Vehicle Dynamics on an Electric Formula SAE Racecar

by

Audrey Gaither

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2021

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ABSTRACT

Vehicle dynamics on a Formula SAE vehicle are inter-dependent with almost all mechanical systems on the car and require a thorough understanding of design tradeoffs in order to maximize the vehicle's acceleration capabilities while maintaining consistent driver feedback. This thesis summarizes the developments and accumulated knowledge on MIT's Formula SAE team with regards to suspension and vehicle dynamics of the 2018 – 2020 seasons in order to inform the design and vehicle development for future years. Vehicle kinematics, vehicle dynamics, and tire selection are covered, in addition to the impact of aerodynamics, steering, and control arms on suspension development. Areas for further research are described. Throughout the thesis, the importance of quantifying and documenting design decisions is highlighted.

Thesis Supervisor: Amos G. Winter
Title: Associate Professor of Mechanical Engineering

Acknowledgements

Table of Contents

1. INTRODUCTION

1.1 Team Background

MIT's Formula SAE Team designs, builds, and races an electric Formula-One stye racecar every year for the international Formula SAE Competition series. Figure 1 shows MIT's 2018 vehicle (MY18) performing straight-line acceleration. MIT Motorsports (aka MIT FSAE) is a student-run team operating out of MIT's Edgerton Center, an organization that, among other pursuits, provides space, funding, and support for student organizations on campus. MIT Motorsports was founded in 2001 to compete in the internal combustion division of the competition. In 2014, the team switched over to electric vehicles. In June 2017, the team won second place at the annual competition in Lincoln Nebraska, and, since then, the team has had its sights set on first place.

Figure 1: Cheyenne Hua driving MY18 (Photo by Leigh Highby)

The competition, hosted by the Society of Automotive Engineers (SAE) provides an opportunity for teams to race their vehicles and present their design rationale to judges. There are four dynamic, or racing, events: Acceleration, Skidpad, Autocross, and Endurance. Acceleration is a 75 meter straight, and top times for this event often cut under 4.0 seconds. Skidpad is an event designed to test lateral acceleration, where drivers circle a 15-meter circle of cones. Top times for this event range between 5 and 5.5 seconds. Autocross records a team's fastest lap time on an autocross track, including straightaways and hairpin turns, and lap times often range between 60-90 seconds. Lastly, the endurance event, with the maximum number of possible points, requires teams to complete a 22 km endurance race, involving multiple laps around a custom track. This event typically takes around 30 minutes and is a grueling test of car & driver

reliability and performance. In addition to these racing events, teams present their design rationale, economic viability, and cost breakdown to a panel of automotive experts. Figure 2 shows MIT Motorsports celebrating with the 2019 vehicle (MY19) after competition in June 2019.

Figure 2: MIT Motorsports and MY19, June 2019

MIT Motorsports is currently composed of around 50 MIT students. The team is mostly undergraduate, with representation from many different majors, including mechanical engineering, aerospace engineering, electrical engineering, computer science, materials engineering, and business. Women constitute around one-third of the team, which is rare in this competition series, and can be attributed to the team's history of inclusion and strong female role models.

MIT Motorsports typically competes in one competition every summer, and the annual timeline is built around that competition. Vehicle design occurs in the fall, followed by manufacturing over IAP and assembly & testing in the spring semester. An efficient design process is critical for enabling a productive spring testing season and requires effective communication and planning. Since 2017, MIT Motorsports has made a substantial push to

streamline documentation and retain knowledge gained in previous years to build faster vehicles on a faster timeline. The path to a completed racecar often requires many long nights of assembly and design (see Figure 3, during spring semester of the MY20 build cycle), but many students remember the development of their racecar as some of their favorite memories at MIT.

Figure 3: MY20 Assembly, Spring 2020

1.2 Thesis Scope

This thesis summarizes the main drivers of suspension design and vehicle dynamics developed on MIT Motorsports from 2018-2020. This thesis is not intended to fully describe any one singular vehicle completely, but rather to combine learnings from multiple design cycles to give an accurate synopsis of the knowledge on MIT Motorsports with the intent to aid future design cycles.

2. TIRES

2.1 Background

A complete understanding of vehicle dynamics and suspension always starts with the tires. The tires are the only component of the vehicle that touches the asphalt, and therefore the only component of the vehicle capable of transmitting forces to the ground. The goal of the

suspension system on a Formula SAE vehicle is to maximize the vehicle's acceleration capability over the course of the competition without providing inconsistent driver feedback. In the case of tires, the goal of the suspension system is to maximize the amount of force that the tires can produce over the course of vehicle operation.

Tire forces are a function of various inputs, shown in Figure 4. At any one moment in time, a tire is capable of producing some amount of force in any given direction. The goal of the vehicle dynamicist is to understand how to produce the maximum full vehicle acceleration at any given moment by adding up the forces from all four tires.

Normal Force Inclination Angle (gamma) Slip Ratio (kappa) Slip Angle (alpha)	→	Tire Function	→	Tire Force Capability Tire Force Direction

Figure 4: Flow chart showing tire function inputs and outputs.

2.2 Definitions

There are four main inputs that define what forces a tire is capable of producing. In addition to forces parallel to the ground, tires are also capable of producing moments about all of their axis, but these will be neglected for the purposes of this thesis.

The first, and perhaps most important input to the tire function is the normal force on the tire. When considering friction force in its simplest case, friction is usually modeled as

$$F_{friction} = F_{normal}*mu,$$

where mu is the coefficient of friction between the object and the ground. This relationship does apply to tires: the maximum force capability of a tire generally increases along with increasing normal force. However, the coefficient of friction of tires *decreases* as normal force increases, which is a key concept that drives many decisions in vehicle dynamics that will be covered later in this thesis. Figure 5 is a plot, developed by Cheyenne Hua (MIT '19) that shows the impact of normal force on the coefficient of friction on a Formula SAE tire. The coefficient of friction is defined as the ratio of a tire's longitudinal or lateral force capability and its normal force.
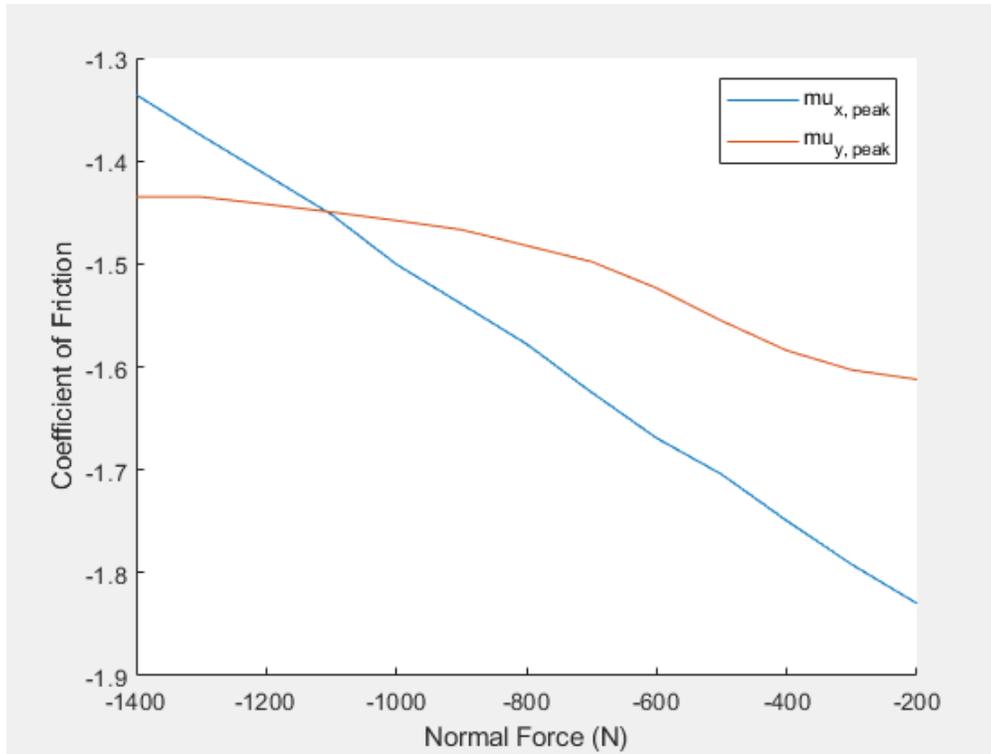
8

Figure 5: Impact of normal force on coefficient of friction on FSAE tire.

This concept is crucial for vehicle dynamics because it implies that a vehicle should strive to minimize weight transfer as much as possible in most cases. For instance, when weight shifts to an outside corner during a turn, those two outer tires have a larger force capability, but the *sum of the force capability* on all four tires is lower.

Another factor in tire force capability is inclination angle, also known as camber. Camber is measured as the inclination of the tire from the vertical access when viewed from the front or back of the tire. Negative camber is defined as when the top of the tire is closer to the vehicle than the bottom. Camber has received a lot of focus on MIT Motorsports because it can vary significantly as a function of suspension geometry. Camber is important because a cambered tire produces camber thrust, as shown in Figure 6. When a tire has negative camber, the rubber on the bottom of one side of the tire is compressed, producing a force towards the center of the vehicle known as camber thrust. When tires have positive camber, a force away from the vehicle is produced, which can pull the driver to steer away from the centerline and drive erratically. Camber can also cause a tire to heat up on the compressed side, leading to uneven tire wear and performance characteristics.
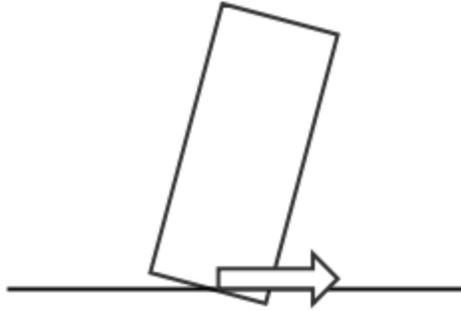
Figure 6: Back view of a tire with camber, arrow showing direction of camber thrust.

Slip Ratio is the driver of a tire's longitudinal force capability. Slip Ratio is defined as

$$SR = R / R_f - 1,$$

where "R" represents the angular velocity of a driven tire, and "R_f" represents the angular velocity of an undriven tire. Another way to think about slip ratio is the ratio between the number of tire rotations and the distance traveled by the vehicle. A slip ratio of zero means that the distance traveled by the vehicle is exactly equal to the number of rotations of the tire multiplied by the circumference of the tire. As the tire slips, it will gain a slip ratio because the distance traveled will be less than the number of rotations multiplied by the circumference.

Figure 7 shows the typical relationship between slip ratio and a tire's longitudinal force capability, taken from Milliken & Milliken's *Race Car Vehicle Dynamics*. At zero slip ratio, the tire is not capable of producing any longitudinal force. As the slip ratio increases, plastic deformation in the rubber enables the tire to produce longitudinal forces. The constant slope shown in the low-slip ratio regime is sometimes referred to as the "tire stiffness." The longitudinal force capability increases up to a peak, typically at less than $SR = 0.1$ for FSAE tires, and then decreases again. The width of this peak varies between tires, and a wider peak makes it easier for the driver to operate the vehicle at an ideal slip ratio during a race. FSAE vehicles typically operate in lower slip ratio regimes, and rarely reach slip ratios of 1 or above.
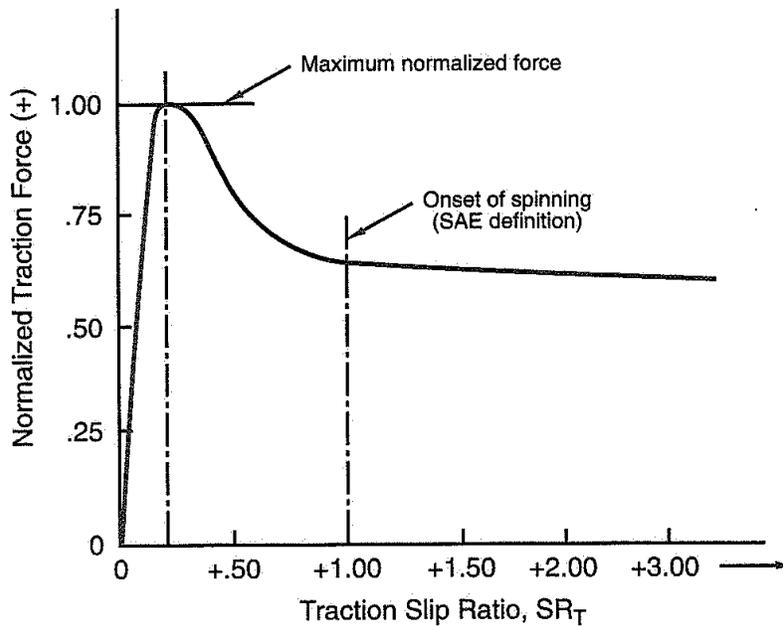
Figure 7: Typical relationship between Slip Ratio and Traction Force. Plot from Milliken & Milliken's *Race Car Vehicle Dynamics*.

The last major input to tire forces is the tire's slip angle, which is the difference between the orientation of the tire and the vehicle's velocity vector. Slip angles are required to provide substantial lateral forces and rely on plastic deformation of the tire, similar to slip ratio and longitudinal forces. Figure 8 shows the relationship between longitudinal force capability and slip angle, also adapted from *Race Car Vehicle Dynamics*. The behavior is very similar to that of longitudinal forces and slip ratio, with a quasi-linear region at low slip angles ("tire cornering stiffness"), followed by a peak at higher angles. The width of this peak is very important for vehicle handling because it directly impacts how drivers should steer the vehicle and the stability of cornering behavior.

Figure 9 shows the optimal slip ratio and slip angle under a variety of normal forces for various tires during the MY20 tire selection process, here to help provide more intuition on normal ranges for both values. Graphs created by Rebecca McCabe (MIT '21). As shown, the optimal slip and slip ratio reach maximums at 13 degrees and 0.08, respectively, for typical performance of an FSAE vehicle.
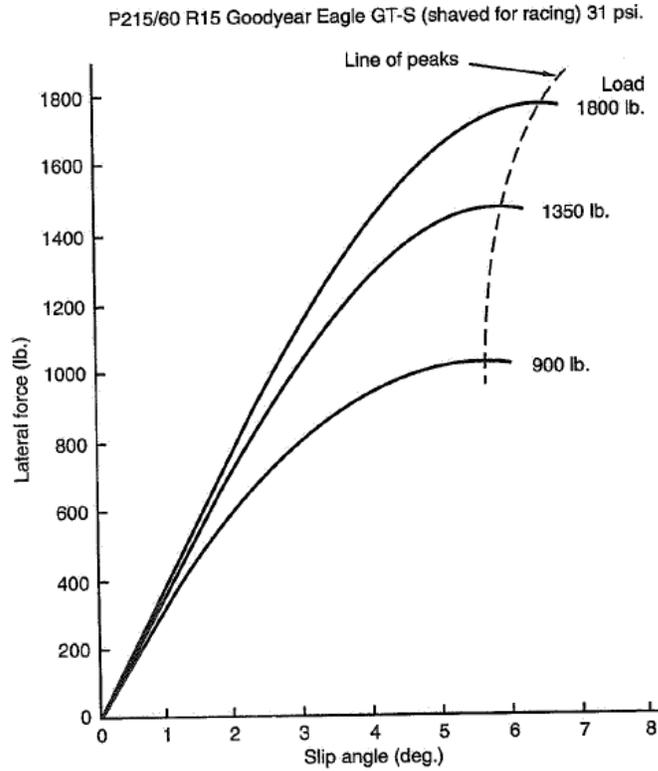
11

Figure 8: Relationship between Slip Angle and Lateral Force on Goodyear tire. Plot from Milliken & Milliken's *Race Car Vehicle Dynamics*.
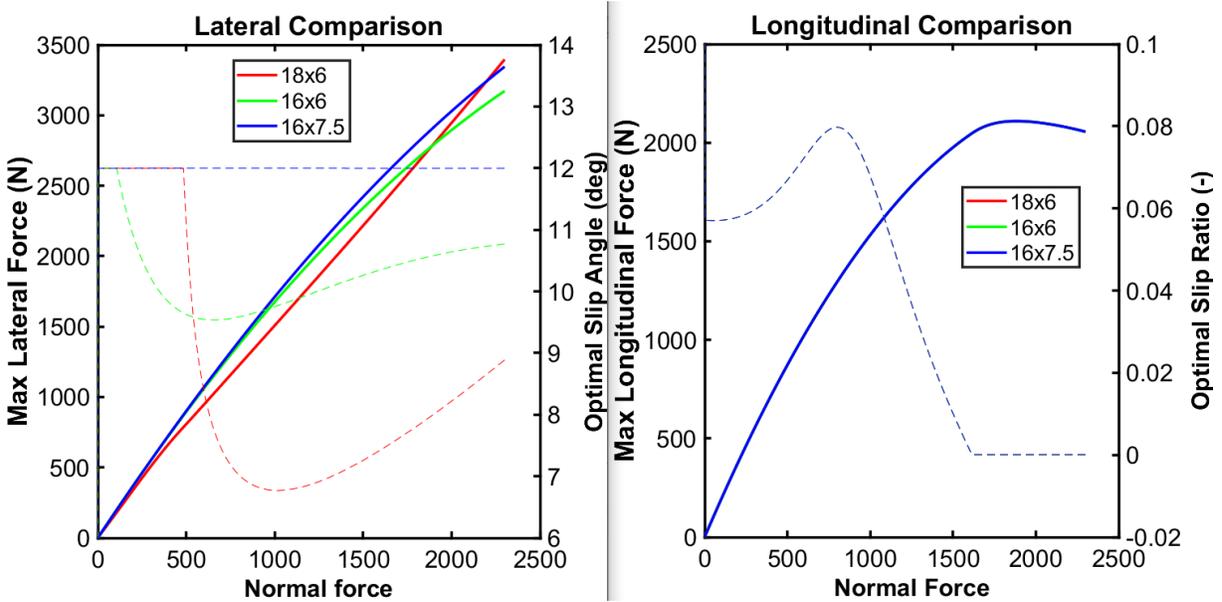

Figure 9: Optimal Slip Angles and Slip Ratios for tires during MY20 selection process.

2.3 Tire Selection Process

Tire selections are made based on the sensitivity of tire forces to any of the four inputs, as well as thermal and tire wear characteristics. Often, the sensitivity of tire forces can be even more important than the theoretical maximum force the tires can produce. For instance, if the maximum lateral force varies significantly with slip angle near the optimal slip angle, the team will often select a less finicky tire to provide an easier driving experience. During the MY20 tire selection process, multiple tires showed similar characteristics. The team chose 16" diameter Hoosier tires (43070 and 43075 for front and rear, respectively) instead of the 18" diameter Hoosier tires that the team had used for MY17, MY18, and MY19. The tires showed very similar dynamic characteristics, but the switch was made due to the lower thermal mass of the 16" tires. Warm tires perform better than cold tires (which is why many competitive race teams warm up the tires before a race), and a smaller tire will heat up faster during a race than cold ones.

3. KINEMATICS

3.1 Inputs

Vehicle kinematics is the study of how a vehicle's geometry moves and changes over the course of a vehicle's operation. The vehicle dynamicist influences the vehicle's kinematics by determining the locations of the suspension linkages. These linkages then define a variety of other geometric parameters that influence vehicle dynamics. One such parameter is called the roll center, shown in Figure 10, from *Race Car Vehicle Dynamics*.
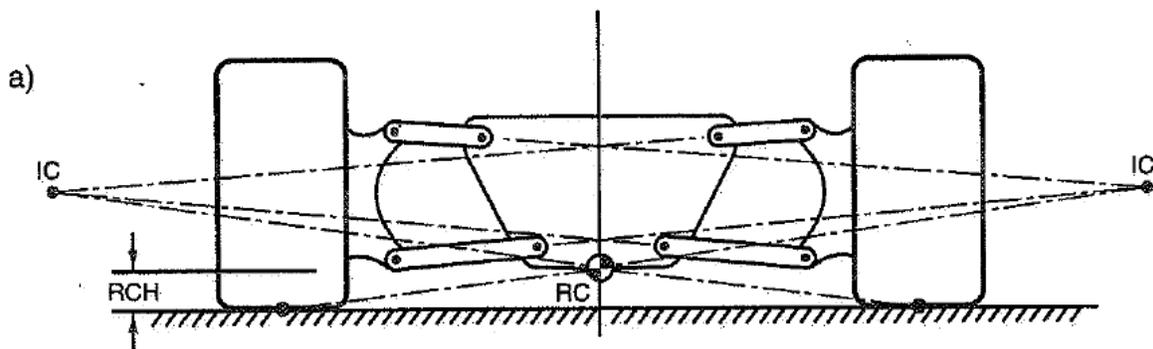

Figure 10: A front view of a suspension system. Roll center (RC) and instant center (IC) on a vehicle are labeled.

From a front view, the point connecting the lines of action of the suspension linkages is called the instant center. If you draw a line of action from each instant center and connect it with the contact patch of the opposite tire (or the point at the center of the tire where it meets the ground), the overlap of these two lines is called the roll center. The roll center is significant because it is the point on the vehicle where lateral forces can be applied to the car without the vehicle rolling. The vehicle rotates about this point.

When a vehicle turns, lateral forces are applied to the car's center of gravity, which is located above the roll center. The moment arm between these two points creates a rotation of the vehicle, which changes how forces are distributed throughout the car. Because of this interaction, minimizing roll center movement over the course of a vehicle's performance is important to maintaining consistent driver feel.

In addition to the roll center, the suspension geometry in the wheel has various impacts on vehicle performance. Figure 11, taken from *Race Car Vehicle Dynamics*, shows many such important geometries. The point where the upper suspension linkages meet in the wheel is called the upper ball joint (UBJ), and the point where the lower suspension linkages meet is called the lower ball joint (LBJ), and the line connecting these two points is referred to as the "steering axis." The tire rotates about the steering axis.
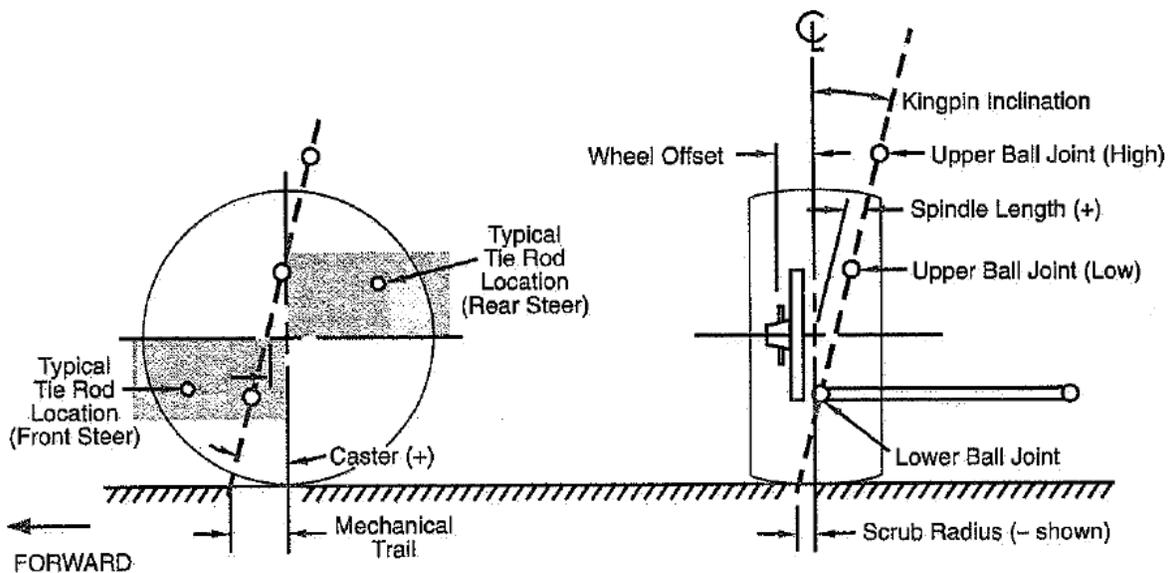

Figure 11: Wheel geometries defined by suspension geometry.

The caster angle is the inclination of the steering axis when viewed from the side of the vehicle. Caster is significant because a positive caster angle increases the directional stability of the vehicle. This is shown in Figure 12, a top view of a wheel with positive caster. The red dot is the intersection of the steering axis with the ground, and the blue rectangle is the region where the tire makes contact with the ground. When the tire is turned, longitudinal tire forces act at a distance d away from the steering axis, creating an "aligning moment" that pushes the driver to steer the tire back to straight.
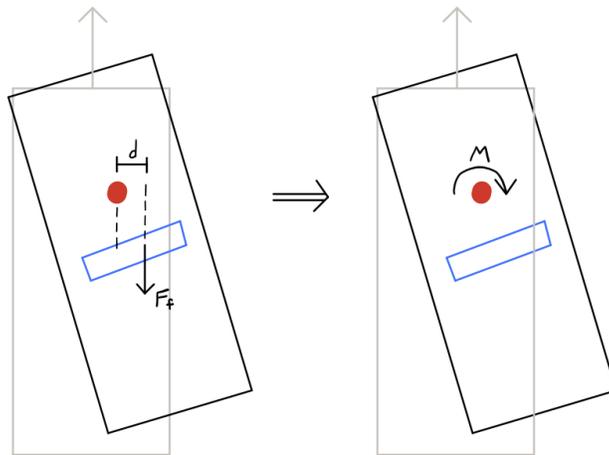

Figure 12: Top view of tire with positive caster.

Associated with caster angle is mechanical trail, or the distance between the center of the tire and the intersection of the steering axis with the ground when viewed from the side of the vehicle. A larger mechanical trail creates a larger lever arm about the steering axis, and therefore increases the force required by the driver to turn the vehicle.

The kingpin angle is defined as the inclination of the steering axis from vertical when viewed from the front of the vehicle. Positive kingpin is defined as when the UBJ is closer to the center of the car than the LBJ. Kingpin angles play a significant impact in camber change over vehicle motion, increasing positive camber on the outside wheel and increasing camber on the inside wheel during turning. A positive kingpin angle also increases the ride height of the vehicle when steered.

15

Another important result of a kingpin angle is the scrub radius, or the distance between the steering axis intersection with the ground and the center of the tire when viewed from the front of the vehicle. A larger scrub radius causes higher driver forces when turning and causes increased tire wear.

3.2 Outputs

Suspension geometry has a variety of important implications for vehicle performance, such as roll center height movement and camber change. One substantial development made during the 2019 season was determining, based on tire parameters, what camber change was optimal for the vehicle. Camber thrust values were calculated for all four tires over the range of expected lateral motions expected during a competition. These values were added together and consolidated to produce the graph shown in Figure 13.
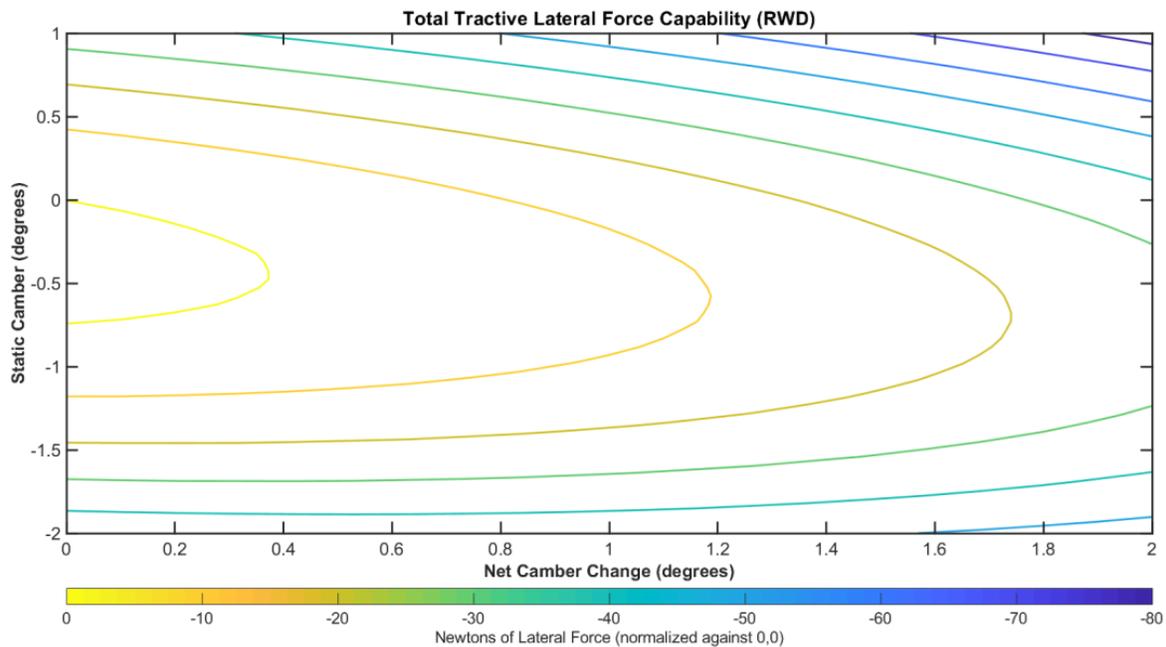

Figure 13: Impact of static and dynamic camber on total lateral force capability.

As shown in this graph, maximum vehicle performance is achieved when the vehicle's static camber (aka the camber on a stationary vehicle) is slightly negative and does not change over the course of the vehicle's operation. These insights allowed the team to tune suspension behavior to minimize camber change, but more importantly to quantify the trade-offs in doing so.

16

3.3 Iteration Process

The iteration process for determining the suspension geometry is a lengthy one and involves extensive communication with many different system owners. MIT Motorsports uses a software called Optimum Kinematics to evaluate the suspension kinematics over the course of a vehicle's motion. The process will start with a proposed version of suspension geometry. A subsystem owner will propose a change (i.e. because of an interference between components), and the vehicle dynamicist will evaluate the impacts of that change by iterating solutions in Optimum Kinematics. An example is shown in Figure 14, which shows the impact of control arm length (suspension linkage length) on roll center movement.

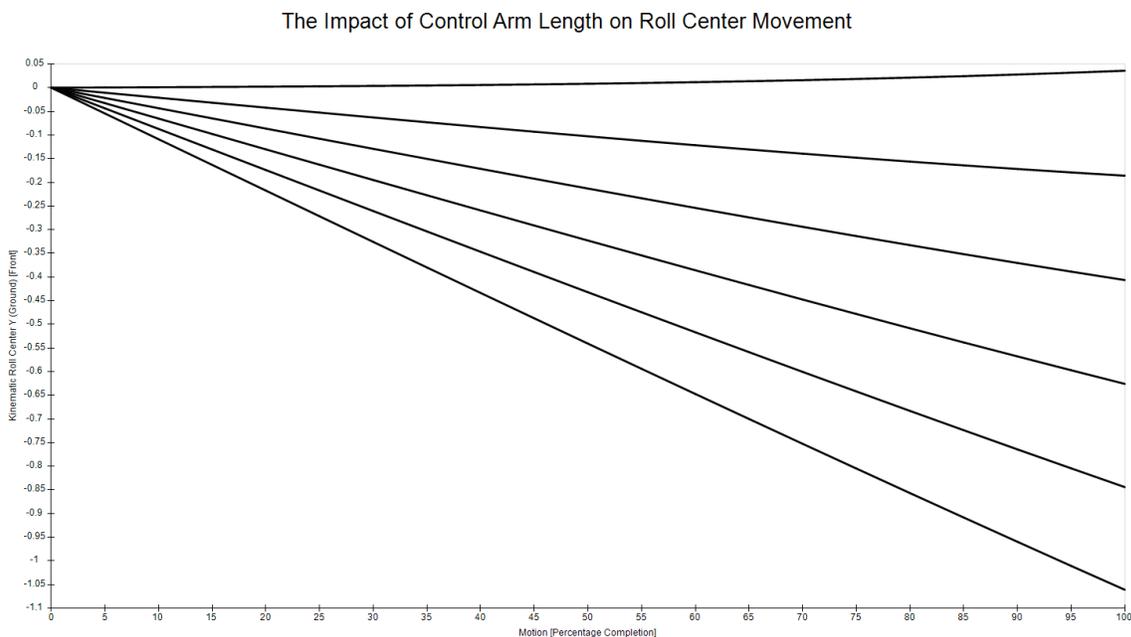The Impact of Control Arm Length on Roll Center Movement

Figure 14: The impact of control arm length on roll center movement over a roll movement in the Optimum Kinematics software. Different lines represent different control arm lengths.

3.4 2019 Results

In the MY19 vehicle, the team was able to minimize camber change to less than 1 degree and roll center height change to less than 0.02" over the course of a vehicle's motion, as shown in Figures 15 and 16. Static values of the ball joint geometry are shown in Figure 17.
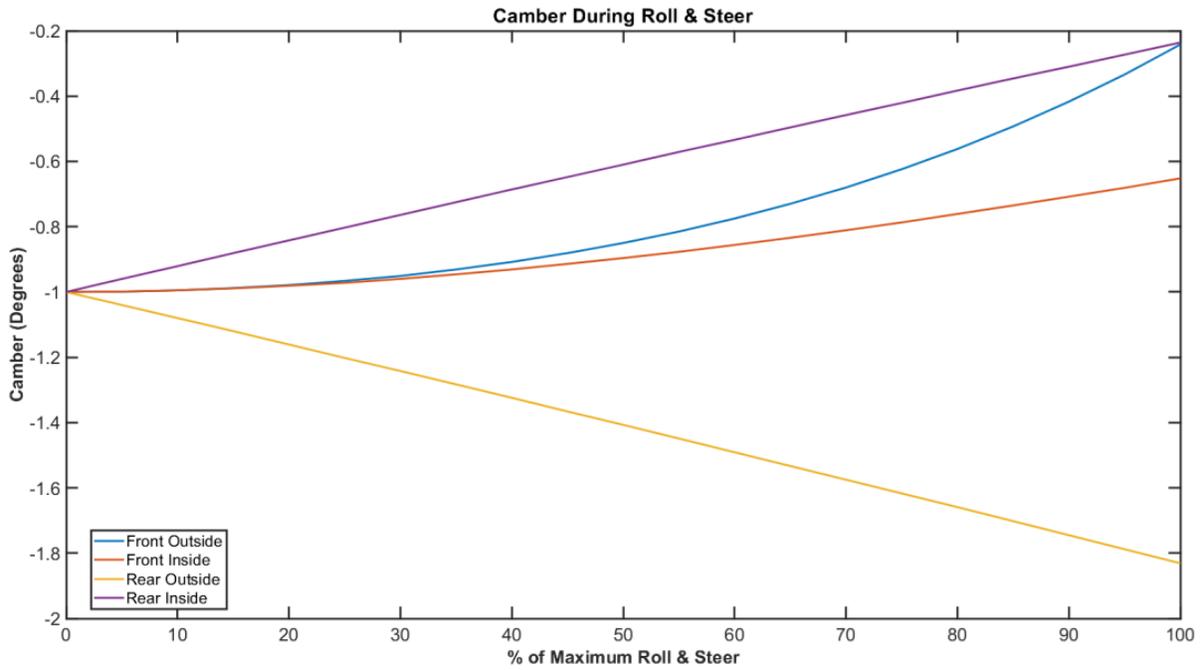
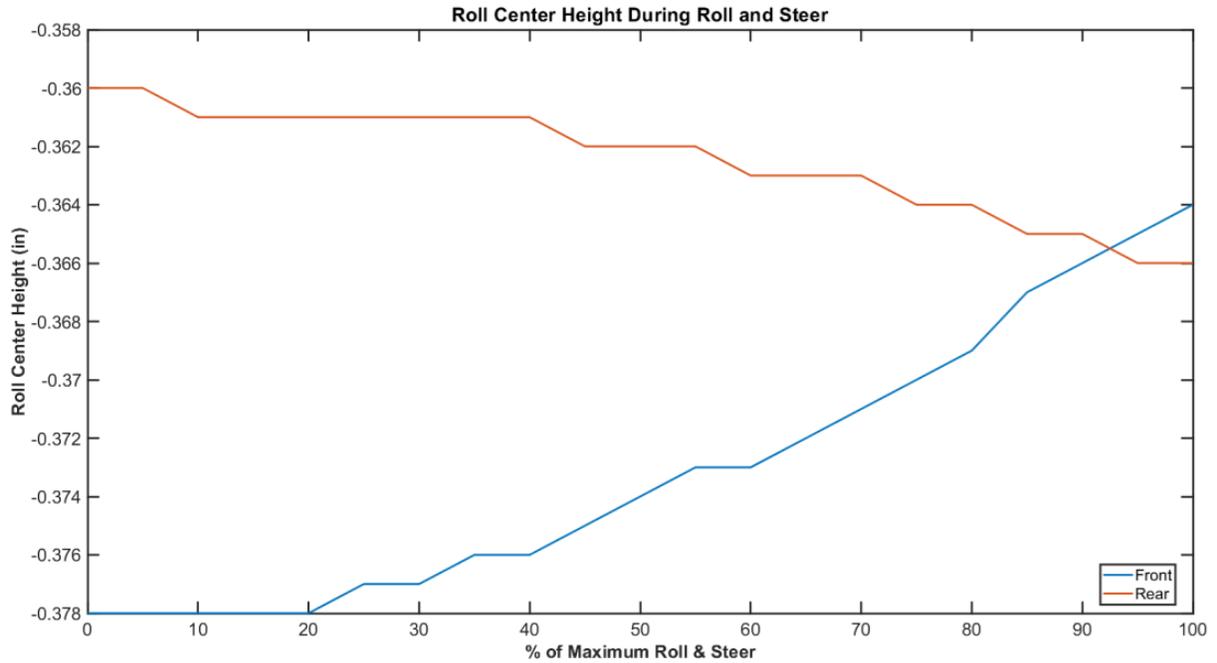Figure 15: Simulation of MY19 camber on all four tires during a combined roll and steer motion.

Figure 16: Simulation of MY19 front and rear roll center heights during a combined roll and steer motion.

Ball Joint Geometry

	Front	Rear
Static Camber	-1 degrees	-1 degrees
Kingpin Angle	4.6 degrees	4.2 degrees
Scrub Radius	1.043 in	0.45 in
Mechanical Trail	1.57 in	0.73 in
Caster Angle	2.9 degrees	2.4 degrees
Roll Center Height	0.38 in	0.36 in
Toe	0 degrees	0 degrees
Front View Swing Arm Length	606.6 in	57.4 in
Instant Center Height	9.49 in	0.87 in

Figure 17: MY19 Ball joint geometry values.

4. DYNAMICS

4.1 Definitions

In addition to considering vehicle kinematics and geometry changes over the course of a competition, the vehicle dynamicist must also consider the dynamics of the vehicle, or how weight transfer and dynamic motion occur. One of the main advances over the 2019 season was the increased understanding of the vehicle's total lateral load transfer distribution, or TLLTD, and optimization thereof.

TLLTD is the ratio of weight transfer between the front and rear of a car during a turn. This ratio impacts the vehicle's total lateral force capability because it changes the normal forces distributed to the tires, impacting their coefficient of friction and force capability. The impact of TLLTD on total lateral acceleration capability in the MY20 vehicle is shown in Figure 18. For that vehicle, the optimal rear TLLTD (rear lateral load transfer divided by the total lateral load transfer) is right around 0.55. TLLTD also has impacts on vehicle handling and steering characteristics. A higher rear TLLTD leads to oversteering because there is less load transfer between the front steering tires and therefore more lateral load capability in the tires that steer, and a lower rear TLLTD leads to oversteering, because there is more load transfer in the front tires, and the associated decrease in mu decreases the total steering capability. Because of this,

MIT Motorsports designs a vehicle with a range of possible TLLTDs (achieved through tuning various suspension components) to allow the driver to see what TLLTD works best for them.
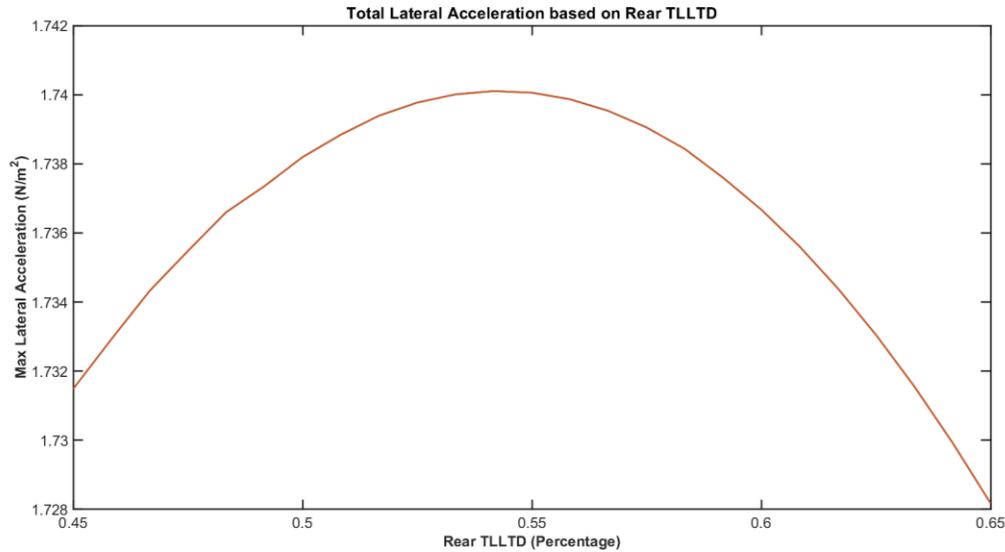

Figure 18: Impact of TLLTD on total lateral acceleration capabilities on MY20 vehicle.

4.2 Process & 2019 Results

The process to calculate the optimal TLLTD and range requires some assumptions about the vehicle's lateral acceleration and car parameters, and then iterates to find a solution. A flow chart describing the process to find the optimal TLLTD is shown in Figure 19. Values that must be considered are the vehicle's overall roll gradient (or the degrees roll per degree of lateral acceleration), roll rate (required torque to rotate the vehicle), and ride rate (required force to raise or lower the vehicle's center of gravity). Vehicle dynamics parameters from MY19 are shown in Figure 20.

To change the TLLTD and roll characteristics of a vehicle, the vehicle dynamicist can change the suspension spring stiffnesses or the anti-roll-bar (ARB) stiffnesses. The anti-roll bars are bars connecting the right and left sides of the suspension system, acting as torsional springs and changing the respective and overall roll rates of the system. In 2019, the team had four different ARB settings on the vehicle to allow for four different TLLTD settings.
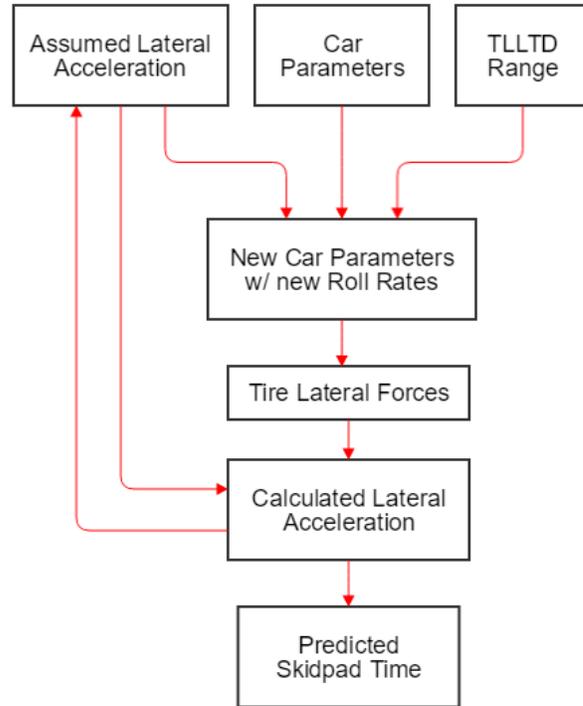
Figure 19: Iteration process to determine optimal lateral acceleration and TLLTD range.

Vehicle Dynamics

Roll Gradient	0.85 degrees / "g" of lateral acceleration
Front Spring Stiffness	200 lbs/in
Rear Spring Stiffness	175 lbs/in
Front Roll Rate	21400 Nm/rad
Rear Roll Rate	23400 Nm/rad
Total Roll Rate	44900 Nm/rad
Front Ride Rate	24700 N/m
Rear Ride Rate	22300 N/m

Figure 20: Vehicle dynamics properties on MY19 vehicle.

5. TEAM INTEGRATION

5.1 Aerodynamics

The suspension and vehicle dynamics system on an FSAE racecar does not exist in a vacuum. To optimize the vehicle as a whole, the vehicle dynamicist must work with almost

every mechanical system to make sure that all trade-offs are understood and quantified as best as possible. One team that plays a significant role in vehicle performance is the aerodynamics team. The center of pressure of the aerodynamics package is included when calculating the normal forces and their distribution on the tires, the normal forces change as a function of velocity when taking aerodynamic performance into account.

From 2017-2019, MIT Motorsports was considering implementing anti-squat and anti-dive geometry into the suspension design. This involves changing the placement of suspension linkages in order to minimize the pitch of the vehicle, or rotation of the vehicle about its lateral axis (shown in green in the corner of Figure 21). This geometry change would not change any weight transfer but could potentially have impacts on the efficacy of the aerodynamic elements.
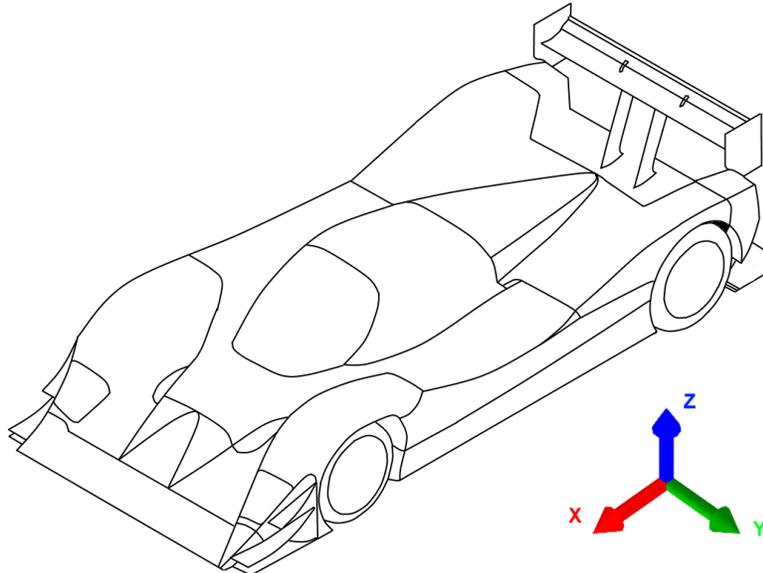

Figure 21: Vehicle axis of rotation. Pitch axis shown in green.

In order to quantify the impact of implementing this geometry, the aerodynamics team ran their CFD model to look at the impact of pitch on the coefficient of lift (CL) and coefficient of drag (CD) on both aerodynamic wings in the fall of the MY20 season. Results are shown in Figure 22 (simulations run by Stefan Borjan (MIT '22)), which show that the rear wing performance is not highly dependent on the pitch, but the CL of the front wing is highly dependent on pitch. This impact was not deemed significant enough to merit an overhaul of the

suspension system based on the increased design time (and associated decrease in vehicle testing time), but simulations like these can be used to continue to quantify this trade-off in the future.
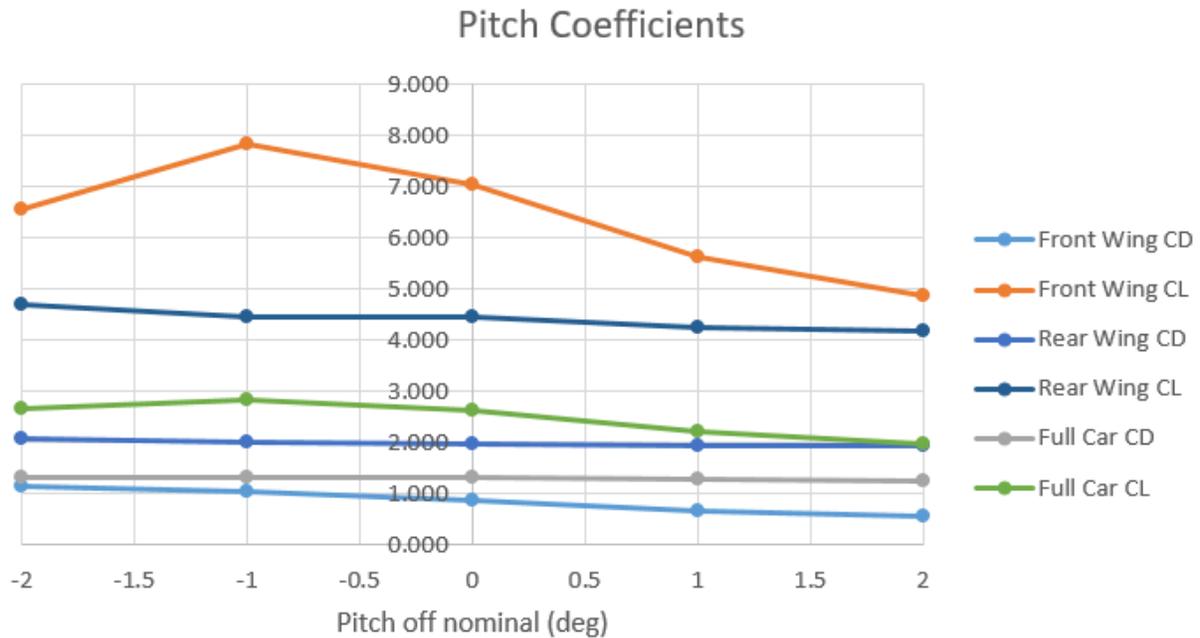
Pitch Coefficients

Figure 22: The impact of pitch on aerodynamic performance of the MY19 vehicle. Note that the front wing CL is highly dependent on pitch.

5.2 Steering

The team's understanding of the relationship between suspension geometry and driver steering forces has also developed significantly over the 2019-2020 seasons. As mentioned previously, the job of the vehicle dynamicist is to maximize the acceleration capabilities of the vehicle while maintaining consistent driver handling. When selecting tires, the sensitivity of the vehicle's performance to steering angle is considered such that the car handles consistently and evenly. Steering forces are also considered, especially when considering the 22 km endurance event. Drivers on MIT Motorsports are students, typically without any processional driving experience. If steering forces on the vehicle are too high, drivers will become very fatigued over the course of the 22 km event, which can cost valuable lap time and be potentially dangerous.

The 2019 vehicle features a much larger scrub radius than in previous years, as well as a longer steering bracket length (or the distance between the steering linkage and the steering axis). These features (along with many others, including the mechanical trail & tire properties)

led to very high steering forces. Drivers were extremely fatigued at the end of the 2019 endurance race, and extensive effort was put into quantifying the impact of suspension geometry on steering forces during the 2020 season.

As shown in Figure 23 (a plot made by Rebecca McCabe (MIT '21)), the torque required to turn the wheels increases in response to both mechanical trail and scrub radius. These plots describe steering torques during combined slip, or a scenario where the vehicle is accelerating longitudinally and laterally at the same time, such as decelerating into a corner. Unstable torque was also plotted in the left graph. Unstable torque is the tendency of the tires to steer away from the center line, and is highly dependent on scrub radius, as mentioned in the kinematics section of this thesis. The steering system is an example of a vehicle system that is highly interdepending with steering geometry, and this understanding will make it that much easier to make design tradeoffs in future design cycles.
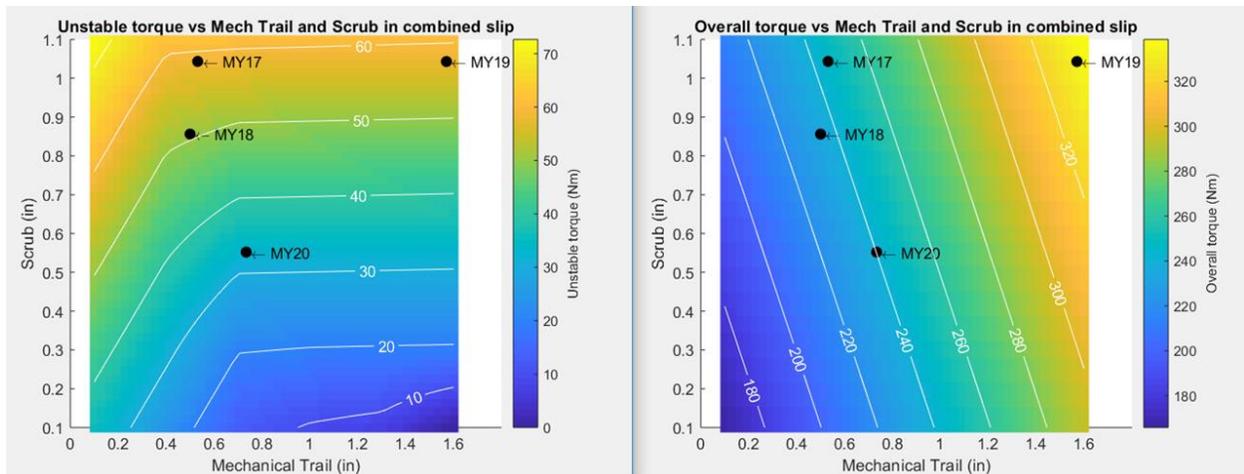

Figure 23: A plot showing unsteady driver torque (left) and total driver torque (right) to turn the wheels as a function of suspension geometry. Vehicles MY17 through MY20 are indicated in black.

5.3 Control Arms

The control arms are yet another vehicle system that vary substantially based on suspension geometry. The control arms system is the system of six steel tubes that connect the tire system to the chassis, or frame structure, of the vehicle. These control arms transmit forces from the tire packages to the rest of the vehicle, connect the tire packages to the vehicle shocks and ARBs, and transmit steering forces from the steering rack to the tire packages. A failure in

any suspension linkage would be very costly, and potentially dangerous, at competition. Because of this, extensive calculations are performed to make sure that the control arms do not fail under any loading conditions.

The vehicle suspension lead dictates the points in space where the control arms attach to the tire packages and the chassis of the vehicle, which in turn impacts the vehicle's kinematics and the loads transferred through the control arms. In 2018, a MATLAB plot was developed that determines the loads in each of the control arms as a function of the lateral, longitudinal, and vertical load applied on each tire. Figure 24 shows this plot for a front tire on the MY20 vehicle. The tire forces are modeled as a vector applied to the bottom of the tire, and the forces are calculated at every degree of possible load application.
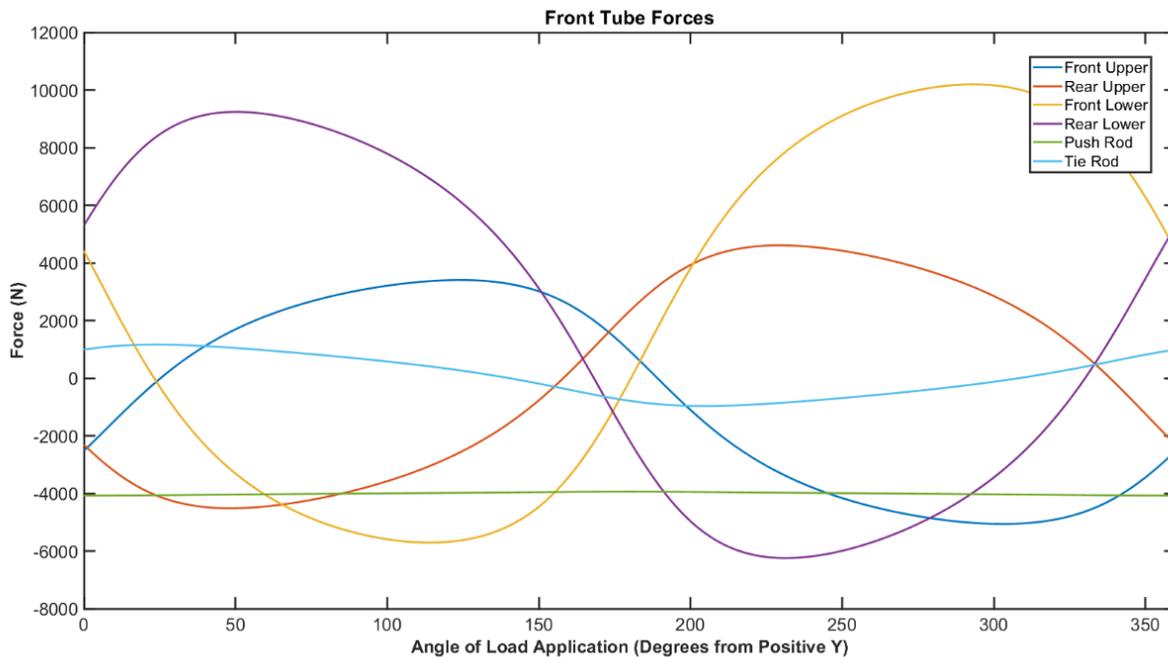

Figure 24: Predicted forces through the six control arms on the front tire of the MY20 vehicle.

Changing the angles and locations of the control arms can have substantial impacts on the forces transmitted through them, which leads to different total system masses as tubes are sized up or down to account for the variance in forces. Typically, the limiting failure mode in sizing the tubes is buckling, as they are long slender members that are required to withstand high compression forces. In addition, some suspension linkages are occasionally placed in bending,

25

which leads to a more complicated structural analysis that is often done in parallel with FEA. Figure 25 shows one screenshot of an ANSYS Static Structural model of a rear control arm on the MY20 vehicle. When selecting suspension geometry, the suspension lead must consider the mass of the control arm system, as well as the sizing. Occasionally, a proposed suspension geometry will result in a control arm that is so large that it interferes with other components on the vehicle, such as the rim of the tire, and must be redesigned.
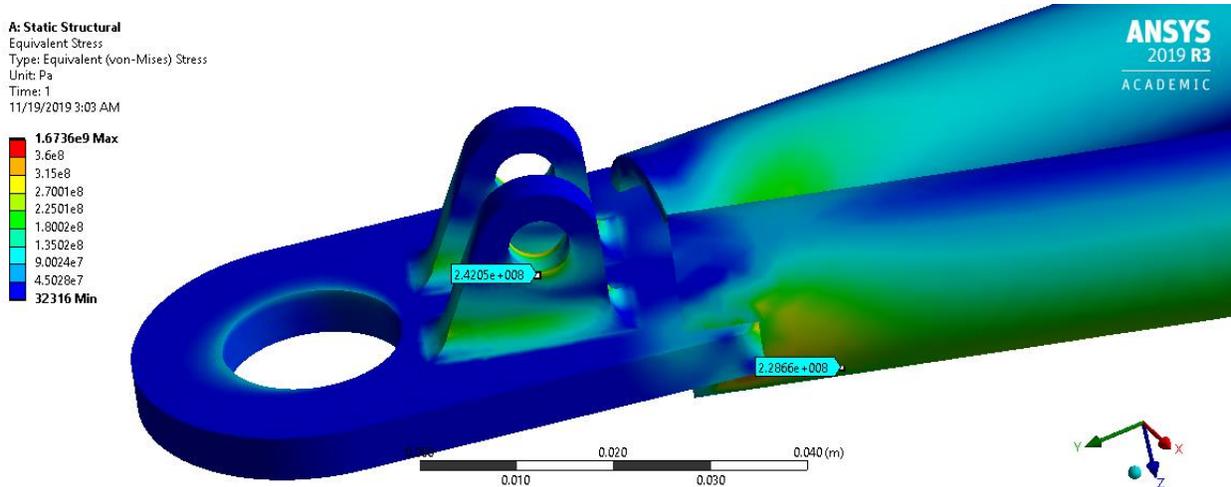

Figure 25: ANSYS Static Structural model of the rear lower control arm on the MY20 vehicle.

6. AREAS FOR FURTHER RESEARCH

6.1 Suspension System

There are many areas for future research in the suspension system that could improve vehicle performance and aid in streamlining the design cycle in future years. Starting with tires (as previously mentioned, the most important aspect of a vehicle's suspension), understanding the impact of tire temperature on force capabilities would help inform both tire selection & vehicle design as well as informing the team on the best ways to warm up the car during competition. As mentioned, the MY20 vehicle tires were chosen partially because of the expected thermal performance. The Calspan TTC data does include some data depicting warm-up behavior of the tires before testing, so a more thorough analysis of that data could be fruitful. In addition, empirical testing of the vehicle (recording acceleration times as a function of tire temperature) could help the team understand how different warmups impact the vehicle's potential.

26

From a vehicle dynamics perspective, validating the vehicle's roll rate, ride rate, and roll gradient could be beneficial. Extensive time is spent in each vehicle design cycle on selecting those roll and ride rates to select ARB stiffnesses and vehicle geometry, and it very well could be that the vehicle does not behave as expected, and other factors (such as frame stiffness, battery enclosure stiffness, etc.) play a large roll in determining transient vehicle characteristics. These measurements could be taken by relating the vehicle's IMU (or inertial measurement unit onboard the chassis) to tire forces. Tire forces can be determined through strain gauges on control arms or, with slightly less precision, load cells on the most vertical suspension linkage on the vehicle.

Lastly, the more accustomed the team drivers are to operating the vehicles, the more able they will be to select the right TLLTD setting for them, as well as giving more detailed feedback on the vehicle handling and performance characteristics. MIT Motorsports attempts to take testing trips on a weekly basis when weather permits to increase driver capability and understanding, as well as testing and tuning various vehicle systems, and a specific focus on the driver's sensitivity to suspension parameters could be beneficial to future testing seasons.

6.2 Related Systems

As mentioned, vehicle dynamics performance is highly dependent on the performance and understanding of other systems as well. The aerodynamics system has a substantial impact in the normal force distribution between tires (as well as the associated friction coefficient), and changes how the vehicle handles and performs as a function of vehicle speed. Over the 2019 and 2020 seasons, effort was spent to better quantify the vehicle's overall drag and lift coefficients. Continuing this progress to achieve even high precision, as well as validating properties on specific wing elements, will lead to a better understanding of the overall system. Currently, the team's aerodynamics system is modeled in Star CCM+, but empirical testing has shown that the team's modeled CL and CD values can differ substantially from reality. The more testing and validation are performed, the better the aerodynamics team can understand how to increase model accuracy and gain intuition into more extensive aspects of vehicle behavior.

Validating the control arms force distribution model would also allow the team to gain confidence in the vehicle's handling and potentially decrease the mass (by decreasing the factor of safety) of a system that is highly dependent on suspension geometry. In fall of 2019, an

attempt was made to start validating this model. Strain gauges were placed on all control arms on the rear right tire of the MY19 vehicle, and the predicted forces (as a function of the vehicle's acceleration) were compared to the measure forces in the strain gauges. As shown in Figure 26, there are some significant deviations between the measured and predicted forces. A more extensive analysis, including a variety of vehicle driving profiles and strain gauges on all four corners of the vehicle, could be beneficial to continuing to understand these discrepancies and gaining confidence in the vehicle's performance.
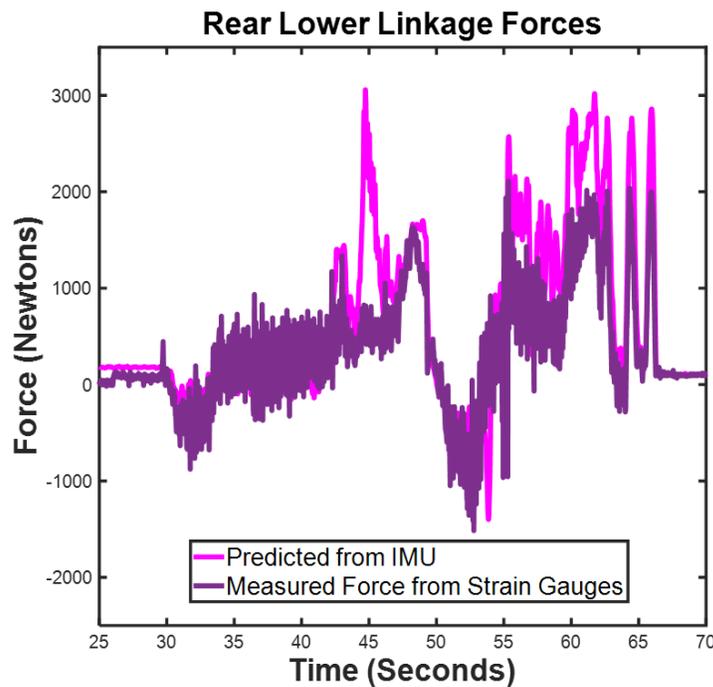

Figure 26: Measured forces in the suspension forces on the rear lower control arm on the rear right tire of the MY19 vehicle during a portion of vehicle testing.

Finally, an increased focus on streamlining documentation and quantifying trade-offs in the suspension system and the vehicle will continue to speed up the vehicle design cycle and leave more time for the team's spring testing season. Testing trips are incredibly valuable to teaching drivers how to handle the vehicle, as well as increasing vehicle reliability and being able to mitigate any recurring vehicle failure before competing. Figure 27 shows the MY18 and MY19 vehicle on a testing trip in the fall of 2019.

Figure 27: MY18 (front) and MY19 (rear right) on a testing trip in fall 2019.

The suspension system (and team structure as a whole) has developed extensively since the team's 2017 success, and is a testament to the organization, dedication, and capability of the team members. By continuing this focus on comprehensive vehicle understanding and validation, MIT Motorsports will remain as one of the most competitive FSAE teams in the United States, providing its members with invaluable opportunities to learn, build, and celebrate their engineering successes.

References

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