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Formula SAE Design Validation through Lap Time Simulation

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ZIPS RACING
THE UNIVERSITY OF AKRON

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Abstract

Lap time simulation is capable of advancing Zips Racing into a new, modern era for future vehicle designs. Through the use of VI-grade simulation software, Zips Racing was able to validate its current combustion and electric vehicle designs in spite of the challenges brought on to the team as a result of the COVID-19 pandemic. Throughout this project, the design team gained an enhanced understanding of suspension designs and optimizations through the usage of computer simulations. As a result, the teams have a better understanding of the fundamental changes that need to occur to enhance the race team's final race car. The design team's simulation software allows the user to analyze in-depth data for driving simulations and assess the strengths and weaknesses of a vehicle design.

Additionally, the design team was able to verify Zips Racing's virtual model designs by performing basic hand calculations utilizing fundamental vehicle dynamic principles. By using formula derived assuming steady state conditions, the design team was able to derive the equations for straight line maximum acceleration as well as the vertical load transfer from the front axle to the rear. By doing this, the design team was also able to verify the validity and correctness of the VI-grade simulations. By using hand calculations and data acquired from 2019, the design team was able to verify the validity of the simulations created. From the design of a lap time simulation software, Zips Racing has been able to benefit from optimizing set ups and improving upon the design of subsystems. Furthermore, this vital information and data from this senior design project can then be used for many future generations of Zips Racing in order to continually improve upon the teams' race cars.

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Introduction

The year of 2020 will forever be remembered for the great turmoil and strain that COVID-19 has put on society. The ensuing pandemic caused many industries and organizations to adapt to the newly issued and ever changing government guidelines and restrictions. In order to continue production and testing of the car without breaking the imposed guidelines and restrictions, Zips Racing needed a method to test the car that did not require extensive in-person vehicle running. Due to this, an alternative source of vehicle testing that could be done with public health and safety in mind needed to be found. This method was found to be driver-in-the-loop lap time simulation. Although this is not a new method of vehicle research and development in both the automotive industry and motorsports, it would be an entirely new venture for Zips Racing at The University of Akron.

Zips Racing During COVID-19

Due to the complications that have come from COVID-19, Zips Racing had to adapt. Initially during the 2020 season, the first shutdown resulted in all Zips Racing personnel being barred from entering the Design Center at The University of Akron. This drastically slowed the building process of the cars. Due to manufacturing the vehicle being incredibly difficult to achieve, Zips Racing focused on certain aspects that could be done virtually. For this senior design project, virtual meetings would need to take place due to the need to socially distance. Furthermore, a topic would need to be found that would allow for this remote environment. However, the continuation of remote learning and social distancing would also result in the ZR20 and ZRE-20 race cars not being finished within the intended timeline. This would lead to any verification and analysis of the cars to be suspended and potentially cancelled due to the inability to test running cars.

COVID-19 has become a major obstacle that continues to hamper Zips Racing. However, this pandemic has also affected The University of Akron and the entire world. With these long shutdowns, businesses have found it difficult to offer Zips Racing support. This has made it extremely difficult to find sponsors that have the capability and ability to offer Zips Racing their support. This led to further delays and tighter budgets for Zips Racing. Due to COVID-19, Zip Racing has had to adapt in order to progress and to keep the team moving forward.

Goals and Needs of Zips Racing for 2021

With many changes due to COVID-19, Zips Racing had to define new goals for the race teams. In a normal year, Zips Racing focuses on designing and building the best race cars possible to compete in Formula Student events in The United States of America or in Europe. With COVID-19, the team was initially unsure if any competitions would be conducted and if the team would be permitted to go. Zips Racing made the goal of completing the incomplete cars from the year prior and to try to attend the U.S. Formula SAE events. Additionally, Zips Racing had begun looking to the future beyond 2021. Due to difficulties in gaining sponsorships and business support, Zips Racing needed to show continual improvement and progress within the team in order to gain future sponsors. Thus, a virtual lap simulator would provide tangible results and progress for Zips Racing and would provide much needed data and analysis for the race cars.

Importance and Impacts of Lap Time Simulation in Motorsport

It is easy to see how automotive manufacturers involved in motorsport, whether it be developing a Formula One car, a homologated GT race car, or even a front wheel drive purpose-built touring car, can utilize driver-in-the-loop lap time simulation. Depending on the racing series, operating costs have changed over recent years. In many instances, the cost for a team to test their car on-site and in-person during the development stages is often expensive and difficult to justify alongside other expenses. As race cars become more complex with extensive computational fluid dynamics simulation, wind tunnels, kinematics and compliance, and shaker rig testing, the preference is to mitigate costs whenever possible.

In professional motorsport, driver-in-the-loop lap time simulation is often preferred for a few reasons. The first is that it allows for the physical development of a race car out of the public eye. This means that a race car can be conceived entirely without having to worry about rival manufacturers, spy automotive photographers, or anyone outside of the development team knowing about the car. A second benefit from this method is that manufacturing costs of vehicle parts to be used in testing can be significantly reduced. This offers more financial benefits to the race car's manufacturer. A third benefit is that the manufacturer can learn what leads to a quicker lap time on a closed circuit earlier than normal and be able to make critical design changes before important design freezes.

The most notable recent instance of this type of vehicle development was in the six-year development of the mid-engine, C8 Corvette and the subsequent FIA-homologated Corvette C8.R race car. Both were revealed to the public in late 2019. The notable switch from a front to mid-engine vehicle layout as well as the transition from a small-block, pushrod V8 engine to a dual overhead cam V8 engine could all be validated and tested in driver-in-the-loop simulation without having to manufacture parts or conduct live testing until the latter months of the six-year development cycle (Dagys).

Importance of Lap Time Simulation in Formula Student/Formula SAE

Very similar to professional motorsport, cost is an important factor in what Formula SAE and Formula Student teams hope to accomplish with each vehicle build. Finding effective ways to continue vehicle development while offsetting costs can often be one of the most effective paths towards a successful race car design. Depending on a Formula Student team's geographical location and money to invest in testing resources such as fuel and tires, being able to physically test the car frequently might not be a viable option. Additionally, having the time to test new ideas and components may be more difficult in a real world environment due to the time and cost involved in such an endeavor. Therefore, lap time simulation could serve as an important alternative option to these Formula Student and Formula SAE teams to continue vehicle development without spending excessive amounts of money towards actual testing, especially during the offseason.

VI-grade

VI-grade is a top of the line tool that can help amateur and professional race teams make the best use of their time. VI-grade is a software package and advanced applications for the usage of vehicle system level simulation and dynamic driver simulation ("Company"). In the software package provided, the software included VI-SuspensionGen, VI-CarRealTime, VI-Road, VI-Animator, VI-TireLimits, and VI-EventBuilder. With these programs, VI-grade allows for the in-depth analysis of one's automobile or race car through simulation.

The Build Process

Other than simplified point-mass model lap time simulation programs, the idea of using a complex lap time simulation software had not usually been considered for design validation of Zips Racing cars until this design. Therefore, building the Zips Racing cars from the ground up would be a new endeavor for the members of this design team. To briefly describe the basics of the build section, this section goes through the simplified version of the setup. However, this build process is incredibly timely in order to get the same exact setup of the physical ZR20 and ZRE-20.

To run an event or simulation in VI-CarRealTime, a car must be built in the software. To begin an event in VI-CarRealTime, a model must be loaded into the program. After loading in this model from one's database, the car can begin to be edited and built. It is important to note that the software comes with pre-defined vehicle models that the user can extensively edit to create a new design unique to the software.

The following figure shows a full car model setup with the different subsystem files built. One is able to click each subsystem and edit any parameter or variable. The program is incredibly complicated, but this is the basis for the simulation software.

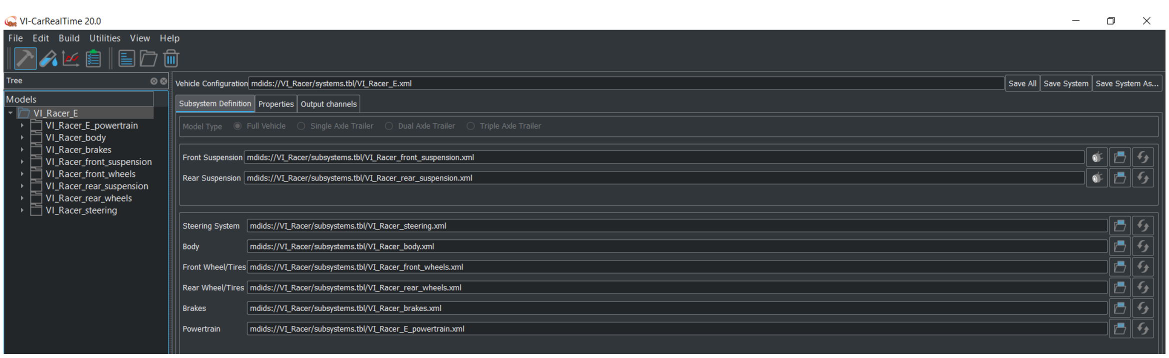

Figure 1: Car Setup with Different Subsystem models

As the figure below shows, a typical VI-grade subsystem shows a range of user-defined options that can affect vehicle performance. For instance, this body file allows the user to define the vehicle wheelbase, center of gravity location properties, vehicle mass with driver, and vehicle inertia values. These values can be defined in any unit system, but for this project, the Metric system was heavily utilized.

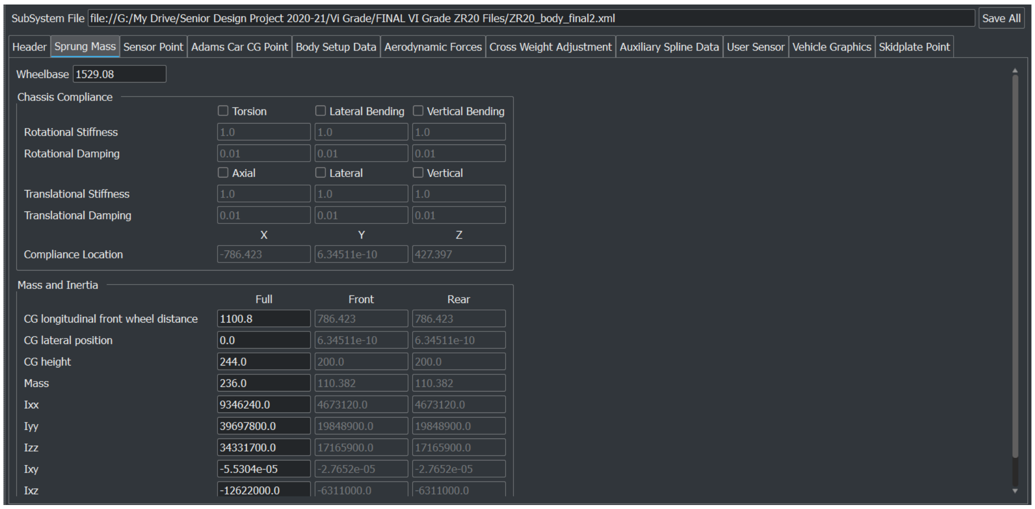

Figure 2: A typical vehicle setup file as seen in VI-grade

Furthermore, VI-grade's SuspensionGen software tool allowed the design team to 3D-plot the vehicle's front and rear suspension points and develop extensive kinematic analysis of the vehicle. In addition to suspension points, the design team was able to define the tire dimensions, coilover spring rates, static and setup camber and toe settings, and static ride height. The output data from this suspension design can then be incorporated into the vehicle setup in CarRealTime.

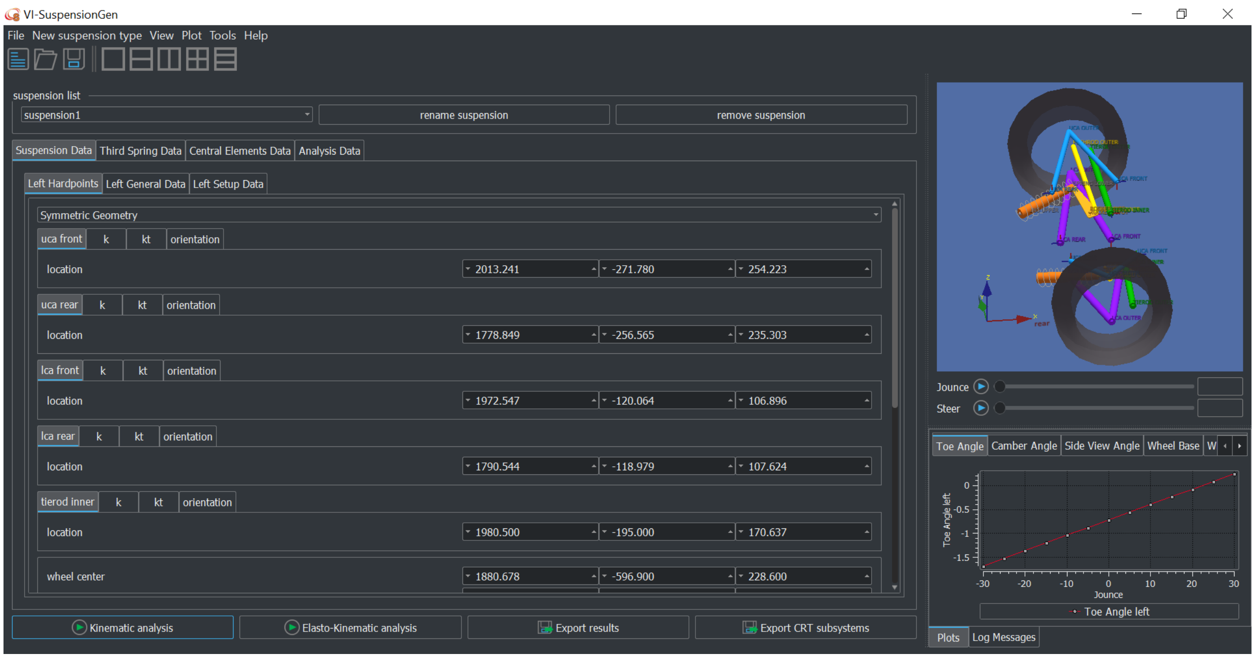

Figure 3: A typical setup screen for a VI-SuspensionGen vehicle suspension design. The software allows the user to plot all inboard and outboard suspension points on an XYZ coordinate system, defined here in mm.

After loading the race cars and changing all of the necessary variables, the design team was able to begin simulations and analysis of the race cars. To run simulations, the design team created the four dynamic events as experienced in previous Formula SAE competitions.

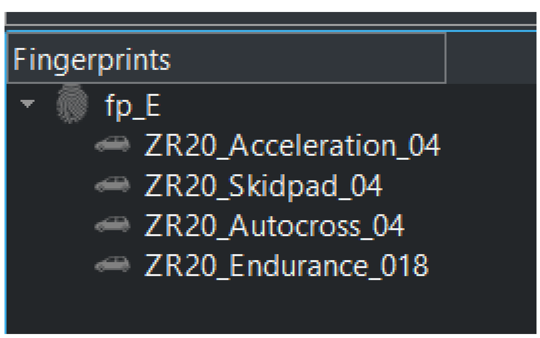

Figure 4: Seeing pre-loaded fingerprints

After running each event, the design team can attain and view a plethora of data. This data can be viewed alongside a computer generated video of the event with graphs shown alongside. Many of the data channels accurately mimic the types of data channels that ZR20's data acquisition system, Motec, is capable of outputting for the actual vehicle. This can be seen in the figure below.

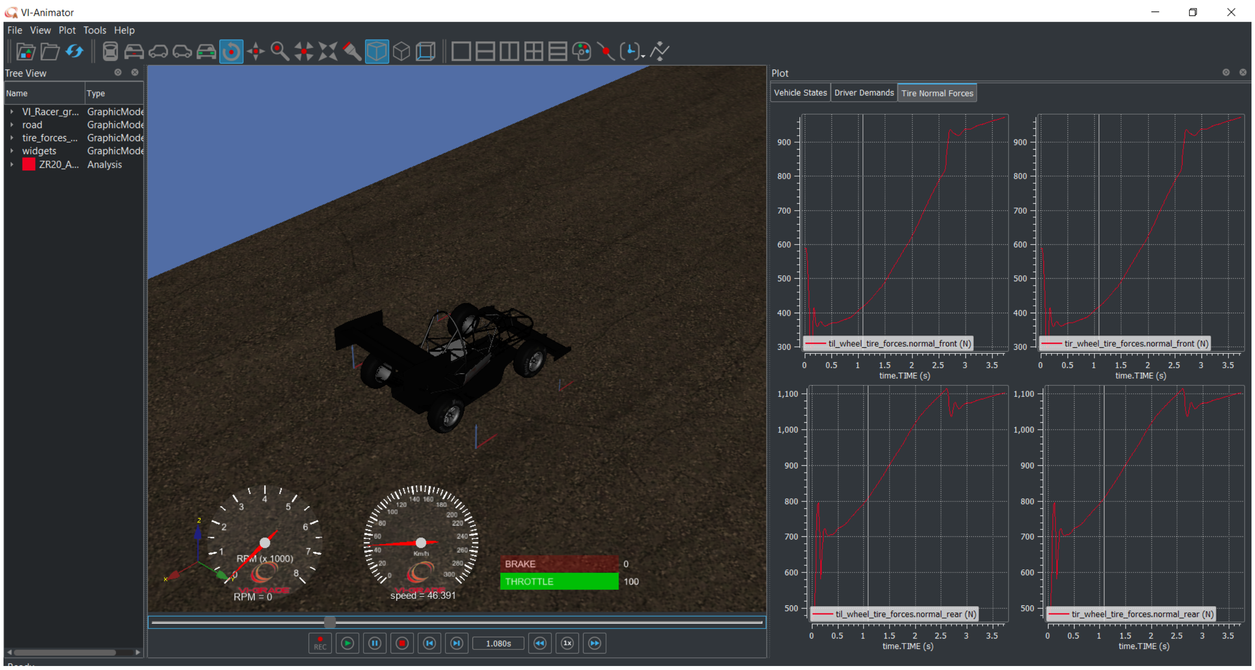

Figure 5: Seeing VI-Animator in action

Validation Between VI-grade and 2019 Performance Data

One way the design team was able to implement the learnings and findings from the developed simulation was in the area of the ZR20 and ZRE-20 suspensions. When comparing the data from the simulations of the ZR19 race car to the on track data, the design team was able to gain useful insight for the ZR20 and ZRE-20 suspensions with the design team's knowledge of vehicle dynamics. When comparing different data, it is important to keep in mind the track characteristics of both. For instance, the friction circle of an autocross course lap that features more left turns than right will have a greater frequency of data points towards the right side of the friction circle. This is because the increased amounts of left hand turns cause the increasingly loaded right side of the vehicle to experience a greater frequency of g-forces than the left side. Therefore, it would be better to compare different vehicles in a skidpad environment.

VI-grade was able to show a typical Formula SAE skidpad run for ZR20 and ZRE-20 using the car's designed suspension system and other parameters. In a typical skidpad run, the car must undergo two clockwise and two counterclockwise circles. This helps show the cornering capabilities of the cars. The car is scored based on the best individual circle lap time that the driver can earn, and a detailed look into a skidpad course for Formula SAE and Formula Student Competition is shown below Typically, the higher lateral and longitudinal g-forces that the resulting friction circle has generated results in a higher cornering speed that the car can carry. The more cornering speed results in a quicker lap time and more dynamic points earned in the competition. The best possible score is the ultimate goal for Zips Racing at every competition.

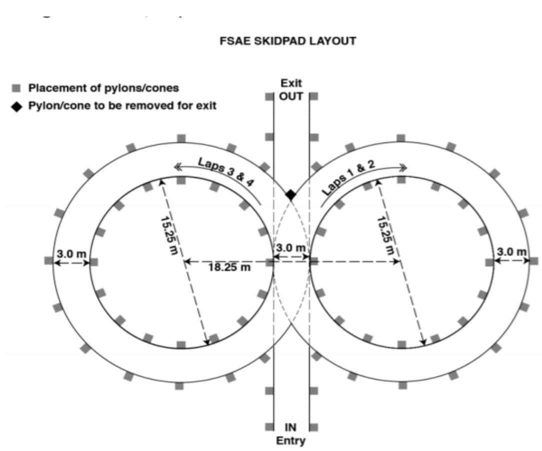

Figure 6: Official layout, including dimensions and cone spacing, of a Formula SAE/Formula Student Skidpad Layout

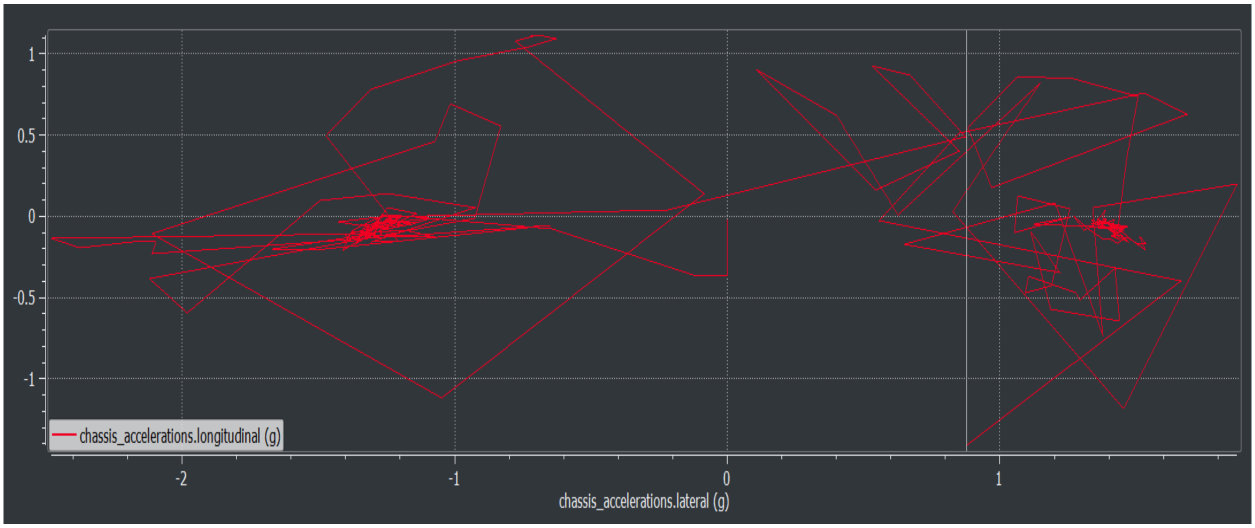

Figure 7: Friction Circle in VI-grade utilizing ZR19's suspension points on a skidpad run. The model was capable of running a 5.21 second skidpad lap time.

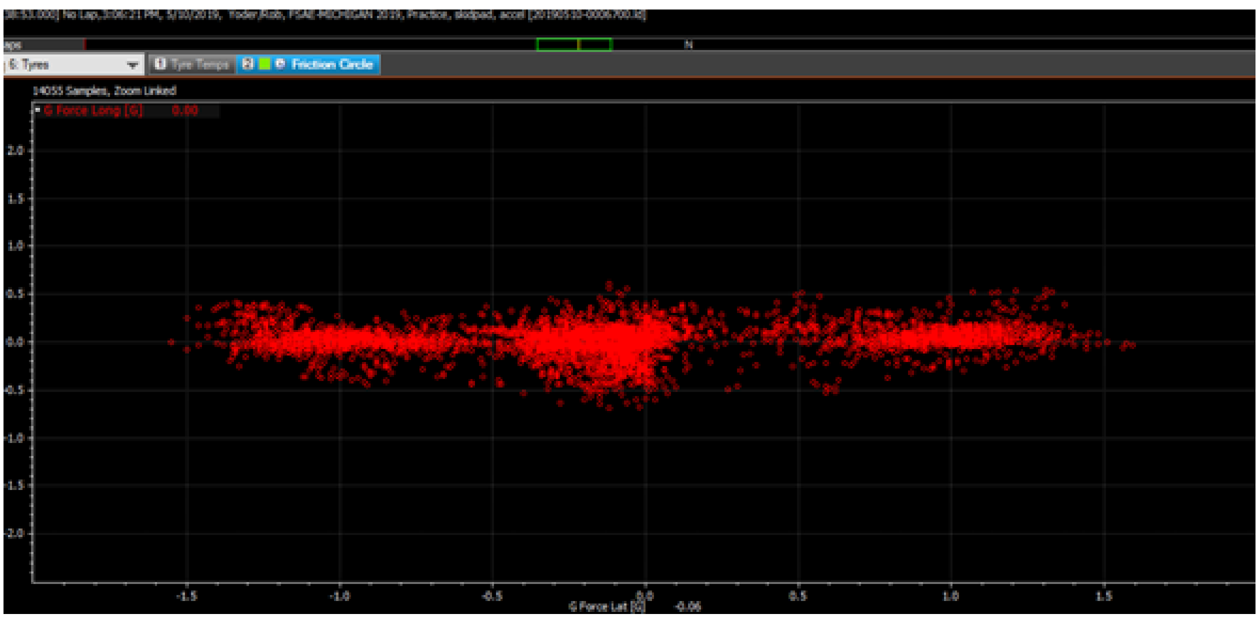

Figure 8: Friction Circle for ZR19 from the skidpad event at Formula SAE Michigan 2019. The best time in this skidpad event was a 5.36 second time, or 33rd out of 109 teams at the event.

The friction circles above show interesting comparisons between a theoretical skidpad run and an actual skidpad run for ZR19 at Formula SAE Michigan in May of 2019. The x-axis of the plots are the lateral g-forces, and the y-axis of the plots are the longitudinal g-forces. The theoretical skidpad, ran in VI-grade using the ZR19 setup and seen in Figure 7, output a single circle skidpad time of 5.21 seconds, while the actual skidpad run from Michigan 2019, seen in Figure 8, was a 5.36 second time as shown in Motec i2 Pro (“Formula SAE Michigan 2019 Results”).

For both plots, there seems to be a correlation between the average peak lateral g-forces generated and the lap times that correspond. The VI-grade iteration of ZR19 with the car’s suspension points that ran on the car was capable of an average peak lateral g-forces around 1.4 g’s in a skidpad. By comparison, the actual run of ZR19 in the skidpad event at Formula SAE Michigan in 2019 was capable of an average peak lateral g-forces of about 1.25 to 1.3 g’s. This slight difference in g-forces equated to a lap time difference of about 0.15 seconds. To put this difference into perspective, the 5.21 second lap time would have placed Zips Racing in 13th in skidpad, or twenty positions higher in the rankings.

This difference in lap times could be attributed to a few different factors. The primary reason is that with the skidpad event being short in overall time elapsed while driving, generating tire temperature based on ambient and track conditions has a significant effect on what lap time the car is capable of generating. At Formula SAE Michigan 2019’s skidpad event, the ambient temperature was about 50℉ with overcast skies and a track temperature of 55℉. Therefore, it would be expected that all teams competing would have been running slower skidpad times compared to their theoretical targets with their cars. This is because the colder track temperatures would make it more difficult for the tires to generate heat and thus decreased the grip of the tires. Therefore, cornering speeds were lower, and skidpad times were slower. The second reason for the better theoretical skidpad time is that VI-grade is capable of aiding the user in determining which vehicle setups are most optimal for lap time in an event through investigations. Therefore, the setup determined on the car at the event in 2019 was not the most optimal setup according to VI-grade. For example, the actual setup used in real-world competition in 2019 was with -3/16” toe out setting in the front suspension and -1/4" toe out setting in the rear suspension. However, using VI-grade, it was discovered that using -1/4" toe out in the front suspension and -1/16” toe out in the rear suspension would help yield the best time with that vehicle and suspension configuration specifically. Thus, the lap time simulation software developed quickly showed its benefits to Zips Racing.

This discovery could be the result of a few different ideas. For example, cars that run too much toe out in the rear suspension could have too much oversteer for the driver to be able to confidently produce a quick skidpad time. While an oversteer-biased car is preferred for Formula SAE driving conditions as opposed to an understeer-biased design, having too much toe-out in the rear suspension can cause an excessive amount of oversteer. However, a minimal amount of toe-out in the rear suspension can more easily help the car rotate in a constant radius corner.

In comparing the suspension points between 2019 and 2020, a few critical suspension kinematic changes were made to improve the cornering performance of the car. Namely, the vehicle's kinematic roll and pitch centers were overhauled with a different approach and philosophy to help the vehicle induce more oversteer and yield quicker lap times.

The kinematic roll center is the axle location about which the vehicle rolls, and it can have a significant contribution to the handling of a vehicle in cornering scenarios. To summarize, it is the principal location where the vehicle's weight transfer in cornering is centralized about. Geometrically, the kinematic roll center location of an axle is the intersection point of the two instantaneous centers generated by the inboard and outboard suspension points and the tire contact patches, as illustrated below.

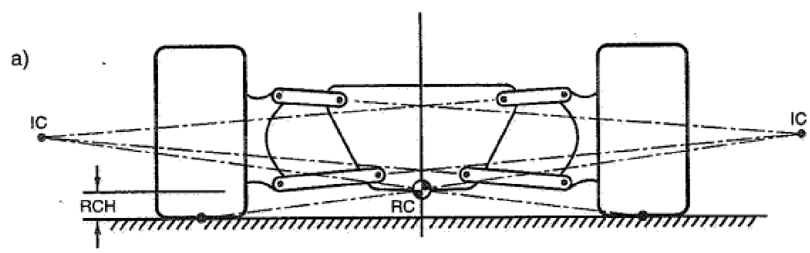

Figure 9: A front view illustration of the kinematic roll center location with regards to the instantaneous centers (IC), tire contact patches, and suspension point geometry (Milliken)

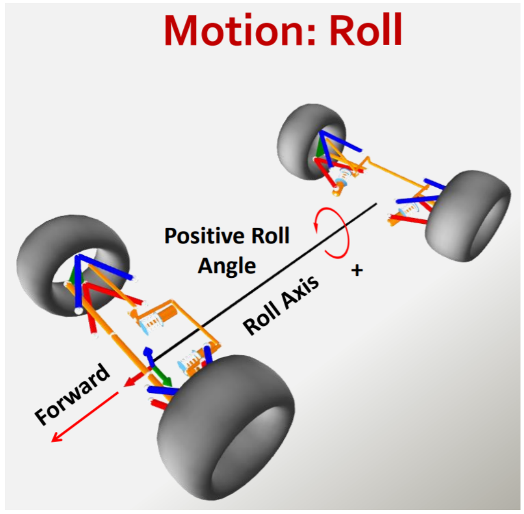

Figure 10: A generalized look at the roll axis and roll behavior of a vehicle in regards to dynamic driving scenarios (Optimum)

Specifically, the roll moment is the distance between the located kinematic roll center and the vehicle's center of gravity height. A larger distance between these points results in a larger roll moment and will cause the vehicle's tendency to experience heavy roll, generally considered "sluggish" in cornering scenarios. However, raising the roll center too high will cause undesirable "jacking forces" that can cause the vehicle to pick up an unloaded corner entirely in a cornering scenario. Therefore, determining the balance between these two instances is an important aspect to vehicle suspension design, and there is no single correct approach or result (Milliken).

It was found that one of the primary causes of ZR19's tendency for low-speed understeer was due to the large roll moment on the front suspension. The front kinematic roll center height was only 6.7 mm and the center of gravity height being about 228 mm for ZR19. Going into the 2020 design, the kinematic roll center height had been raised to approximately 32.1 mm with a center of gravity height being about the same. This would help decrease the roll moment of the vehicle and would serve as an interesting factor to consider during VI-grade lap time simulation runs.

The kinematic pitch center is the axis about which the vehicle rotates under acceleration and braking scenarios. Depending on the pitch center location, the front dampers and rear dampers could be traveling under different rates from each other. For instance, a more rearward pitch center under braking would cause the front of the car to dive considerably as opposed to the rear rebounding at a much less substantial rate.

Anti-dive is a method of controlling the front inboard suspension geometry in a way that limits pitch center migration and prevents the car from “diving” under braking. Anti-dive is generally used as a means to help control this pitch center migration and make it more “centralized” between the front and rear axles. Too much anti-dive, however, can cause the longitudinal weight transfer to be absorbed into the control arms more than the dampers in compression. This can result in structural control arm failures in the suspension system (Milliken). While ZR19 had 0% anti dive in the front suspension geometry, ZR20 took an ambitious leap towards centralizing the pitch center by making the anti-dive front suspension geometry have 29% anti-dive. This amount would theoretically help the suspension kinematics without transferring too much load into the control arms.

Similarly, anti-squat is a method of controlling the rear inboard suspension geometry in a way that limits pitch center migration and prevents the car from “squatting” in the rear under acceleration. Too much anti-squat can have a similar effect as too much anti-dive. However, too much anti-squat can cause the longitudinal loads to be transmitted into the control arms and potentially cause failure in the event of under-designed control arms (Milliken). Since the primary focus of ZR20’s suspension kinematics design was to address the issue of corner to mid-entry understeer, anti-squat was kept generally the same as ZR19’s with a change of 14% anti-dive in 2019 to 16% in the current car. Combined, these characteristics helped move pitch center migration from behind the rear axle to the center of the vehicle in 2019 to consistently migrating in between the front and rear axles with the current design.

Combined, all of these aforementioned suspension design characteristics helps a Formula SAE car gain performance both on the initial turn into a skidpad circle as well as speed throughout the circle. The following figures illustrate the pitch center migration for both ZR19 and ZR20:

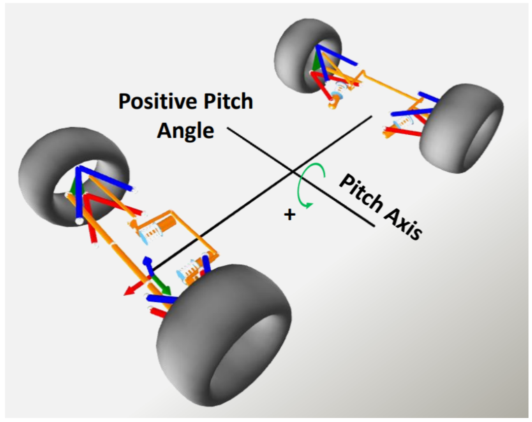

Figure 11: A generalized look at the pitch axis and pitch behavior of a vehicle in regards to dynamic driving scenarios.

Figure 12: ZR19's kinematic pitch center as seen in its most rearward position during a typical acceleration.

Figure 13: ZR19's kinematic pitch center in its center position; this can be assumed to be the pitch center during a steady state driving scenario.

Figure 14: ZR19's kinematic pitch center in its frontward-most position during a typical heavy braking scenario.

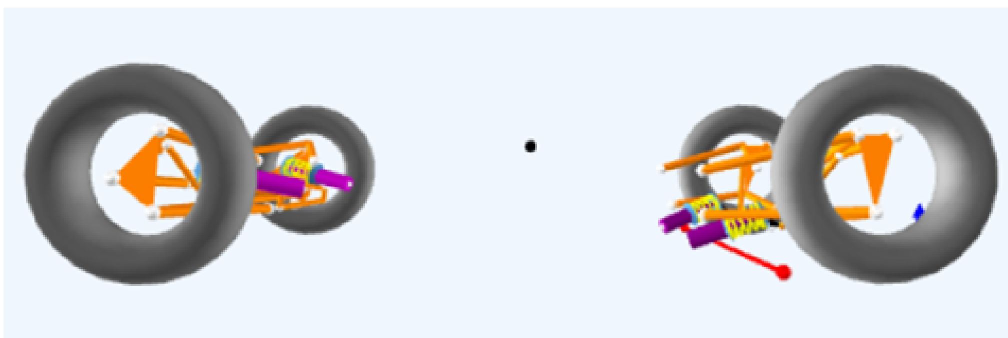

Figure 15: ZR20's kinematic pitch center in its most rearward position during a typical acceleration.

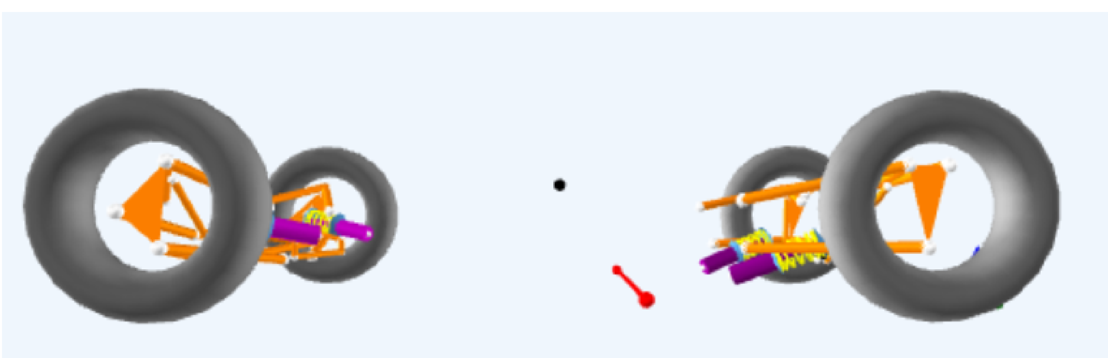

Figure 16: ZR20's kinematic pitch center in its center position; this can be assumed to be the pitch center during a steady state driving scenario.

Figure 17: ZR20's kinematic pitch center in its frontward-most position during a typical heavy braking scenario.

After importing the pre-designed ZR20 suspension points and running the same friction circle lap time study with all other variables kept constant, the lap time improved by nearly 0.3 seconds in a skidpad. For a short event and small time intervals between all the cars, this type of lap time improvement is substantial. The only changes made were the suspension kinematics as a result of the movement of suspension points for the new vehicle, as well as the expected change from a 13" wheel to a 10". Figure 18 below shows the corresponding VI-grade friction circle, and it is interesting to observe the differences between this friction circle and the one generated for ZR19 in Figure 7.

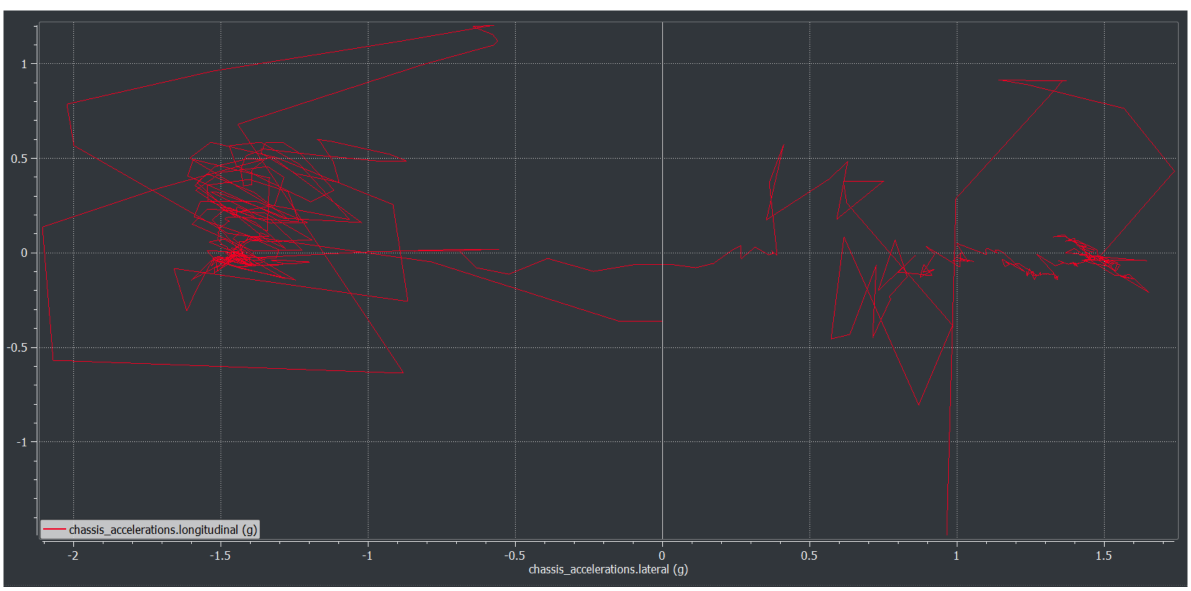

Figure 18: Friction Circle in VI-grade utilizing ZR20's suspension points on a skidpad run. The model was capable of running a 4.93 second skidpad lap time.

A few important conclusions can be drawn from the data graphs from the simulations done by the design team. The first is that ZR20's improved performance resulted in generated lateral g-forces frequently at or exceeding 1.5 g's. This ultimately meant greater lateral acceleration and increased cornering speeds. The second conclusion is that the increased lateral g-forces were accompanied with increased longitudinal forces. This resulted in the g-forces frequently being more than 0.5 longitudinal g's.

The second is that the increased lateral and longitudinal g-forces achieved could be largely attributed to the improved suspension geometry for 2020. While the engine package simulated had remained similar in performance to the actual Yamaha WR450 engine housed in ZR19, including the gear ratios of the transmission, the suspension points had changed drastically. The kinematic pitch center had become much more centralized as opposed to the suspension points used in 2019, and the roll centers had been raised higher towards the vehicle's center of gravity since then as well.

All of the aforementioned information is neatly summarized in the table below:

	ZR19	ZR20
Kinematic Roll Center Height (Front) (mm)	6.7	32.1
Kinematic Roll Center Height (Rear) (mm)	26.1	59.0
Kinematic Pitch Center Location (Acceleration) (mm)	-337.0 (behind rear axle)	556.7 (in front of rear axle)
Kinematic Pitch Center Location (Braking) (mm)	900.9 (in between front and rear axles)	1304.3 (behind front axle)
Anti-Dive % (Front)	0	29
Anti-Squat % (Rear)	14	16
Average Peak Lateral G's in Skidpad on VI-grade (g's)	1.4	1.5
Average Peak Lateral G's in Real World Skidpad (g's)	1.25	TBD (Vehicle not driving yet as of 4/25/21)
VI-grade Skidpad Single Lap Time (sec)	5.21	4.93
Real World Skidpad Single Lap Time (sec)	5.36	TBD (Vehicle not driving yet as of 4/25/21)

Table 1: A summary of the data comparing ZR19 and ZR20 in a skidpad environment.

From this information, a few valuable conclusions could be drawn regarding the suspension design of ZR20 and possible areas of further improvement as seen between 2019 and 2020. First, the centralization of the kinematic pitch center within the wheelbase was a positive step towards a more predictable and responsive race car for the driver. The ability for the dampers to compress and rebound in a way that would not upset the handling of the vehicle in a cornering scenario is a valuable step towards designing a quicker race car.

Second, raising the kinematic roll centers would serve as a beneficial way for the vehicle to experience a more desirable amount of roll in cornering scenarios and prevent a “sluggish” feel that would ultimately cause the vehicle to be inclined to understeer and lose lap time. This avoidance of a sluggish feel for the vehicle would thus allow the driver to be able to generate greater g-forces in a skidpad event for instance.

While the Zips Racing Electric Team might not have the data acquisition that the Zips Racing Combustion Team has, the team must adhere to the same set of rules and have correct design justifications. A quick glance at the ZRE-20 car in pitch showed the design team that the pitch center is not within the wheelbase as mentioned above. This leads to an unstable and unpredictable car due to the pitch center being so far away from the center of the car.

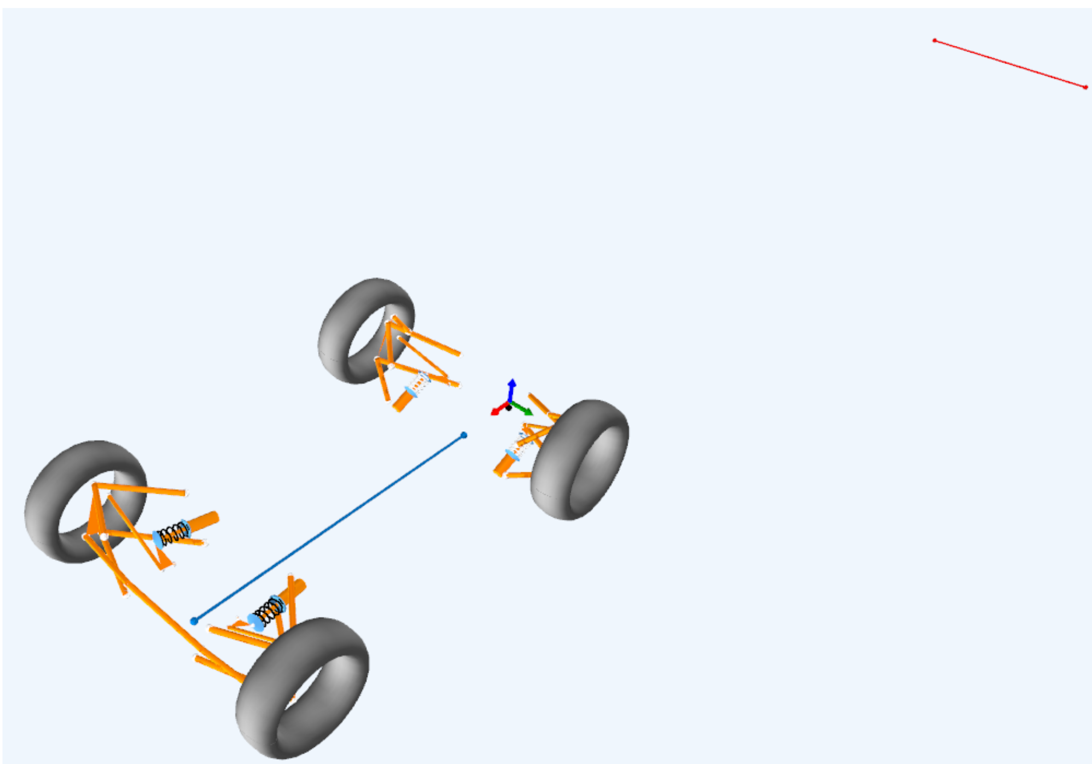

Figure 19: Pitch Center of ZRE-20

The roll center of the car also changes quite a bit under roll. The roll is measured from -2 degrees to 2 degrees. Under these 4 degrees of pure rolling, the front and rear roll centers both move over 480 mm in the y-directions. This is undesirable because this promotes bump steer which is change in toe due to up and down motion.

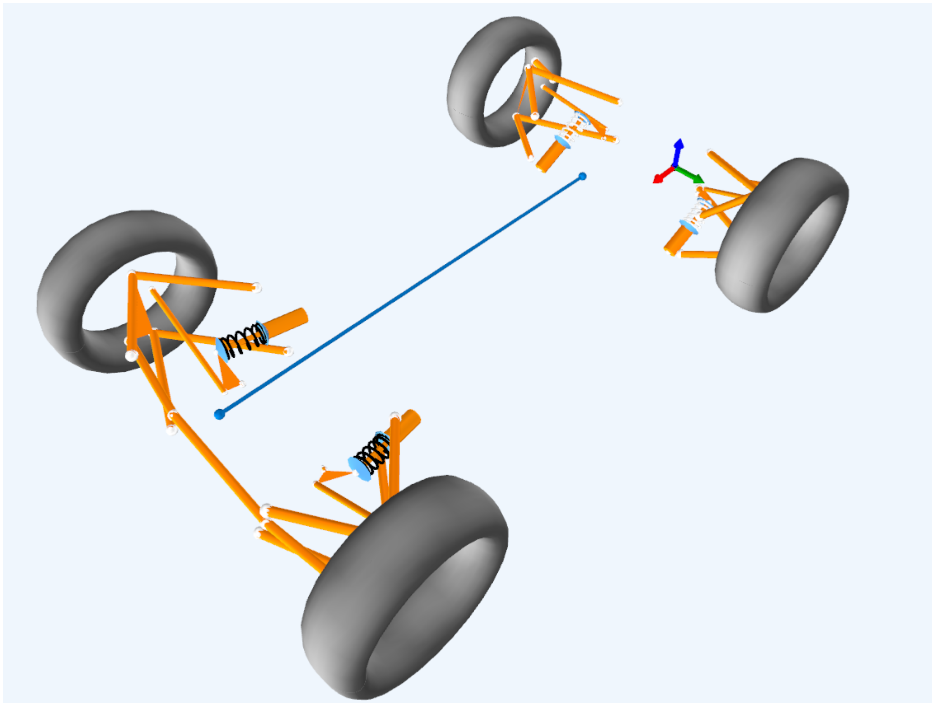

Figure 20: Roll Center of ZRE-20 at -2 Degrees of Roll

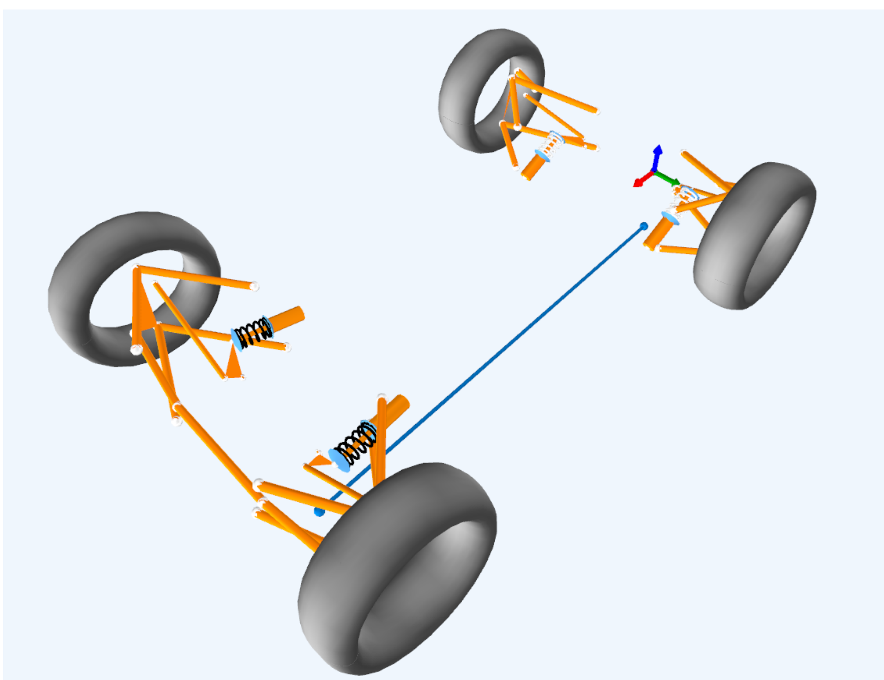

Figure 21: Roll Center of ZRE-20 at 2 Degrees of Roll

One can graph the front and rear toe angles in OptimumKinematics to verify that there will be a large amount of bump steer under roll. The following graph shows us that under 4 degrees of body roll, the front toe changes more than 2 degrees and the rear toe changes by 1.6 degrees. This makes the car unstable and very difficult to drive due to the extreme amount of toe change.

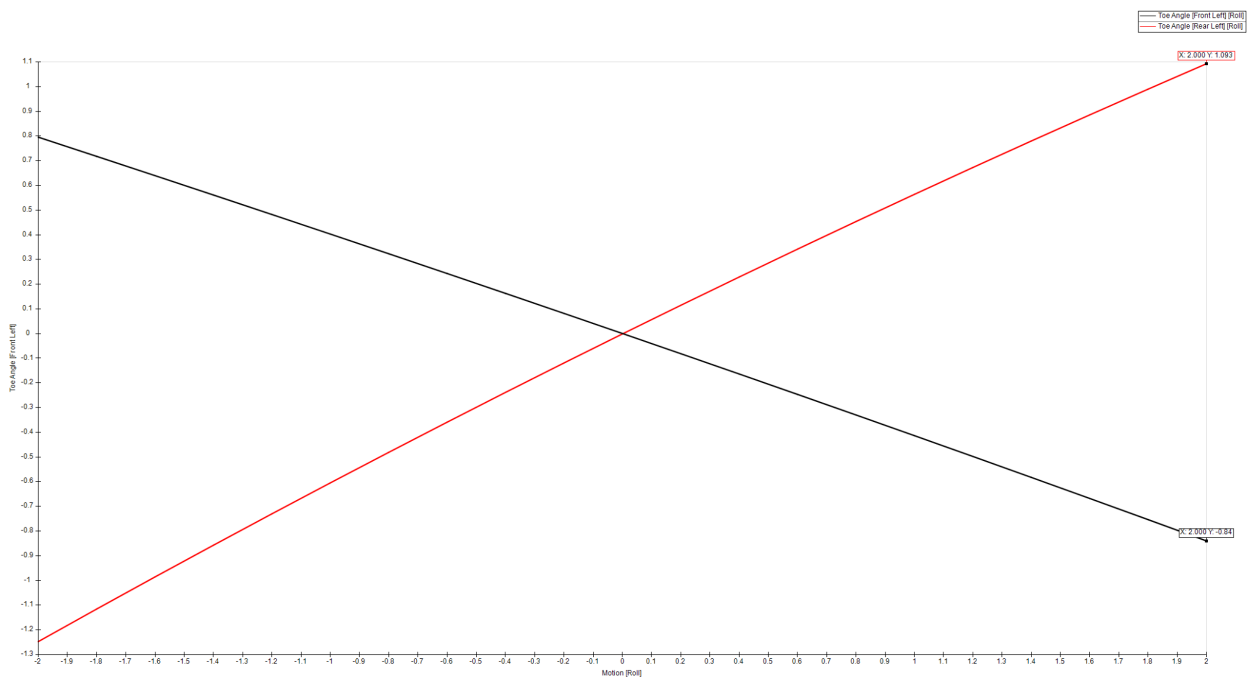

Figure 22: Toe Angle of ZRE-20 under Roll

Another issue that arose is that, under maximum roll, the damper will hit the pullrod. This is undesirable because it will damage parts and not allow the team to utilize the suspension fully as designed. It will also be uncomfortable for the driver to be feeling smacks in the rear of the car which are created due to the hitting of the pullrod.

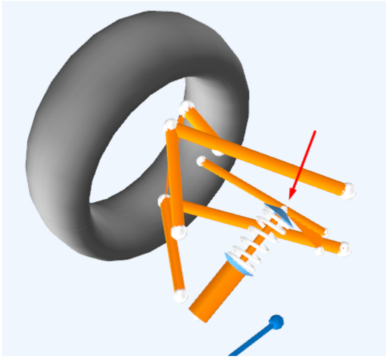

Figure 23: Damper hitting Pull-Rod

The new suspension system was developed for the 2022 FSAE season for Zips Racing Electric due to the fact that there are many issues with the 2020 suspension. This iteration has a much more balanced pitch center that will remain between the wheelbase.

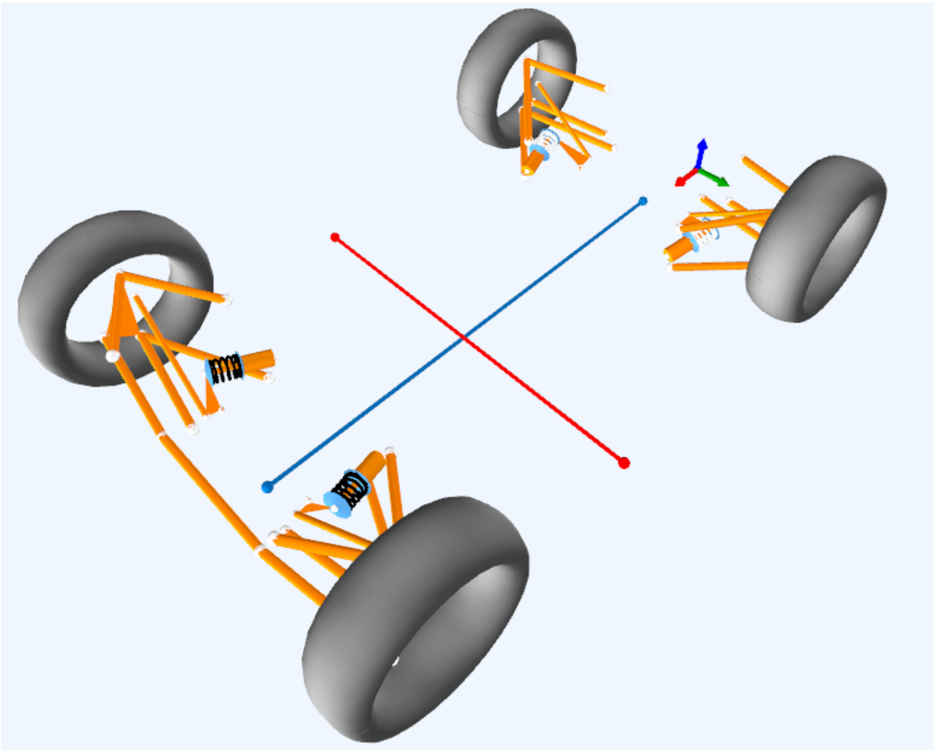

Figure 24: ZRE-21 Suspension Model

The roll center heights will also change much less under roll even in 4 degrees of roll. The camber angles under roll will also be mostly negative even in the most extreme situations.

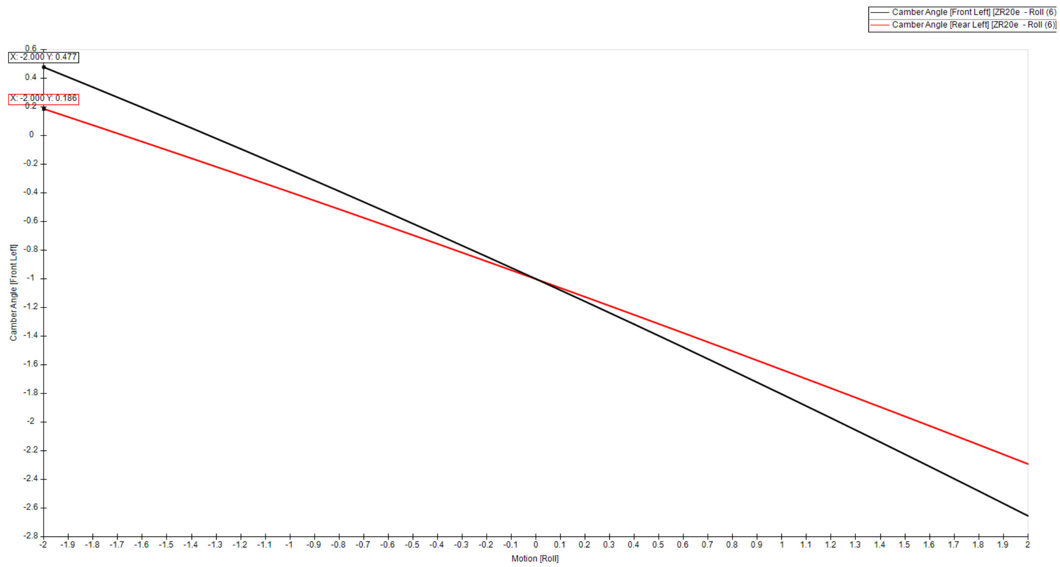

Figure 25: Camber Angle of ZRE-21 under Roll

The toe angles will also change much less in roll. Reduced from 2 degrees in the front to 0.18 degrees and from 1.6 degrees to 0.16 degrees in the rear

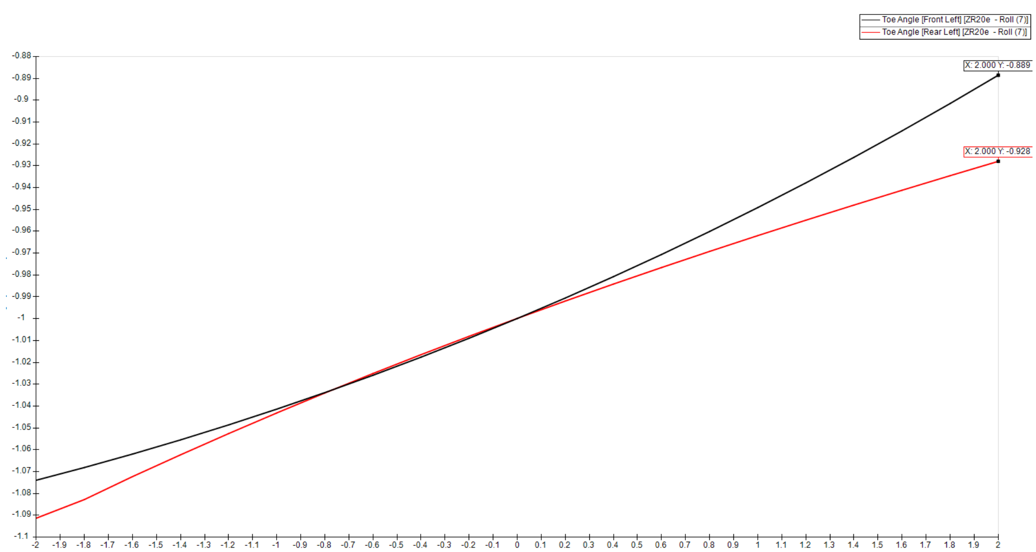

Figure 26: Toe Angle of ZRE-21 under Roll

Lastly, the amount of body roll has been massively reduced as seen in the two pictures below. The amount of body roll in the front is 41.8 mm and 134.4 mm in the rear. This is compared to over 480 mm of travel in both the front and rear in the 2020 car.

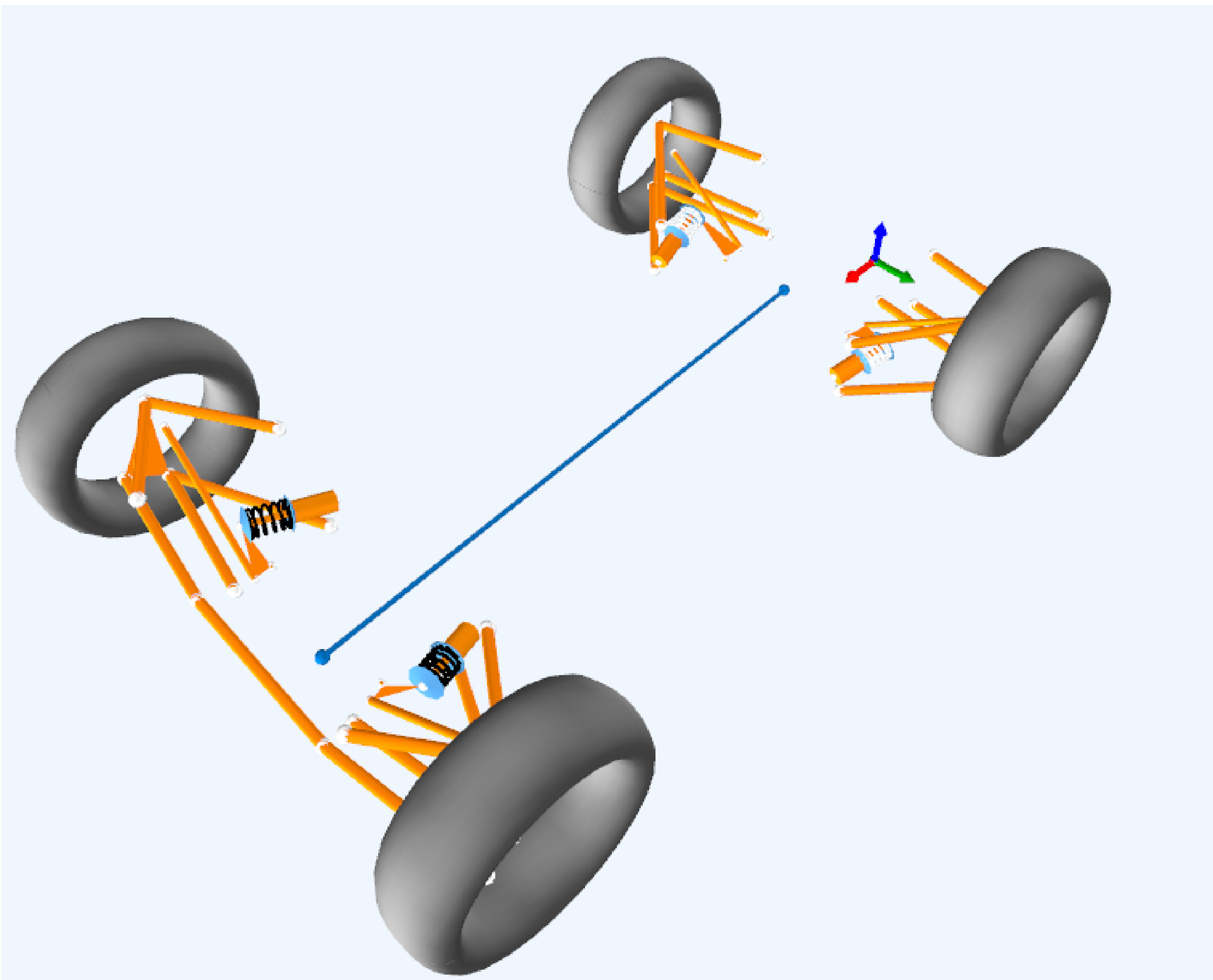

Figure 27: Roll Center of ZRE-21 at -2 Degrees of Roll

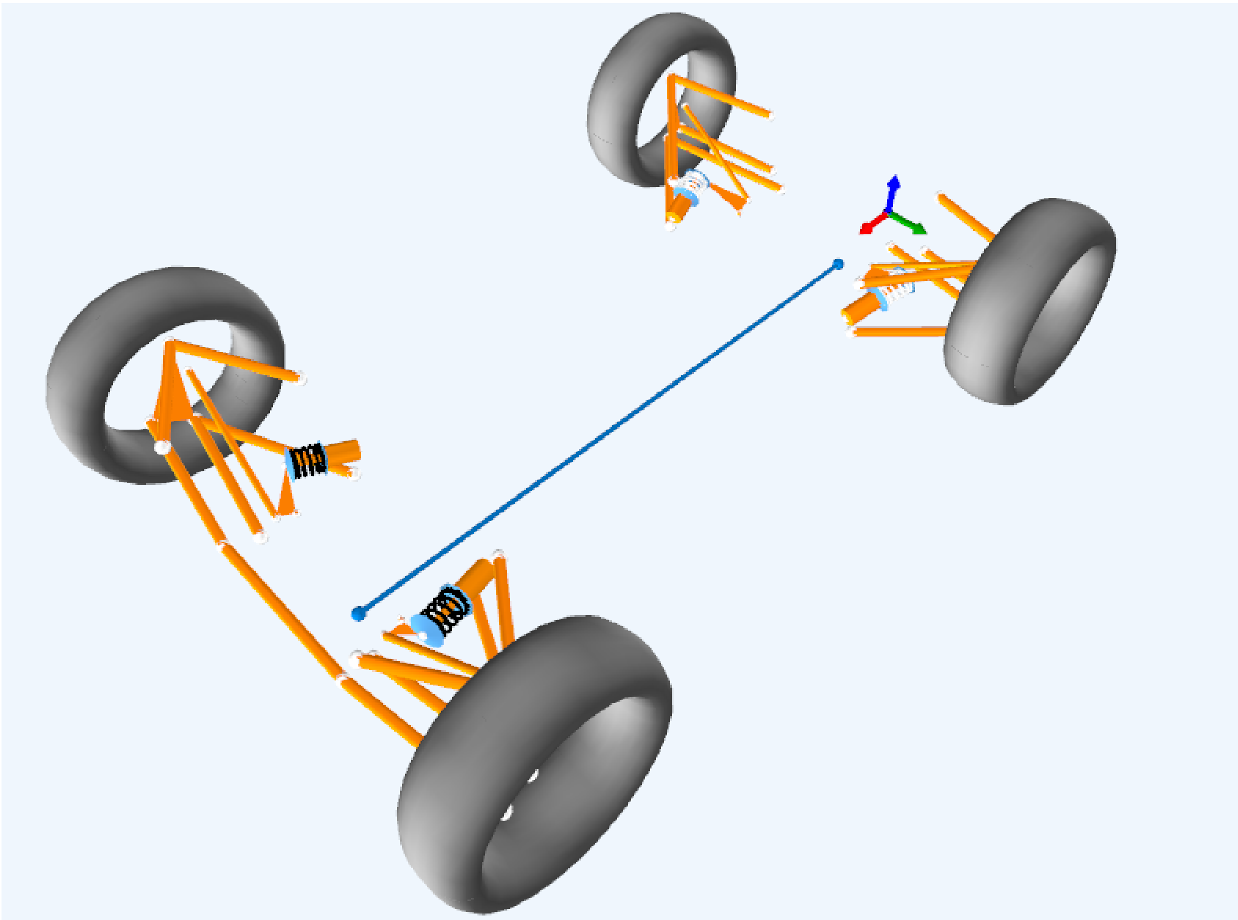

Figure 28: Roll Center of ZRE-21 at 2 Degrees of Roll

Through the usage of the simulation software created in this senior design project and the data collected during simulations, the design team has been able to implement the knowledge of vehicle dynamics and mechanical engineering in order to better develop the current iterations of ZR20 and ZRE-20. Without the simulation software and data, Zips Racing would be encountering some of the same issues as the ZR19 and ZRE-19 experienced.

Engineering Principles and Analysis

In the past, an intimate knowledge of vehicle dynamics was required to gather performance data on the vehicles prior to physical testing. This knowledge, without the use of additional software, did not allow the teams the ability to perform multiple iterations of calculations and was only based on a simple steady-state, mostly two-dimensional, model of the car. In order to validate the success of our VI-grade models, the senior design team performed these analyses utilizing vehicle dynamics principles. With this proven baseline, the design team was able to further explore more complex tests within the simulation software. These baseline or benchmark calculations began with simple traction limited load transfer calculations such as finding the normalized front and rear axle loads as well as determining the maximum acceleration of the vehicles. After this, the design team was able to also calculate the stopping distance with aerodynamic drag and then determine the average deceleration.

As shown in the figure below, one can see the forces acting upon this two (2) dimensional SAE conventional vehicle model.

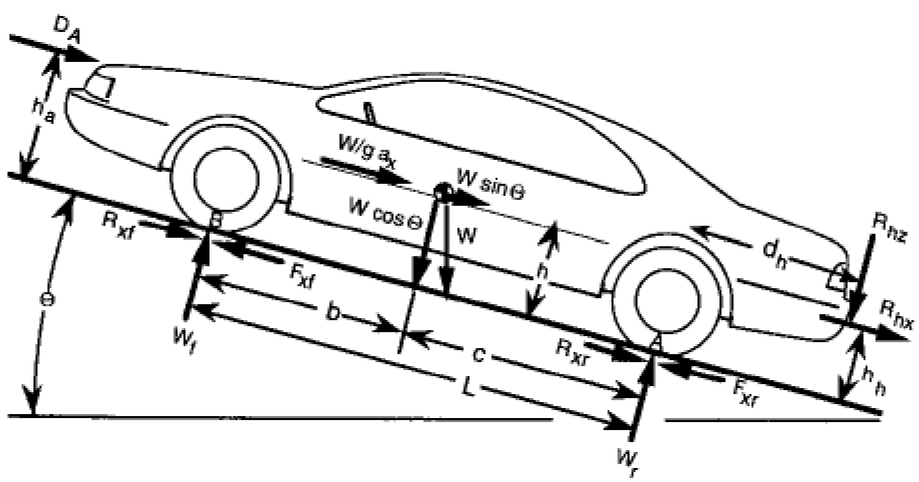

Figure 29: Arbitrary forces acting on a Vehicle (Gillespie 11)

By performing a sum of forces in the X and Z directions and taking a sum of moments about the center of gravity, we are able to develop our equations of motion to perform our calculations. We can also assume that all of our rear hitch and aero forces are negligible.

$$\Sigma F_x: F_{xf} + F_{xr} - mgsin(\theta) = ma_x \ldots\ldots\ldots\ldots\ldots..(1)$$

$$\Sigma F_y: - F_{zf} - F_{zr} + mgcos(\theta) = 0 \ldots\ldots\ldots\ldots..\ldots(2)$$

$$\Sigma M_{CG}: F_{zf}b - F_{zr}c + (F_{xf} + F_{xr})h = 0 \ldots\ldots..\ldots(3)$$

All respective variables can be defined in the referenced text by Gillespie. Due to the cars being rear wheel drive, we can assume the front forces in the x-direction to be 0. We can also assume that the inclination angle will be 0°. Another simplification we can make is that because the coefficient of friction (μ) is the ratio of the rear wheel tire forces in the x and z direction, that $F_{xr} = \mu F_{zr}$. With this in mind, we can simplify the above equations to be as listed below.

$$\Sigma F_x: \mu F_{zr} = ma_x \ldots\ldots\ldots\ldots\ldots...........(4)$$

$$\Sigma F_y: F_{zf} - F_{zr} + mg = 0 \ldots\ldots.....\ldots..(5)$$

$$\Sigma M_{CG}: F_{zf}b - F_{zr}c + \mu F_{zr}h = 0 \ldots...(6)$$

By rearranging and solving for a_x, F_{zf}, and F_{zr} we obtain the following normalized (g's) equations for our RWD model.

$$\frac{a_x}{g} = \mu(\frac{b}{l-\mu h}) \text{ for maximum acceleration}\ldots\ldots(7)$$

$$\frac{F_{zf}}{mg} = (\frac{c-\mu h}{l-\mu h}) \text{for front axle vertical load}\ldots\ldots.(8)$$

$$\frac{F_{zr}}{mg} = \frac{b}{l-\mu h} \text{for rear axle vertical load}\ldots\ldots...\ldots(9)$$

From the formula above, we are now able to perform our baseline hand calculations. The table shown below depicts and compares the hand calculations to the simulation results during a straight line acceleration event in order to determine the maximum acceleration as well as the load transfer from the front axle to the rear. The coefficient of friction for the road and the tire model is assumed to be 1.0 and 1.14, respectively. It is important to note that these calculations are based on a very simple linear model, and this is a good reason why we need to utilize a software such as VI-grade.

Vehicle Data	
Mu	1.14
b (mm)	1100.8
c (mm)	428.3
l (mm)	1529.1
h (mm)	244.0
mass (kg)	272.0
gravity (m/s^2)	9.81

Table 2: Vehicle Data

Static Forces		
Units	g's	N
Fzr	1920.95	0.72
Fzf	747.37	0.28

Table 3: Static Force Calculations

Hand Calc			VI-Grade		
Units	g's	N	Unit's	g's	N
ax	1.00	2676.84	ax	1.18	3148.62
Fzr	0.88	2348.10	Fzr	0.91	2419.20
Fzf	0.12	320.22	Fzf	0.10	273.60

Table 4: Hand Calculations Vs. VI-grade Results

As stated above, the reason we performed these calculations was to gather a baseline for our VI-grade model and to see how they compare against each other. Specifically speaking, one of the largest differences found was the contribution of aerodynamics within the VI-grade model. Shown in the “Results” table above, we can see that the VI-grade model and simulation ended up with an 18% increase in lateral acceleration and the vertical force on the rear axle. Alternatively, we can see a 15% decrease in the front axle vertical force as a result of the increased weight transfer to the rear. One could infer that the difference in these results could be a contribution of the models aerodynamics data as well as the active tire data given. Overall, the senior design team believes that the friction coefficient that was used in the hand calculations was the biggest limiting factor in comparing to the VI-grade results. This is because the program uses a coefficient of friction that is constantly changing based on multiple factors such as the vertical forces at any given time. Based on these hand calculations, we are able to be confident that our VI-grade model is correct and that it also yields better results due to the availability of more complex and interactive data during more detailed events than the straight line acceleration that was performed. We can now utilize some of the softwares more complex events and quickly perform multiple iterations of them. One of the main benefits of this is the ability to perform dynamic calculations and no longer have to rely on the principle steady state equations that we normally have. It is important to note that many other steady state calculations can be performed to verify and better understand the differences between VI-grade and the hand calculations.

VI-grade Virtual Formula Competition

During the design year, the design team was made aware of a competition sponsored by VI-grade. This competition, occurring over a couple months, pitted formula student teams from around the world against each other. Based on the rules and regulations of the Formula SAE and Formula Student competitions, this competition provided the design team and Zips Racing the ability to compete and compare the 2020-2021 race cars against other formula student teams. Due to COVID-19 restrictions around the country and the world, Zips Racing was fearful the team would be unable to compete in-person against other teams. The VI-grade Virtual Formula provided the team a perfect solution to test the vehicle against other competitors in a socially distanced fashion. Additionally, VI-grade provided all competing teams with two software packages and licenses. Due to this, the design team was able to ascertain an additional four licenses for the duration of the competition for free. This ultimately allowed the senior design team and Zips Racing to conserve budget's in this difficult monetary year. These additional licenses along with the licenses from the beginning of the school year allowed for each member of the team to have the VI-grade software package and a license on their personal computer. This further improved the design team's ability to work on this project while maintaining social distancing. With these many benefits to competing, the senior design team with support from Zips Racing entered into both the electric and combustion classifications for VI-grade Virtual Formula.

The Rules and Regulations of the Virtual Competitions Impacts

For this competition, most of the rules and regulations were based on the rules and regulations of Formula SAE and Formula Student competitions. During in-person Formula Student competitions, there are only four dynamic events which are Acceleration, Skidpad, Autocross, and Endurance. Additionally, in-person Formula Student competitions test efficiency by measuring fuel consumption or energy usage. Similarly, the Virtual Formula competition consisted of these same events of Acceleration, Skidpad, Autocross, Endurance, and Efficiency. However, these events were weighted differently with Endurance being the most important event. Ultimately, The goal for this competition was to design the ZR20 and ZRE-20 cars in VI-grade and then optimize the setup of the vehicle. In order for the car to be able to compete, the race cars must be set up within certain legal parameters. These legal parameters, divided into the subsystems of Body, Brakes, Front Suspension, Rear Suspension, Steering, Front Wheels, Rear Wheels, and Powertrain, provided the design team with endless possibilities of specific car setups. Unlike in Formula Student competitions, this competition forced all teams to choose between five different tire files and five different aerodynamic body files. Furthermore, Virtual Formula competition varies from in-person Formula Student competitions due to the usage of a computer for the driver. Due to the computer replacing a human driver, the Virtual Formula competition requires each team to submit a pathing file unique to each vehicle for the Autocross and Endurance events. Furthermore, the aggressiveness of the computer simulated driver can also be altered for the Autocross, Endurance, and Skidpad events. With these rules and regulations, the design team was given a template in order to maximize the potential of the ZR20 and ZRE-20 cars in the competition.

Optimization

After building the ZR20 and ZRE-20 cars in VI-grade for the competition, the design team utilized statistical analysis in order to optimize the performance of the cars. After testing the current, real-world setup of the cars in the simulation software, the team began altering different parameters of the cars to determine their effects on the track performance. Due to the endless possibilities of potential setups, the design team needed to implement a mathematical approach in order to optimize the vehicles. Fortunately, VI-grade allows for many opportunities for optimization. VI-grade allows for the opportunity to run several setups at the same time in order to maximize efficiency in their Investigation Mode. By running many investigations and tracking the changes, the design team was able to record these results and the effects on the cars in spreadsheets. The limiting factor for these investigations and optimization of the car was the computing power of the computer running the simulations. Many of these simulations and investigations would take hours or potentially days to complete and generate results. Due to this and the time constraints of the competition, the design team could only spend a certain amount of time on each subsystem. However, the team formulated a systematic approach in order to maximize computational efficiency and time for the competition by putting a large amount of effort towards maximizing the cars' performances in the endurance event.

Identifier	properties.final vi grade zr20 files. zr20_body_final.body. ZR20_body_final.aero_forces. frontDownForceLocation.z	properties.zr20front.zr20front. front_suspension.ZR20Front. suspensionSetupData. leftRideHeightSensor.rideHeight	properties.zr20front.zr20front. front_suspension.ZR20Front. suspensionSetupData. rightRideHeightSensor.rideHeight	properties.final vi grade zr20 files. zr20_body_final.body. ZR20_body_final.aero_forces. rearDownForceLocation.z	properties.zr20rear.zr20rear. rear_suspension.ZR20Rear. suspensionSetupData. centerRideHeightSensor.rideHeight	Success	Laptime
v0001	25.0000	25.0000	25.0000	25.0000	25.0000	✗	N/A
v0002	25.0000	25.0000	25.0000	50.0000	50.0000	⚠	64.6600
v0003	25.0000	25.0000	25.0000	75.0000	75.0000	⚠	65.8100
v0004	25.0000	25.0000	25.0000	100.000	100.000	⚠	66.4800
v0005	50.0000	50.0000	50.0000	25.0000	25.0000	✗	N/A
v0006	50.0000	50.0000	50.0000	50.0000	50.0000	⚠	64.6600
v0007	50.0000	50.0000	50.0000	75.0000	75.0000	⚠	65.8100
v0008	50.0000	50.0000	50.0000	100.000	100.000	⚠	66.4800
v0009	75.0000	75.0000	75.0000	25.0000	25.0000	✗	N/A
v0010	75.0000	75.0000	75.0000	50.0000	50.0000	⚠	64.6600
v0011	75.0000	75.0000	75.0000	75.0000	75.0000	⚠	65.8100
v0012	75.0000	75.0000	75.0000	100.000	100.000	⚠	66.4800
v0013	100.000	100.000	100.000	25.0000	25.0000	✗	N/A
v0014	100.000	100.000	100.000	50.0000	50.0000	⚠	64.6600
v0015	100.000	100.000	100.000	75.0000	75.0000	⚠	65.8100
v0016	100.000	100.000	100.000	100.000	100.000	⚠	66.4800

Figure 30: Investigation of Down Force locations and Ride Heights

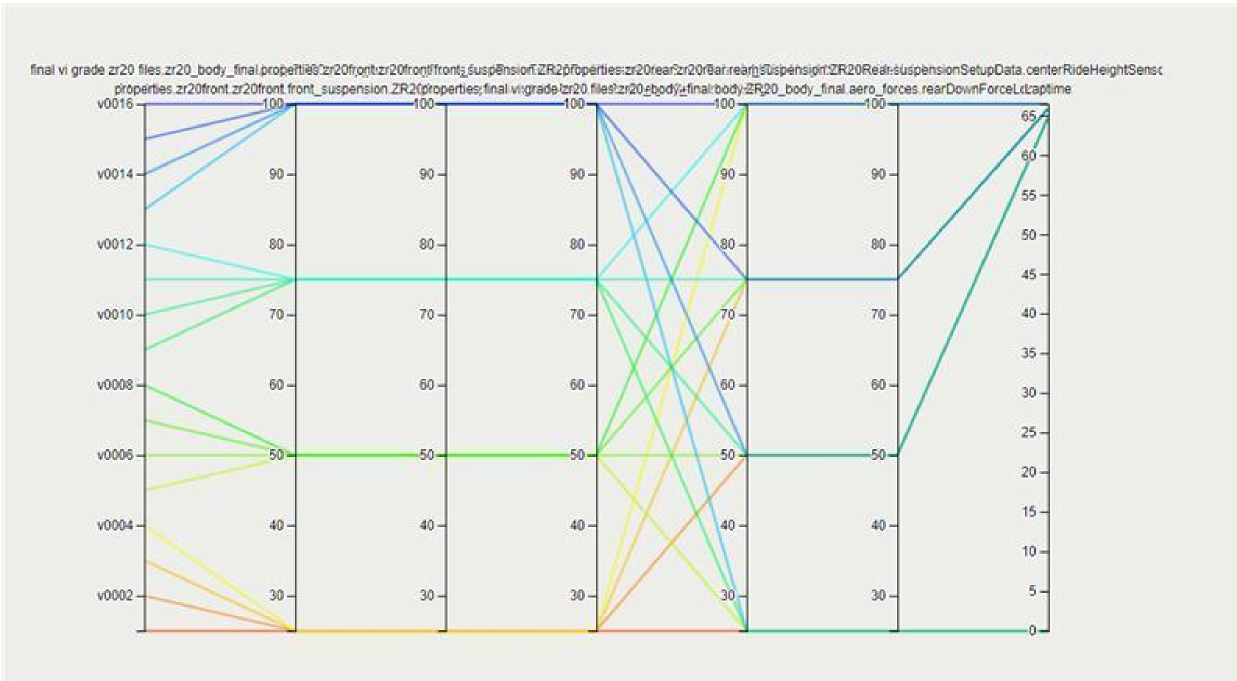

Figure 31: Graph of Investigation of Down Force locations and Ride Heights

13	Change	Laptime	Power Usage (kWh)	Notes
Baseline		60.652		
1	Mass to 180kg	59.7	0.373	Can't have 180kg
2	Suspension/Brakes	59.62	Doesn"t show for some reason	Can't have 180kg
3	Lat PF back to 1.0, changed hub motor transmission ratios to 13 from 15	59.63	Doesn"t show for some reason	Can't have 180kg
4	Aero Package B	58.95		Can't have 180kg
5	**Base Setup ZR20**	60.51		**Base**
6	17.5 Gear Ratio	60.79		
7	15 Gear Ratio	61.85	0.385	
8	18 Ratio	61.64	0.404	
9	17 Ratio	61.66	0.40137	
10	Front Tires B, Rear Tires C, Aero B, 17 Ratio	59.63	0.402	
11	720 CG Long 15 GR	60.52		
12		59.83		
13	17.5 Ratio	59.52	0.399	
14	17.5 front, 17 rear	59.63	0.399	
15	17 front, 17.5 rear	59.52	0.407	
16	16 front, 18 rear	59.47	0.403	
17	14 front, 18 rear BC	59.44	0.405	
18	Front E, Rear E 16,18	59.14	0.3827	
19	-4 camber front	59.64		
20	16 front, 18 rear	59.21	0.3824	
21	16, 18 E C	59.28	0.378	
22	14 18 BB	59.31	0.398	
23	0 rear camber	59.54	0.418	
24	1.1 Performance Factor	58.52	0.44	
25	Camber and toe changes	57.904	0.4497	
26	Added smoothed path	57.8	0.49	

Figure 32: Spreadsheet for Optimization of ZRE-20

While optimizing the setup of the vehicle in the competition, the design team needed to also focus on optimizing the performance of the computer simulated driver. In the competition, each team had the ability to develop their own pathing file for the car to follow around the endurance and autocross track. The development of the best pathing file was important to the competition because it was necessary to find the best way around the track with the design team's car. Due to the varying setups of every competitor's car, each car handles differently around each sector of the track. Minimizing understeer or oversteer in each corner, maintaining speed in fast corners, and the usage of the curbs were all things the design team needed to consider in the design of the pathing file of the competition. By changing certain parameters of the pathing file, the design team was able to observe the changes to the altercation. These observations were then noted in spreadsheets and further optimized. To observe these changes, the VI-Animator software was used. This software provides an animated version of the vehicle circumnavigating the track, and allows the team to make all necessary observations. Along with making the pathing file, each team had the ability to control the aggressiveness of the computer simulated driver. The factors that can be changed are called the Longitudinal Acceleration Performance Factor, the Longitudinal Brake Performance Factor, and the Lateral Performance Factor. Each of these performance factors can be changed and optimized for the ten different sectors for the track. Occasionally, the performance factors set will lead to the car spinning or running off track. When this occurs, an iteration will take place. These iterations will alter the performance factors by a correction step. In most cases, this correction step is 0.05. By increasing the number of iterations and decreasing the correction step, the most optimal performance factors are achieved for the computer simulation. However, large numbers of iterations leads to lengthy simulation times due to limitations by the computing power of the computer running the events. Thus, the design team sought to find the best starting values in order to increase efficiency and find the best performance on track. by the computer simulated driver.

```
Final scaling values:

          Segment          Acc     Dec     Lat    Iterations
   0 [   0.00-  94.50]:  1.000   0.951   0.999        1
   1 [  94.50- 248.23]:  0.950   0.950   1.000        2
   2 [ 248.23- 329.13]:  0.950   0.950   1.000        2
   3 [ 329.13- 403.16]:  1.000   1.000   1.000        0
   4 [ 403.16- 500.86]:  0.950   0.918   0.932        4
   5 [ 500.86- 581.60]:  0.950   0.950   1.000        2
   6 [ 581.60- 707.49]:  1.000   0.950   1.000        1
   7 [ 707.49- 830.38]:  1.000   1.000   1.000        0
   8 [ 830.38- 893.58]:  0.950   0.950   1.000        2
   9 [ 893.58- 961.18]:  0.950   0.950   1.000        2
Done
```

Figure 33: Performance Factors Table

Findings from Virtual Formula

Following this competition, the design team learned a great amount that was carried over to the design project. Firstly, the Virtual Formula placed heavy emphasis on optimizing the cars. From the extensive optimization efforts and analysis, the design team has gathered great data to give to Zips Racing for the future iterations of the car. By finding these improvements through the competition, Zips Racing has learned what subsystems need the most attention and what impacts certain changes on the car will have on the performance of the vehicles. Before this competition, the focus of the design project was validation of the ZR20 and ZRE-20 race cars. The benefit of this competition is that it showed where the cars can be improved for future iterations and provided the design team with more licenses for all team members to become heavily involved with the design process.

Standards

As with any work within the field of engineering, standards and engineering codes have provided the backbone for this senior design project. To begin, Zips Racing competes as a Formula SAE race team through The University of Akron. Formula SAE is a program of the Society of Automotive Engineers International. As for all competitors in Formula SAE events, Zips Racing must follow strict rules and regulations in order to compete and must meet all safety standards as set forth by SAE International. Additionally, Zips Racing must follow all codes and standards put forth by SAE International in the designing and building of the races cars. While the number of standards may seem numerous, it is imperative that all engineers follow these standards in order to create a safe and functional design.

In motorsport, safety has been and continues to be the number one priority. Over the many years of motorsports, many have tragically lost their lives in the enjoyment and glory of this sport. These many events have shaped the future in creating and providing safer automobiles in order to race. In Formula SAE and for Zips Racing, the creation of safe race cars by following the rules, regulations, and standards has been and continues to be the most important task to accomplish every year. In this senior design project, the senior design team found it beyond important to follow the standards as set forth by Formula SAE and SAE International. The senior design team had to build a vehicle simulation software incorporating only parts that met the standards of SAE International and Formula SAE. This senior design project has not only been able to shape the current race cars for Zips Racing but also the future iterations of the race cars. Due to this, the design team found it a great burden to provide the most safe and accurate data due to future students expanding upon our data and knowledge to build future racing cars. Although the members of the design team will be graduating and no longer be involved with Zips Racing, the members desire to know that the future race cars designed and built by Zips Racing continue to be safe vehicles in order to enjoy the greatness of motorsport.

Costs

During the entirety of the design project, the senior design team placed a great emphasis on maintaining low monetary constraints on Zips Racing. Due to very tight budgetary constraints, the design team began the project seeking to minimize costs at all points. For the entire project, the senior design team and Zips Racing spent no money for this project.. This was due to the ability to ascertain the VI-grade software and licenses for free. To begin the year, VI-grade were incredibly generous in sponsoring Zips Racing. By sponsoring the team, the design team were able to attain two licenses and software in exchange for the name of VI-grade on the race cars. These licenses, valued at €5,100 each, were initially planned to be sufficient for the entirety of the school year. As mentioned earlier, the design team became aware of the VI-grade sponsored Virtual Formula. By agreeing to compete in this competition in both the electric and combustion classifications, the design team was able to attain four more softwares and licenses. There were no costs associated with entering the competition, so the four additional licenses were free. The only limitation of these licenses was that the licenses were only for three months. Again, each license and software package is valued at €5,100 each, so the total potential cost for this project would be €30,6000 or $36,988. However, the design team and Zips Racing were able to get this all for no costs through sponsorship and participation and performance in the Virtual Formula Competition.

In the real world, a professional racing outfit would have mechanical engineers specifically trained to run their own simulation software. These engineers would have varying pay depending on their years of service and knowledge of the programs. To simplify things, an entry level race engineer with a background in mechanical engineering would likely have a starting salary between $42,000 and $50,000 from a professional race team (Ferguson). With the amount of time the senior design team spent on the project, this would equate to approximately two full-time, entry level race engineers. Thus, the cost of labor for this project would be estimated to cost somewhere between $84,000 and $100,000. Through the fruits of the design team's labor, Zips Racing have been able to reap the financial benefits from this senior design project.

Conclusion

The school year of 2020-2021 has been a difficult year for Zips Racing and for all engineering students. At the beginning of the year, the senior design team was tasked with improving upon Zips Racing while striving to maintain social distancing and mitigating all costs. To do this, lap time simulation software was developed utilizing the ZR20 and ZRE-20 race cars. By expanding upon the design team's knowledge of mechanical engineering and vehicle dynamics, the race cars were able to be built and optimized in the software of VI-grade. Furthermore, the creation of simulations has allowed the design team to validate the current and previous iterations of the race cars and to begin collecting vital information and data for the future.

The Future Aspects for Zips Racing

For the foreseeable future of Zips Racing, computer generated simulations will be an integral part for the race team in order to analyze and verify future designs. Simulations will allow for in-depth testing and analysis of pre-made parts before approving them for manufacturing. However, there are several key steps Zips Racing should undergo following the return to normalcy after COVID-19. To begin, Zips Racing should verify the simulation analysis and data with live, in-person testing. Upon the completion of ZR20 and ZRE-20 vehicles, testing data can be compared to the simulation data to ensure accuracy. Following this, the team can set about improving the current iteration of the cars through setup changes tested and trialed on the simulation software created. By altering different parameters on the simulations, Zips Racing can determine the best setup to be run at each event for each competition. Lastly, Zips Racing should take the data that the design team has culminated and utilize it in designing the future race cars.

Another major aspect of the future of Zips Racing will be the implementation of driving simulators to allow for training of future drivers. This will allow drivers to better understand the dynamics and handling capabilities of the new vehicle before work has even begun to build the vehicle. This will allow Zips Racing to be much more efficient at racing events as drivers will have months of training both before the vehicle has been built and after it is running before competition.

Driving Simulation Rig

One aspect of this senior design project that should be implemented and expanded upon is the building and utilization of a computer driving simulation rig. While the design team was initially hoping to build such a simulator, the COVID-19 pandemic and monetary constraints prevented the senior design team and Zips Racing from building such a simulator. VI-grade and the simulation built by the design team, however, allows for a driver to virtually drive the race cars. This alone has many unique benefits that could help Zips Racing and The University of Akron. To begin, the computer driving simulation rig could aid in mitigating costs for Zips Racing. Instead of using live, in-person running to determine the best driver on the race team, the simulation rig can be used. The simulator will allow for Zips Racing to better analyze their drivers and to determine who is truly the best driver for each event. Additionally, the computer driving simulator will allow the driver to gain experience driving the car without the costly, in-person testing. The driver can also give feedback on what the car feels like it's doing on track and what setup they like the best to optimize their driving potential and skills. Lastly, the driving simulator will help Zips Racing and The University of Akron with recruitment and sponsorships. Any prospective student or sponsor could easily have a chance at driving the student built car through the driving simulator and simulation developed. There are many potential benefits to a driving simulator and the design team has provided the necessary information for Zips Racing to attain one in the future.

What to Pass On

Upon the completion of this senior design project, the senior design has found it incredibly important to document everything to give to the younger members of Zips Racing. It is incredibly important to document everything because this simulation software can be used for many future years of Zips Racing. The most important piece of information being given to Zips Racing is the build and analysis portion of the simulation software VI-grade. It is vitally important that the simulation is built upon the correct parameters and specifications of the race cars in order for the simulation to be accurate. Additionally, this knowledge will allow the future generations of Zips Racing the ability to utilize lap-time simulations in their design and verification processes. This information has already been given to Zips Racing and continues to be crucial leading up to the upcoming competitions.

The ZR20 and ZRE-20 files and ZR19 files have already been copied and stored with Zips Racing, and the senior design team has documented the progress of the vehicles setups through the usage of the simulations. Additionally, the knowledge and methods learned during the VI-grade Virtual Formula have also been documented in order for Zips Racing to compete for many more years. While the senior design team has learned a great amount during this project, it is in the best interests of both the design team and Zips Racing for this knowledge to be utilized and expanded upon for many years to come.

Works Cited

"Company." *VI-Grade*, VI-Grade GmbH, 2020, www.vi-grade.com/en/about/company/.

Dagys, John. "Corvette C8.R Tech Details Confirmed." *Sportscar365*, John Dagys Media, LLC., 10 Oct. 2019, sportscar365.com/imsa/iwsc/corvette-c8-r-tech-details-confirmed/.

Ferguson, Donna. "6 Surprisingly Well-Paid Jobs." *Business Insider*, The Guardian, 7 Aug. 2014, www.businessinsider.com/6-surprisingly-well-paid-jobs-2014-8.

"Formula SAE Michigan 2019 Results." SAE, 2019.

Gillespie, Thomas D. *Fundamentals of Vehicle Dynamics*. Society of Automotive Engineers, 1994.

Milliken, William F., and Douglas L. Milliken. *Race Car Vehicle Dynamics*. Society of Automotive Engineers, 1995.

"Optimum Kinematics Case Study Generic Formula Student Car." Optimum G, May 2015.