problem was developed to break down our goal of reducing skidpad time. The two primary factors affecting skidpad time were determined to be tire grip and vehicle mass. Based off of the two factors, the team then specified additional factors that contributed to Skidpad performance. We used concept generation techniques of brainstorming, design heuristics, and competitive analysis to create a variety of concepts applicable to our factors. Our concept evaluation methods involved gut check, discussion with stakeholder, vehicle simulation, benchmarking, and a Pugh chart. Our final solution concept was to create a quick setup jig with a new full vehicle simulation to optimize vehicle setup for the skidpad event.

A set of requirements and specifications was developed for the setup jig using feedback from MRacing stakeholders and a detailed CAD model was created that met these requirements. A bill of materials was created with the total cost estimated at $458. Due to the COVID pandemic, manufacturing and validation will be postponed until next year. To simulate full vehicle performance during the skidpad event, the commercial software package CarSim was chosen. We input our vehicle parameters into the CarSim full vehicle model and an initial L9 design of experiments was performed. Lap times were suspect due to driver model issues, so we opted to move to a L18 design of experiments following ISO standard 4138, a constant radius test designed to calculate the understeer gradient of the vehicle. We were able to verify that the simulated car behaved similarly to how we expect, but further comparisons will be completed against the actual MRacing car next year to fully validate the model.

Overall, the setup jig once manufactured, will provide a base for the MRacing team to evaluate vehicle setup at any location. A practically indefinite lifespan will ensure that it is used for many years. The vehicle simulation, once validated, will be a tool which any MRacing member can use to evaluate changes to the car's design.

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Problem Description and Background

Introduction to MRacing

MRacing is a multidisciplinary design team, consisting of approximately 20 undergraduate students, based in the Wilson Student Team Project Center at the University of Michigan. The MRacing team competes in Formula SAE. This is a collegiate design competition run by the Society of Automotive Engineers and has an international counterpart called formula student with nearly identical rules. In this competition, students: design, build and test a single seated, formula style race car. During a competition, teams compete in both static and dynamic events. These events are organized to test the vehicle performance as well as project management abilities of each student team. Over 600 teams compete in FSAE and Formula Student world wide at 17 competitions held in 16 countries. The largest of which is held at the Michigan International Speedway, just 40 minutes away from the University of Michigan campus. The field improves rapidly each year so teams must always innovate to remain competitive.

Top FSAE vehicles have very high performance compared to road cars. MRacing's 2019 vehicle weighed only 420 pounds and featured a turbocharged 4 cylinder, 600 cc engine which produced a peak power of 85 horsepower. It was able to accelerate from 0-60 miles per hour in 3.1 seconds. A full aerodynamics package and racing slick tires enabled the vehicle to have 2.2 g's of peak lateral acceleration.

Formula SAE Competition

The competition is divided into a total of eight different events, each worth a specified number of points, with a total of 1000 points possible. The eight events are divided into two categories, Statics, and Dynamics. The statics events the vehicle and include: Design presentation (150 points), Business presentation (75 points) and Cost presentation (100 points). Dynamics are events based off of the performance of the vehicle and include; skidpad (75 points) which tests low speed cornering, Acceleration (100 points) which tests straight line acceleration capability, Autocross (125 points) which tests all capabilities of the vehicle as well as driver skill, Endurance (275 points) which tests the vehicles capabilities and long term durability, and Efficiency (100 points) which is a measure of fuel efficiency based on the fuel consumed and the time taken to complete the endurance event.

At the 2019 MIS competition MRacing scored 4th overall out of the 108 teams. The competition results of the top 4 teams are listed in Table 1.

Table 1. MIS 2019 Top 4 Teams Results

Team	Placement	Overall Points
Universität Stuttgart	1st	892
Graz Technical University	2nd	885
Ecole De Technologie Supérieure	3rd	771
University of Michigan - Ann Arbor	4th	762

MRacing finished 130 points below 1st overall, 123 points below 2nd, and 9 points below 3rd.

Figure 1, shows the competition results for each event normalized by the total number of points possible for that event

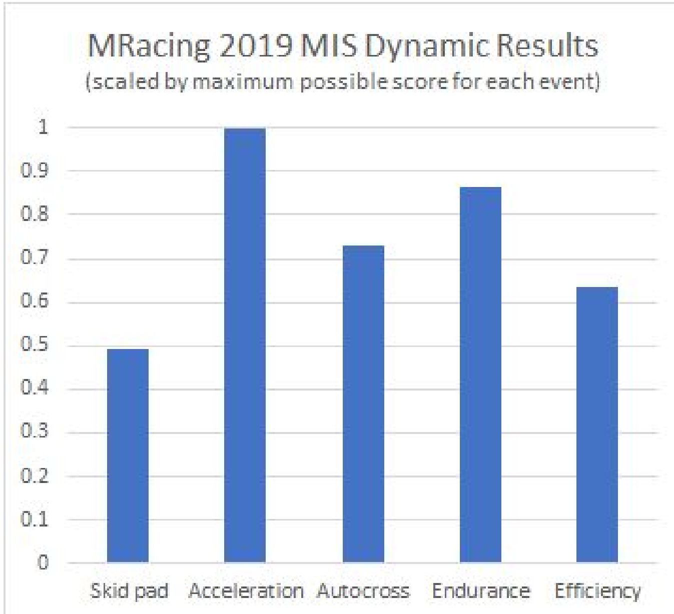

Figure 1: MRacing dynamic event results normalized by maximum possible event points

From this data, we can conclude that the MRacing team performs well in the acceleration and endurance events. MRacing's performance in the autocross and efficiency events were above average but skidpad performance was relatively poor, scoring less than half of the possible points.

Table 2 shows the results of the dynamic events, including each points deficit to the highest scoring team.

Table 2: MIS 2019 Dynamic Event Results

	Acceleration	Autocross	Endurance	Efficiency	Skidpad
Placement	1st	9th	3rd	18th	33rd
Points Possible	100	125	275	100	75
Points Scored	100	91	238	63	37
Points Deficit	0	34	37	37	38

In order to gain the most points overall, MRacing optimizes the vehicle setup for the higher speed events such as acceleration, autocross, and endurance. Limited time during the competition prevents the team from changing vehicle setup exclusively for the skidpad event. This limits not only the points that MRacing can score in the skidpad event, but also the overall competition result.

The Skidpad Event

The skidpad event is a test of low speed, steady state cornering performance. The Formula SAE rules [2] define the layout for the skidpad event, and a map can be seen in Figure 2.

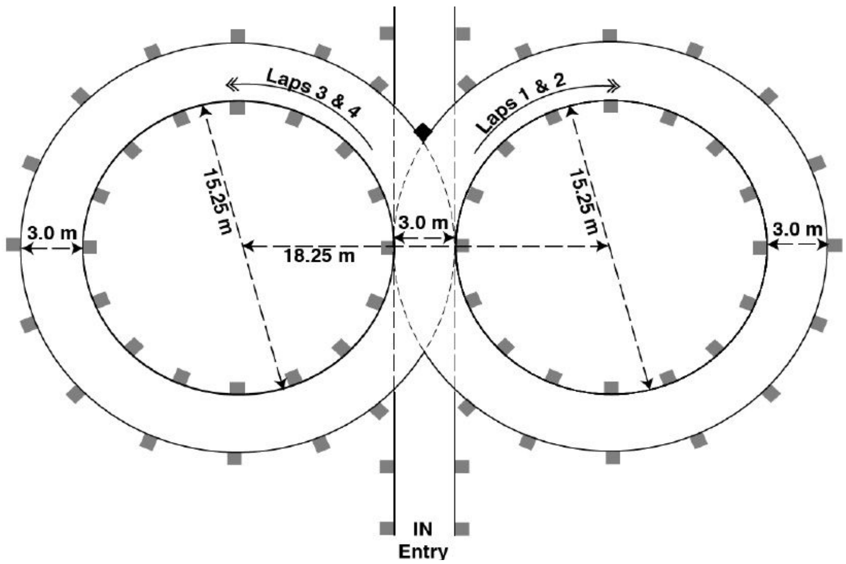

Figure 2: Formula SAE skidpad

To complete one attempt at the skidpad, the car first enters from the bottom then proceeds to complete two right hand circles, before switching to the left hand side, and completing two additional circles. The vehicle then exits out of the top. The first revolution is done to achieve steady state cornering, and the second is to time the vehicle. The left and right side times are then averaged together to determine the time for that specific attempt. Each vehicle may attempt the event a maximum of four times, with two drivers each attempting it twice. The fastest event time for any of the attempts will count towards the skidpad and overall competition score.

Problem Description

In order to improve on the 4th place finish at MIS 2019, MRacing would need to score an additional 10 points. Looking at the skidpad results, a finish of 13th place instead of 33rd would have resulted in the necessary 10 points. This result would have required the MRacing 2019 vehicle to have a 3% time reduction in skidpad. This data is summarized in Table 3.

Table 3: MRacing MIS 2019 skidpad improvement to get 10 additional points

skidpad Placement	Time (s)	Points	Time Reduction (%)
1st	4.865	75	10
13th (Target)	5.248	47	3
33rd (MRacing)	5.412	37	0

We chose a 3% time reduction over a specific skidpad time target since a vehicle's performance varies highly with changes in track conditions. Additionally, the performance increase of other teams is difficult to predict. To create a quantifiable target for this project, assumptions about our vehicle and the competition had to be made. We assumed that the overall competitiveness of our 2021 car will be the same relative to the competition and therefore we would achieve a similar result in skidpad. Therefore a 3% decrease in our 2021 car's skidpad time would be necessary.

In addition because no dynamic events were held in 2020 due to COVID-19, MRacing will be using the same chassis which was built for 2020 in 2021. This means that any solution must be adaptable to the existing 2020 vehicle.

Requirements and Specifications

In order to determine our requirements and specifications, we communicated with the MRacing management and Harvey Bell, our sponsor, to identify the needs of this project. After discussions with the project team leads and Harvey Bell, we were able to create a list of requirements that describe the needs and scope of this project. Table 4 below describes the requirements and specifications of the project.

Table 4: Project Requirements and Specifications

Requirement (Decreasing priority)	Specifications	Justification
Increases points scored at competition	● Reduce skidpad time by 3% ● Doesn't reduce points scored in other dynamic events	Reducing skidpad time by 3% gains the 10 points needed to achieve a 3rd place overall finish
Competition legal	● Must pass FSAE Michigan 2021 technical inspection	FSAE rules must be met to compete
Integrates with MR20	● Cannot interfere with or obstruct the movement of other systems ● Can be affixed to current car	MRacing is reusing current chassis and suspension for 2021 competition.
Manufacturable	● Must be able to be manufactured in Wilson Center	MRacing cannot rely on sponsors due to COVID-19 pandemic
Reliable	● Remain functional after 300 miles of testing	Solution must endure typical testing season
Driveability	● Repeated skidpad times must stay within ±5% for each driver	Allow drivers to consistently maximize performance
Within budget	● < $1000	MRacing has allotted $1000 to this project

Increasing points at competition was established as the most critical requirement of the project, as a third place finish at FSAE Michigan 2021 is the ultimate goal for the team. Based on the points scored at FSAE Michigan 2019, MRacing needs 10 more points to achieve this, which is equivalent to a 3% reduction in skidpad time. In addition, the proposed solution cannot affect points scored in other dynamic events, as the total score at competition must improve by 10 points, not just the skidpad score. Another requirement from the MRacing management was for the project to be legal to use in FSAE competitions. These regulations are largely open ended and mostly serve as a safety precaution. Each team's cars are inspected during the first day of competition, and we must pass this inspection in order to race and win any dynamic points.

The project must integrate with MR20, the MRacing vehicle originally built for the 2020 competition season. MRacing has elected to use the MR20 vehicle in 2021 FSAE competitions. This means that our solution must be compatible with MR20. This is possible to work around, but would require MR20 systems to be redesigned and manufactured. The 'manufacturable' requirement was created due to limited time in the Wilson Center this year due to COVID, as well as sponsors being less willing to contribute manufacturing assistance during the economic downturn. 'Reliable' is very important as well, otherwise valuable time will be wasted while trying to prepare for competitions. 'Driveability' ensures that the solution is consistent enough to not malfunction at competition and cost MRacing points. The budget requirement is left for last, as we are providing our own budget and it is subject to change.

To assess our requirements and specifications for completeness, we chose to use David Garmin's eight basic dimensions of product quality. We considered the 'performance', 'features', 'reliability', 'durability', and 'conformance' dimensions to be well-written in our project specifications and requirements. Particular dimensions were reflected in similar requirements, such as 'serviceability' to 'manufacturable' in our requirements. Some dimensions of Garmin's system were less applicable to our project, such as 'aesthetics' and 'perceived quality', as these were not deemed to be appropriate requirements for a collegiate motorsport competition. However, particular requirements of ours addressed our team background and motorsport background, namely 'drivability' and 'integrate with MR20'. Overall, these measures for quality allowed us to identify requirements that filled the whole scope of our project.

Concept Generation and Development

Functional Decomposition

To begin our concept generation, we performed a functional decomposition of parameters that impact skipad performance. The skidpad event can be simplified as a mass in circular motion. Since the diameter of the circle is fixed (See Figure 2) the only way to decrease skidpad time is to increase the velocity of the car. Based on fundamental physics principles, increasing the velocity of the car will require an increase in the centripetal acceleration. This can be seen in equation 1 from Engineering Mechanics: Dynamics, 8th Edition [3]. Where a_c is the centripetal acceleration, v is the tangential velocity and r is the radius of the circle.

$$a_c = \frac{v^2}{r} \quad (1)[3]$$

Using Newton's second law, we know that the two factors which impact centripetal acceleration (a_c) are vehicle mass (m) and lateral tire force (F_t), seen in equation 2 [3].

$$F_t = ma_c \quad (2)[3]$$

Using this knowledge in our functional decomposition of the skidpad event, we determined the two primary factors which affect the skidpad time are vehicle mass and tire grip. It is worth noting that there may be additional factors such as "driveability" however these are primarily out of the scope of this project, or appear separately in the performance of specific solutions. Under these factors, we listed all the important parameters that impact each. The resulting functional decomposition is shown in Figure 3.

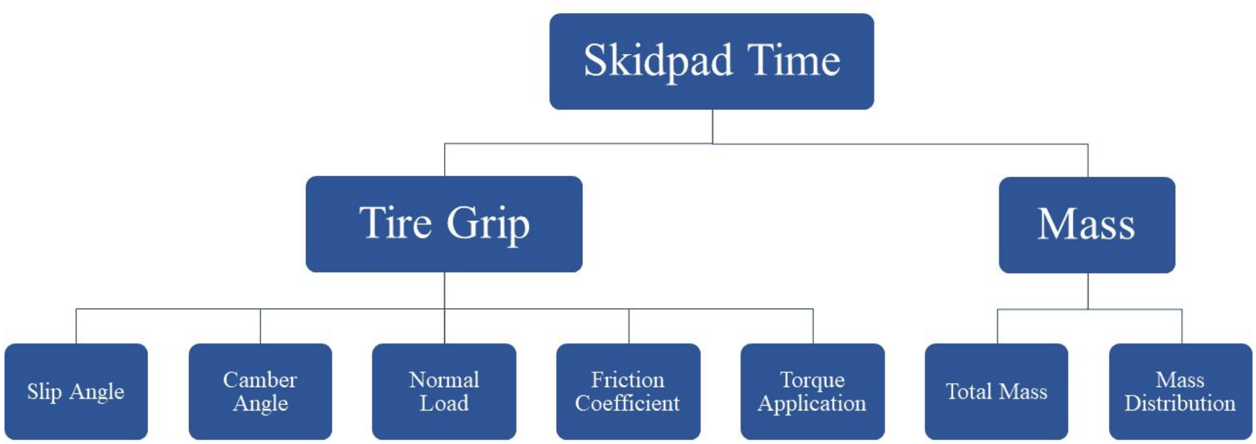

Figure 3. Skidpad time functional decomposition

To define each of the factors affecting Tire Grip and Mass: Slip angle is the angle between the direction the tire is pointing and the direction in which it is traveling [4]. This is shown below in a top down view in Figure 4.

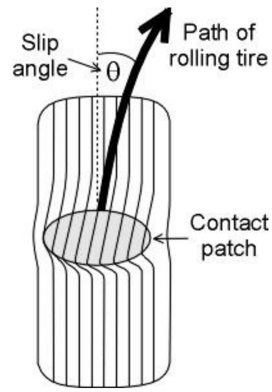

Figure 4. Top down tire view showing slip angle [4]

Camber angle is the angle between a plane normal to the road surface and the tilted plane of the wheel. This may be better understood as a tire leaning towards or away from the car. This is shown below in Figure 5

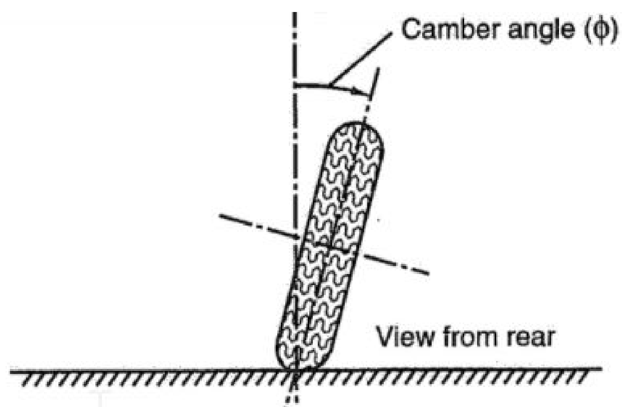

Figure 5. Rear view of the tire showing camber angle [4]

Normal load is the amount of force applied to the tire normal to the road surface. Friction coefficient is the coefficient of friction of the tire. Torque application describes the manner in which the tire is rotated to speed up or slow down the vehicle. Total mass and Mass Distribution describe the mass of the vehicle and how it is placed in the vehicle space. Further information for all of the Tire Grip factors can be found in chapter 2 of reference [4].

Generating Concepts

After creating this functional decomposition, we analyzed each system of our vehicle to determine possible concepts which would improve one of our seven skidpad factors. These systems included: Chassis, which is the structure of the car, Suspension, which consists of the tires, brakes, linkages, springs, dampers, and driver steering system, Drivetrain, which primarily consists of the differential, Powertrain, which includes the engine and throttle controls, and Aerodynamics, which is made up of the existing front wing, rear wing, and undertray. We generated ideas under each of these sections using a combination of brainstorming, competitive analysis, and design heuristics.

Through brainstorming, we were able to generate a wide variety of concepts in our systems level review of the car. For example, many of our torque application concepts come from brainstorming ways to modify the drivetrain system to induce a yawing moment on the car. Once we created a preliminary list of concepts with this method, we developed these concepts further using design heuristics cards. One concept that arose as the result of design heuristics was using the brakes system to create a torque vectoring system. Initially, torque vectoring was a single concept, but then we applied the card, 'apply existing mechanism in a new way', and it evolved into two separate concepts. We realized that the brakes system already on the car could be used to control the torque delivered to the inside and outside wheels. This could be done by adding an electronic pump that would apply the brakes to the inside wheels during cornering. After applying design heuristics to the remaining concepts, we finalized our list, shown in Tables 5 and 6.

Table 5: Initial list of tire grip concepts. Full description of each concept can be found in appendix A

Slip Angle	**Camber Angle**	**Normal Load**	**Frictional Coefficient**	**Torque Application**
Rear steer Bump steer Improve Ackermann Quick toe adjustment Setup jig+simulation*	Camber curve Active camber	More downforce Active roll bars Active caster angle Active dampers Active front wing	Custom tires Tire heating method	Torque vectoring (brakes) Torque vectoring (driveline) Four wheel drive Variable diff preload Advanced traction control

Table 6: Initial list of mass concepts. Full description of each concept can be found in appendix A

Total vehicle mass	**Mass Distribution**
Single cylinder engine Carbon suspension links Corner redesign Remove fluids for skidpad	Variable lateral CG position Adjust driver seating position Add ballast Move driver

Concept Evaluation and Selection

Gut check and Stakeholder Meeting

The first method used to evaluate the concepts was a simple gut check, where obviously infeasible ideas were removed. Some of these include a change to our camber curve, which could potentially be beneficial, but would require a redesign of suspension pickup points and a new chassis. This isn't possible right now as we've chosen to use last year's car for the coming summer of competitions. Another example was ballast, which was eliminated based off of a lack of performance gain, as previous simulations have shown that adding mass to lower the center of gravity of our vehicle decreases total points at competition.

The concepts were further reduced after discussions with our stakeholders, including discussions with the MRacing project team, a review of the FSAE 2021 rulebook, and meeting with Don Wirkner, a former GM vehicle dynamics engineer. MRacing has decided to eliminate a few concepts based on complexity, such the active anti-roll bars and active front wing projects. Other projects such as carbon fiber suspension links were eliminated due to failures in recent attempts to add these to the MRacing car. The list of remaining potential concepts can be seen in Table 7. Note that all of the potential concepts from the camber angle and mass distribution categories were eliminated.

Table 7: List of remaining solution concepts after gut check and stakeholder meetings.

Slip Angle	**Normal Load**	**Frictional Coefficient**	**Torque Application**	**Total vehicle mass**
Rear steer ~~Quick toe adjustment~~ Setup jig+Simulation*	Cornering Aero ~~Active roll bars~~ ~~Active aero~~ ~~Active Dampers~~	Custom tires	Torque vectoring (brakes) ~~Torque vectoring (driveline)~~ Four wheel drive Variable diff preload	Single cylinder engine ~~Carbon suspension links~~ ~~Corner redesign~~ ~~Remove fluids for skidpad~~

Modeling

After narrowing down the list of potential concepts, we evaluated the potential performance of two of the concepts (Rear Steer and a Setup Jig) using a three degree of freedom rigid body simulation. In this model, we are able to vary the static camber and toe of each tire, allowing us to simulate a variety of vehicle setups, as well as a variety of other vehicle parameters (wheelbase, mass, center of gravity height, downforce, etc.). We ran simulations of a baseline vehicle setup, a rear steer setup, and an improved vehicle setup.The results of the simulations are shown in Table 8. Our improved setup for skidpad from testing this fall outperformed the baseline with over a 3% reduction in time. This shows that a tool that allows for fast vehicle setups could give the performance gain we seek. Rear steer outperformed the baseline by an even wider margin, approximately 5% less time than the baseline. These simulations gave us an expectation for potential performance improvement to use in our Pugh chart.

Table 8: Results of skidpad simulation

Setup	Time (s)
Baseline (2019 Setup)	5.25
Fall 2020 Setup	5.09
Rear wheel steer	4.97

The MATLAB model we currently use is limited by its lack of a roll degree of freedom, which is essential to accurately model our vehicle. In addition, our MATLAB model is clunky and hard to modify, which made simulation of various concepts difficult or impossible. For example, we could not model the traction control concept due to assumptions made in the dynamics of the MATLAB simulation. For this reason, a new simulation tool will be developed. We plan to develop a skidpad simulation in CarSim, because it appears to be well documented and available through CAEN.

To determine if our rear steer concept can be packaged into our 2020 chassis, we created two preliminary CAD designs. A top mounted rack and pinion concept is shown in figure 6 and a dual linear actuator concept is shown in figure 7.

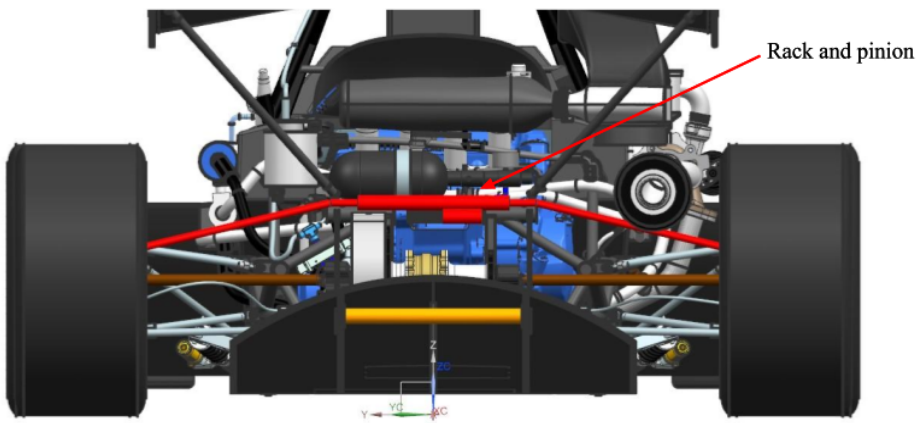

Figure 6: Rear Steer concept 1. Single steering rack placed over the rear of the car.

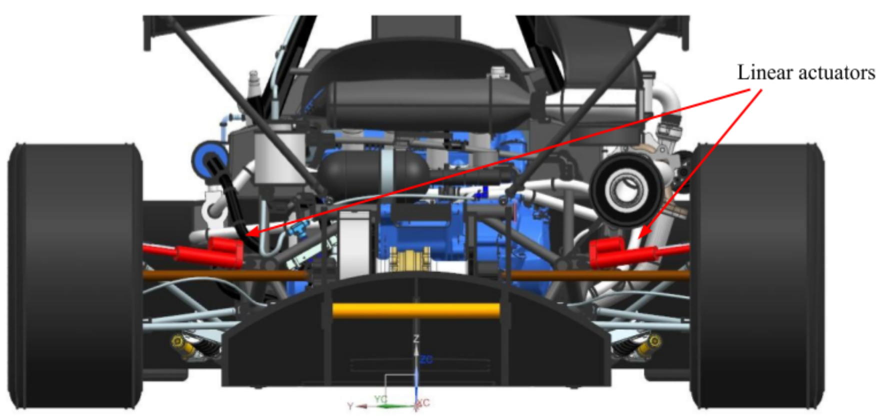

Figure 7: Rear Steer concept 2. Dual actuators, placed in place of the toe links in the suspension.

Benchmarking

To further explore this concept, we looked at two historically top performing teams that have explored a rear steer concept, the Technical University of Graz (TUG) and The University of Esslingen. TUG did very well at the 2019 MIS competition where they achieved a 2nd place finish. They claimed to only use their rear steer system for the autocross and endurance events and not for skidpad, saying it was unsettling to their drivers. They did still achieve a good result in the skid pad however with a 6th place finish. In autocross and endurance with their rear steer system enabled, they achieved 1st place in both. A picture of their solution is shown in figure 8 below.

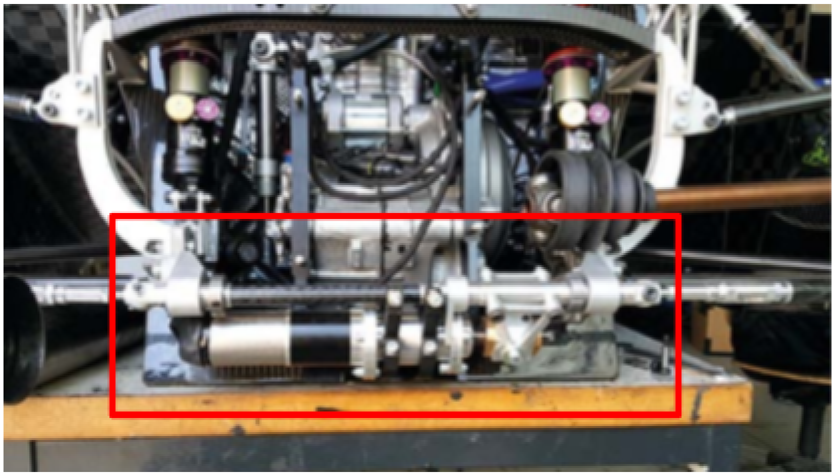

Figure 8: TU Graz 2019 Rear Steer System. Single steering rack is similar to our concept 1

The University of Esslingen is another team that explored a rear steer concept in the 2019 season. Since they have not competed in US events recently, we looked at their performance at the German formula student competition, FSG. In 2019, they won that event overall. From our research, they implemented and tested a rear steer system during their design phase but chose not to run it during competition due to its complexity and difficulty or tuning. Without the system, they were able to achieve 6th in skidpad, 1st in endurance, and also 1st in the design event. From this benchmarking, we have noticed that a rear steer solution is difficult to implement, especially in the skidpad event. TUG's results in the autocross and endurance MIS 2019 lead us to believe that rear steer could have a large impact on those events.

The University of Esslingen team also optimized their aerodynamics for cornering on their 2019 car. This involves simulating a vehicle in a curved windtunnel using computational fluid dynamics (CFD) and optimizing the wings to produce the most downforce in a cornering condition. This in theory should increase a vehicle's overall performance as downforce is most important while cornering. MRacing currently only performs straight line simulation due to limited computing resources and a lack of knowledge on performing cornering simulations. A picture on Esslingen's aerodynamics package is shown in figure 9.

Figure 9: University of Esslingen 2019 Cornering Optimized Aerodynamics Package

Another team that optimizes their aerodynamics package for cornering is the Norwegian University of Science and Technology or NTNU. They placed 10th in the 2019 FSG electric competition. If not for a failed resinspection, they were on track for at top 2 finish. They placed 2nd in skid pad, 2nd in autocross, and also notably 1st in design among electric cars. We noticed that cars with cornering optimized aerodynamics packages won first in design in both the combustion and electric events. We cannot draw the conclusion that this was due to their aerodynamics work, but suspect it played a significant factor.

For our setup jig concept we looked at the performance of the École de technologie supérieure (ETS) team at the 2019 MIS competition. They placed 3rd overall and achieved 1st place in skidpad, 4th in autocross and 2nd in design. A picture of their jig is shown in figure 10.

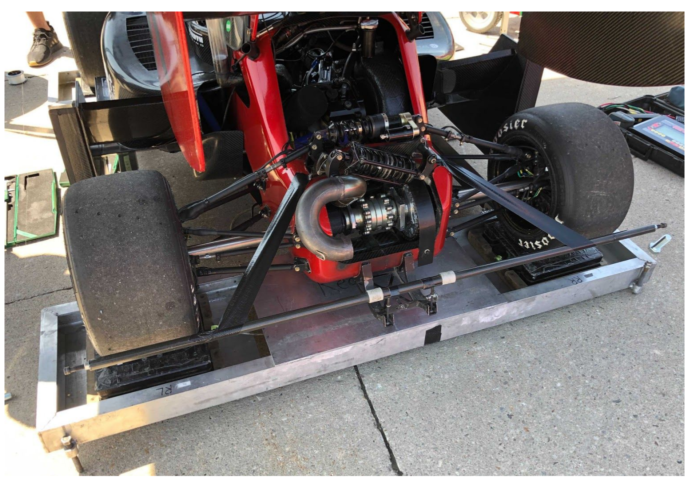

Figure 10: ETS 2019 Setup Jig Being Used at Competition

This solution involves a jig that would allow us to determine a flat plane on which we can alter our suspension setup between events at competition and allow us to accurately perform setups during testing. This solution would not only benefit us at competition but also help us further validate our full vehicle model for better accuracy.

Pugh Chart

From our benchmarking and vehicle simulation data, we created a Pugh chart (Table 9) shown on page 16. Each category was weighted based on importance, and each concept was scored on a scale of 0-5. The Pugh chart below was used as a screening tool to identify the concepts that are the most likely to succeed. We based our scores off of our benchmarking of other teams, simulation results, knowledge of competition rules and our best judgement.

Table 9: Pugh matrix of remaining concepts

	Skidpad Performance Gain	**Effects on Other events**	**Integratibility**	**Feasibility of Manufacturing and Design**	**Reliability**	**Cost**	**Weighted Score**
Weight	**5**	**4**	**4**	**4**	**4**	**2**	
Rear Steer	3	4	0	1	2	2	47
Cornering Aerodynamics	2	2	4	2	4	1	**60**
Setup Jig +Simulation	2	2	5	5	4	3	**80**
Single Cylinder	3	0	0	0	1	0	19
Torque vectoring	2	3	3	3	2	2	**58**
Custom Tires	3	4	2	0	0	0	39
Variable diff preload	1	1	3	4	3	3	55
4 Wheel Drive	2	0	0	3	1	1	28

Using the Pugh chart, we were able to select a final concept: setup jig with simulation. This concept scored highest in the Pugh chart and we believe that based on our benchmarking and other analysis, this is the best solution to our problem. This concept will involve developing a 'jig' which can be used to measure vehicle parameters such as corner weight, ride height, camber, caster, and toe. This would allow for faster setup changes between events as well as quick setup changes during vehicle testing. Coupled with the jig, a full vehicle simulation will be developed to study the effects of changing various vehicle parameters to identify the optimal skidpad setup in a design of experiments. This concept is the most easily integratable into our vehicle, as it doesn't require the redesign of any systems on the car. This also helps us limit the amount of in person manufacturing time. The potential for performance increase was proven in our MATLAB simulation, and our design of experiments will further improve that performance gain by identifying the optimal vehicle setup. In addition, the simulation will be a useful tool to evaluate vehicle setups virtually, which is especially useful with COVID and in the winter when testing is no longer possible due to low temperatures and snow. We believe this concept will have the most benefit to our team in the long run as it can easily be used on future cars with little redesign and the full vehicle simulation developed from this project will help future team members in suspension design and setup.

Solution Development

Setup Jig

To develop a design for the setup jig, a separate set of requirements and specifications for the setup jig specifically were developed through discussions with MRacing stakeholders. Then, initial concepts were explored in CAD to assess designs against the developed requirements and specifications, before a design was selected for detailed CAD and analysis.

Requirements and specifications for the setup jig were developed through discussions with the MRacing technical director and suspension team. The full list of developed requirements and specifications is shown in table 10.

Table 10: Requirements and specifications for the setup jig.

Requirement	Specification
Can be assembled quickly on location	• Assembly time < 15 minutes • Weight < 120 lbs total • Can be stored in MRacing trailer • Can be setup on variety of paved surfaces
Measure corner weight	• Each corner weight is within 0.1 lbs of value compared to measuring on chassis plate
Measure static toe	• Precision: 0.1 degrees
Measure ride height	• Validates that car passes minimum ride height rules
Decreases vehicle setup time so that changes are feasible between events during competition	• Total setup time (not including assembly) < 25 minutes
Cost	• < $1000

The specifications for the requirements that the setup jig can be assembled quickly on location and decreases vehicle setup time were given to us by MRacing based on their prior experience at testing and competition.

The setup jig is intended to measure camber, toe, and ride height, which are the parameters that MRacing currently adjusts during vehicle setup. Measuring these requires that the car be level, which is reflected in the specification that the measured vehicle corner weights be within 0.1 lbs of their values when measured on the chassis plate, which is known to be level. The value of 0.1 lbs is used because it is the resolution of the scales that MRacing currently uses to measure corner weights.

There is no requirement concerning camber measurement because MRacing already possesses camber gauges to measure camber. The only requirement for their use is that the vehicle be level. Static toe measurement, however, will be integrated into the setup jig. The resolution of MRacing's current toe measurement and adjustment is 0.1 degrees, which we have adopted as the specification for the setup jig toe measurement. For ride height, FSAE rules stipulate a minimum ride height for the vehicle, so MRacing would like the setup jig to be able to verify that the vehicle passes the FSAE rules.

The cost requirement of the setup jig was derived from the cost specification we developed for our overall project. Since the simulation side of the project will not cost anything, we have allocated all of the project budget for the setup jig.

From these requirements and specifications and the results from our concept generation and benchmarking, we developed a CAD model of the setup jig as shown in figure 11 below. The proposed design consists of a front half and rear half connected by two beams. The halves can be separated to allow storage in the MRacing trailer. The total projected weight of the setup jig is 88 lbs.

Each half of the setup jig contains two scales that are positioned below the tires. In order to minimize the setup jig's mass while maintaining ease of manufacturability and material sourcing, aluminum was selected as the material for the setup jig. The front/rear frames will be welded out of aluminum c-channel tubing, while the connecting beams will be made out of the same c-channel tubing and bolted to brackets welded to the front/rear halves.

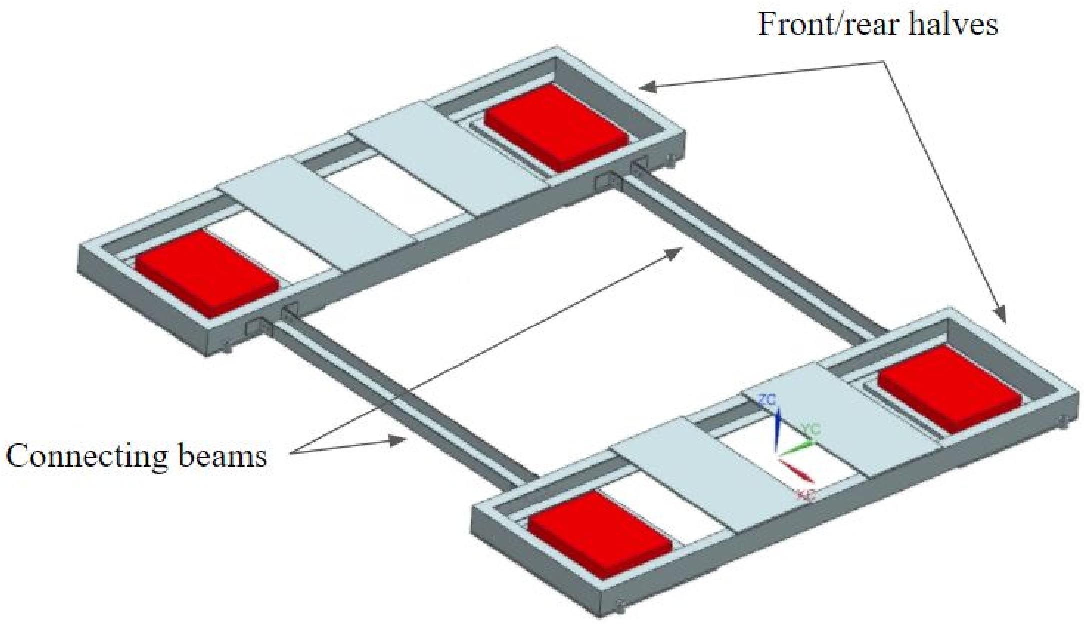

Figure 11: Setup Jig Leveling Hardware and Scales

To adjust the setup jig level and achieve the desired corner weights, four threaded aluminum tubes will be located at the corners of each half of the setup jig as shown in figure 12. Screws threaded into the tubes can be screwed in and out to fine-tune the height of each corner. Using this method, very small adjustments can be made at each corner individually to achieve our specification of matching corner weights to the chassis plate values.

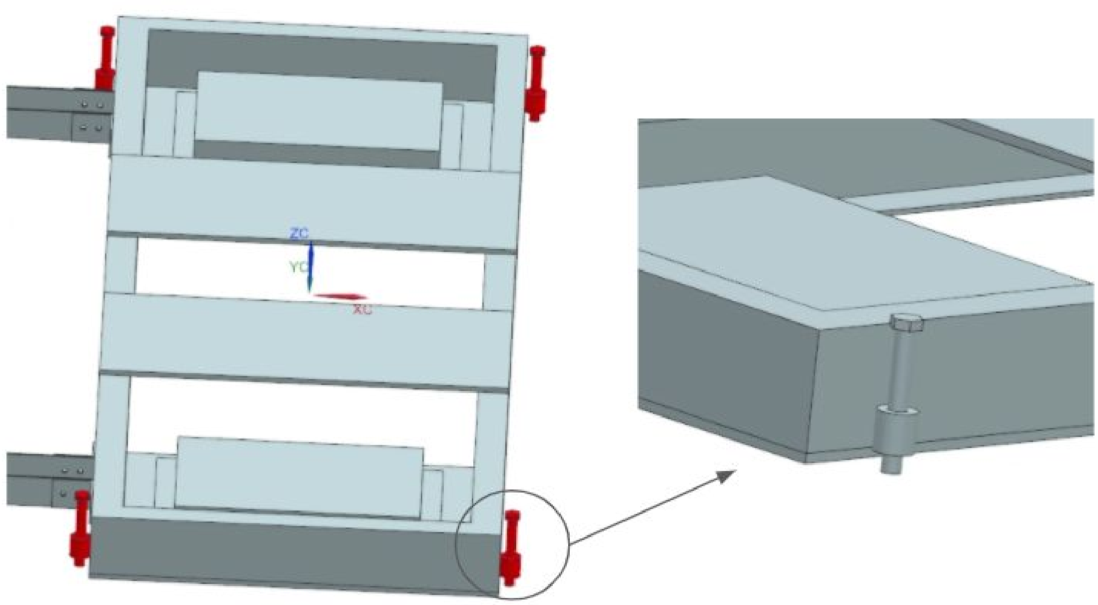

Figure 12: Screw "feet" for adjusting setup jig leveling. Feet are marked in red.

The connecting beams between the front and rear halves also serve as a level base along which a beam the height of the FSAE minimum ride height requirement can be slid to ensure that no point along the bottom of the car is below the FSAE minimum ride height as shown in figure 13.

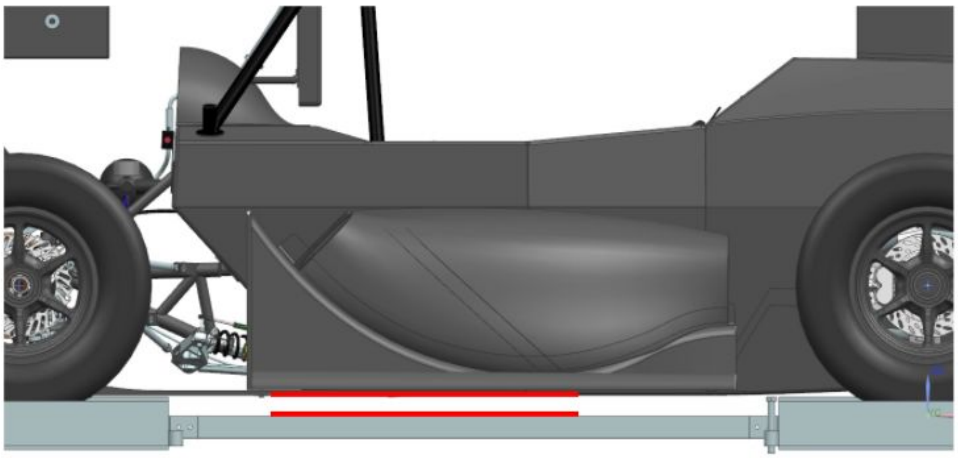

Figure 13: Ride height measurement using connecting beams. Ride height clearance is marked in red.

A string alignment method was chosen to measure each wheel's toe angle. This method involves aligning a string parallel with the car longitudinal axis. In our design, the string attaches to the ends of two poles mounted to the front wing brackets and jackbar. This can be seen in figure 14. Fixing these points to the car prevents the team from needing to align the strings for each toe measurement session and improves repeatability between measurements.

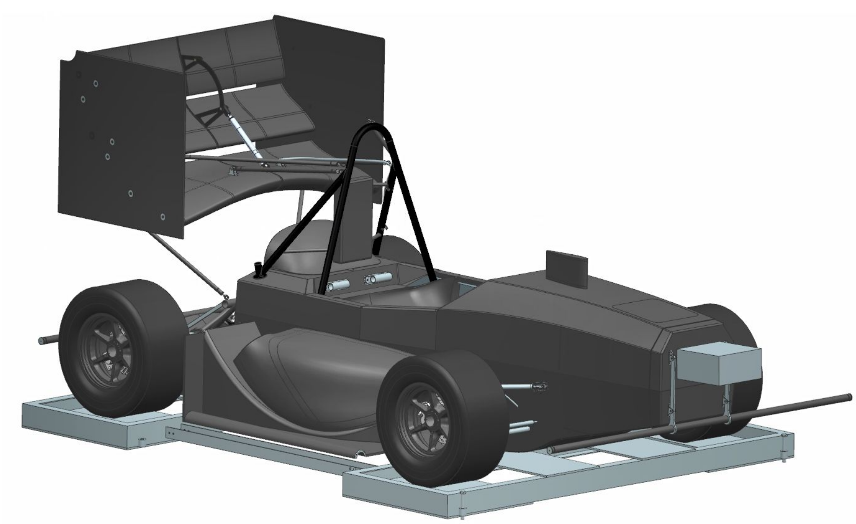

Figure 14: Toe Alignment Hardware

The distance from the string to the front and rear of the rim of every wheel is measured initially. The wheel center distance is interpolated from these measurements. The bolts at the end of the poles allow for the string endpoints to be adjusted laterally until the wheel center distances indicate the string is parallel with the car longitudinal axis. Figure 15 shows front and rear rim measurements as well as the adjustment bolt near the rear wheel.

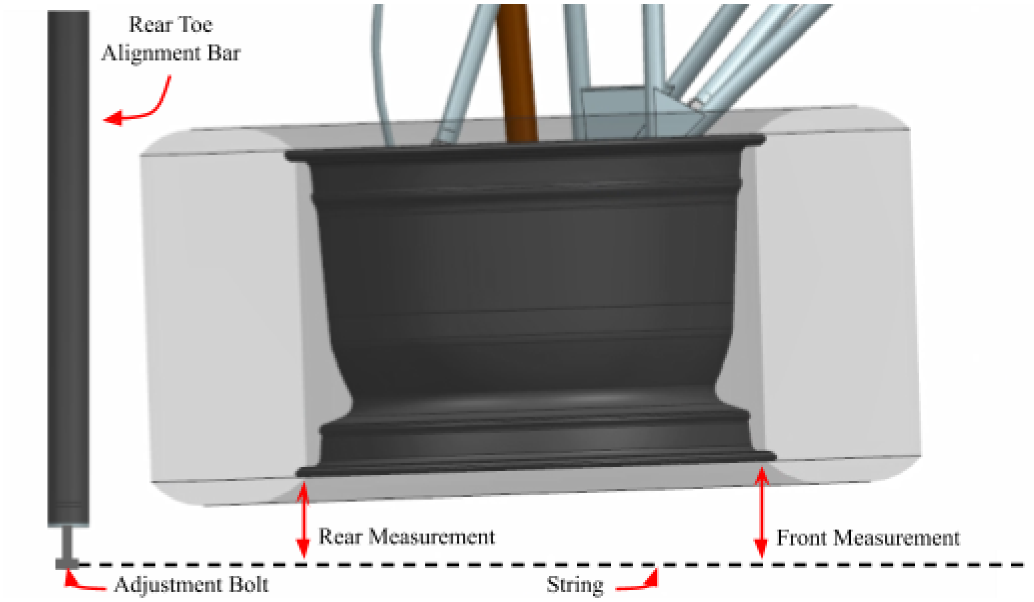

Figure 15: Rear Wheel Toe Alignment

Our criteria for a parallel string is when the difference in measurements to the front and rear wheel centers match the expected values due differing front and rear track widths. Since the front track width is one inch wider, a wheel center measurement from the front should be half an inch less than the rear on each side. MRacing does not currently have a way of accurately measuring wheelbase so uses the assumption that the wheel locations of the manufactured car match CAD exactly. This limits the confidence the team has in its toe measurements however relative changes can still be measured precisely. After the string is aligned, the bolts can be locked using jam nuts so that they don't need to be realigned for the next measurement. The front and rear rim to string distances are measured a final time and the toe angle of each wheel can be determined using trigonometry. The trigonometric setup is shown in figure 16.

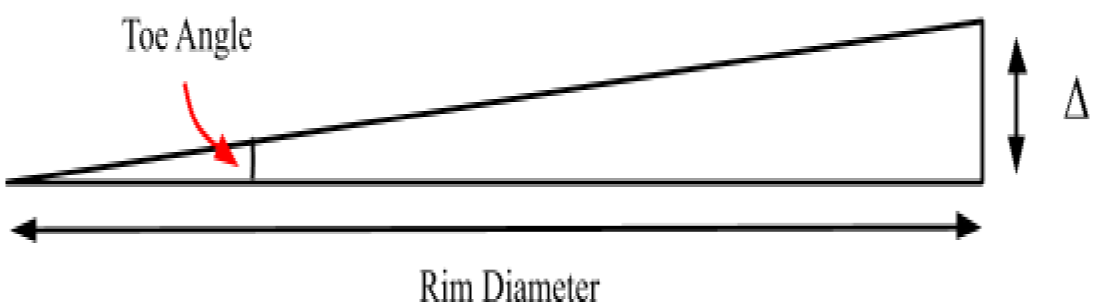

Figure 16: Toe Angle Calculation Diagram

In this diagram Δ is the difference between the front and rear rim to string measurements. From these distance measurements, the toe angle can be calculated using equation 3 below.

$$Toe\ Angle\ (^\circ) = Arctan(\Delta\ /\ Rim\ Diameter) \tag{3}$$

Validation - Setup Jig

Due to COVID-related restrictions, we were unable to manufacture and test a physical prototype of the setup jig. We will pass our design to MRacing, and order and manufacture parts next semester. To validate that we met our requirements and specifications, we performed a detailed analysis of our CAD model; however, concrete validation can only be conducted next semester once the setup jig has been manufactured. The plan for validation of the manufactured setup jig is to compare the corner weights/toe/camber/ride height measured using the setup jig to the values obtained by measuring on the chassis plate at the Wilson Center. To verify repeatability, multiple measurements will be taken at different locations using the setup jig, and assembly/setup times will be recorded to ensure they meet our requirements.

The specification for assembly time under 13 minutes was assessed by listing out the steps involved in assembling the setup jig, and providing time estimates for each step based on consultations with the team and prior experience. The steps and their time estimates are listed below. The total estimated time was 15 minutes, which met our specification.

1. Bolt front and rear jig together (2 mins)
2. Level front and rear jigs (2 mins)
3. Level jigs to each other (2 mins)
4. Roll on vehicle (2 mins)
5. Adjust setup jig to match measured corner weights (5 mins)

The specification for weight was assessed by measuring the volumes of components in CAD and multiplying the volumes by the densities of the materials we plan to use. Calculating the weight using this method yields an estimated weight of 88 pounds, which meets our specification for weight.
The specification for being able to be stored in the MRacing trailer was assessed through a visual inspection and measurement of the fully loaded MRacing trailer. Due to the ability to separate the setup jig into multiple pieces, it was easy to find enough space to store the components.

The specifications for being able to be set up on a variety of paved surfaces and being able to level the jig to achieve corner weights to within 0.1 pounds of their values measured on the chassis plate are more difficult to assess without a physical prototype. We are highly confident that the eight screw feet installed on the setup jig will allow us to achieve these specifications based on our past experience with similar devices; however, we will perform more detailed testing and validation when a physical prototype is manufactured.

The specification for static toe precision was assessed by plugging in the caliper measurement precision of 0.01” for Δ and MRacing tire rim diameter of 10.6” for rim diameter in equation 3 on page 22. This gives a projected toe measurement precision of 0.05 degrees, which meets our 0.1 degree precision specification.

The specification for verifying that the vehicle passes minimum ride height rules is also difficult to assess without a physical prototype. We plan to jig the setup jig on the chassis plate while manufacturing it to ensure that all portions of the setup jig are level with each other, including the connecting beams. We are highly confident that this will allow the connecting beams to be used as a parallel surface to measure the ride height along the length of the car.

The specification that the total setup time, not including assembly, is less than 25 minutes was assessed using a similar method to the specification for assembly time. The steps involved in vehicle setup using the setup jig were listed out, and time estimates for each step were formed through discussions with MRacing based on previous experiences with vehicle setup. The steps and their time estimates are listed below. The total estimated time for vehicle setup is 15 minutes, which meets the specification.

1. Measure Corner weights (1 min)
2. Adjust Camber (5 mins)
3. Adjust Toe (9 mins)

The specification of costing under $1000 was assessed adding up the costs of new materials needed in our BOM. The full BOM can be found in Appendix B. Adding shipping, the total estimated cost of this project is $558, well under budget. Manufacturing costs were neglected as all manufacturing work can be done for free in the Wilson Center by MRacing team members.

Risk Evaluation - Setup Jig

To assess the risks of our setup jig solution, we performed a Failure Modes and Effects Analysis (FMEA) following the FSAE format. The full FMEA can be seen in appendix H on page 40. Failures of our solution are very unlikely to risk bodily injury so we redefined the severity ratings to rate the inability of the setup jig to perform our defined requirements with 5 being the most severe.

From this analysis, we determined that yielding of the setup jig frame poses the largest risk. If the frame were to yield, the setup jig would not be able to accurately measure corner weights. If this failure were to occur, the replacement of the frame would be necessary Additionally, the detection of this failure mode is difficult as yielding would not be easily seen from visual inspection. The likelihood of the failure occurring is low as the typical loading of the setup jig frame is relatively low at around 150 lbs per corner. Additionally this loading occurs at the ends of the frame right above the supporting bolts, minimizing bending stresses. To combat this risk, we designed the setup jig frames with large plates on the top and bottom to resist applied bending loads and increase the jig's resistance to yield. Additionally frequent inspection of the frame's flatness using the chassis plate could be performed to ensure this failure has not happened. Although we determined this failure mode to be high risk, we believe that the likelihood of occurrence is low. If MRacing handles the setup jig with care, we believe the level of risk to be acceptable.

We determined that all of the other failure modes we analyzed were low risk as their detections were certain and could be repaired or replaced. Repair to the setup jig would be difficult to conduct during a competition however so the MRacing team should take extra care when using it then.

Simulation - CarSim

To simulate full vehicle performance during the skidpad event, the commercial software package CarSim was chosen. This software is already included as part of University of Michigan CAEN (Computer-aided Engineering Network), This enables all team members to quickly and reliably access the software. In addition multiple team members can be working on the simulation at the same time. CarSim also has an intuitive GUI and a database of prewritten testing procedures, tracks, and vehicles. In particular there is an example FSAE vehicle, skidpad event procedure, and an MCity 3D track model, all of which can be used by the MRacing team to to compare the real life vehicle performance to the simulation. CarSim is also compatible with external models, such as many different tire models and Simulink.

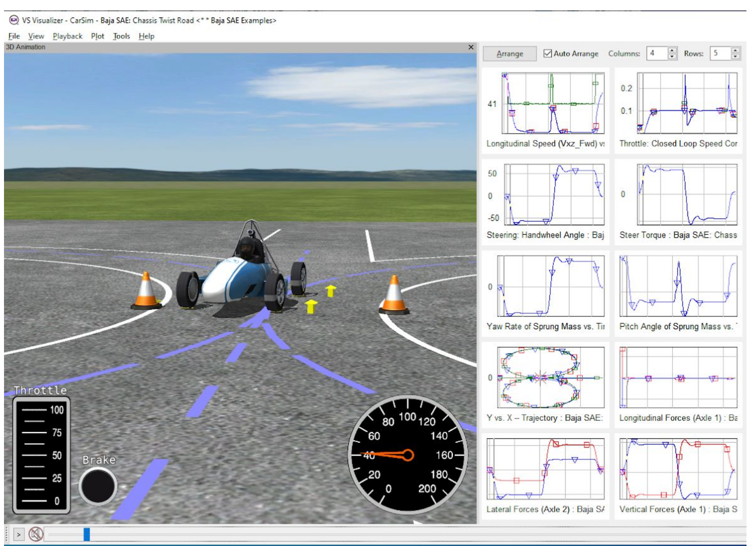

Figure 17: CarSim animator window, showing position of the vehicle (example FSAE car) and various plots of vehicle parameters during a skidpad attempt

CarSim models each vehicle as two independent axle systems joined by a body. For the version of CarSim included with CAEN the joining body is assumed to be rigid. To define the properties of the vehicle, CarSim has a system based structure (Figure 18). Within each system there are a specific set of variables required by the model. An example, from the “sprung mass” category can be seen in Figure 19. Each variable can be manually entered by the user, and if desired, manipulated during the simulation with user entered code or from an external model such as simulink.

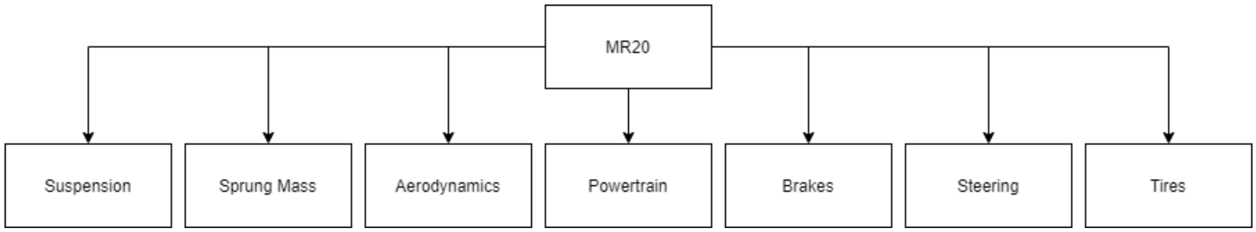

Figure 18: CarSim vehicle system structure

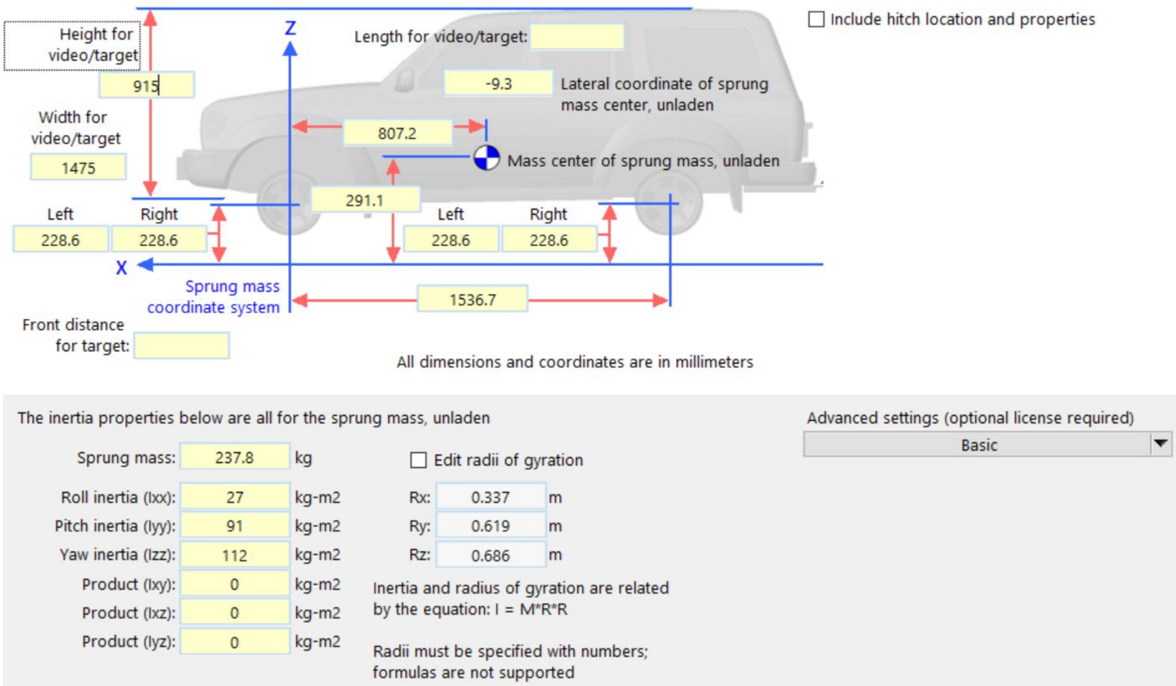

Figure 19: CarSim sprung mass data sheet.

From preliminary tests in CarSim some limitations have been determined. The most prominent is the accuracy of the simulation. Due to the large number of parameters necessary to properly define the vehicle, and because many of these require other analysis methods, such as; kinematic solvers for suspension relationships, FEM for chassis stiffness, CFD for aerodynamic parameters, and tire models to capture the effects of camber, toe, pressure, and vertical load, many small inaccuracies can add up to poor overall simulation results. In addition some quantities are nearly impossible to calculate within the scope of ME 450 due to the necessary resources and time (such as chassis torsional damping). Another limitation within CarSim is the built in driver model. The model uses a combination of path following based on steering angle and maximum lateral and longitudinal acceleration targets. While this model works well for basic maneuvers with specified driver inputs, the model does not directly consider the effects of driver inputs on vehicle performance. We have seen that the driver model does not properly react to large slip angles, and therefore does not reach the true limit of the vehicle. Additional limitations are the road surface and rigid chassis approximation. The baseline road surface is modeled as perfectly flat, and while this can be changed easily, we do not know the correct roughness profile for the real life tracks. The rigid chassis approximation can be solved with an additional CarSim license, however current rigid chassis approximation is sufficient since we are looking for steady state behavior.

To validate the MRacing vehicle model simple maneuvers will be performed, such as a swerve, braking, accelerating, and the response to wind. There are two ISO standards which may also be used. ISO 19364: Steady State Cornering, and ISO 19365: Increasing Sine Steer. These tests will be replicated on the real vehicle (sometime early 2021) to validate the model.

Simulation - Design of Experiments

In order to evaluate the design space of possible setups, we opted to perform a design of experiments. We Created a preliminary list of design variables which we are able to control in CarSim that we know affect our skidpad time. This list became quite large, and so we chose to narrow it down to four variables: front camber, rear camber, front toe and rear toe. The choice to do so was driven by the fact that these variables are the quickest and easiest to adjust, and will be adjustable using our setup jig design. Other variables such as spring rates also affect our skidpad times, but we chose to limit our design variables to avoid excessively large design matrices.

Table 12: Design variables and noise factors for design of experiments.

Design Variables (Controllable)	Noise Factors (Uncontrollable)	Performance Metric (Measurable)
Camber front Camber rear Toe front Toe rear ~~Caster~~ ~~Ride height front~~ ~~Ride height rear~~ ~~Spring Rate front~~ ~~Spring Rate rear~~ ~~Roll bar front~~ ~~Roll bar rear~~ ~~Damping~~	Tire temperature Driver skills/judgements Compliance	Skidpad Time

With the four design variables, we elected to conduct an orthogonal array instead of a full factorial experiment. The main benefit of an orthogonal array over a full factorial matrix is that it minimizes the number of tests while mixing up the effects of interactions between design variables. We chose three levels of values for each of the four design variables to use a L9 orthogonal array. Based on the team's previous experience on vehicle setups, a course set of low, middle, and high values were selected for the three levels of each design variable. The experiment setup parameters and results were summarized in Table 13 on page 26.

Table 13: Parameters and results of the first round design of experiments.

Experiment	A:Camber Front	B: Camber Rear	C: Toe Front	D: Toe Rear	**Skidpad Time (s)**
1	-3	-3	-2	-1	4.951
2	-3	-1.5	-0.5	0.5	4.936
3	-3	0	1	2	4.961
4	-1.5	-3	-0.5	2	4.931
5	-1.5	-1.5	1	-1	4.927
6	-1.5	0	-2	0.5	4.965
7	0	-3	1	0.5	4.915
8	0	-1.5	-2	2	4.929
9	0	0	-0.5	-1	4.967

The simulated skidpad lap times were reasonable compared to tested skidpad times from the MRacing vehicle, which based on fall testing were in the range of 4.9 - 5.1 seconds. However, the differences between lap times were small compared to the large setup changes. We believe that the underlying reason for the strange results is the result of CarSim's driver models. The driver models in CarSim present a problem, because the driver does not necessarily drive to the limit of adhesion. The driver models work by using a PID controller for throttle and steering to reach target speeds and follow paths set out by the user. Because of this, the driver often gets confused when the vehicle begins to reach the limit of the tire, and the driver goes to 100% throttle, sending the car into a spin. To remedy this issue, we moved to a different testing procedure to evaluate setups.

Instead of measuring lap time, we chose to measure understeer gradient for our second procedure. The understeer gradient is a measure of a vehicle's sensitivity to steering. In a car that oversteers (negative understeer gradient), steering angle decreases with increasing lateral acceleration, and the opposite is true for a car that understeers (positive understeer gradient). This can intuitively be thought of as an understeering car lacking front axle grip, and an oversteering car lacking rear axle grip.

Understeer gradient is a useful parameter to measure for skidpad, because theoretically maximum lateral acceleration can be achieved at neutral steer (zero understeer gradient) in steady state. This is because the car is not limited by a lack of front axle grip as it is in understeer, or rear axle grip as it is in oversteer. The understeer gradient can also be measured at low lateral accelerations, avoiding the issue with the driver model when approaching the adhesive limit of the tires.

ISO 4138:2012 lays out a set of steady state cornering procedures to evaluate the understeer gradient of a passenger car or light truck. We used the constant radius test laid out in the standard, where turning radius is held constant, and speed is increased in discrete steps (i.e. 5 m/s, 10 m/s, etc.). Assuming constant radius, we can then define understeer gradient by the following:

$$\frac{\partial \delta_H}{\partial a_Y} \times \frac{1}{i_S}$$

[5]

Here, $\partial\delta_H / \partial a_Y$ is the slope of the line when plotting steer angle as a function of lateral acceleration. The variable 'i_s' is the overall steering ratio, which can be calculated using our steering geometry and steering rack.

For this design of experiments, we chose to also include spring stiffness for both the front and rear, increasing our total number of design variables to six. We did this because the roll stiffness of the vehicle plays a big factor in determining the understeer gradient of the vehicle, and without it we would not get a full picture of the scope of possible setups. This required the use of an L18 matrix. As before, a range for these variables was chosen based on what we believed to be a reasonable range. For spring rate, we chose the range of spring rates that we owned that fit our current suspension system. Ranges for toe settings were slightly changed because positive front toe and negative rear toe are known to be unstable.

Table 14: Results of second round design experiment. The five setups closest to neutral steer are highlighted.

	Camber Front	Toe Front	Camber Rear	Toe Rear	Spring Rate Front (N/mm)	Spring Rate Rear (N/mm)	**15m/s Lateral accel (m/s), Steering angle (deg)**		**30 m/s Lateral accel (m/s), Steering angle (deg)**		**Understeer Gradient (deg/g)**
1	-3	-1	-3	0	35.03	35.03	4.500	17.144	18	17.771	0.46
2	-3	-0.5	-1.5	0.5	61.29	61.29	4.500	18.526	18	21.289	2.01
3	-3	0	0	1	87.56	87.56	4.500	19.578	18	19.914	0.24
4	-1.5	-1	-3	0.5	61.29	87.56	4.500	14.92	18	13.526	-1.01
5	-1.5	-0.5	-1.5	1	87.56	35.03	4.500	18.976	18	23.665	3.41
6	-1.5	0	0	0	35.03	61.29	4.500	16.558	18	14.404	-1.57
7	0	-0.5	-3	0	87.56	87.56	4.500	15.423	18	16.128	0.51
8	0	0	-1.5	0.5	35.03	35.03	4.500	17.313	18	19.062	1.27
9	0	-1	0	1	61.29	61.29	4.500	19.057	18	23.481	3.21
10	-3	0	-3	1	61.29	35.03	4.500	18.261	18	20.298	1.48
11	-3	-1	-1.5	0	87.56	61.29	4.500	18.343	18	19.72	1.00
12	-3	-0.5	0	0.5	35.03	87.56	4.500	18.64	18	17.595	-0.76
13	-1.5	-0.5	-3	1	35.03	61.29	4.500	18.131	18	20.897	2.01
14	-1.5	0	-1.5	0	61.29	87.56	4.500	16.113	18	15.031	-0.79
15	-1.5	-1	0	0	87.56	35.03	4.500	19.187	18	22.845	2.66
16	0	0	-3	0.5	87.56	61.29	4.500	16.191	18	18.435	1.63
17	0	-1	-1.5	1	35.03	87.56	4.500	18.468	18	22.113	2.65
18	0	-0.5	0	0	61.29	35.03	4.500	17.198	18	18.388	0.86
Best Setup	-1.5	-0.2	-0.5	0.2	61.29	52.53	4.500	17.293	18	17.398	0.08

From these simulations, a few trends arise. Stiffer rear springs than front springs tend to produce cars that oversteer, with all four setups that produced oversteer fitting this trend. Similarly, stiffer front springs than rear springs tend to produce understeer. This makes sense intuitively, as we know from our experience and knowledge of vehicle dynamics that increased roll stiffness in the front will produce understeer, and an increased roll stiffness in the rear produces understeer. In addition, the simulation shows that there is a trend with camber as well, with more camber in the front producing oversteer, and camber in the rear producing understeer. This is because camber produces ‘camber thrust’, which is a lateral force created by the deformation of the tire while cornering. This effectively increases the lateral grip of the axle, and so the effect on understeer gradient makes sense.The effects of toe are unclear and don’t show a strong correlation to understeer gradient. More simulations will have to be done to isolate the effects of toe, because the design of experiments is currently dominated by the effects of camber and spring rates. Overall, we can say that the simulation matched the general trends that are expected, and that the simulation’s data is ok to use.

Using this information, we ran a series of experiments to identify the best setup for skidpad. We balanced the effects of spring rate and camber, while keeping toe at a low value typical to MRacing setups because of the unclear effects of toe from our design of experiments. The goal of this setup is to achieve as close as possible to neutral steer as mentioned earlier. After some testing, we have identified an optimal setup, as shown in the last row of table 14. This setup’s understeer gradient is 0.08 deg/g, which is acceptable for our use. For example, road cars are typically 2.00 deg/g or more, so defining 0.08deg/g as neutral steer is appropriate.

Validation - Simulation

Given the absence of physical car testing due to Covid shutdowns, the primary methods used to verify the simulation were simple sanity checks based on known and expected car behaviors. System parameters were checked for expected behavior using simplified simulations. For example, aerodynamic effects were validated by comparing the aerodynamics forces versus speed, checking that the lift and drag produced is reasonable and matches previous year wind tunnel data. Most importantly, the overall vehicle behavior during skidpad was analyzed during our design of experiments to check that it matches the actual car. The effects of camber and spring stiffness on understeer vs oversteer behavior were found to give the same trend of results we would expect to find in the real world. In addition, skidpad times found in the first design of experiments, while slightly suspect due the driver models, are actually very close to tested times completed this fall (4.9-5.1 seconds). While these results prove that the simulation is on the right track, they do not guarantee that the solution will apply to the real car. Validation against the real car will be carried out in the spring of 2021 using identical tests to compare the simulated to on track data.

The simulation passes most of the requirements and specifications quite easily. The simulation doesn’t modify anything on the physical car, so it is obvious that it is legal for our competition. It also doesn’t interfere with other systems on the car or decrease other systems performance, passing the integratable requirement. The simulation requires no manufacturing and is free to use through CAEN, so it is manufacturable and within budget. The driveability requirement is also not an issue, as setups can be changed quickly using the setup jig if the driver is uncomfortable with the current setup. This leaves us with the only requirement that the simulation does not obviously pass, our points goal.

The points goal was written at a time in the project when we believed that lap time optimization would be possible, and so the specification for this requirement was written in terms of a time decrease in skidpad. However, due to driver model issues discussed earlier, this was not possible. We did not directly achieve our goal of reducing the skidpad time by 3% as stated in our specification. We did, however, succeed in evaluating the scope of possible setups and arriving at a theoretically best setup for skidpad. We cannot correlate this result directly to a 3% lap time reduction, but this achievement will still allow us to improve our team's skidpad performance. Our simulation was successful in evaluating skidpad setups, but simply didn't fulfill the specific wording of our performance specification.

Risk Evaluation - Simulation

In generating vehicle simulation results, the primary sources of error are; the parameters entered into the model, the physics based calculations within the simulation tool, the procedure simulated, and any controllers used for dynamic simulations. In this case the high risk areas are the parameters entered and the controllers used. There are many parameters used in the vehicle model which are based on inertial or stiffness properties. These are difficult to measure, particularly for the MRacing team since only one vehicle is produced per year, with limited spare components to test on. In addition the tests necessary to quantify these properties can be time consuming or expensive.

The highest source of risk comes from the controllers used for the dynamic simulations. In this case a steering, braking, and throttle controller which is built into CarSim was used. After initial testing it was clear that the included controller was not robust enough to handle the large slip angles of the MRacing vehicle. We found that as the vehicle naturally oversteered, and slowed down due to tire drag, the built in driver controller increased throttle application in an attempt to counteract the loss of speed. However since the vehicle was already sliding the result was complete loss of control. There is no method to counteract this problem within the controller while still allowing for the vehicle to be simulated near the traction limit of the tires. As a result we switched from analyzing the time to complete a skid pad event to utilizing an ISO standard to evaluate the vehicle understeer gradient. The understeer gradient will provide a more general overview of vehicle behavior which we can use to increase confidence in simulation results when compared with the real car.

Discussion and Recommendations

From our design and analysis, we believe that the setup jig will be a robust, easy to use tool that improves our setup process substantially. It will allow for less wasted time at testing days, roughly cutting setup time in half. In addition, the ability to use the jig at competitions gives us a great advantage, where we can change setup at any location and even between events. The setup jig uses a very similar method of adjusting toe and camber to what we have used previously, and will be easy for our team to learn to use. In addition, our simulations offer insight into optimal skidpad setups, and allows us to evaluate different setups more quickly than in real life.

One of the biggest drawbacks of our setup jig design is the weight. At around 88 pounds, the setup jig will take a team of people to assemble and move. This will be hard on the team and makes the setup jig harder to use for those with disabilities. Before manufacturing in the spring, we will attempt to lightweight our solution while still hitting our stiffness targets through the use of finite element analysis and basic stiffness calculations. The chosen thicknesses of components of the setup jig are currently conservatively designed to hit our stiffness targets, and so there is a sizable weight reduction possible.

In addition, the mounting points for the toe alignment rods are awkward to use. To access them, the nose cone and front wing must first be removed, and then the rod is bolted into the front wing mounting holes. This wastes some time, and adds tools to our setup process. In the future, we would like to design dedicated mounting holes for the front and rear toe alignment rods, so that we can complete this process more quickly in the future.

The next steps for the team are to finish validation of the simulation through a set of ISO standard test procedures, and comparing real life results to that of our simulation. We will also manufacture and test the setup jig, to see how accurately we are able to set up the car in remote locations.

Conclusion

Our team has designed a vehicle setup jig, which will allow for fast and accurate changes to vehicle parameters such as ride height, corner weights, camber angle, and toe angle. In addition our team is in the process of developing a full vehicle simulation which will be used to evaluate the potential performance gains made from varying these parameters. The team was initially tasked with determining a solution which would improve the MRacing vehicle’s skidpad event performance. The team met with the project stakeholders, MRacing and Harvel Bell, to set appropriate requirements and specifications. From there a functional decomposition of the skidpad event was performed, which gave the seven critical factors for skidpad performance. Using these factors, the team analyzed each system of the MRacing vehicle (Chassis, Suspension, Drivetrain, Powertrain, and Aerodynamics) along with utilizing concept generation techniques such as brainstorming, competitive analysis, and design heuristics to generate concepts which would improve the skidpad performance.

The large list of initial design concepts was first reduced utilizing a simple gut check. Some ideas were simply not feasible or known to not provide any performance increase. From there the team met with the stakeholders to discuss the remaining concepts, and eliminate several more. For the remaining concepts a combination of a three degree of freedom rigid body matlab simulation, benchmarking, preliminary CAD drawings, and a Pugh chart were used to assess various aspects of the design concepts. The vehicle setup jig and simulation was chosen based on its ability to be integrated with the current car, low cost, design feasibility and potential for improvement in skidpad as well as the other dynamic events.

Setup jig design was started by developing a specific set of requirements and specifications based on input from MRacing team members and their experience with vehicle setup. From here initial concepts were generated and explored in CAD. The chosen design utilizes two rectangular sections, each slightly wider than the MRacing vehicle, to house two scales. One fixture is placed under the front of the vehicle and the other under the rear. Leveling screws under each fixture ensure that the vehicle meets the requirements for measuring corner weight accurately. Two bars, one attached to the front and the other to the rear of the vehicle with a string run between them, are used to measure toe angle by measuring the distance between the string and the wheel. Simple trigonometry is used to calculate the angle. A BOM was generated, with the total cost estimated to be $458. Due to COVID shutdowns the setup jig will not be manufactured until 2021.

To simulate the full vehicle behavior the commercial software CarSim was chosen. This package is available via CAEN, has an intuitive user interface, and comes with premade vehicles, tracks, and test procedures. These existing models were modified to replicate the MRacing vehicle and skidpad track, and known MRacing parameters were entered. Several limitations to the CarSim model have been discovered since simulation work began, and work is in progress to resolve the issues. The complete model can't be fully validated until identical tests are run with the real MRacing vehicle. Which will happen in spring of 2021. Regardless, a preliminary set of experiments were run to analyze the initial effects of setup parameter changes. The difference between the results is not intuitively accurate and it is believed to be a result of the current limitations of the driver model. In addition to the skidpad tests, a test of understeer gradient was performed based on ISO 4138:2012 and utilizing two additional design variables, front and rear spring rate. From the results for these tests we determined a vehicle setup which we believe has the best potential of being an improvement over the currently used skidpad setup. Further validation of the vehicle model and of improvements to the skidpad setup will be tested in the spring of 2021 when the MRacing car is driven.

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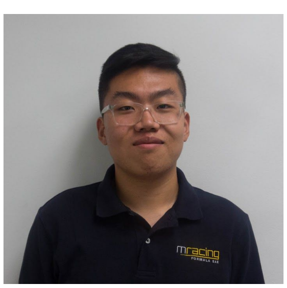

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References

[1] SAE International. *Formula SAE Michigan 2019 Overall Results*. 16 May 2019. https://www.sae.org/attend/student-events/formula-sae-michigan/awards-result.

[2] SAE International. *Formula SAE Rules 2021,* Version 1.0, 30 July 2020. https://www.fsaeonline.com/cdsweb/gen/DocumentResources.aspx.

[3] Kraige, L. G., and Bolton, J. N. Engineering Mechanics. Dynamics. Eighth edition., Wiley, 2015.

[4] Milliken, Milliken, 1995, Race Car Vehicle Dynamics. Society of Automotive Engineers Inc, Pennsylvania.

[5] British Standards Institution, BS ISO 4138:2012 *Passenger cars. Steady-state circular driving behaviour. Open-loop test methods.* Geneva, Switzerland: International Organization for Standardization (ISO), 2012.

Appendix

Appendix A: Initial design concepts

- **Tire Grip Concepts**
    - **Slip Angle**
        - **Rear steer:** Use some form of an actuator to 'steer' the rear tires. Note that the FSAE rules only allow 6 degrees total movement per tire. By steering the rear tires the slip angle is controlled and therefore the amount of grip at each tire and the direction of the tire force.
        - **Bump steer:** During suspension travel the wheel and tire will change the amount of toe angle. By changing the suspension geometry the amount of bump steer can be changed to better modulate the slip angle, improve grip, and change tire force direction.
        - **Improve Ackermann:** Ackerman is the difference between the steering of the inside and outside tires relative to the rotation of the steering wheel. Having ackerman in the steering system means the inside tire will turn more than the outside tire. Optimizing the angles of each tire during the skidpad can increase the total grip from the front tires
        - **Quick toe adjustment:** The toe value is the static difference in steering of a specific tire with reference to a vertical plane. This concept would involve developing a faster and more accurate way to change the toe value during competition events. The MR20 car utilizes dual rod ends on a two-force member, with left and right handed threads to adjust the toe. These are not accurate and lose dimension easily.
        - **Setup jig+simulation*:** This concept would involve developing a 'jig' which can be used to measure vehicle parameters such as corner weight, ride height, camber, caster, and toe. This would allow for faster setup changes between events, as well as quick setup changes during vehicle testing. Coupled with the jig, a full vehicle simulation can be developed to study the effects of changing the various vehicle parameters.
    - **Camber Angle**
        - **Camber curve:** During suspension travel the camber angle will change, by modifying the suspension geometry the camber angle at a specific load can be optimized
        - **Active camber:** Utilizing an actuator to change the camber angle
    - **Normal Load**
        - **More downforce:** Adding downforce adds normal force, increasing tire grip.
        - **Active roll bars:** The roll bars couple the left and right side of an axle, by changing the stiffness of the roll bar the amount of load on each tire can be changed
        - **Active caster angle:** Caster is the "backward" or "forward" lean of the steering axis, as a result during steering one tire is pushed into the surface and the other lifts from it. Changing the caster angle changes the normal load on the tires.
        - **Active dampers:** changing the damper characteristics to react to surface imperfections or driver inputs.
        - **Active front wing:** Changing the amount of direction of the force from the front wing changes the amount of force generated into the front tires.
    - **Frictional Coefficient**
        - **Custom tires:** Developing new tires with an increased frictional coefficient
        - **Tire heating method:** Tires are known to have an improved frictional coefficient when they are hotter. By preheating the tires there will be more grip. Note that this can be interpreted as a violation of the FSAE rules.
    - **Torque Application**
        - **Torque vectoring (brakes):** Would require an open differential. By applying the brakes to the inside rear tire during a cornering event, a moment is generated about the car

helping it turn. In addition, due to the open diff additional torque is sent to the outside tire further increasing the moment.

- **Torque vectoring (driveline):** Can be done multiple ways, including utilizing a clutch or brake on one side of an open diff, or having a gear ratio to change the torque output between the different sides of the diff.
- **Four wheel drive:** Provive torque to all four wheels
- **Variable diff preload:** Diff preload is the amount of static torque within the diff required to rotate the wheels independently. When turning the preload produces a counter moment. Changing the preload can modify vehicle behavior.
- **Advanced traction control:** Improve on the existing traction control system to control vehicle yaw moment from torque application.

- **Mass Concepts**
  - **Total Vehicle Mass**
    - **Single cylinder engine:** Replace existing four cylinder engine with a lighter single cylinder engine. Would likely reduce power.
    - **Carbon suspension links:** Reduce vehicle mass (and partially unsprung mass) by designing lightweight carbon fiber suspension links.
    - **Corner redesign:** Reduce vehicle mass (and partially unsprung mass) by designing lightweight hub assemblies.
    - **Remove fluids for skidpad:** Temporarily remove water, fuel, and some oil for the skidpad event. Potential for vehicle damage.
  - **Mass Distribution**
    - **Variable lateral CG position:** Move the vehicle center of gravity to change weight transfer during cornering. Affects load on each tire
    - **Adjust driver seating position:** Change the driver seating position to affect weight transfer
    - **Add ballast:** Change the center of gravity location utilizing ballast. Would likely hurt skidpad time due to increase in force required from the tires. Existing tire data says that the increase in normal load is not equivalent to the increase in force required.

Appendix B - Setup Jig Bill of Materials

Part	Dimensions	Quantity	Vendor	Part #	Cost
Aluminum C Tube L brackets	3"x1.5" C-channel tube, 25' Length, 0.258" Thick	2	industrialmetalsupply.com	61C03B	200
Frame Aluminum Plate Front Mount Sheet Stock	20"x26" Plate, 0.25" Thick	5	Yarde Metals	6061 T651 PL .25	252.15
Aluminum stock for scale locators	2"x1"	16	MRacing	N/A	0
Aluminum round stock for foot mounts + toe measurement inserts	1" OD, 10" Length	1	Wilson Center	N/A	0
1/4-20 bolts for feet	3" Length	8	McMaster	92865A554	5.84
1/4-20 bolts for connectors	0.75" Length	16	MRacing	N/A	0
Carbon Fiber Tube	1" OD, 1/8" Wall Thickness, 52.125" Length	2	MRacing	N/A	0
Round Stock	0.5" OD, 1" Length	2	Wilson Center	N/A	0

Appendix C - Engineering Standards

For use in our simulation, we followed ISO 4138. This standard lays out the procedure necessary to calculate the understeer gradient of a passenger car or light truck. We opted to perform the constant radius discrete speed test as outlined in the standard, where turn radius is held constant, and longitudinal speed is increased in discrete steps (as opposed to continuously increasing velocity). This allowed us to plot steer angle versus lateral acceleration. This slope of this relation, when turn radius is held constant, is the understeer gradient of the vehicle. This standard allowed us to evaluate setups in a way that didn't involve lap time optimization, which was beneficial as CarSim's library of driver models was unpredictable when approaching the limit of tire adhesion, and couldn't give reproducible results.

Appendix D - Engineering Inclusivity

To ensure the team would be capable of developing the most inclusive design, the team members were chosen so as to have a wide range of skill sets from the sponsor (MRacing). This way the needs of the sponsor are already understood by the team. When defining the exact problem the team had a form of visible power over the sponsor, since the project would need to fit into the guidelines of ME 450, primarily the timeline for the semester. Overall the team was very inclusive in the design process, working closely with the MRacing team. One possible improvement would have been to communicate with more experts outside of the MRacing team. Since these people would not share the same bias about MRacing activities that the both the 450 team and the MRacing team share.

Appendix E - Environmental Context Assessment

1. Does the system make significant progress towards an unmet and important environmental or social challenge?

Since the project was based exclusively on the MRacing Formula SAE student org there is no effect on environmental or social challenges.

2. Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits?

The system has been designed for long term use exclusively by the MRacing team. This way the system only needs to be manufactured once, limiting any long term impact to the environment. In addition, should the system need to be rebuilt it is made of recyclable materials so components may be able to be reused.

The design decision with the largest environmental impact was choosing between steel and aluminum for our setup jig. The energy cost of using aluminum to construct this setup jig is over twice that of steel at 1.9e6 kcal and 9.2e5 kcal respectively. However, from our CAD design, we found that a setup jig made out of steel would weigh approximately 260 pounds. This does not fulfill our weight requirement and would be difficult for MRacing team members to move. An aluminum construction would only weigh around 88 lbs. We believe that this weight reduction is worth the extra environmental cost as it would increase the likelihood that MRacing will continue to use it consistently in the future. As long as the setup jig is properly maintained, we hope to see this solution to be used for many years.

Appendix F - Social Context Assessment

3. Is the system likely to be adopted and self sustaining in the market?

Since this project was aimed exclusively for the MRacing project team, there is no plan to release it as a product. However, if this setup jig solution were to be released into the market, there is a likelihood that it could become self sustaining. There are over 600 FSAE/FS teams world wide, almost all of which would benefit from such a product. From MRacing's experience, current setup jig products in the market are extremely expensive and not well suited for FSAE needs. Companies such as Hoosier, Multimatic, and OZ have proven that products targeted specifically at the FSAE market can be viable.

4. Is the system so likely to succeed economically that planetary or social systems will be worse off?

It is unlikely that this solution would succeed to such a point that the planet would be worse off. The FSAE market is small, and even if every team purchased / manufactured one the effect on the environment would be negligible.

5. Is the sustainable technology resilient to disruptions in business as usual?

As the Covid pandemic has proved, the solution is not completely resilient to disruptions since it would not have been physically used. Should the solution be distributed to the FSAE market, it will only be successful if the teams are operating as normal.

Appendix G - Ethical Decision Making

The primary ethical decisions made during the design process were related to ensuring that the design solution we chose (setup jig and vehicle simulation) would in fact be the best option for the MRacing team, and ensuring that the setup jig would be safe during use. We had many discussions with MRacing team members, and used a combination of benchmarking and known vehicle data to assess the design solutions available. With the setup jig and vehicle simulation proving to be the best. Our main method for ensuring the setup jig would be safe was including a weight limit in our requirements, this way it can be carried easily and will do less harm if dropped.

Appendix H - Setup Jig FMEA

FMEA No.	Component	Function	Failure Mode	Failure Cause	Failure Effect	Severity	Severity Reasoning	Occurance	Occurance Reasoning	Detection	Detection Reasoning	Risk
1	Setup Jig Frame	Weigh either front or rear two wheels	Yielding of Frame	Excessive loading	Left and right scales are no longer in plane so corner weight measurements would not longer be accurate	5	All scales must be in plane for accurate corner weight measurement, the main requirement for this solution.	2	Setup Jig Frames are robust and are unlikely to yield under typical loads	4	Yielding of the setup jig will be difficult to detect without frequent detailed inspection	40
2	Setup Jig Frame	Weigh either front or rear two wheels	Weld failure	Poor weld quality	Structural integrity of setup jig frame will be affected. Jig can no longer support the weight of vehicle safely	4	Frame should be easy to be rewelded together. However, MRacing will have a limited ability to do this at a competition	2	Welding was not performed correctly	1	A failed weld should be easy to detect by a quick visual inspection	8
3	Setup Jig Halves Connecting Beam	Connect front and rear jig halves and serve as a base for ride height measurement	Bending of Beam	Unintentional loading	Beams can no longer serve as a level base and will lead to inaccurate ride height measurement	2	Beams must be in plane for accurate ride height measurement. Ride height measurement can be done with other methods however.	3	The connecting beams are less stiff than the setup jig frame and will experience higher bending loads	1	Beams can be placed on chassis plate to check flatness	6
4	1/4-20 Bolts for Connecting Beam	Bolt setup jig halves with connecting beam	Bolt Thread Stripping	Overtightening	Beams may not be assembled or disassembled correctly	1	There is more than one bolt connecting the beams to the setup jig halves. Beams are still functional if one bolt fails	1	Bolts overtightened when assembling setup jig	1	Damage to the threads can be detected if bolts cannot be turned correctly	1
5	1/4-20 Bolts for Setup Jig Feet	Adjust setup jig levelness	Bolt Thread Stripping	Overtightening	Bolts can no longer be adjusted and can be hard to take out	4	Setups must be performed with leveled setup jig halves. Setups cannot be performed if plane is not level	2	Bolts overtightened when assembling setup jig	1	Damage to the threads can be detected if bolts cannot be turned correctly	8
6	Carbon Fiber Tubes	Attach strings for toe measurement		Unintentional loading	Tubes are no longer intact to attach strings	4	Strings must be attached for toe measurement	1	Tubes are not subjected to any significant loading	1	Failure in carbon fiber is visable	4