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MÁSTER EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

Design and Manufacture of a Formula Student Suspension

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Director: Ignacio Granell Heredero

Madrid

Junio de 2023

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Design and Manufacture of a Formula Student Suspension

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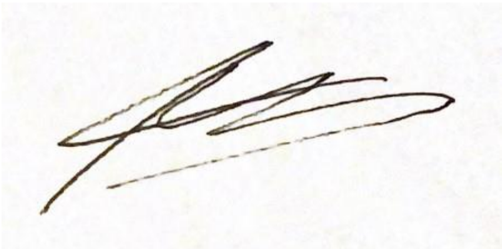

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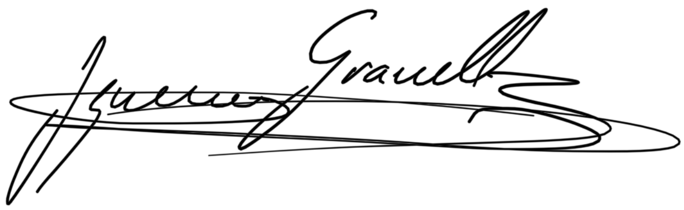

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DESIGN AND MANUFACTURE OF A FORMULA STUDENT SUSPENSION

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Supervisor: Ignacio Granell Heredero

ABSTRACT

In the realm of Formula Student racing, the suspension system plays a pivotal role in ensuring optimal vehicle performance and safety. This study delves into the design and optimization process of a cutting-edge suspension system for a Formula Student race car. Building upon the prototypes from previous years, the suspension geometry will be refined and enhanced to optimize manoeuvrability and suspension performance, calculating the loads, and designing the suspension arms to withstand the racetrack conditions.

Keywords: Formula Student, suspension design, double wishbone suspension, pushrod, Lotus Suspension Analysis, camber, toe, caster, kingpin, Ackermann geometry, suspension arms, manoeuvrability, load calculation, adhesive design, simulation, ANSYS, performance, safety factor.

1. Introduction

Formula Student is an international engineering competition cantered around the design and fabrication of a single-seater racing car. The primary goal is to engage students in a real engineering project, competing with a race car in both dynamic track tests and static assessments to evaluate the engineering principles incorporated in the car's design. [1]

The suspension system connects the vehicle's wheels to the chassis. Its fundamental role is to absorb road irregularities and optimize the tire's contact patch with the ground, thus maximizing grip during straight-line and cornering manoeuvres. Additionally, it serves several other functions outlined below: [2]

- Providing driving comfort, stability, and control, along with conveying feedback and sensations to the driver regarding tire and track conditions.
- Isolating impacts caused by surface imperfections from transmitting directly to the chassis, ensuring constant contact between tires and the road surface.
- Managing suspension movements to keep the tire as perpendicular to the ground as possible during suspension travel and front-wheel turning in corners. It also addresses roll and pitch movements occurring during lateral and longitudinal accelerations.
- Enhancing steering handling and response, enabling precise and adaptable driving across various conditions, and affording the driver greater control over the vehicle.

2. Objectives

The design goals of the IFS05 suspension are stablished considering upgrades from the last prototypes and problems of previous designs:

- Implement antidive and antisquat geometry in the suspension to effectively control excessive pitch by distributing loads between the springs and suspension components during acceleration and braking.

- Reduce the wheelbase of the car from 1730mm to 1570mm, increasing the steering angle for improved manoeuvrability in curves.

- Equalize the track width of both axles to 1200mm to facilitate symmetrical design and manufacturing of suspension components.

- Optimize the layout and design of the suspension to enhance overall performance and behaviour.

- Fix the static camber angle of the tires and control their movements during suspension travel and wheel steering to optimize the tire contact patch.

- Redefine the roll centers and steering geometry to improve stability and handling characteristics.

- Reduce excessive caster angle that generates large steering forces and excessive camber gain during turning, which can lead to undesirable suspension behaviour.

- Improve and control camber gain throughout the steering travel by adjusting the caster and kingpin angles to achieve more consistent and reasonable camber angles.

- Achieve steering geometry close to 100% Ackermann to improve cornering performance and minimize tire slip.

- Select suitable bearings, such as angle contact ball bearings, to minimize free rotation between the upright and hub.

- Optimize the design of the uprights to reduce mass and minimize potential contact with other components, enhancing overall efficiency and performance.

These objectives guide the design process, aiming to enhance the overall performance, stability, and handling characteristics of the IFS05 race car. Later, it will be explained the meaning and effects of each parameter.

3. State of the Art

The intricate world of Formula Student racing demands a profound understanding of suspension geometry and dynamics to achieve optimal performance and handling. Vehicle dynamics, the science of vehicle movement on roads, serves as the bedrock for designing suspensions that excel in acceleration, cornering, and ride quality.

Vehicle dynamics explores how vehicles move and respond on roads, influencing acceleration, stability, control, and ride quality. A myriad of factors - mass distribution, suspension design, tires, aerodynamics, and external forces - synergistically impact a vehicle's behavior. Engineers harness these interactions to bolster safety, performance, and comfort. [3]

Central to this dynamic landscape are several pivotal concepts:

- **Suspension Systems**: The cornerstone of connecting wheels to the vehicle chassis, suspension configurations span from McPherson setups to air suspension. In the realm of high-performance vehicles, the double wishbone suspension with push or pull actuator arms takes center stage, seamlessly linking springs, dampers, and anti-roll bars.

- **Kinematics**: The art of dissecting wheel and body motion unveils a universe of geometric influences that mold vehicle performance. Tire angles such as camber and toe, wishbone and upright geometry encompassing caster, kingpin, antidive, antisquat, roll center, and steering geometry, demand meticulous orchestration to optimize the behavior of the vehicle.

- **Tire Mechanics**: Understanding tire-road interaction and characteristics like grip, traction, and slip angles that influence handling.

- **Vehicle Stability**: Ensuring a vehicle maintains its intended path and counteracts undesirable motions.

- **Load Transfer**: During acceleration, braking, and cornering, weight shifts across wheels affecting tire grip. Controlling load transfer optimizes tire grip distribution and traction.

- **Aerodynamics**: Aerodynamic forces like downforce and drag influence vehicle behavior, improving grip at high speeds. However, these forces must be managed to avoid destabilizing effects.

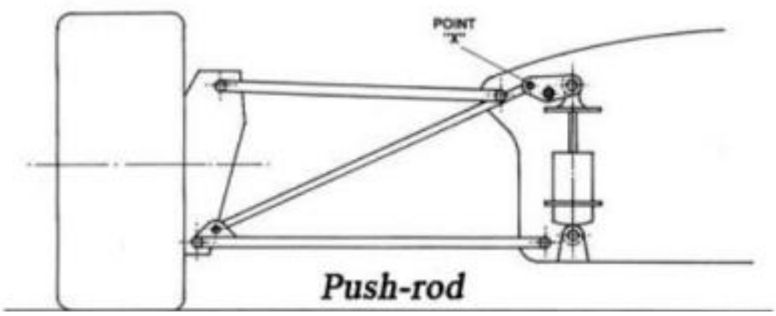

Figure 1: double wishbone pushrod suspension

4. Suspension design

The design of the suspension system for the IFS05 Formula Student car is a critical aspect that influences its performance and handling characteristics. The chosen configuration for the suspension is the double wishbone with rocker and push bar as it allows precise control through the tire angles and movements. The Lotus Suspension Analysis (LSA) software has been employed to simulate and evaluate various suspension parameters and configurations, optimizing performance. LSA employs mathematical models to predict suspension behavior under different conditions, considering geometry, kinematics, and forces on components. This enables engineers to make informed design choices.

- **Camber**: Achieving optimal camber angles is vital for racing applications. Negative camber is preferred to adapt tire contact to turns and body roll. Static camber targets of -2.5º and -2º for front and rear axles, respectively, have been set, as it can be tuned by adding camber shims to the uprights.

- **Toe Angle**: Adjusting toe angles enhances balance. A neutral toe angle of 0º is aimed for, with adjustability via tie rod length changes. Converging tie rods at the same rotation point minimizes wheel travel variations, ensuring consistent toe angles.

- **Roll Center Height**: Positioning the roll center above the ground reduces pitch due to height difference with the center of gravity. Rear roll center is set higher than front for stability during corner entry. Static roll center heights are 15.8mm for front and 31mm for rear, maintaining positive and stable values during roll.

- **Kingpin Inclination and Scrub Radius**: Excessive kingpin angles in front lead to camber loss during steering and lifting the car. Kingpin angle reduced to 7º to reduce steering forces and camber gain. Positive scrub radius is maintained.

- **Caster and Trail**: Caster angle's role in generating self-aligning torque and camber gain is vital. The caster angle in front is set to 6.2º, being reduced to enhance driver drivability without losing driver feedback.

- **Anti-dive and Anti-squat**: target values (30% front, 20% rear) for anti-dive and anti-squat help control pitching during braking and acceleration.

- **Motion Ratio**: Optimized motion ratio of 1.2 maintains vehicle stiffness and predictable suspension behavior throughout wheel travel.

- **Ackermann**: Close-to-100% Ackermann minimizes tire slip during low-speed cornering since the Formula Student circuits have very tight turns.

- **Other Considerations**: Damper static length (175mm), alignment of suspension brackets, optimized suspension layout, and longitudinal rear spring configuration are essential design elements.

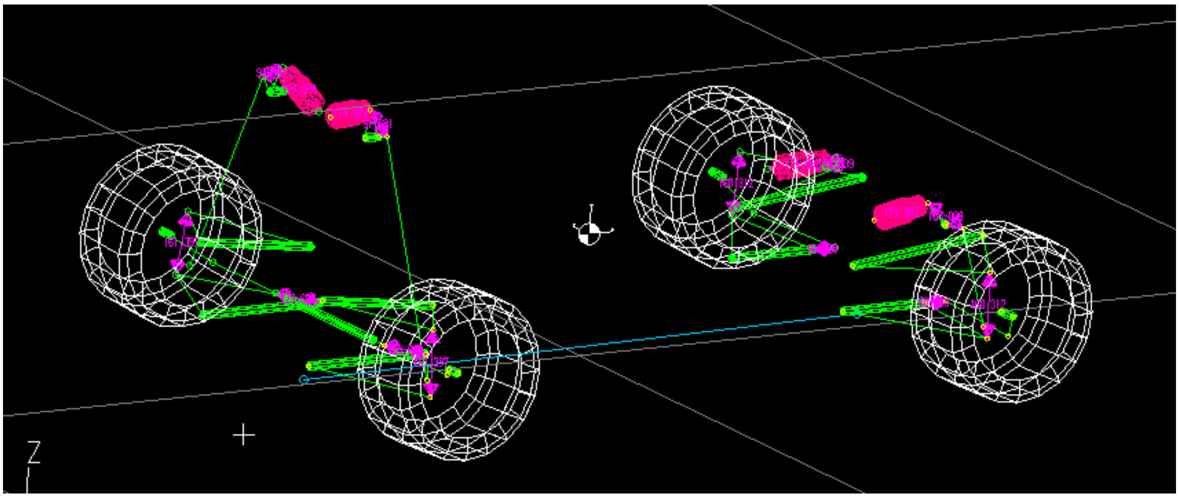

Figure 2: Final suspension configuration using LSA

5. Structural design

Once that the geometry of the suspension is defined, the next step is calculating the forces that it must withstand and designing consequently the suspension arms.

Six critical tubes in this suspension setup include upper and lower wishbones (fore and aft), a push rod, and a steering tie rod. To accurately analyze the suspension forces, a recommended method is the Static Free Body Diagram 6x6 Matrix Method [4]. This method considers all six suspension tubes and their respective forces using a matrix equation, providing a more accurate result than simple assumptions or trigonometry. Different scenarios are considered to calculate the forces in each one. For load calculations, the vehicle's weight distribution, tire characteristics, and lateral and longitudinal accelerations are considered.

	Highest operating force front						
	Up-Fore	**Up-Aft**	**Low-Fore**	**Low-Aft**	**Push/Pull**	**Tie/Toe**	
Fatigue	-165	-1874	-11370	-4314	-515	-1510	N
Buckling	6701	3035	1748	5886	2541	1566	N
Comp	6701	3035	1748	5886	2541	1566	N
Tens	-165	-2503	-16754	-5733	-961	-2302	N

Table 1: Highest operating force front

	Highest operating force rear						
	Up-Fore	**Up-Aft**	**Low-Fore**	**Low-Aft**	**Push/Pull**	**Tie/Toe**	
Fatigue	-279	-1659	-9371	-7735	-492	-1032	N
Buckling	6262	2916	5878	2927	4632	4003	N
Comp	6262	2916	5878	2927	4632	4003	N
Tens	-435	-2343	-14377	-12776	-811	-1427	N

Table 2: Highest operating force rear

The structural analysis of a wishbone evaluates its integrity and durability under loads using carbon fiber tubes and adhesive. Carbon fiber properties, such as tension yield, compression yield, fatigue strength, and Young's modulus, are provided. The analysis focuses on three failure modes: tension, compression (buckling), and fatigue. Tension analysis calculates the stress using force and area, ensuring a safety factor ≥1.2. Fatigue analysis considers cyclic loading and a 25% reduced allowable stress. Buckling analysis uses Euler's formula and requires a safety factor ≥1.2.

Carbon fiber tubes front							
OD	**15**	**15**	**15**	**15**	**15**	**15**	mm
Wall	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	mm
Area	63.61725	63.6172512	63.61725	63.61725	63.61725	63.61725	mm2
Inertia	1467.173	1467.17286	1467.173	1467.173	1467.173	1467.173	mm4
Length	307.0516	316.428396	347.7154	377.3841	568.5749	270.7065	mm
k	1	1	1	1	1	1	
Pcr	10751.18	10123.4413	8383.611	7117.244	3135.478	13831.89	N
Tension Yield	612	612	612	612	612	612	MPa
Comp Yield	456	456	456	456	456	456	MPa
Fatigue	459	459	459	459	459	459	MPa
σ Tension	-2.59705	-39.337537	-263.357	-90.1101	-15.1092	-36.179	Mpa
σ Compression	105.328	47.7021767	27.47888	92.521	39.93525	24.62214	Mpa
σ Fatigue	-2.59705	-29.456907	-178.732	-67.8122	-8.09719	-23.731	Mpa
n tension	235.6518	15.5576594	2.323841	6.791695	40.50505	16.91587	
n compression	1.604492	3.33591573	4.795757	1.209196	1.234163	8.830411	
n fatigue	176.7389	15.5820843	2.568084	6.768693	56.68635	19.34177	

Table 3: Front carbon fiber tubes results

For adhesive design, the selected 3M™ Scotch-Weld™ EC-9323-2 B/A adhesive is considered. structural values are given. Adhesive design involves tension and fatigue cases, with a safety factor of 5. Proper surface preparation is crucial for effective adhesion, involving solvent cleaning, abrasion, or chemical treatments. [5]

Adhesive front							
OD	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	mm
Length	**30**	**30**	**45**	**45**	**30**	**30**	mm
Area	1102.699	1102.69902	1654.049	1654.049	1102.699	1102.699	mm2
Tension Yield	30	30	30	30	30	30	Mpa
comp yield	30	30	30	30	30	30	Mpa
Fatigue	22.5	22.5	22.5	22.5	22.5	22.5	Mpa
σ Tension	-0.14983	-2.2694733	-10.1291	-3.46577	-0.87169	-2.08725	Mpa
σ comp	6.076614	2.75204866	1.05688	3.5585	2.303957	1.420508	Mpa
σ fatigue	-0.14983	-1.6994369	-6.87433	-2.60816	-0.46715	-1.3691	Mpa
n tension	200.227	13.2189263	2.961758	8.656082	34.41605	14.37296	
n comp	4.93696	10.9009701	28.38543	8.430519	13.02108	21.11921	
n fatigue	150.1703	13.2396795	3.273049	8.626766	48.16487	16.43418	

Table 4: Adhesive calculation front

Results involve iterative design for optimal tube and adhesive dimensions. Tube dimensions are chosen based on calculated forces and stresses to meet safety factors. Adhesive thickness of 0.15mm is considered, and insert length is iterated for a bonding area with a safety factor of 5. The final designs ensure structural integrity, durability, and adhesive reliability for the wishbone assembly.

To validate the structural analysis, simulations were performed using ANSYS software to analyze the behavior of carbon fiber tubes, with the aim of comparing results with the previous study. The ANSYS Composite module was employed to model the carbon fiber tubes' behavior. The simulation involved creating a finite element model of the composite material, considering fiber orientation, and stacking sequence provided by the manufacturer. [6]

A parametric model was generated using ANSYS Workbench for efficient analysis. This model allows adjustment of variables for exploring different design configurations. The model's input parameters were maximum load and length of the tubes.

The simulation process included creating geometry, meshing, defining carbon fiber composite properties (fiber orientation, stacking sequence), and exporting the model to the Static Structural module. Tension and compression scenarios were simulated by applying forces and fixing tube ends. Results included von Mises stress and tube displacement.

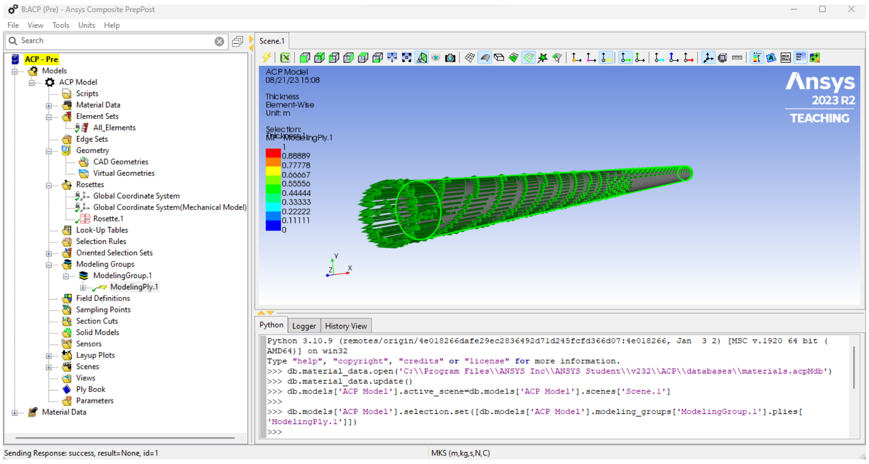

Figure 3: ANSYS composite model

The ANSYS simulations confirmed the validity of the previous structural study with similarities in tension results. Discrepancies in compression results were attributed to the consideration of buckling effects. The overall outcome supported the assumption of tube rigidity and demonstrated the efficiency of the parametric model for evaluating various design configurations.

6. Conclusions

The design and development of the IFS05 suspension system for the Formula Student car have been successfully executed, resulting in substantial performance enhancements. Based on rigorous analysis, validation, and track testing, significant improvements were implemented to address previous version shortcomings and elevate overall car performance.

Key modifications to the IFS05 suspension geometry include:

- Integration of antidive and antisquat geometry to control pitch during braking and acceleration.
- Wheelbase reduction to 1570mm for improved car maneuverability and reduce the minimum turning radius to 3.9m.
- Equalization of track width at 1200mm for enhanced stability.
- Motion ratio optimization to 1.2 for optimal suspension operation.
- Optimization of suspension rod layout for structural integrity and weight reduction.
- Fine-tuning of camber gain and static targets for better tire contact and traction.
- Accurate definition of roll centers to minimize roll forces during dynamics.
- Careful design of steering geometry for 100% Ackermann with maximum steer travel.
- Reduction of steering forces by 22% for improved response and feedback.
- Adjustments to caster and kingpin angles for controlled steering forces and camber gain.

These changes collectively enhance performance, handling, and stability of the IFS05 suspension, providing a refined setup for the Formula Student car. Mechanical design progress includes meticulous analysis of suspension stresses and component design, focusing on load calculations and suspension arm design. Iterative design iterations balanced weight reduction and structural robustness, ensuring reliability and longevity using carbon fiber tubes and adhesive.

The IFS05 suspension design marks a significant leap in performance, safety, and sustainability for the Formula Student car. Successful implementation paves the way for future advancements and underscores the importance of continuous innovation in automotive engineering.

7. References

[1] FSAE, Formula Student Rules, 2023.

[2] W. F. Milliken y D. L. Milliken, Race Car Vehicle Dynamics, 1995.

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DISEÑO Y FABRICACIÓN DE LA SUSPENSIÓN DE UN FORMULA STUDENT

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RESUMEN DEL PROYECTO

Dentro del ámbito de la Formula Student, el sistema de suspensión desempeña un papel fundamental en garantizar un rendimiento y seguridad óptimos del vehículo. Este estudio profundiza en el proceso de diseño y optimización de un sistema de suspensión de vanguardia para un coche de carreras Formula Student. Partiendo de los prototipos de los años anteriores, se corregirá la geometría de la suspensión y se mejorará la maniobrabilidad y el rendimiento de la suspensión, calculando las cargas y diseñando los brazos de suspensión para resistir las condiciones de la pista.

Palabras clave: Formula Student, diseño de la suspensión, suspensión de doble trapecio, pushrod, Lotus Suspension Analysis, camber, toe, caster, kingpin, geometría de Ackermann, brazos de la suspensión, maniobrabilidad, cálculo de fuerzas, diseño de adhesivo, simulación, ANSYS, rendimiento, coeficiente de seguridad.

1. Introducción

La Formula Student es una competición internacional de ingeniería cuyo objetivo es el diseño y la fabricación de un monoplaza de carreras. El objetivo principal es motivar a estudiantes a introducirse en un proyecto real de ingeniería, compitiendo con un coche de carreras en pruebas dinámicas con el coche en pista y en pruebas estáticas para valorar los principios de ingeniería que se han seguido a la hora de diseñar el coche. [1]

La suspensión es el sistema que conecta las ruedas con el chasis del vehículo. Su función principal es absorber las irregularidades del asfalto y optimizar el uso de la huella de contacto del neumático con el suelo, con el fin de aprovechar al máximo su adherencia en recta y en curva, además de otras funciones que se exponen a continuación: [2]

- Proporcionar comodidad, estabilidad, y control al conducir, así como feedback y sensaciones al piloto del estado de los neumáticos y de la pista.

- Absorber los impactos causados por las imperfecciones de la superficie de contacto para que no se transmitan directamente al chasis, manteniendo en todo momento a los neumáticos en contacto con el asfalto.

- Controlar los movimientos que se producen en la suspensión, para mantener al neumático lo más vertical con respecto al suelo durante el recorrido de la suspensión y giro de las ruedas delanteras en curva, así como los movimientos de balanceo y cabeceo que se producen ante aceleraciones laterales y longitudinales.

- Optimizar el manejo y respuesta de la dirección para tener una conducción precisa y adaptable a diferentes condiciones de conducción, permitiendo al piloto tener un mayor control sobre el vehículo.

2. Objetivos

Los objetivos de diseño de la suspensión IFS05 se establecen teniendo en cuenta las mejoras de los prototipos anteriores y los problemas de diseños previos:

- Implementar geometría de antidive y antisquat en la suspensión para controlar eficazmente el exceso de cabeceo distribuyendo las cargas entre los muelles y los componentes de suspensión durante la aceleración y el frenado.

- Reducir la batalla del coche de 1730 mm a 1570 mm, aumentando el ángulo de dirección para mejorar la maniobrabilidad en curvas.

- Igualar el ancho de vía de ambos ejes a 1200 mm para facilitar el diseño simétrico y la fabricación de los componentes de suspensión.

- Optimizar la disposición y el diseño de la suspensión para mejorar el rendimiento y el comportamiento en general.

- Fijar el ángulo estático de caída de los neumáticos y controlar sus movimientos durante el recorrido de la suspensión y la dirección de las ruedas para optimizar la superficie de contacto del neumático.

- Redefinir los centros de balanceo y la geometría de dirección para mejorar la estabilidad y las características de manejo.

- Reducir el ángulo de caster excesivo que genera grandes fuerzas de dirección y un aumento excesivo de la caída durante el giro, lo que puede llevar a un comportamiento no deseado de la suspensión.

- Mejorar y controlar el aumento de caída a lo largo del recorrido de la dirección ajustando los ángulos de caster y Kingpin para lograr ángulos de caída más consistentes y razonables.

- Lograr una geometría de dirección cercana al 100% de Ackermann para mejorar el rendimiento en las curvas y minimizar el deslizamiento de los neumáticos.

- Seleccionar rodamientos adecuados, como rodamientos de bolas de contacto angular, para minimizar la rotación libre entre el soporte y el cubo.

- Optimizar el diseño de las manguetas para reducir la masa y minimizar el contacto potencial con otros componentes, mejorando la eficiencia y el rendimiento en general.

Estos objetivos guían el proceso de diseño, con el objetivo de mejorar el rendimiento general, la estabilidad y las características de manejo del automóvil de competición IFS05. Posteriormente, se explicará el significado y los efectos de cada parámetro.

3. Estado del arte

El mundo de la Formula Student demanda un profundo entendimiento de la geometría y dinámica de la suspensión para lograr un rendimiento y manejo óptimos. La dinámica del vehículo, la ciencia que estudia el movimiento de los vehículos en las carreteras, sirve como base para diseñar suspensiones que sobresalen en aceleración, curvas y calidad de marcha.

La dinámica del vehículo explora cómo los vehículos se mueven y responden en las carreteras, influyendo en la aceleración, estabilidad, control y manejo. Existen muchos factores que influyen en su rendimiento, desde la distribución de masas y el diseño de la suspensión hasta las propiedades de los neumáticos, la aerodinámica y las fuerzas externas que tienen un impacto sinérgico en el comportamiento de un vehículo. Los ingenieros aprovechan estas interacciones para fortalecer la seguridad, el rendimiento y la comodidad del vehículo. [3]

En el centro de este panorama se encuentran varios conceptos fundamentales:

- **Sistemas de Suspensión**: Son la base de la conexión entre las ruedas y el chasis del vehículo, y abarcan desde sistemas McPherson hasta suspensiones neumáticas. En el ámbito de los automóviles de alto rendimiento, la suspensión de doble trapecio con brazos de control en push o pull se destaca, conectando de manera fluida muelles, amortiguadores y barras estabilizadoras.

- **Cinemática**: Esta técnica de analizar el movimiento de las ruedas y la carrocería desvela un conjunto de influencias geométricas que definen el desempeño del automóvil. Los ángulos de los neumáticos, como la inclinación y la convergencia, junto con la geometría de los brazos de control y mangueta, que incluye aspectos como el ángulo de avance, el de salida, el centro de balanceo y la geometría de la dirección, requieren una coordinación meticulosa para optimizar el comportamiento del vehículo.

- **Neumáticos**: Implica entender cómo interactúan los neumáticos con la carretera y las características como el agarre, la tracción y los ángulos de deslizamiento que afectan la conducción.

- **Estabilidad del Vehículo**: Garantiza que el vehículo mantenga su trayectoria prevista y contrarreste movimientos no deseados.

- **Transferencia de Carga**: Durante la aceleración, el frenado y las curvas, el peso se desplaza entre las ruedas, lo que afecta el agarre de los neumáticos. Controlar esta transferencia optimiza la distribución y tracción del agarre de los neumáticos.

- **Aerodinámica**: Las fuerzas aerodinámicas, como la carga y la resistencia, influyen en el comportamiento del vehículo, mejorando el agarre a altas velocidades. No obstante, estas fuerzas deben ser controladas para evitar efectos que provoquen inestabilidad.

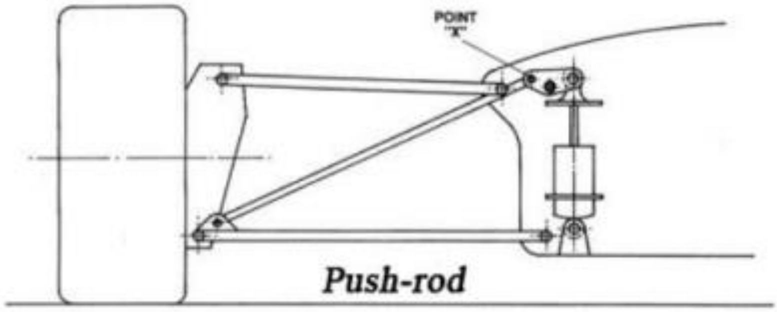

Ilustración 1: configuración push rod

4. Diseño de la suspensión

El diseño del sistema de suspensión para el IFS05 es un aspecto crítico que influye en su rendimiento y características de manejo. La configuración elegida para la suspensión es la de doble trapecio con balancín y pushrod, ya que permite un control preciso de los ángulos y movimientos de los neumáticos. Se ha utilizado el software Lotus Suspension Analysis (LSA) para simular y evaluar varios parámetros y configuraciones de suspensión, optimizando el rendimiento. LSA emplea modelos matemáticos para predecir el comportamiento de la suspensión en diferentes condiciones, considerando la geometría, la cinemática y las fuerzas en los componentes.

- **Camber**: Lograr ángulos de caída óptimos es vital para aplicaciones de carreras. Se prefiere la caída negativa para adaptar el contacto de las llantas a las curvas y al balanceo del cuerpo. Se han establecido objetivos estáticos de caída de -2.5º y -2º para los ejes delantero y trasero, respectivamente, ya que se pueden ajustar agregando cuñas de caída a los soportes.

- **Ángulo de Toe**: Ajustar los ángulos de toe mejora el equilibrio. Se busca un ángulo de toe neutro de 0º, con ajustabilidad mediante cambios en la longitud de la barra de dirección. La convergencia de las barras de suspensión en el mismo punto de rotación minimiza las variaciones de toe en el recorrido de las llantas, asegurando ángulos de toe consistentes, con lo que se conoce como bumpsteer y rollsteer.

- **Altura del centro de balanceo**: Posicionar el centro de balanceo por encima del suelo reduce el balanceo debido a la diferencia de altura con el centro de gravedad. El centro de balanceo trasero se ubica más alto que el delantero para lograr estabilidad en la entrada de las curvas. Las alturas estáticas del centro de balanceo son 15.8 mm para el eje delantero y 31 mm para la parte trasera, manteniendo valores positivos y estables durante el balanceo.

- **Ángulo de Kingpin y Scrub radius**: Ángulos excesivos de Kingpin del eje en el eje delantero provocan pérdida de caída durante la dirección y levantan el coche. El ángulo de Kingpin del eje se redujo a 7º para disminuir las fuerzas de dirección y la ganancia de caída. Se mantiene un scrub raius positivo.

- **Caster y Trail**: El papel del ángulo de caster en la generación de momento de autoalineamiento. El ángulo de caster delantero se establece en 6.2º, y se reduce para mejorar la manejabilidad del piloto sin perder la retroalimentación en el volante.

- **Anti-dive y Anti-squat**: Valores objetivo (30% delantero, 20% trasero) para anti-dive y anti-squat ayudan a controlar el cabeceo durante la frenada y la aceleración.

- **Motio Ratio**: El motion ratio optimizado de 1.2 mantiene la rigidez del vehículo y un comportamiento predecible de la suspensión a lo largo del recorrido de la llanta, al mantenerse constante la relación entre la subida de la rueda y la compresión del muelle.

- **Ackermann**: El Ackermann cercano al 100% minimiza el deslizamiento de los neumáticos durante las curvas a baja velocidad, ya que los circuitos de Formula Student tienen curvas muy cerradas.

- **Otras consideraciones**: La longitud estática del amortiguador (175 mm), la alineación de los soportes de la suspensión, la disposición optimizada de la suspensión y la configuración longitudinal del resorte trasero son elementos de diseño esenciales.

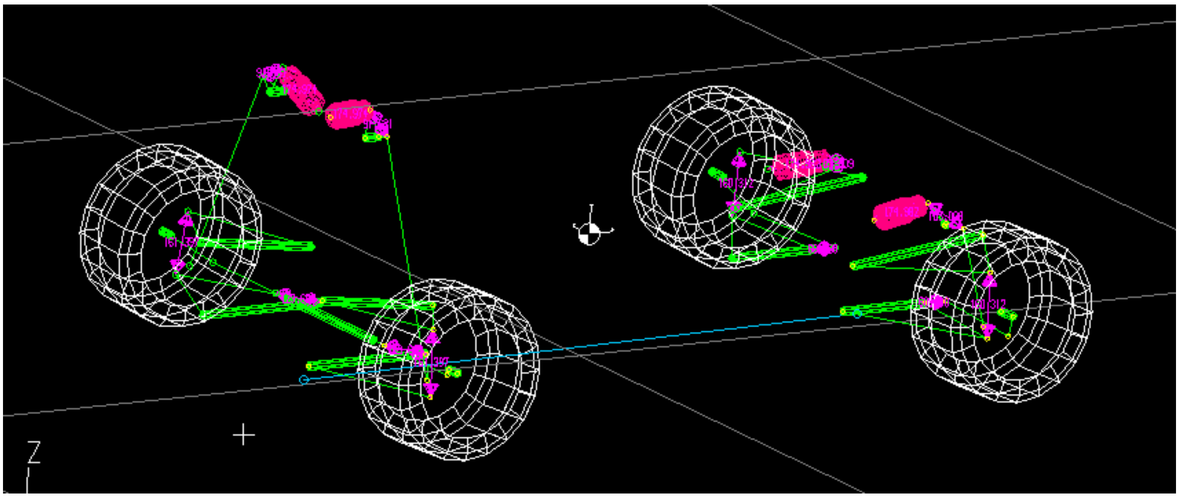

Ilustración 2: diseño final de la suspensión en LSA

5. Diseño estructural

Una vez definida la geometría de la suspensión, el siguiente paso es calcular las fuerzas a las que debe resistir y diseñar en consecuencia los brazos de suspensión.

Seis tubos críticos en esta configuración de suspensión incluyen brazos superiores e inferiores (delanteros y traseros), una barra tipo pushrod y una barra de dirección. Para analizar con precisión las fuerzas en la suspensión, un método recomendado es el Método de la Matriz de Diagrama de Cuerpo Libre Estático 6x6 [4]. Este método considera los seis tubos de suspensión y sus respectivas fuerzas utilizando una ecuación de matriz, lo que proporciona un resultado más preciso que simples suposiciones o trigonometría. Se consideran diferentes escenarios para calcular las fuerzas en cada uno. Para los cálculos de carga, se considera la distribución del peso del vehículo, las características de los neumáticos y las aceleraciones laterales y longitudinales.

	Highest operating force front						
	Up-Fore	Up-Aft	Low-Fore	Low-Aft	Push/Pull	Tie/Toe	
Fatigue	-165	-1874	-11370	-4314	-515	-1510	N
Buckling	6701	3035	1748	5886	2541	1566	N
Comp	6701	3035	1748	5886	2541	1566	N
Tens	-165	-2503	-16754	-5733	-961	-2302	N

Tabla 1: fuerzas máximas eje delantero

	Highest operating force rear						
	Up-Fore	Up-Aft	Low-Fore	Low-Aft	Push/Pull	Tie/Toe	
Fatigue	-279	-1659	-9371	-7735	-492	-1032	N
Buckling	6262	2916	5878	2927	4632	4003	N
Comp	6262	2916	5878	2927	4632	4003	N
Tens	-435	-2343	-14377	-12776	-811	-1427	N

Tabla 2: fuerzas máximas eje trasero

El análisis estructural de un brazo de suspensión evalúa su integridad y durabilidad bajo cargas utilizando tubos de fibra de carbono y adhesivo. Se proporcionan propiedades de fibra de carbono, como límite de elasticidad a tracción, límite de elasticidad a compresión, resistencia a la fatiga y módulo de Young. El análisis se centra en tres modos de fallo: tensión, compresión (pandeo) y fatiga. El análisis de tensión calcula el estrés utilizando la fuerza y el área, asegurando un factor de seguridad ≥1.2. El análisis de fatiga considera la carga cíclica y un estrés admisible reducido en un 25%. El análisis de pandeo utiliza la fórmula de Euler y requiere un factor de seguridad ≥1.2.

Carbon fiber tubes front							
OD	**15**	**15**	**15**	**15**	**15**	**15**	mm
Wall	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	mm
Area	63.61725	63.6172512	63.61725	63.61725	63.61725	63.61725	mm2
Inertia	1467.173	1467.17286	1467.173	1467.173	1467.173	1467.173	mm4
Length	307.0516	316.428396	347.7154	377.3841	568.5749	270.7065	mm
k	1	1	1	1	1	1	
Pcr	10751.18	10123.4413	8383.611	7117.244	3135.478	13831.89	N
Tension Yield	612	612	612	612	612	612	MPa
Comp Yield	456	456	456	456	456	456	MPa
Fatigue	459	459	459	459	459	459	MPa
σ Tension	-2.59705	-39.337537	-263.357	-90.1101	-15.1092	-36.179	Mpa
σ Compression	105.328	47.7021767	27.47888	92.521	39.93525	24.62214	Mpa
σ Fatigue	-2.59705	-29.456907	-178.732	-67.8122	-8.09719	-23.731	Mpa
n tension	235.6518	15.5576594	2.323841	6.791695	40.50505	16.91587	
n compression	1.604492	3.33591573	4.795757	1.209196	1.234163	8.830411	
n fatigue	176.7389	15.5820843	2.568084	6.768693	56.68635	19.34177	

Tabla 3: análisis estructural de los tubos de fibra

Para el diseño del adhesivo, se considera el adhesivo 3M™ Scotch-Weld™ EC-9323-2 B/A seleccionado. Se proporcionan valores estructurales. El diseño del adhesivo implica casos de tensión y fatiga, con un factor de seguridad de 5. La preparación adecuada de la superficie es crucial para una adhesión efectiva, lo que implica limpieza con solvente, abrasión o tratamientos químicos. [5]

Adhesive front							
OD	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	mm
Length	**30**	**30**	**45**	**45**	**30**	**30**	mm
Area	1102.699	1102.69902	1654.049	1654.049	1102.699	1102.699	mm2
Tension Yield	30	30	30	30	30	30	Mpa
comp yield	30	30	30	30	30	30	Mpa
Fatigue	22.5	22.5	22.5	22.5	22.5	22.5	Mpa
σ Tension	-0.14983	-2.2694733	-10.1291	-3.46577	-0.87169	-2.08725	Mpa
σ comp	6.076614	2.75204866	1.05688	3.5585	2.303957	1.420508	Mpa
σ fatigue	-0.14983	-1.6994369	-6.87433	-2.60816	-0.46715	-1.3691	Mpa
n tension	200.227	13.2189263	2.961758	8.656082	34.41605	14.37296	
n comp	4.93696	10.9009701	28.38543	8.430519	13.02108	21.11921	
n fatigue	150.1703	13.2396795	3.273049	8.626766	48.16487	16.43418	

Tabla 4: análisis estructural del adhesivo

Los resultados se obtienen a partir de un método iterativo para obtener dimensiones óptimas de tubos y adhesivos. Las dimensiones de los tubos se eligen en función de las fuerzas y tensiones calculadas para cumplir con los factores de seguridad. Se considera un espesor de adhesivo de 0.15 mm y la longitud del inserto se itera para un área de unión con un factor de seguridad de 5. Los diseños finales aseguran la integridad estructural, durabilidad y confianza del adhesivo para la fabricación de los brazos de suspensión.

Para validar el análisis estructural, se realizaron simulaciones utilizando el software ANSYS para analizar el comportamiento de los tubos de fibra de carbono, con el objetivo de comparar los resultados con el estudio previo. Se empleó el módulo ANSYS Composite para modelar el comportamiento de los tubos de fibra de carbono. La simulación involucró la creación de un modelo de elementos finitos del material compuesto, considerando la orientación de las fibras y la secuencia de apilado proporcionada por el fabricante. [6]

Se generó un modelo paramétrico utilizando ANSYS Workbench para un análisis eficiente. Este modelo permite ajustar variables para explorar diferentes configuraciones de diseño. Los parámetros de entrada del modelo fueron la carga máxima y la longitud de los tubos.

El proceso de simulación incluyó la creación de la geometría, la generación de la malla, la definición de las propiedades del compuesto de fibra de carbono (orientación de las fibras, secuencia de apilado) y la exportación del modelo al módulo Estructural Estático. Se simularon escenarios de tensión y compresión aplicando fuerzas y fijando los extremos de los tubos. Los resultados incluyeron el esfuerzo de Von Mises y el desplazamiento del tubo.

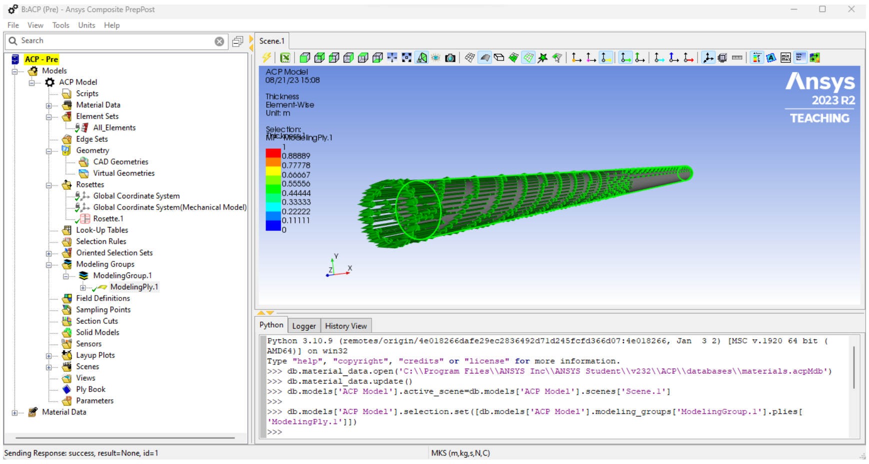

Ilustración 3: modelo del tubo de fibra en ANSYS

Las simulaciones ANSYS confirmaron la validez del estudio estructural previo con similitudes en los resultados de tensión. Las discrepancias en los resultados de compresión se atribuyeron a la consideración de los efectos de pandeo. El resultado general respaldó la suposición de rigidez del tubo y demostró la eficiencia del modelo paramétrico para evaluar varias configuraciones de diseño.

6. Conclusiones

El diseño y desarrollo del sistema de suspensión IFS05 para el coche de Formula Student se ha llevado a cabo con éxito, resultando en mejoras significativas en el rendimiento. Basados en un riguroso análisis, validación y pruebas en pista, se implementaron mejoras significativas para abordar los problemas de versiones anteriores y elevar el rendimiento general del vehículo.

Las modificaciones clave en la geometría de la suspensión IFS05 incluyen:

- La integración de la geometría de antidive y antisquat para controlar el cabeceo durante el frenado y la aceleración.
- La reducción de la batalla a 1570 mm para mejorar la maniobrabilidad del automóvil y reducir el radio de giro mínimo a 3.9 m.
- La igualación del ancho de vía a 1200 mm para una mayor estabilidad y facilidad de diseño.
- La optimización del motion ratio a 1.2 para un funcionamiento óptimo de la suspensión.
- La optimización del diseño de los brazos de suspensión para la integridad estructural y la reducción de peso.
- La afinación de la ganancia de caída y los valores objetivo estáticos para un mejor contacto y tracción de los neumáticos.

- La definición precisa de los centros de balanceo para controlar las fuerzas de balanceo durante la conducción.

- El diseño cuidadoso de la geometría de dirección para un 100% de Ackermann con máxima rotación de dirección.

- La reducción de las fuerzas de dirección en un 22% para una mejor respuesta y retroalimentación.

- Ajustes en los ángulos de caster y pivote de dirección para fuerzas de dirección controladas y ganancia de caída.

Estos cambios mejoran colectivamente el rendimiento, manejo y estabilidad de la suspensión IFS05, proporcionando una configuración refinada para el vehículo. El progreso en el diseño mecánico incluye un análisis meticuloso de las tensiones de la suspensión y el diseño de componentes, centrándose en cálculos de carga y diseño de brazos de suspensión. Las iteraciones de diseño equilibraron la reducción de peso y la robustez estructural, asegurando la confiabilidad y longevidad mediante el uso de tubos de fibra de carbono y adhesivo.

El diseño de la suspensión IFS05 marca un salto significativo en el rendimiento, la seguridad y la sostenibilidad para el automóvil de la Formula Student. La implementación exitosa abre el camino para futuros avances y subraya la importancia de la innovación continua en la ingeniería del automóvil.

7. Referencias

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Chapter 1. INTRODUCTION

1.1 FORMULA STUDENT

Formula Student, also known as Formula SAE, is a renowned international university competition that originated in the United States in the 1980s. Over the years, it has grown exponentially to become one of the largest and most prestigious competitions of its kind worldwide. Each year, thousands of students from universities around the globe come together to participate in the multiple events organized as part of Formula Student. [1]

The heart of Formula Student lies in the construction and development of a single-seater, formula-style racing car by student teams. This multidisciplinary project combines various aspects of engineering, business, and motorsport. Participants are responsible for managing every facet of the project, including business planning, marketing, team management, procurement and sponsorships, component design, manufacturing and assembly, data analysis, logistics, and more. The holistic approach ensures that students gain valuable hands-on experience in all aspects of a real-world engineering project.

The competitions within Formula Student serve as a platform for students to apply their engineering knowledge and skills in a competitive environment. It challenges them to push the boundaries of innovation, design, and performance while adhering to strict technical regulations. The events consist of dynamic challenges, such as acceleration, skid pad, autocross, and endurance races, as well as static events like design presentation, cost analysis, and business plan presentation. Each competition evaluates the performance of the teams, their ability to innovate, and their overall understanding of engineering principles.

Participating in Formula Student offers students numerous benefits beyond technical expertise. It fosters the development of essential skills such as teamwork, project management, problem-solving, and effective communication. The competition also provides a unique networking opportunity, allowing students to interact with industry professionals, potential employers, and other like-minded individuals from the automotive and motorsport industries.

Furthermore, Formula Student serves as a catalyst for innovation in automotive engineering. It encourages students to explore new technologies, lightweight materials, energy-efficient designs, and advanced manufacturing techniques. Many groundbreaking ideas and concepts in the automotive industry have originated from Formula Student projects, demonstrating its significant impact on the field.

Figure 4: Formula Student Italy 2022

It consists in the following events, including statics and dynamic tests:

Engineering design: During the engineering design phase, teams are required to present their car's design to the judges. The presentation focuses on justifying the chosen design over other alternatives, emphasizing the meticulous analysis and development that went into each decision. This includes considerations of aerodynamics, weight distribution, suspension geometry, and overall performance. Judges assess the teams' ability to articulate their design choices and demonstrate a comprehensive understanding of engineering principles.

Cost & Manufacturing: Teams must provide a detailed report outlining the costs associated with the project and the manufacturing processes for each component. This report is thoroughly evaluated by judges, who scrutinize the accuracy of cost estimations and the teams' comprehension of manufacturing techniques. Demonstrating cost-effective solutions and efficient manufacturing strategies contributes to the overall evaluation of the team's practicality and resource management skills.

Business plan: The business plan event simulates a pitch to potential investors. Judges evaluate the quality of the presentation, assessing the team's ability to communicate their project's vision, market potential, and financial viability. Originality, feasibility, and an understanding of market dynamics are key factors in this evaluation. A well-crafted business plan demonstrates the team's entrepreneurial mindset and strategic thinking.

Acceleration: The acceleration event tests the car's ability to achieve rapid acceleration in a straight 75-meter track. Factors such as powertrain performance, traction, and weight distribution play a crucial role in this event. Judges evaluate the teams based on the car's acceleration times, which reflect their engineering prowess in optimizing power-to-weight ratios and maximizing overall performance.

Skidpad: Teams must navigate a figure-eight-shaped circular track known as the skidpad. This event emphasizes the car's performance in steady-state cornering. This test assesses the car's lateral grip, handling, and stability, evaluating the team's ability to design an effective suspension system, select appropriate tires, and optimize vehicle dynamics for improved cornering.

Autocross: The autocross event challenges teams to achieve the fastest lap time on a cone-marked circuit. It assesses the car's overall handling, responsiveness, and agility. The autocross evaluates the teams based on their driving skill, car control, and the ability to set up the vehicle for optimal performance. The times achieved in this event determine the starting order for the Endurance race.

Endurance: The endurance event is the pinnacle of the competition and showcases the car's reliability and efficiency. Teams must complete a gruelling 22-kilometer race, where endurance and fuel efficiency are critical factors. It assesses the teams based on their ability to finish the race and the car's overall performance under demanding conditions.

Figure 5: IFS04 during the autocross test

These events in Formula Student encompass a wide range of engineering disciplines, including mechanical design, aerodynamics, vehicle dynamics, cost analysis, and business planning. They provide a comprehensive evaluation of the teams' engineering capabilities, innovation, practicality, and ability to execute a successful project, being the winner of the competition the team that scores the most points overall in all disciplines.

Event Points Distribution	
Engineering Design	150 - 200 points
Cost & Manufacturing	100 - 150 points
Business Plan	75 - 100 points
Acceleration	75 - 100 points
Skidpad	50 - 75 points
Autocross	100 - 125 points
Endurance	300 - 400 points

Table 5: Formula Student Scoring points

1.2 MOTIVATION

Ever since I can remember, I have been captivated by the world of motorsports, particularly high-performance racing. My lifelong dedication to following Formula 1 led me to pursue an engineering career with the ultimate goal of designing and manufacturing cars.

During my university years, I had the privilege of participating in the Formula Student project, a competition where students from around the globe design and construct their own formula-style racing cars for inter-university challenges. Over the past three years, I have embraced the Formula Student experience, taking on the responsibility of leading the Dynamics and Suspension department. Witnessing the team's growth and relentless pursuit of knowledge throughout the project has been incredibly rewarding.

As I am close to the completion of my engineering studies, I am thrilled to seize the opportunity to focus my master's thesis on the realm that truly ignites my passion, the world of racing, specifically with the ISC Formula Student Racing Team. This team has become an integral part of my journey, and the countless hours invested in its success have brought me immense joy.

My thesis serves as a conduit to merge my ardour for motorsports with my engineering expertise, empowering me to contribute to the advancement and optimization of race car performance. I am grateful for the chance to further expand my comprehension of the intricacies within racing engineering and to make a meaningful impact in the field.

I am eagerly prepared to embark on this new chapter, leveraging the knowledge and skills acquired throughout my academic pursuits and practical experiences within the Formula Student project. It is my aspiration that this research will not only propel my personal growth but also catalyse positive transformations within the racing industry.

I express deep gratitude for the unwavering support and opportunities provided by both the university and the ISC Formula Student Racing Team. They have been pivotal in shaping my career aspirations and nurturing my passion for motorsports. Anticipating the challenges and rewards that lie ahead, I eagerly embrace the journey of delving deeper into the realm of racing engineering, striving to leave an indelible mark on this exhilarating and ever-evolving field.

The 2022/2023 season presented significant challenges for the suspension systems of our Formula Student car. The existing design exhibited various issues stemming from the project's early stages, demanding a fresh approach to enhance competitiveness.

Driven by the desire to overcome these hurdles, I embarked on my master’s thesis project to document the process of designing a new suspension system that could effectively address the car's problems. Leading the department added to my responsibility, compelling me to complete the project within a year to participate in Formula Student competitions and showcase the extensive behind-the-scenes work.

Moreover, the suspension of a race car holds relevance beyond the Formula Student realm and finds practical application in the broader automotive industry. The knowledge and skills gained from researching and designing a Formula Student suspension have the potential to be transferable to projects and positions in the field of high-performance vehicles and engineering.

Through meticulous documentation and comprehensive analysis of the challenges faced during the suspension design process, my aim is to contribute not only to the success of our Formula Student team but also to the advancement of suspension design practices in the automotive industry at large. By addressing the shortcomings of our current system and exploring innovative solutions, I hope to make a meaningful impact on the future of suspension technology.

Figure 6: Me with some of the Dynamics & Suspension team members

1.3 THE IFS04 AND IFS05

The IFS04, the fourth concept car of the ISC Formula Student Racing Team, served as an upgrade to the IFS03 for the 2021/2022 season. It participated in Formula Student Italy and Formula Student Spain, becoming the first prototype to pass technical inspections and successfully complete dynamic tests.

Figure 7: IFS04 during the autocross test

During track testing, it became apparent that the car had several dynamic issues, primarily related to the suspension system. Manoeuvrability was a significant concern, as the car struggled to navigate tight turns and lacked agility when required. Additionally, the geometry of the tires was inconsistent with wheel travel, resulting in suboptimal tire contact patches.

Excessive pitch was another challenge, leading to impacts on the front wing during braking manoeuvres. Recognizing the need for improvement, the team decided to focus on enhancing the suspension system for the IFS05, the prototype for the 2022/2023 season.

The IFS05 represents a substantial improvement over the IFS04, with a strong emphasis on car performance and functionality. The goal of this new project is to address the mechanical and electrical issues encountered during previous competitions.

To ensure a successful season, the team meticulously planned and defined objectives for each department, aiming to overcome challenges, optimize performance, and achieve their desired goals.

Figure 8: Detail of the front suspension of the IFS04

1.4 OBJECTIVES

This report presents the design of the suspension system for the IFS05, which represents an evolution of the previous suspension setup. The primary objective is to improve the car's behaviour and performance. To achieve this, the front uprights will undergo a redesign with the following goals in mind. However, it is worth noting that the rear uprights will remain unchanged from the IFS03 and IFS04 due to cost reduction and reuse of pieces. Taking this in consideration, the design goals are as follows:

- Implement antidive and antisquat geometry in the suspension to effectively control excessive pitch by distributing loads between the springs and suspension components during acceleration and braking.
- Reduce the wheelbase of the car from 1730mm to 1570mm, increasing the steering angle for improved manoeuvrability in curves.
- Equalize the track width of both axles to 1200mm to facilitate symmetrical design and manufacturing of suspension components.
- Optimize the layout and design of the suspension to enhance overall performance and behaviour.
- Fix the static camber angle of the tires and control their movements during suspension travel and wheel steering to optimize the tire contact patch.
- Redefine the roll centers and steering geometry to improve stability and handling characteristics.
- Reduce excessive caster angle that generates large steering forces and excessive camber gain during turning, which can lead to undesirable suspension behaviour.
- Improve and control camber gain throughout the steering travel by adjusting the caster and kingpin angles to achieve more consistent and reasonable camber angles.
- Achieve steering geometry close to 100% Ackermann to improve cornering performance and minimize tire slip.

- Select suitable bearings, such as angle contact ball bearings, to minimize free rotation between the upright and hub.
- Optimize the design of the uprights to reduce mass and minimize potential contact with other components, enhancing overall efficiency and performance.

These objectives guide the design process, aiming to enhance the overall performance, stability, and handling characteristics of the IFS05 race car. Later, it will be explained the meaning and effects of each parameter.

1.5 WORKING METHODOLOGY

The working methodology in this master's thesis project aligns with the needs and timelines of the Formula Student team, which follows well-defined stages of design, manufacturing, and on-track validation to ensure the timely preparation of the car for competitions.

1. **Conceptual Design**: During this stage, the suspension design objectives and requirements for the Formula Student car are conceptualized and defined. Different configurations are explored, and preliminary evaluations of each conceptual design are conducted. Building upon the previous car, the most significant changes to be implemented in the new season are determined.

2. **Planning**: In this phase, a detailed work plan is established, including deadlines, required resources, and specific activities. The work sequence is determined, and responsibilities are assigned to team members. Possible risks are identified, and strategies for risk mitigation are developed.

3. **Design Phase**: This stage involves the detailed design of the suspension. Computer-aided design (CAD) tools are utilized to create 3D virtual models of the suspension

components and their assembly. Dimensions, materials, and manufacturing methods for each component are defined. Additionally, finite element analysis (FEA) is conducted to assess the structural performance and strength of the components.

4. **Validation and Optimization Phase**: During this stage, the proposed suspension design is validated and optimized. Virtual tests and simulations are performed to evaluate the performance of the suspension under different loading and handling conditions. The results obtained from these tests are used to make adjustments and improvements to the initial design.

5. **Manufacturing and Assembly Phase**: Once the suspension design is validated and optimized, the manufacturing of the suspension components begins. Appropriate materials are selected, and manufacturing techniques such as machining or adhesive methods are employed to produce the components according to specifications. The suspension is then assembled on the vehicle, ensuring proper installation and adjustment of all components.

It is essential to note that these stages may vary depending on the specific focus and objectives of the Formula Student suspension thesis. Adapting the methodology to the project's requirements and having the support of the project supervisor are crucial for ensuring the quality and success of the work.

1.6 RESOURCES

The resources to be used for the completion of the master’s thesis project are as follows:

- **Lotus Suspension Analysis**: This tool developed by Lotus is utilized for modelling and analysing suspension geometry. It provides free licenses for Formula Student teams and offers multiple configuration options to maximize suspension performance and optimize associated parameters. Additionally, Lotus can visually represent suspension parameters based on various car movements such as wheel travel, vehicle roll, and steering input.

- **MATLAB**: MATLAB is a programming and numerical computing platform widely used in the engineering field. It is an interactive program that enables calculations, numerical simulations, data visualization and analysis, and model creation. In this project, MATLAB will be employed for calculating car stiffness, determining spring and anti-roll bar rates, and optimizing the damping system's geometry.
- **Excel**: Microsoft Excel is a spreadsheet program commonly used for tasks related to numerical data analysis and management. It is a valuable tool for organizing, manipulating, analysing, and visualizing data efficiently. In engineering applications, Excel can be utilized to automate calculations swiftly, such as determining forces in suspension components.
- **SolidWorks**: SolidWorks is a widely used CAD (Computer-Aided Design) tool employed in the industry for designing complex parts and assemblies. It will be utilized in this project to design suspension components, create their assembly, and generate engineering drawings.
- **Ansys**: Ansys is a comprehensive Multiphysics CAE (Computer-Aided Engineering) software used for finite element analysis (FEA). Critical suspension components will undergo validation in Ansys to verify their structural integrity and optimize their properties.

These resources collectively provide the necessary tools for modelling, analysing, and optimizing the suspension system, ensuring its performance, reliability, and functionality in the Formula Student car.

Chapter 2. STATE OF ART

2.1 *INTRODUCTION TO VEHICLE DYNAMICS*

Vehicle dynamics is a branch of engineering that focuses on the study of how vehicles move and behave on the road. It encompasses the principles and concepts related to the motion, stability, handling, and control of the car. Understanding vehicle dynamics is crucial for designing and optimizing various aspects of vehicle performance, including acceleration, braking, cornering, and overall ride quality.

The behaviour of a vehicle is influenced by numerous factors, such as its mass distribution, suspension design, tire characteristics, aerodynamics, and the forces acting upon it, such as gravity, aerodynamic drag, and tire-road interaction. By analysing these factors and their interactions, engineers can make informed decisions to improve vehicle performance, safety, and comfort. [7]

Vehicle dynamics involve the study of various fundamental concepts and principles, including:

- **Kinematics**: Kinematics deal with the study of vehicle motion without considering the forces that cause that motion. It focuses on parameters such as position, velocity, and acceleration of different vehicle components, including the body, wheels, and suspension.
- **Tire Mechanics**: Tire mechanics is concerned with understanding the behaviour of tires and their interaction with the road surface. It involves studying tire characteristics such as grip, traction, and slip angles, which greatly influence vehicle handling and stability.

- **Suspension Systems**: Suspension systems play a critical role in controlling the vehicle's ride comfort, handling, and stability. Understanding the design and behaviour of suspensions is essential for optimizing vehicle dynamics. Suspension components, such as springs, dampers, and anti-roll bars, affect how the vehicle responds to bumps, cornering forces, and braking.
- **Vehicle Stability**: Vehicle stability refers to the ability of a vehicle to maintain its desired path and resist undesirable motions, such as oversteer and understeer. Achieving stability involves balancing the forces acting on the vehicle and designing systems that enhance stability, such as electronic stability control.
- **Vehicle Control Systems**: Advanced vehicle control systems, such as anti-lock braking systems (ABS), traction control systems (TCS), and electronic stability control (ESC), are designed to enhance vehicle safety and performance. These systems use sensors and actuators to monitor and adjust various vehicle parameters in real-time, improving stability and control.

The field of vehicle dynamics combines engineering principles, mathematical modelling, computer simulations, and experimental testing to analyse and optimize the performance of vehicles in different operating conditions. By understanding and applying the principles of vehicle dynamics, engineers can design safer, more efficient, and better-performing vehicles for various applications, including passenger cars, racing vehicles, commercial trucks, and motorcycles.

First, it is essential to understand how a vehicle responds to external forces it experiences on the track.

One aspect to consider is the transfer of longitudinal and lateral loads, which occurs due to the balance of forces between the forces acting at the vehicle's center of gravity and the reactions at the tires.

During acceleration, the rear axis becomes loaded (which is why many competition cars have rear-wheel drive), while during braking, the front tires bear the load. In cornering, the outer tires experience increased loading due to lateral forces. The magnitudes of these load transfers depend on the vehicle's dimensions and the height of its center of gravity. Minimizing load transfer is important to maximize and distribute tire grip evenly.

By understanding these load transfer mechanisms, engineers can optimize the vehicle's weight distribution, suspension geometry, and setup to achieve better handling and performance. This includes adjustments to components such as springs, anti-roll bars, and dampers to control the transfer of loads and optimize tire contact with the road surface.

Additionally, aerodynamic forces, such as downforce and drag, also affect the vehicle's behaviour. Downforce generated by aerodynamic elements, such as wings and spoilers, increases tire grip and stability at high speeds. However, it also introduces additional load transfer effects that need to be carefully managed to maintain a balanced and predictable vehicle response.

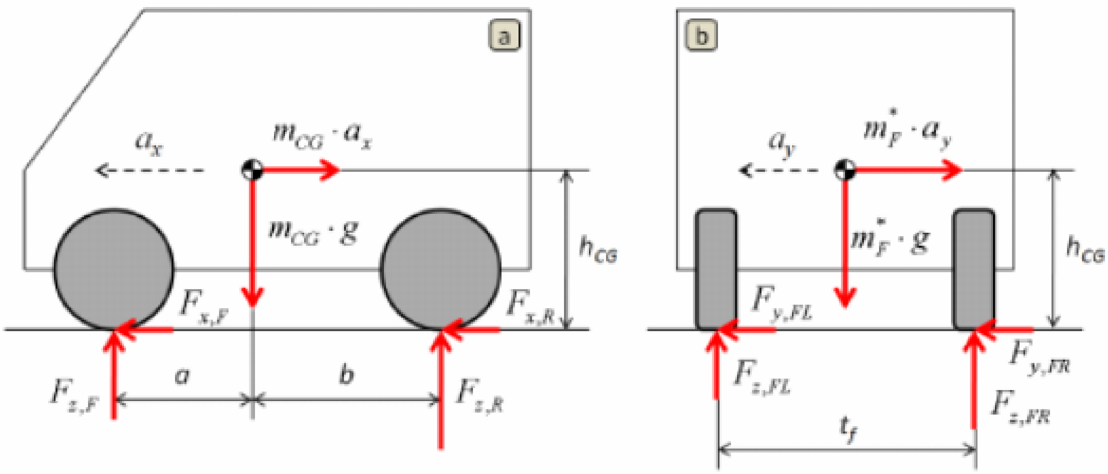

Figure 9: Load transfer in vehicles

The formulation behind the load transfer is an equilibrium of forces and momentums, with dependency on the geometry of the car and the accelerations. [8]

$$\Delta \text{Wlong} = \frac{\text{m} \cdot \text{ax} \cdot \text{h}}{L} \qquad \Delta \text{Wlat} = \frac{\text{m} \cdot \text{ay} \cdot \text{h}}{t} \tag{1}$$

The forces acting on a vehicle induce relative motion between the chassis and the suspension, resulting in rotational movements:

- **Roll**: This refers to the rotation around the longitudinal axis of the vehicle, caused by lateral forces during cornering. It leads to a tendency for the vehicle to roll or tilt sideways.
- **Pitch**: It involves rotation around the lateral axis of the vehicle, caused by longitudinal forces such as acceleration and braking. During acceleration, the front end rises, and the rear end dips. Conversely, during braking, the front-end dips, and the rear end rises.
- **Yaw**: This refers to rotation around the vertical axis of the vehicle. Yaw motion occurs when the vehicle experiences side-to-side movement, such as during skidding or steering by the driver.

Managing these rotational motions is crucial for vehicle dynamics as they directly impact stability, handling, wheel travel, and overall performance. Suspension design and tuning, including components like anti-roll bars, dampers, and springs, play a vital role in controlling these movements and maintaining vehicle balance.

To analyse and predict the behaviour of the vehicle during roll, pitch, and yaw motions, mathematical models and simulation tools are utilized. These models consider the vehicle's geometry, suspension characteristics, and external forces acting on the vehicle. By optimizing suspension design and fine-tuning components, engineers can enhance stability, handling, and the overall driving experience.

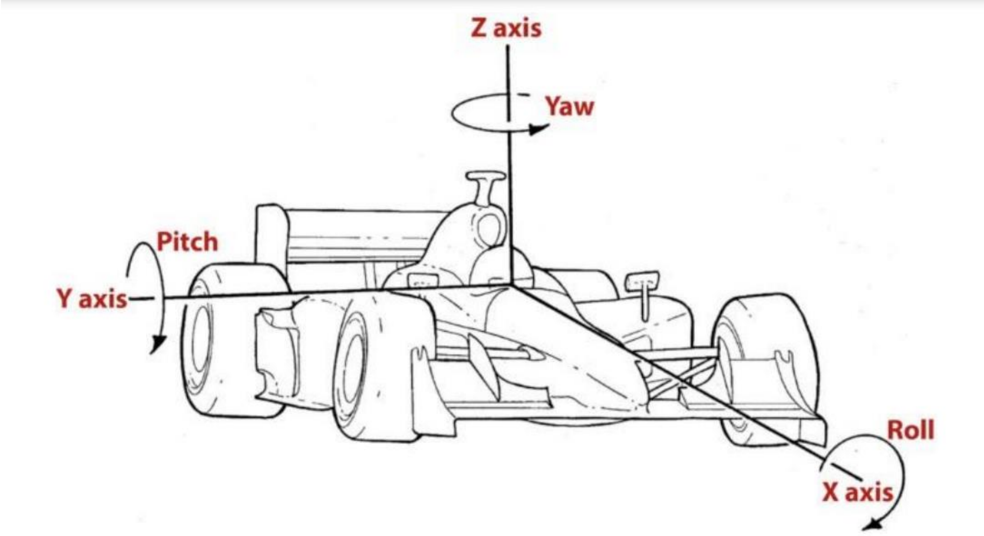

Figure 10: Car movements

2.2 *SUSPENSION TYPES*

Since the invention of wheeled vehicles, suspension systems have been continually developed to enhance stability and comfort for users. In recent decades, significant progress has been made with the emergence of modern motorized vehicles. Engineers and manufacturers have devoted substantial effort to improving the performance, stability, and manoeuvrability of these high-performance vehicles, with a focus on key areas of development, including:

- **Suspension Geometry**: Optimization of suspension geometry is paramount in achieving an optimal balance between comfort and performance. This entails adjusting parameters such as camber, caster, toe, and convergence to enhance suspension response in various driving scenarios.
- **Materials and Weight**: Weight reduction is critical in race car suspension design. Lighter and stronger materials, such as aluminium alloys and composites, have been employed to minimize unsprang mass and enhance vehicle agility.

- **Damping Systems**: Dampers, or shock absorbers, play a vital role in suspension performance. The development of electronically adjustable damping systems enables drivers to adapt suspension stiffness and response in real-time, based on track conditions and driving preferences.
- **Aerodynamics**: Aerodynamics significantly influence the efficiency and stability of race cars. Certain suspension systems are designed to collaborate with active aerodynamic elements like wings and diffusers, improving grip and stability at high speeds.

These advancements in suspension design and technology have substantially improved overall vehicle performance and driving experiences. Ongoing research and development endeavours continue to push the boundaries, aiming to achieve even higher levels of performance, stability, and comfort.

Different constructive solutions have been developed to meet the requirements of suspensions. However, there is no perfect suspension model that optimizes every parameter and can be used in all circumstances. Instead, different models have been proposed to adapt to specific vehicle usage, specific conditions, or budget constraints. Several types of suspensions are used in vehicles, both in race cars and everyday automobiles. Here are some of the most common types:

- **McPherson Suspension**: This type of suspension features the spring-damper system directly acting on the upright. It is widely used in passenger cars as it allows for a compact suspension design in a limited space. However, it is not commonly used in racing vehicles due to the requirement of a heavy spring-damper system and the inability to adjust wheel travel.

Figure 11: McPherson suspension

- **Double Wishbone Suspension**: Also known as an A-arm suspension, this design utilizes two triangular upper and lower control arms to connect the wheel to the chassis. It offers precise control over wheel movement, resulting in excellent stability and handling. It is commonly used in high-performance vehicles and race cars.

Figure 12: Double wishbone suspension

- **Solid Axis Suspension**: This type of suspension connects both wheels of an axis through a rigid axle. While simple and robust, this suspension tends to offer a less smooth ride quality and may have limitations in terms of grip and comfort, especially on uneven surfaces.

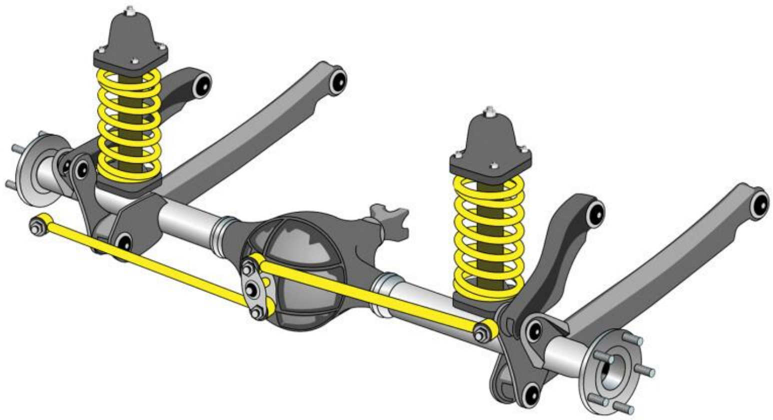

Figure 13: Solid Axle Suspension

- **Air Suspension**: This system uses airbags instead of conventional metal springs. It allows for electronic height adjustment and can adapt to different loads and driving conditions. Air suspension provides improved comfort, height control, and enhanced load-carrying capability.

Figure 14: Air Suspension

- **Leaf Spring Suspension**: This type of suspension is commonly used in vehicles, especially trucks and off-road vehicles. It consists of curved steel bars, called leaf springs, placed longitudinally beneath the vehicle chassis, and connected to the axles and wheels. It provides a robust suspension capable of supporting heavy loads but may offer a rougher and less comfortable ride compared to more advanced suspension systems. Although it has been largely replaced by other suspension designs, it is still used in specific applications that require high strength and load-carrying capacity.

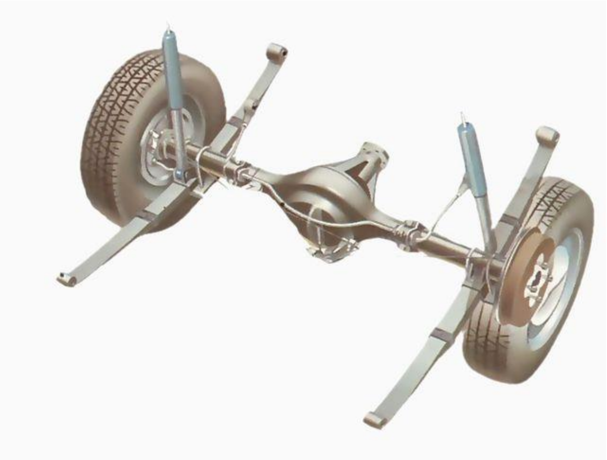

Figure 15: Leaf Spring Suspension

These are just a few examples of suspension types used in vehicles. Each type has its own characteristics and advantages, and the choice of suspension type depends on the vehicle's usage, performance requirements, and preferences.

For the suspension of the Formula Student, the chosen suspension is the double wishbone push-rod suspension. The double wishbone push rod suspension offers several advantages that contribute to its superior performance and handling characteristics.

The double wishbone suspension allows for precise control of wheel movement and geometry throughout its range of motion. The design of the upper and lower control arms provides a balanced and symmetrical setup, resulting in improved handling, stability, and responsiveness. This precise control is especially evident during cornering and high-speed manoeuvres, where the suspension, if it is designed correctly, keeps the tire in optimal contact with the road surface.

The double wishbone configuration also offers better control over the camber angle, which is the vertical tilt of the wheel. By optimizing the camber angle, the tire's contact patch can be maximized, ensuring consistent and optimal grip. This feature is crucial for maintaining traction and enhancing cornering performance, especially during aggressive driving or in speed competitions.

The push rod arrangement in the double wishbone suspension allows for a more compact and streamlined design. By using push rods to transfer forces from the suspension to the dampers or shock absorbers, the suspension components can be better positioned, providing more space for other vehicle systems, and optimizing weight distribution. This leads to improved handling and responsiveness, as well as enhanced overall vehicle performance. Also, the fact that the inboard end of the pushrod come to the top of the chassis helps making any quick adjustment easily, as it is more accessible than with pullrod configurations.

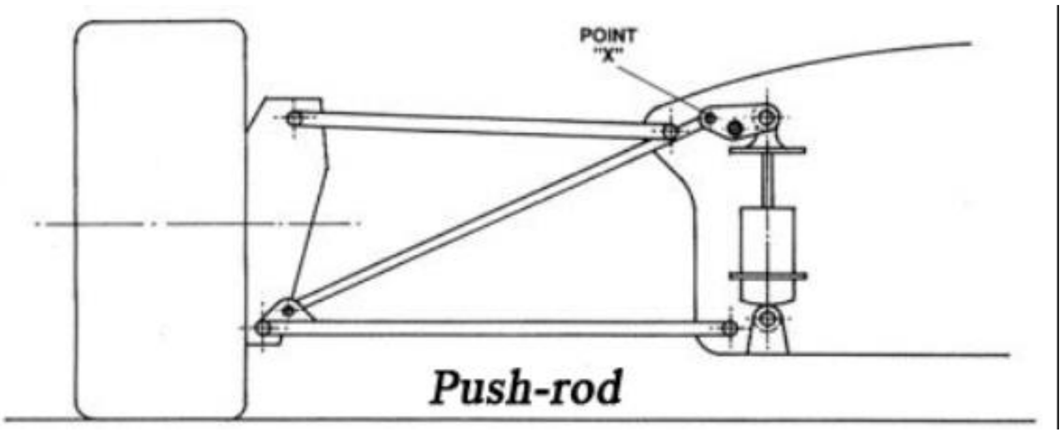

Figure 16: Push-rod suspension

Additionally, the push rod suspension offers the ability to fine-tune and adjust suspension settings. The push rod can be designed with adjustable attachment points, allowing for changes in suspension geometry, damping characteristics, and ride height. This adjustability provides flexibility in adapting the suspension to different driving conditions, preferences, and track requirements.

Overall, the double wishbone push rod suspension delivers improved control, stability, and responsiveness, making it a popular choice in high-performance vehicles and race cars. Its precise wheel control, optimized camber angles, compact design, and adjustability contribute to enhanced handling, traction, and overall driving experience.

2.3 SUSPENSION COMPONENTS

The suspension to be used for this project is the double wishbone push-rod suspension, based on the reasons previously discussed. It consists of the following main components:

1. **Upright**: Its function is to house the wheel hub, allowing the wheel to rotate, and connect it to the suspension arms.
2. **Upper Control Arm**: Connects the upright to the chassis at the top.
3. **Lower Control Arm**: Connects the upright to the chassis at the bottom.
4. **Tie Rods**: These rods fix the direction to which the wheels are steered.
5. **Push-rod**: Transmits vertical forces to the spring-damper system.
6. **Rocker**: Connects the push bar to the spring-damper system. It defines the motion ratio, which represents the relationship between the wheel's upward movement and the compression of the damper.

7. **Spring-Damper Assembly**: Absorbs vertical forces from the wheel, allowing suspension movement, dissipating energy, and keeping the wheel in contact with the ground.
8. **Anti-Roll Bar**: Controls the vehicle's roll during cornering.

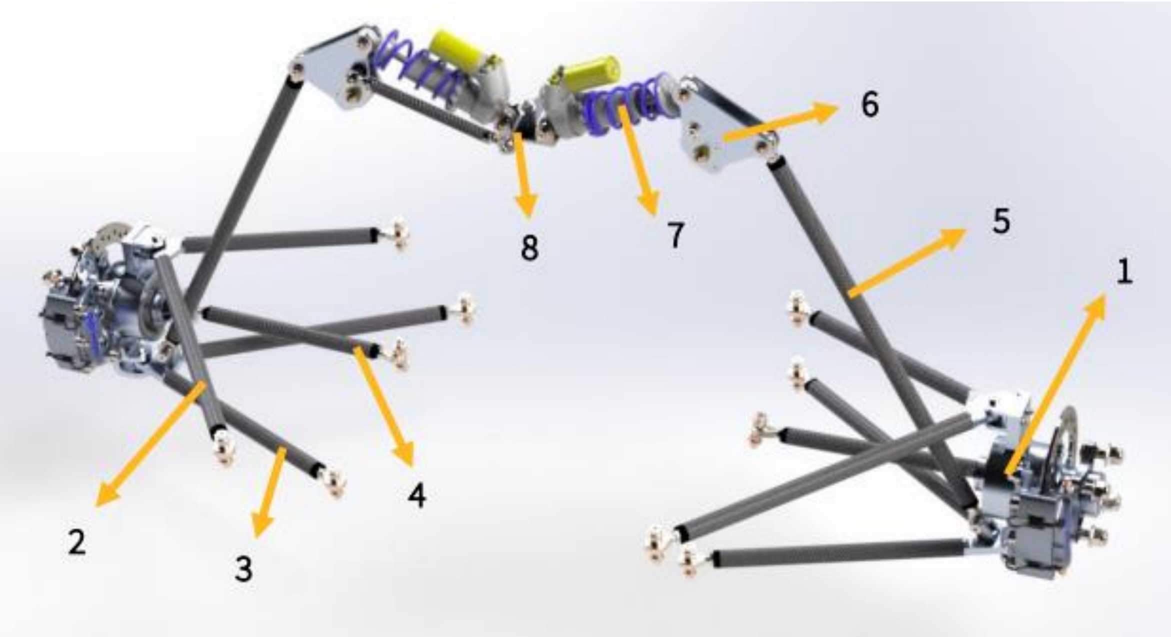

Figure 17: Suspnesion components

These components work together to provide precise control over wheel movement, optimize camber angles, and ensure stability and grip. The suspension design allows for adjustments to fine-tune performance according to specific track conditions and driver preferences. The double wishbone push-type suspension is commonly used in high-performance vehicles and race cars due to its superior handling capabilities.

2.4 *SUSPENSION GEOMETRY*

Suspension geometry refers to the arrangement and design of the various components that make up a vehicle's suspension system. It plays a crucial role in determining the behaviour and performance of the suspension, including handling, stability, and ride quality. [9]

2.4.1 *CAMBER*

Camber refers to the angle that the wheel plane makes with the vertical axis when viewed from the front of the vehicle. It is an essential suspension geometry parameter that affects tire performance and vehicle handling.

Positive camber is when the top of the wheel tilts away from the vehicle's centerline, creating a "V" shape. Negative camber, on the other hand, is when the top of the wheel tilts towards the centerline, forming an inverted "V" shape.

Camber plays a crucial role in optimizing the tire contact patch during cornering. When a vehicle corners, the body rolls and weight transfers to the outside wheels. Positive camber helps counteract the effects of body roll by tilting the wheels more vertically, increasing the contact patch and maintaining better grip. It helps improve cornering stability and prevents excessive tire wear on the outer edges during turns.

However, excessive positive camber can lead to a reduction in straight-line stability and cause uneven tire wear on the inner edges. Negative camber, on the other hand, enhances cornering performance by tilting the wheels inward, maximizing the contact patch during aggressive turns. It improves grip and handling characteristics.

The optimal camber angle depends on various factors such as the vehicle's suspension design, tire characteristics, driving conditions, and driver preferences. It is typically set by engineers based on a balance between tire wear, handling performance, and comfort. In racing or performance applications, camber angles may be adjusted to suit specific track conditions and driving styles. [2]

Figure 18: Negative Camber angle in a Formula 1

2.4.2 TOE

Toe angle refers to the angle formed between the wheel plane and the vertical plane when viewed from above. It is an important suspension geometry parameter that influences the vehicle's handling characteristics. [2]

Toe angle can be adjusted dynamically as the steering wheel is turned, but it can also be set statically to slightly modify the vehicle's behaviour. Toe-in occurs when the leading edges of the wheels are closer together than the trailing edges, creating a "V" shape from the top view of the car. On the other hand, toe-out refers to the leading edges of the wheels being farther apart than the trailing edges, forming an inverted "V" shape.

Toe angle directly affects the vehicle's stability, straight-line tracking, and cornering performance. A slight amount of toe-in is commonly used to enhance straight-line stability by creating a slight resistance to changes in direction. It helps the wheels naturally align with the direction of travel, promoting better tracking and reducing the tendency for the vehicle to wander.

Toe-out, on the other hand, promotes improved cornering behaviour by allowing the wheels to turn more easily and with reduced scrubbing during turns. It helps initiate quicker and more responsive turn-ins, providing better agility and cornering grip.

However, excessive toe-in or toe-out can have negative effects on tire wear and handling. Excessive toe-in may lead to accelerated tire wear on the outer edges and increased rolling resistance, while excessive toe-out can cause wear on the inner edges and make the vehicle less stable in a straight line.

The optimal toe setting depends on factors such as the vehicle's design, suspension characteristics, driving conditions, and intended use. Manufacturers typically specify recommended toe values for each vehicle model to provide a balance between stability, handling, and tire wear.

It is important to note that toe settings can also interact with other suspension parameters, such as camber and caster. Therefore, proper alignment and periodic checks are crucial to maintain optimal toe angles and ensure safe and efficient vehicle operation.

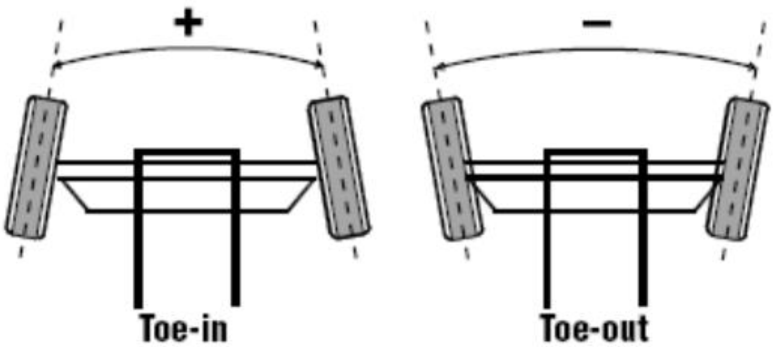

Figure 19: Toe settings

2.4.3 KINGPIN INCLINATION AND SCRUB RADIUS

Kingpin inclination is the angle formed by the axis of the suspension pivot points on the wheel and the vertical axis when viewed from the front of the vehicle. It is the axis around which the steering wheels rotate, affecting the rotation of the front wheels. The kingpin inclination influences the camber change during steering input, allowing the wheels to tilt inward or outward.

The scrub radius is the distance between the center of the tire contact patch and the extended axis of the kingpin, when viewed from the front of the vehicle. It induces a tendency for the tire to move in a straight line, which can be beneficial for stability in wheel movement if not increased excessively. However, it causes a slight rise in the vehicle with steering input, which can make it more challenging to turn the steering wheel.

The kingpin inclination and scrub radius play significant roles in the vehicle's steering characteristics and overall handling. The kingpin inclination affects the camber change during steering, helping maintain optimal tire contact with the road surface and improving cornering grip. The scrub radius influences the tire's self-aligning torque, contributing to the vehicle's straight-line stability and steering response.

A properly designed kingpin inclination and scrub radius can provide a balance between stability, steering effort, and responsiveness. It is essential to consider these parameters in the overall suspension geometry design to achieve the desired handling characteristics and ensure safe and predictable steering behaviour.

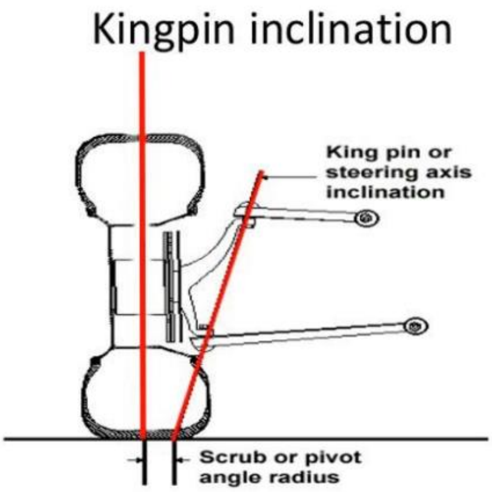

Figure 20: Kingpin inclination and scrub radius

2.4.4 CASTER ANGLE AND TRAIL

Caster is the angle formed between the suspension pivot axis and the vertical axis when viewed from the side of the vehicle. It has a significant influence on the self-aligning moment, which is the force that the tire exerts to return to its original position when the steering wheel is turned. A larger caster angle results in a greater self-aligning moment for the same steering input, but it can also lead to increased instability.

Trail is the distance between the intersection point of the caster line with the ground and the center of the tire contact patch. It represents the longitudinal offset between the tire contact patch and the point of intersection with the caster line. Trail plays a crucial role in determining the self-aligning torque and steering stability of the vehicle. [2]

The caster angle affects the vehicle's straight-line stability, steering feel, and returnability. A positive caster angle, where the pivot axis is inclined rearward from the vertical axis, helps promote straight-line stability and enhances the self-aligning torque. It creates a self-centering effect that improves the vehicle's ability to track straight and reduces the steering effort required to maintain a straight path but increases the steering forces in the steering wheel.

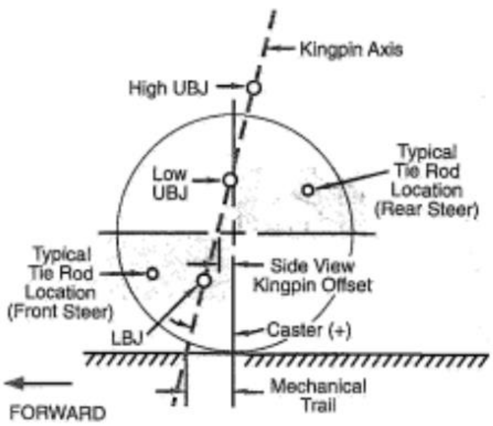

Figure 21: Caster angle and trail

2.4.5 ROLL CENTER

Roll Center: The roll center is the point around which the vehicle tends to roll when lateral forces are applied at the center of gravity. When lateral forces act at the vehicle's center of gravity, a proportional roll moment is generated, which depends on the distance between the center of gravity and the roll center. If the roll center coincides with the center of gravity, there will be no roll moment. [2]

The roll center is typically designed to be located close to the center of gravity to limit body roll during cornering. By positioning the roll center near the center of gravity, engineers can optimize the vehicle's handling and stability. However, it's important not to position the roll center too high to avoid jacking forces, which can lift the vehicle's body during cornering.

The roll center height affects the vehicle's weight transfer characteristics, cornering stability, and response. A higher roll center can lead to a greater weight transfer during cornering, potentially improving grip and stability. On the other hand, a lower roll center can enhance the vehicle's handling agility but may reduce stability. Finding the appropriate roll center height involves considering various factors, such as the vehicle's weight distribution, suspension geometry, and intended performance characteristics.

Proper roll center design and tuning are crucial for achieving optimal handling balance and minimizing body roll. By carefully adjusting the suspension geometry and roll center height, engineers can optimize the vehicle's responsiveness, cornering behaviour, and overall stability.

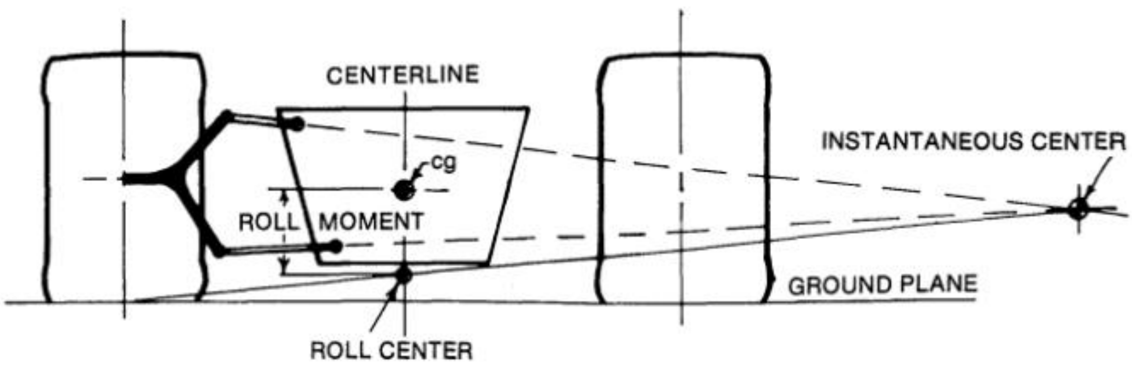

Figure 22: Roll center calculation

2.4.6 ANTI-DIVE AND ANTI-SQUAT

Anti-Dive is the ratio between the height of the vehicle's center of gravity and the height of the pitching rotation center (corresponding to the front axle), expressed as a percentage.

When the two centers coincide, the anti-dive is 100%, and when the pitching center is on the ground, the anti-dive is 0%. [2]

Anti-dive influences the vertical load distribution between the springs and the control arms. With 0% anti-dive, the entire load is carried by the springs, limiting the compression of the spring-damper system during braking. By reducing the dive under braking, anti-dive helps maintain a more level and stable vehicle platform, improving braking performance and reducing nosedive.

Anti-Squat is defined in the same way as anti-dive but for the vehicle's rear axle. It represents the relationship between the height of the vehicle's center of gravity and the height of the squatting rotation center of the rear axis.

Anti-squat affects the distribution of vertical load between the rear suspension components, particularly the springs and the control arms. When there is a significant anti-squat percentage, the rear suspension geometry is designed to resist squatting under acceleration forces, transferring more load to the rear tires and improving traction. This helps prevent the rear end from compressing excessively, maintaining a more balanced weight distribution, and maximizing rear tire grip during acceleration.

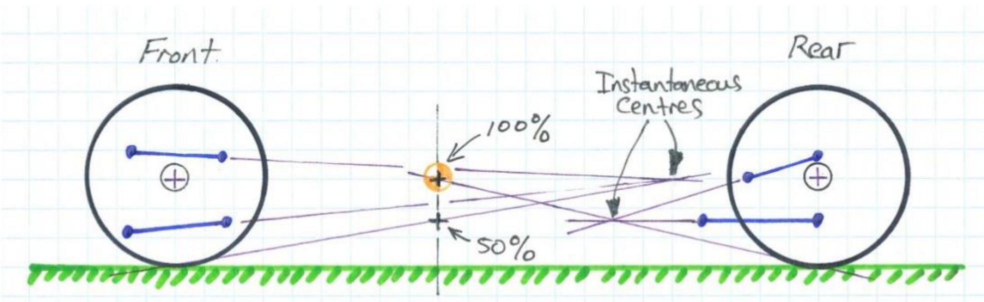

Figure 23: Anti-dive and Anti-squat geometry

2.4.7 MOTION RATIO

It is the ratio between the movement of the wheel and the movement of the spring. The motion ratio is an important parameter in suspension design as it determines how the suspension responds to wheel movement.

Ideally, the motion ratio should be as consistent as possible throughout the suspension travel to ensure predictable and controllable vehicle behaviour. A consistent motion ratio allows engineers to tune the suspension more accurately and optimize its performance.

A lower motion ratio is desirable as it allows for the use of softer springs while still achieving the desired suspension stiffness. Softer springs can contribute to weight reduction in the vehicle, as they require less material to achieve the same force. Additionally, softer springs can improve ride comfort and traction by providing more compliance and better tire contact with the road surface.

$$MR = \frac{Wheel\ Travel\ Damper}{displacement} \tag{2}$$

2.4.8 ACKERMANN GEOMETRY

Ackermann refers to the steering geometry in which all wheels turn with respect to the same instant center of rotation. The Ackermann geometry aims to minimize tire slip at low speeds by minimizing the occurrence of slip angles.

In the Ackermann steering geometry, each front wheel is steered at a different angle, allowing the wheels to follow different radius while turning. This configuration ensures that the inside wheel turns at a sharper angle than the outside wheel during a turn. As a result, the tires maintain better alignment with their respective turning radius, reducing tire slip, and thus minimizing tire wear. [10]

The Ackermann geometry is particularly beneficial in situations where low-speed manoeuvrability and tight cornering are important, such as in Formula Student racing, which often involves navigating tight and twisty circuits. By reducing tire slip angles, the Ackermann geometry improves traction, stability, and overall handling performance during cornering.

Designing and optimizing the Ackermann geometry involves careful consideration of various factors, including the wheelbase, track width, steering arm lengths, and steering angles. Engineers use mathematical calculations, simulations, and real-world testing to achieve the desired Ackermann effect.

It is worth noting that while the Ackermann geometry is advantageous in low-speed cornering, at higher speeds and larger turning radius, slight deviations from the ideal Ackermann geometry may be necessary to accommodate the natural tendency of the vehicle to understeer. Vehicle dynamics engineers carefully balance the Ackermann effect with other factors to achieve the desired handling characteristics for a specific vehicle application.

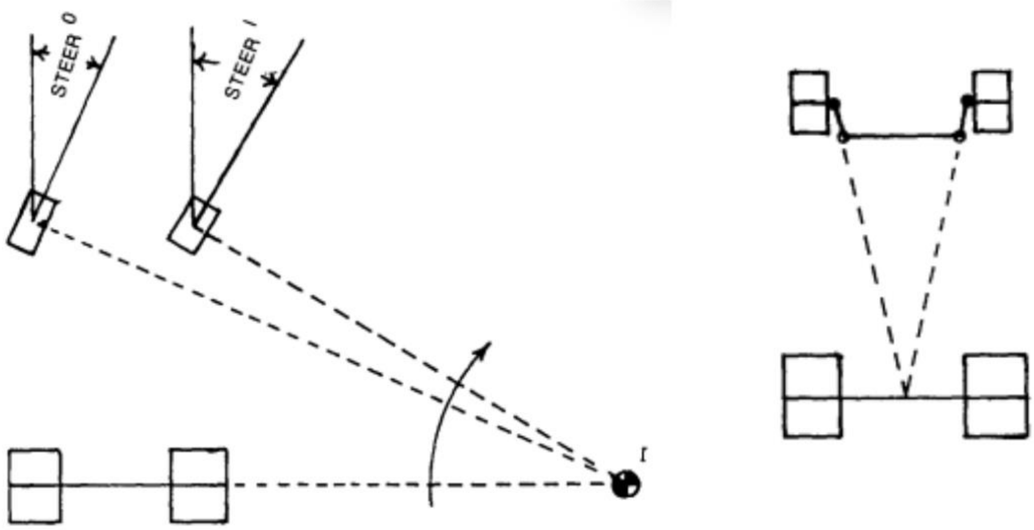

Figure 24: Ackermann geometry

Chapter 3. SUSPENSION DESIGN

3.1 SUSPENSION GEOMETRY DESIGN

The suspension has been designed using Lotus Suspension Analysis (LSA), a software tool commonly used in the automotive industry for suspension design and analysis. LSA allows engineers to simulate and evaluate various suspension parameters and configurations to optimize performance and handling characteristics. [11]

LSA utilizes mathematical models and simulation algorithms to predict the behaviour of the suspension system under different operating conditions. It considers factors such as geometry, kinematics, and forces acting on the suspension components. By inputting the relevant vehicle and suspension data, LSA can generate comprehensive analysis results and visualizations to assist engineers in making informed design decisions.

With LSA, the suspension geometry can be analysed, including the positions and orientations of suspension components, and evaluate their impact on parameters such as camber, toe, and roll center. The software enables the assessment the effects of different settings and make adjustments to optimize handling, stability, and ride comfort.

Additionally, LSA provides insights into suspension forces, such as load transfer, vertical motion, and wheel forces, allowing engineers to assess the performance and behaviour of the suspension system under various driving conditions. This information helps in the selection of appropriate spring and damper rates, as well as other suspension components, to achieve desired performance objectives. However, the load calculation and spring and damper analysis will be done with another programs.

The design of the IFS05 suspension system is based on the previous prototype, the IFS04, with a focus on maintaining the proportions and geometry that have been successfully utilized for several years. This approach allows for consistency and familiarity in terms of the overall layout and performance characteristics of the suspension.

By keeping the proportions intact, the design team ensures that the suspension system retains its established balance and dynamics. This includes maintaining the relative positions and orientations of key components such as control arms, uprights, and tie rods, making changes with this initial point to ensure the compatibility with the chassis.

Furthermore, preserving the geometry of the previous prototype allows for easier integration with other vehicle systems, such as steering and braking. It ensures compatibility and minimizes the need for major structural modifications or adaptations.

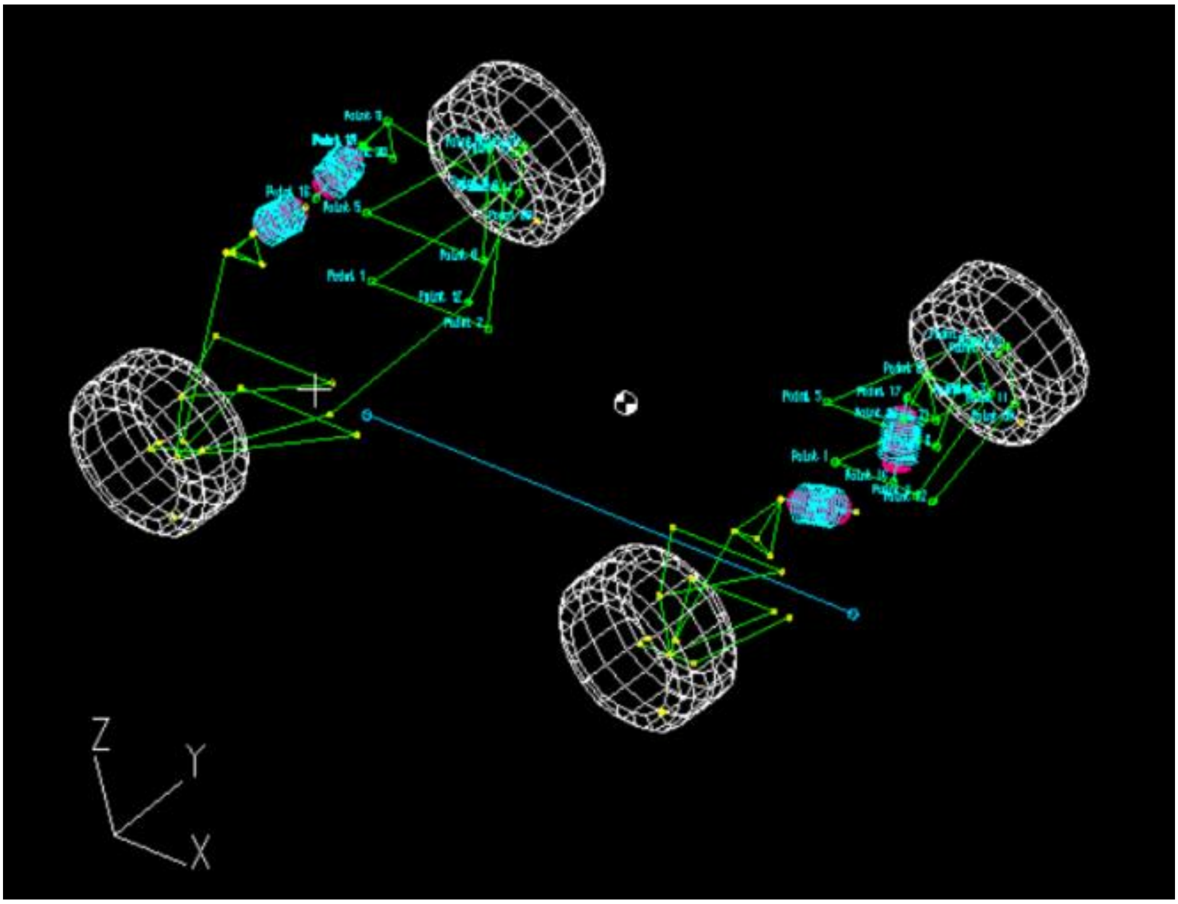

Figure 25: IFS04 Suspension in Lotus

With this starting point, the geometry of the suspension components is modified to meet the previously established requirements. All the final values are summed up at the end of the chapter.

The performance targets have been meticulously evaluated and analysed to ensure thorough understanding., taking into consideration factors such as stability, handling, comfort, and overall vehicle dynamics, reaching recommended and coherent values for each parameter.

Based on the specific requirements, adjustments are made to various aspects of the suspension geometry. These include optimizing the length and angles of the control arms, adjusting the position of the front uprights, fine-tuning the location of attachment points, and optimizing the motion ratios.

After considering input from various departments, including chassis and steering, multiple iterations were conducted to refine the suspension geometry. Taking into account the specific requirements and performance targets, the final layout of the suspension geometry was determined. This comprehensive design process ensures that the suspension system is optimized for stability, handling, and overall vehicle performance.

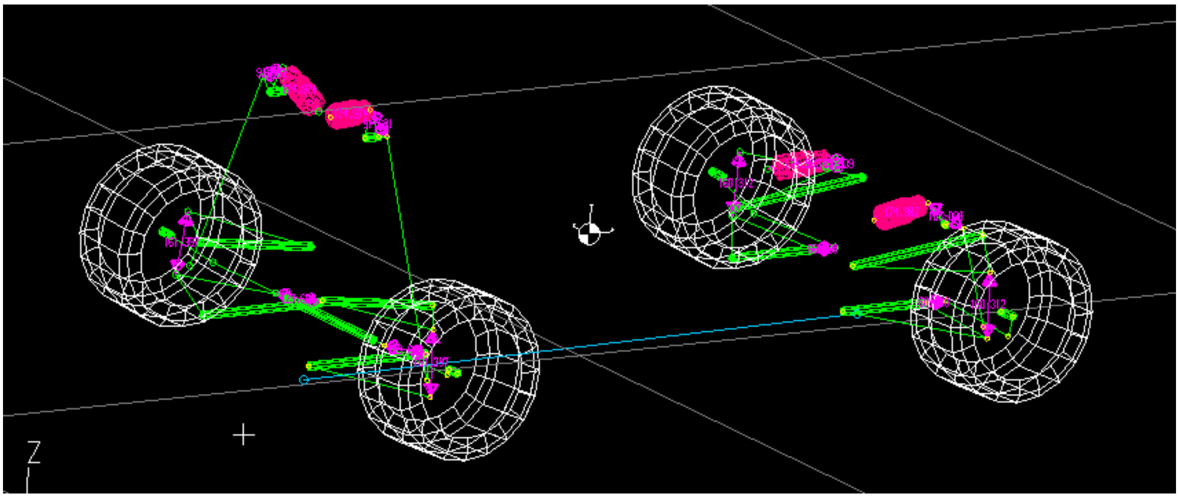

Figure 26: Final layout of the IFS05 suspension

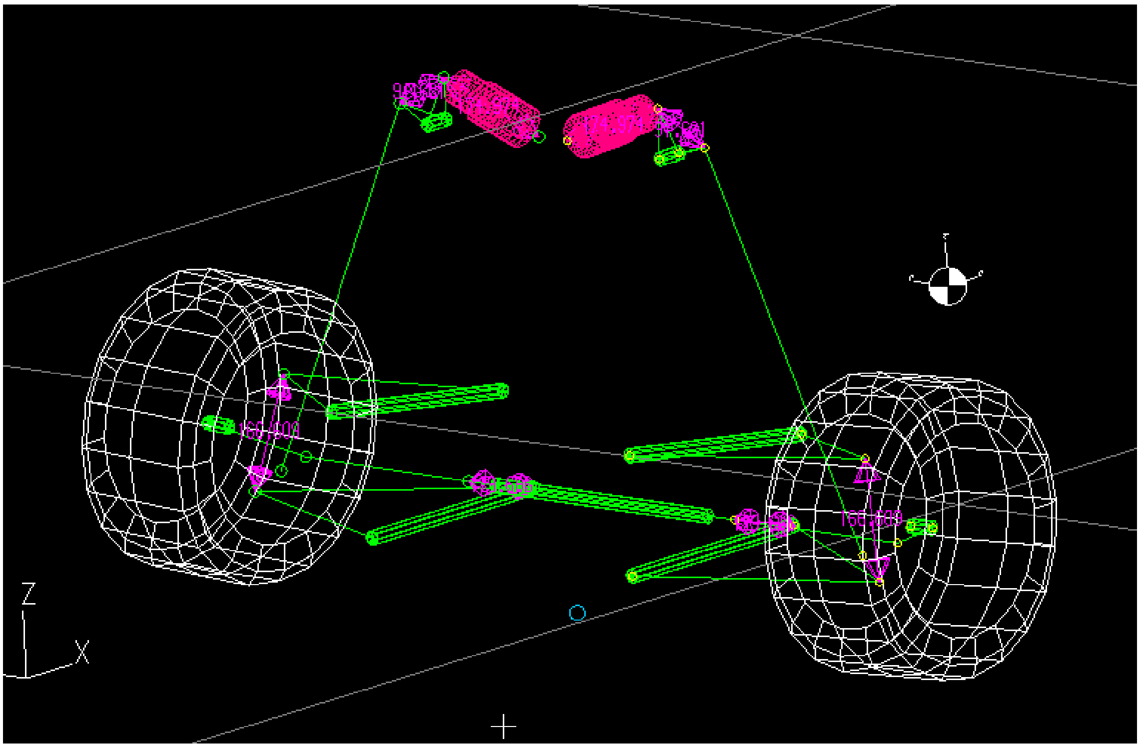

Figure 28: Front suspension of the IFS05

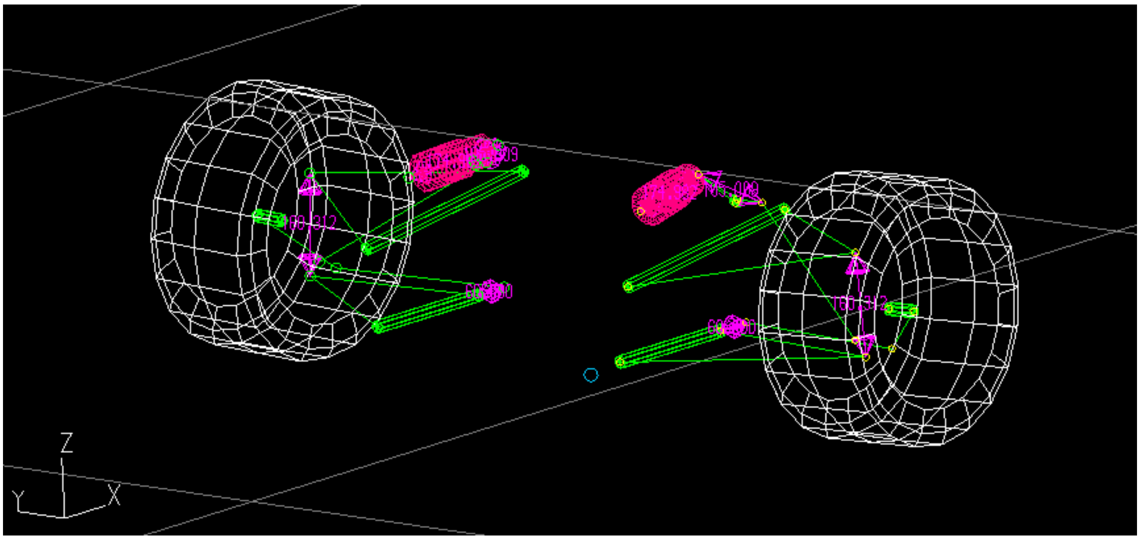

Figure 27: Rear Suspension of the IFS05

3.1.1 CAMBER

The camber angle is a crucial parameter to control in the suspension system, particularly in racing applications. For our purposes, a negative camber is desired to adapt the tire contact patch to the turns and body roll of the car, opposite as normal street cars that have positive camber values. We are targeting camber static values of -2.5º and -2º for the front and rear axles, respectively. Camber shims allow for adjustability, so it is preferable to set these values slightly higher, as excessive camber can be corrected using the shims, displacing slightly the upright upper tab to change the tire inclination.

However, it is important to note that the dynamic camber, or how the camber changes with the car's movements, is more significant for optimizing the contact patch during cornering. The ideal camber targets are approximately -2º for the outer wheel and -1º for the inner wheel when experiencing a 1º roll during skidpad testing, with a roll stiffness of 0.75º/g. [2]

In the front axle, it is essential to consider how camber changes when steering the tires. Increasing the caster angle leads to camber gain, while increasing the kingpin angle results in a reduction of camber gain. Previous prototypes exhibited excessive variations in camber, up to 6º, due to extreme angles. To address this, the IFS05 incorporates new front uprights to minimize camber variations.

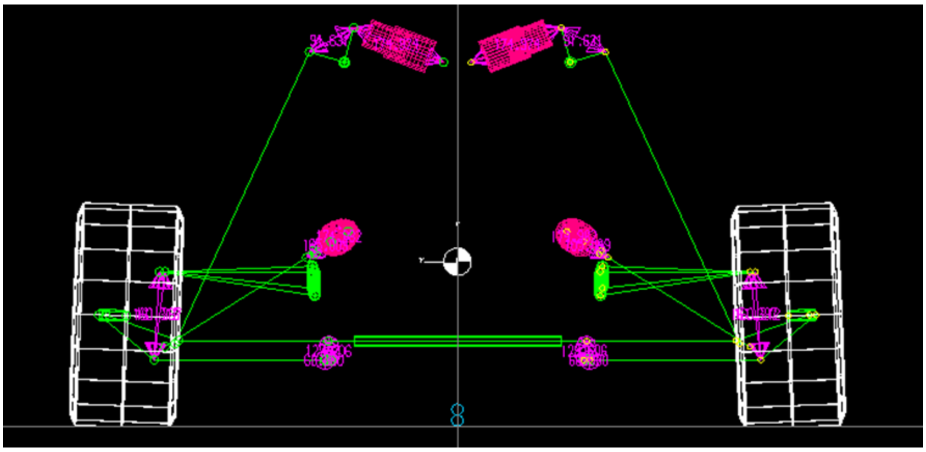

Figure 29: Front view of the suspension

Ultimately, fine-tuning the camber adjustment will be done through track testing, carefully analysing each situation to ensure optimal performance.

Camber gain is designed to have a linear and progressive relationship with the car's roll, aiming to achieve the desired camber values in both the inner and outer wheels.

To control camber gain during steering, adjustments are made to the caster and kingpin angles. By reducing these angles, the camber gain can be managed effectively.

By carefully optimizing the suspension geometry, including the caster and kingpin angles, we can ensure that the camber gain remains within the desired range throughout various driving conditions. This allows for improved tire contact and grip during cornering, enhancing overall performance and handling of the vehicle.

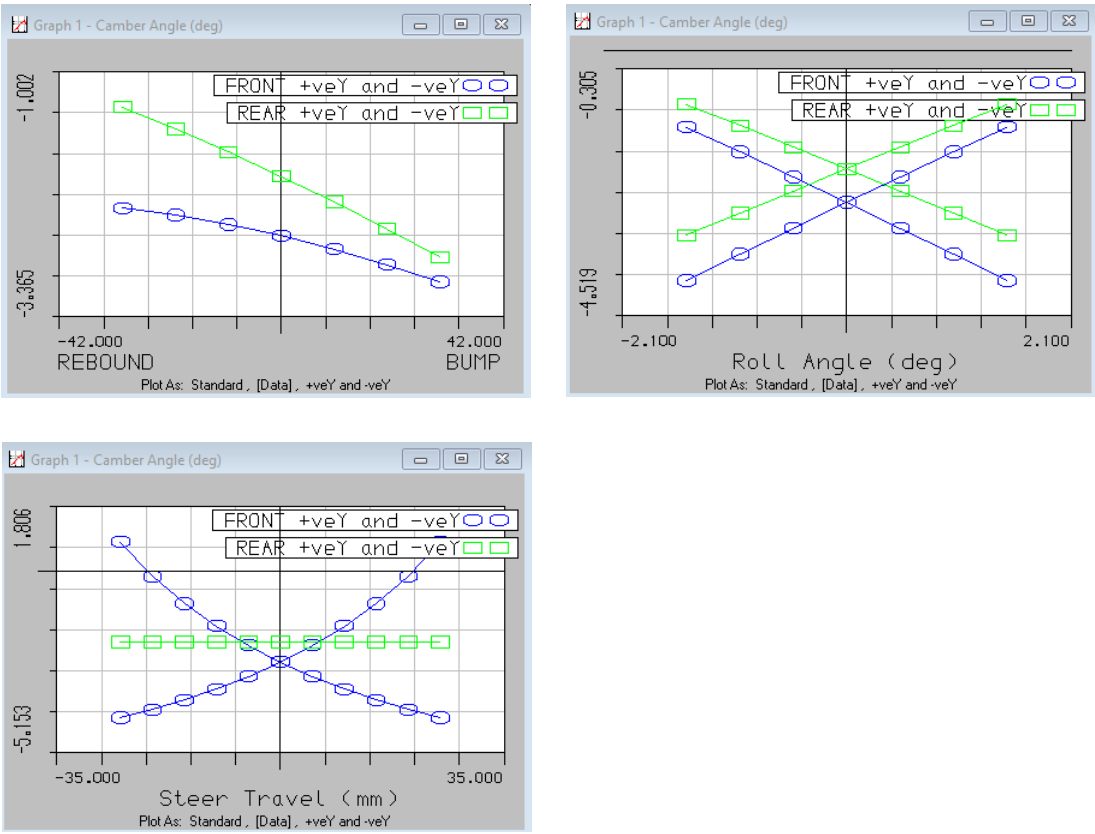

Figure 30: Camber angle variation with the wheel travel (degrees)

3.1.2 TOE ANGLE

Toe adjustments play a crucial role in improving the car's cornering balance. The suspension design aims to achieve a neutral toe angle of 0º, but it also provides adjustability by changing the length of the tie rods.

One of the key considerations in toe design is to minimize variations in wheel travel. To achieve this, all the tie rods should converge at the same rotation point. This ensures that the toe angle remains consistent throughout the suspension's range of motion.

By carefully adjusting the toe angle, the suspension can optimize the car's handling characteristics, promoting stability and predictable behaviour during cornering manoeuvres. Track testing allows for fine-tuning of the toe settings to achieve the desired balance and performance.

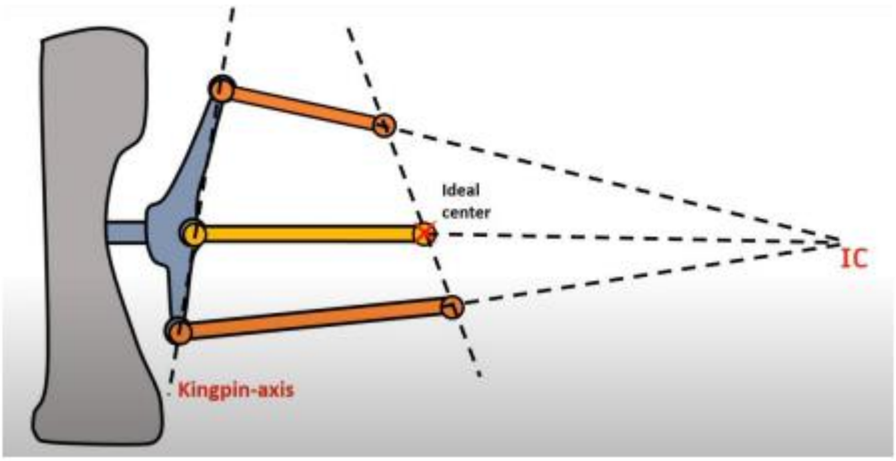

Figure 31: Rotation centre of the suspension arms

Great attention is given to minimizing bumpsteer and rollsteer effects in the suspension design to ensure stable driving conditions. Bumpsteer, which refers to unwanted changes in toe angle during suspension travel, is minimized to maintain consistent steering response.

Similarly, rollsteer, which involves changes in suspension geometry during cornering, is carefully controlled to preserve balance and handling.

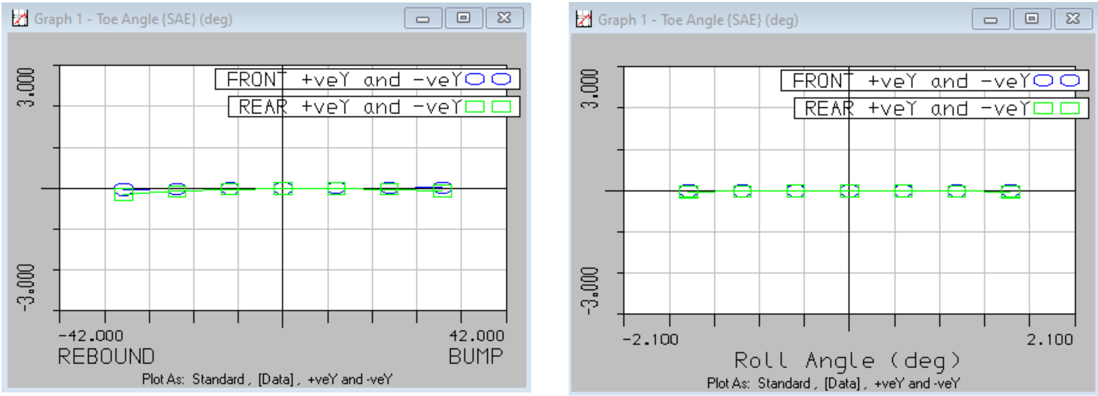

Figure 32: Toe angle variation with the roll and wheel travel (degrees)

3.1.3 ROLL CENTER HEIGHT

In previous car designs, the roll center was positioned below the ground, resulting in significant roll forces due to the height difference with the center of gravity. In the IFS05, this issue will be addressed by positioning the roll center above the ground, although not excessively to avoid jacking forces. Additionally, the roll center height of the rear axis will be set higher than the front axis to assist the rear axis in maintaining stability and catching up with the front during corner entry.

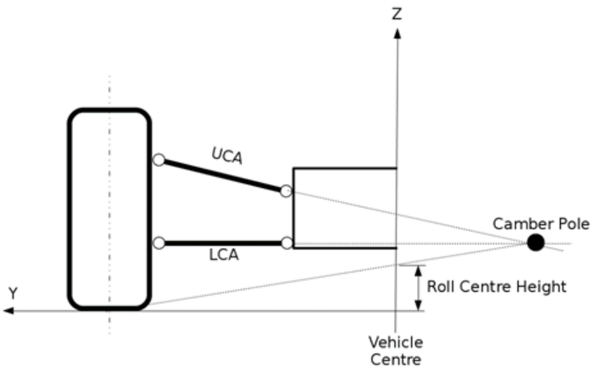

Figure 33: Roll center

The roll center height remains consistently positive and stable throughout the roll movement, ensuring effective control of the vehicle's body roll. It also maintains the desired relationship between the roll center heights of the front and rear axles. In the IFS05, the static roll center heights from the ground have been set at 15.8mm for the front axis and 31mm for the rear axis. These values have been carefully determined to optimize the vehicle's handling and stability, with a higher value in the rear axis to compensate the fact that the front axis enters the turn first, so the rear axis has to follow the body movement as fast as possible.

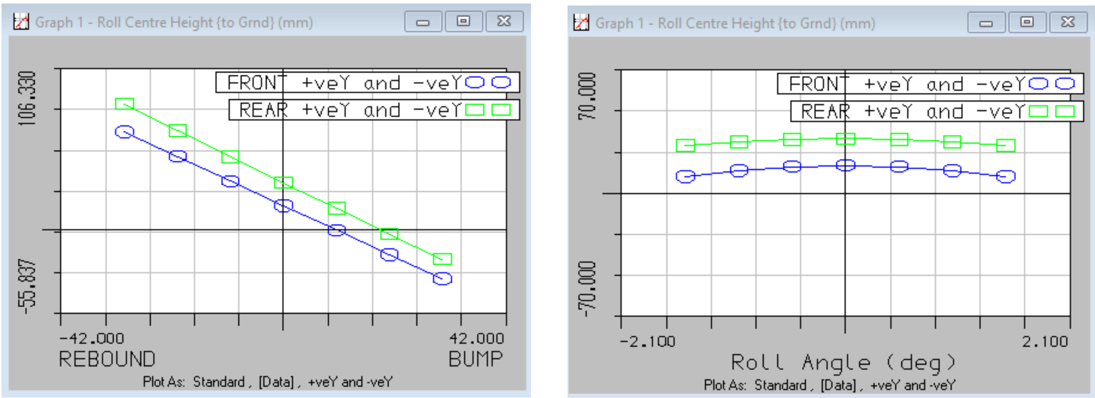

Figure 34: Roll center height variation with wheel travel and roll angle (mm)

3.1.4 KINGPIN INCLINATION AND SCRUB RADIUS

These parameters will be modified with the new front uprights. The rear ones will be the same as the previous seasons, so this is something to study in the next years.

In the previous cars, the kingpin angle in the front axis was excessively high, reaching up to 11º in the IFS04. This resulted in adverse effects such as camber loss during steering and excessive lifting of the car, which increased the steering forces required. To address these issues, the kingpin angle has been reduced to 7º in the IFS05. It is important to note that throughout these modifications, the scrub radius has been maintained in a positive range, which is recommended for rear-wheel-drive cars. These adjustments aim to optimize the suspension performance and enhance the overall handling characteristics of the vehicle.

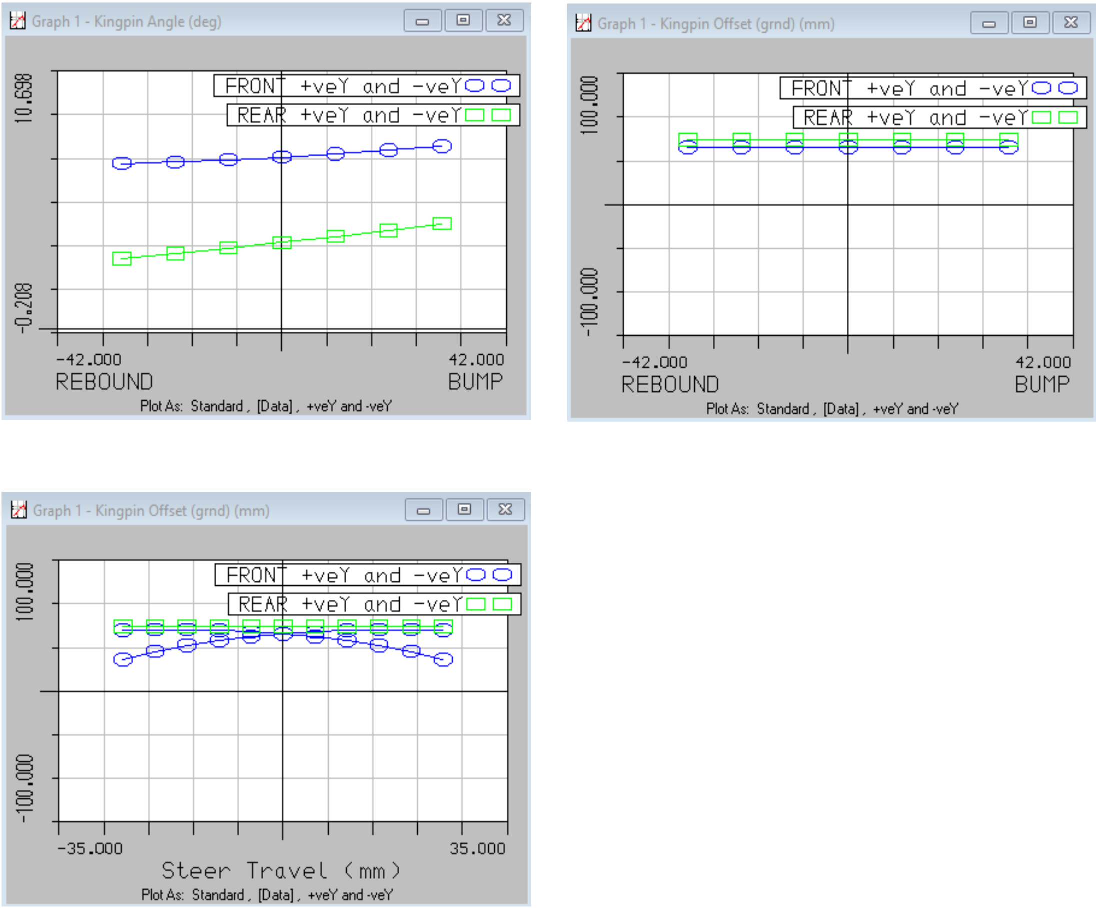

Figure 35: Kingpin (degrees) and Scrub (mm) variation with wheel travel and steering

3.1.5 CASTER AND TRAIL

The caster angle plays a crucial role in generating the self-aligning torque and camber gain when steering the tires. In the previous iterations, such as the IFS03 and IFS04, the caster angle was set at 9.8º, resulting in a significant trail offset of 32mm. However, these values were found to be excessive as they caused high steering forces and camber gain during steering manoeuvres. Therefore, in the IFS05, the caster angle will be significantly reduced to optimize the steering characteristics and minimize unwanted effects.

The caster angle in the front axis must always remain positive to ensure the generation of auto aligning torque in the wheels, which is crucial for steering stability. However, in the rear axis, the caster angle does not play a significant role as the toe angle is fixed. Nevertheless, for future considerations, a slight positive caster angle may be preferred in the rear as well.

In the previous iterations, the excessive caster angle in the front axis led to high steering forces and significant changes in camber gain during steering manoeuvres. To address these issues, the IFS05 has undergone modifications. The trail has been reduced by 22%, from 32mm to 25mm, to enhance the car's performance and driveability. Additionally, the caster angle in the front axis has been reduced from 9.8º to 6.2º.

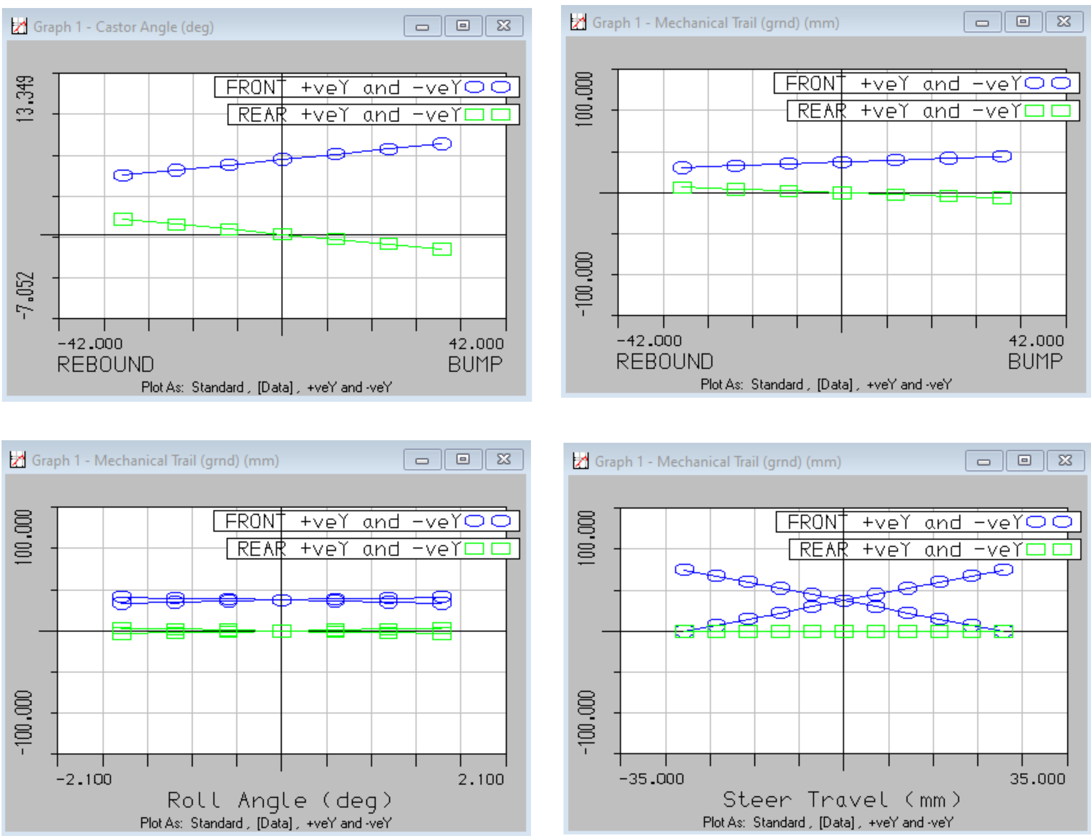

Figure 36: Caster (degrees) and trail (mm) variations during roll and wheel travel

It is important to note that the parameters associated with the rear uprights could not be modified in the IFS05 suspension due to the carry-over design. To sum up, in the IFS05 we will reduce the kingpin and caster angles to minimize the steering forces and smooth the camber gain of the tires.

3.1.6 ANTI-DIVE AND ANTI-SQUAT

One of the significant changes implemented this season aims to reduce the pitching motion when braking. Based on recommendations from specialists in the field, our target static objective is to have 30% of the load transferred to the control rods and 70% to the springs. This configuration helps to decrease the pitch of the car by 30%, resulting in improved stability and handling during braking and accelerating manoeuvres.

The anti-dive feature has been designed with a target value of 30% in the front axis and 20% in the rear axis. This design choice aims to effectively reduce the pitching motion of the car when braking, providing enhanced stability during deceleration. Similarly, the anti-squat feature has been optimized to achieve a 30% value in the rear axis, minimizing the pitch when accelerating. These adjustments contribute to improved overall performance and stability of the vehicle without compromising the wheel travel.

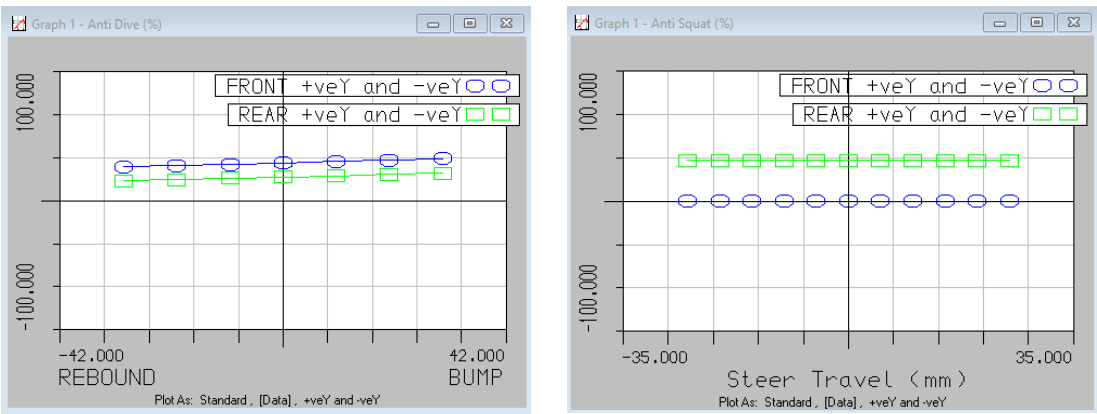

Figure 37: Antidive and Antisquat of the IFS05 (%)

3.1.7 MOTION RATIO

The motion ratio plays a crucial role in optimizing the suspension's performance and ensuring the desired stiffness of the car. Using the Kinematic 3D analysis software [12], the suspension points are pre-designed to achieve an optimized motion ratio. In the case of the IFS05, a motion ratio of 1.2 has been targeted. This value has been carefully selected to maintain the recommended stiffness of the vehicle and ensure the use of compatible and consistent springs throughout the suspension system. It is essential that the motion ratio remains as linear and constant as possible throughout the wheel travel, providing predictable and reliable suspension behaviour.

The motion ratio of both the front and rear axles has been meticulously optimized, yielding excellent results. The targeted value of 1.2 has been achieved, ensuring a linear and consistent motion ratio throughout the entire range of wheel travel.

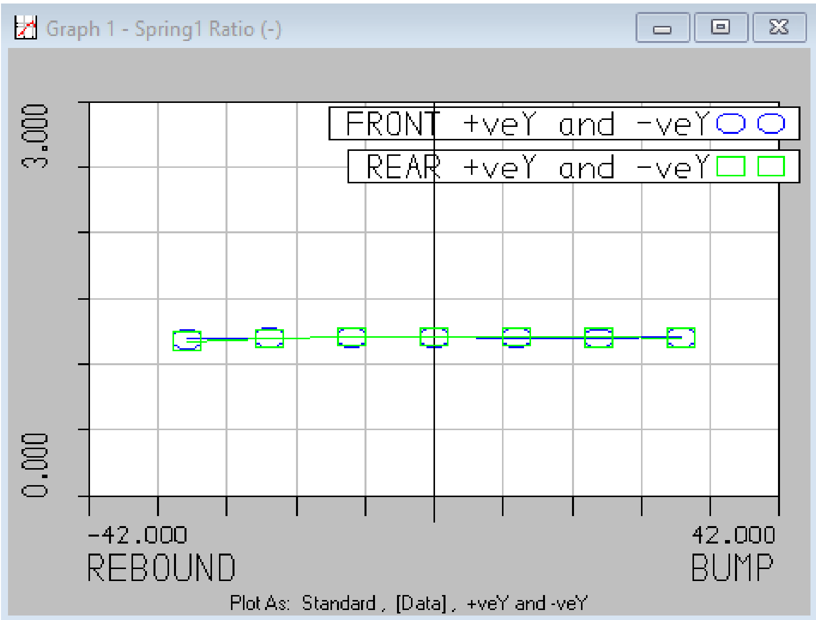

Figure 38: Motion ratio variation with the wheel travel

3.1.8 ACKERMANN

The implementation of the new suspension design results in a significant reduction in the wheelbase of the car. To effectively compensate for this variation, we will adjust the attachment point of the toe link on the upright. This adjustment is crucial to maintain proper handling and stability during cornering.

Considering the nature of Formula SAE car racing, which involves tight corners and lower velocities, it becomes essential to optimize the Ackermann geometry as closely as possible to 100%. By doing so, we aim to minimize tire slip during cornering, thereby maximizing traction and overall performance. The Lotus Software provides us with the tools to optimize the Ackermann geometry by adjusting the positioning of the toe link, ensuring optimal performance in these demanding conditions.

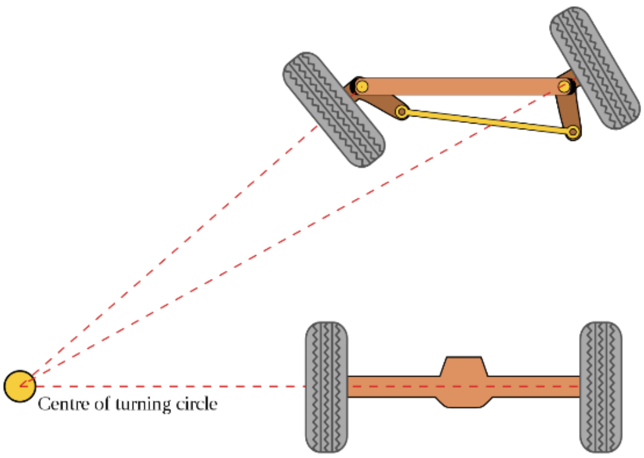

Figure 39: Ackermann steering geometry

In the IFS05, we made a significant reduction in the wheelbase, decreasing it by 160mm to achieve a total of 1570mm. This change has a significant impact on the Ackermann steering geometry. To ensure optimal steering performance and achieve 100% Ackermann with maximum steering angle, we have adjusted the upright link of the tie rod.

The reduction in wheelbase also allows for a decrease in the minimum turning radius of the car. With the new wheelbase and steering upgrades, our goal is to utilize the full range of steering travel while avoiding any contact between the suspension elements. As a result, the final turning radius of the car has been reduced to 3.9m.

These modifications in the wheelbase and steering geometry contribute to improved manoeuvrability and agility, allowing the car to navigate tight corners and challenging track conditions with enhanced performance.

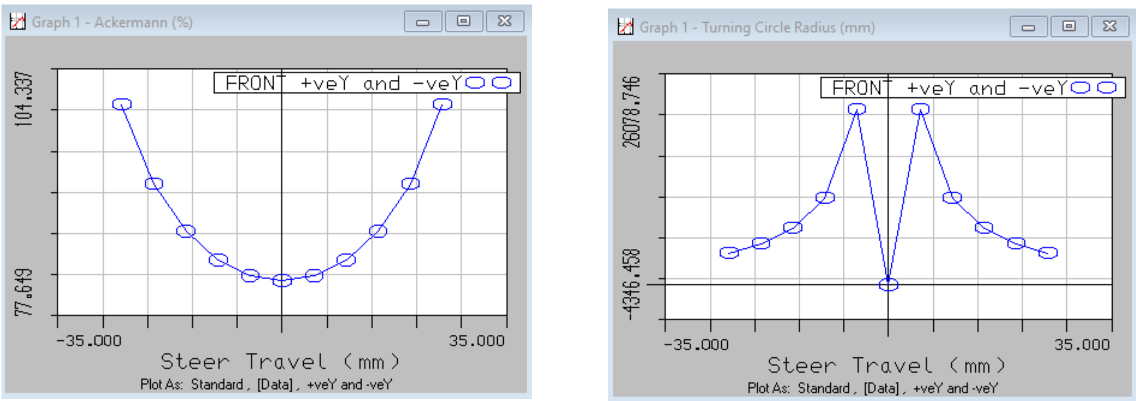

Figure 40: Ackermann percentage and turning radius variation with the steer travel (%)

3.1.9 OTHER CONSIDERATIONS

In addition to the design considerations mentioned earlier, there are other important requirements that the suspension must fulfil:

- **Damper Static Length**: The suspension has been designed with a specific damper static length of 175mm. This parameter ensures proper functionality and compatibility with other suspension components.

- **Suspension Brackets**: The brackets that hold the suspension elements in place have been carefully designed to align with the direction of the rods. This ensures proper positioning and optimal performance of the suspension system.
- **Optimization of Suspension Layout**: The suspension layout has been optimized, taking into account various factors such as the Anti-Roll Bar (ARB) and other components of the car. The goal is to achieve a well-packaged design that allows for efficient utilization of space and optimal integration with other systems.
- **Rear Spring Configuration**: To further optimize packaging and accommodate other components, the decision was made to position the rear springs longitudinally. This arrangement helps to maximize space utilization and ensure a balanced distribution of weight and forces within the suspension system.

By considering these requirements and incorporating them into the suspension design, we can achieve a well-integrated and efficient suspension system that meets the performance and packaging needs of the car.

3.1.10 RESULTS

With careful consideration of all the requirements, we have successfully designed the IFS05 suspension to meet our objectives. The suspension incorporates optimized camber angles, adjustable toe settings, minimized bumpsteer and rollsteer, a strategically positioned roll center, controlled kingpin angles and scrub radius, reduced caster and trail, appropriate anti-dive and anti-squat percentages, an optimized motion ratio, 100% Ackermann steering geometry, and efficient packaging. These design elements collectively ensure improved performance, stability, and handling characteristics for the IFS05, fulfilling the intended goals of the suspension system.

STATIC VALUES FRONT				
X (mm)	Y (mm)	Z (mm)		
14.2	229.1	230	POINT:1	Lower wishbone front pivot
346.7	229.1	230	POINT:2	Lower wishbone rear pivot
148.1	550	230	POINT:3	Lower wishbone outer ball joint
14.2	263	400	POINT:5	Upper wishbone front pivot
332.7	263	360.3	POINT:6	Upper wishbone rear pivot
165.5	530	390	POINT:7	Upper wishbone outer ball joint
148.1	515.5	250	POINT:8	Push rod wishbone end
148.1	268.3	773.7	POINT:9	Push rod rocker end
221.75	505.2	265.1	POINT:11	Outer track rod ball joint
221.75	234.5	264	POINT:12	Inner track rod ball joint
148.1	25	755.1	POINT:16	Damper to body point
148.1	188.2	818.2	POINT:17	Damper to rocker point
160	638	311.7	POINT:18	Wheel spindle point
160	600	310	POINT:19	Wheel centre point
128.1	205	755.1	POINT:20	Rocker axis 1st point
168.1	205	755.1	POINT:21	Rocker axis 2nd point

Table 6: Static values front

STATIC VALUES REAR				
X (mm)	Y (mm)	Z (mm)		
1523.3	240	230	POINT:1	Lower wishbone front pivot
1756	240	230	POINT:2	Lower wishbone rear pivot
1730	550	230	POINT:3	Lower wishbone outer ball joint
1529.1	259	347	POINT:5	Upper wishbone front pivot
1895	259	390	POINT:6	Upper wishbone rear pivot
1730	540	390	POINT:7	Upper wishbone outer ball joint
1725	515	250	POINT:8	Push rod wishbone end
1858.9	279.5	485.8	POINT:9	Push rod rocker end
1790	550	230	POINT:11	Outer track rod ball joint
1816	240	230	POINT:12	Inner track rod ball joint
1640.8	231.1	512.4	POINT:16	Damper to body point
1811.8	213.5	545.1	POINT:17	Damper to rocker point
1730	650	311.9	POINT:18	Wheel spindle point
1730	600	310	POINT:19	Wheel centre point
1816.2	274.2	514.9	POINT:20	Rocker axis 1st point
1818.8	246.6	486.1	POINT:21	Rocker axis 2nd point

Table 7: Static values rear

3.2 SUSPENSION LOADS CALCULATION

The calculation of suspension loads is a crucial aspect in the design and analysis of vehicle suspensions. It involves determining the forces and moments that act on the suspension components under various operating conditions, such as acceleration, braking, cornering, and road irregularities. By accurately calculating these loads it can be ensured that the suspension system is adequately designed to withstand the forces and provide optimal performance, handling, and comfort. This process requires a thorough understanding of vehicle dynamics, including weight distribution, tire characteristics, and the effects of suspension geometry and kinematics.

In double wishbone suspension systems, commonly found in FSAE cars, there are six tubes that connect the wheel assembly to the vehicle and play critical roles in the suspension setup. These tubes include the following:

1. **Upper Wishbone, Fore**: This tube connects the upper part of the wheel assembly to the vehicle's chassis in the forward direction. It helps control the vertical movement of the wheel and contributes to maintaining stability during cornering.
2. **Upper Wishbone, Aft**: Similar to the upper wishbone in the forward direction, this tube connects the upper part of the wheel assembly to the vehicle's chassis in the rearward direction. It works in conjunction with the other suspension components to provide precise control over wheel movement.
3. **Lower Wishbone, Fore**: The lower wishbone, positioned in the forward direction, connects the lower part of the wheel assembly to the vehicle's chassis. It assists in controlling the vertical movement of the wheel and plays a crucial role in optimizing handling and grip.
4. **Lower Wishbone, Aft**: Positioned in the rearward direction, the lower wishbone connects the lower part of the wheel assembly to the vehicle's chassis. It

complements the other suspension components in providing stability, responsiveness, and traction during dynamic driving manoeuvres.

5. **Push/Pull Rod or Spring/Damper (direct suspension)**: This tube, often referred to as the push or pull rod, acts as a linkage between the suspension arm and the spring/damper assembly. It transmits the vertical forces from the wheel to the spring/damper system, ensuring effective suspension movement and energy dissipation.
6. **Steering Tie Rod**: The tie rod is responsible for connecting the steering system to the wheel assembly. It allows for precise control over the wheel's direction and is crucial for maintaining proper alignment and handling characteristics.

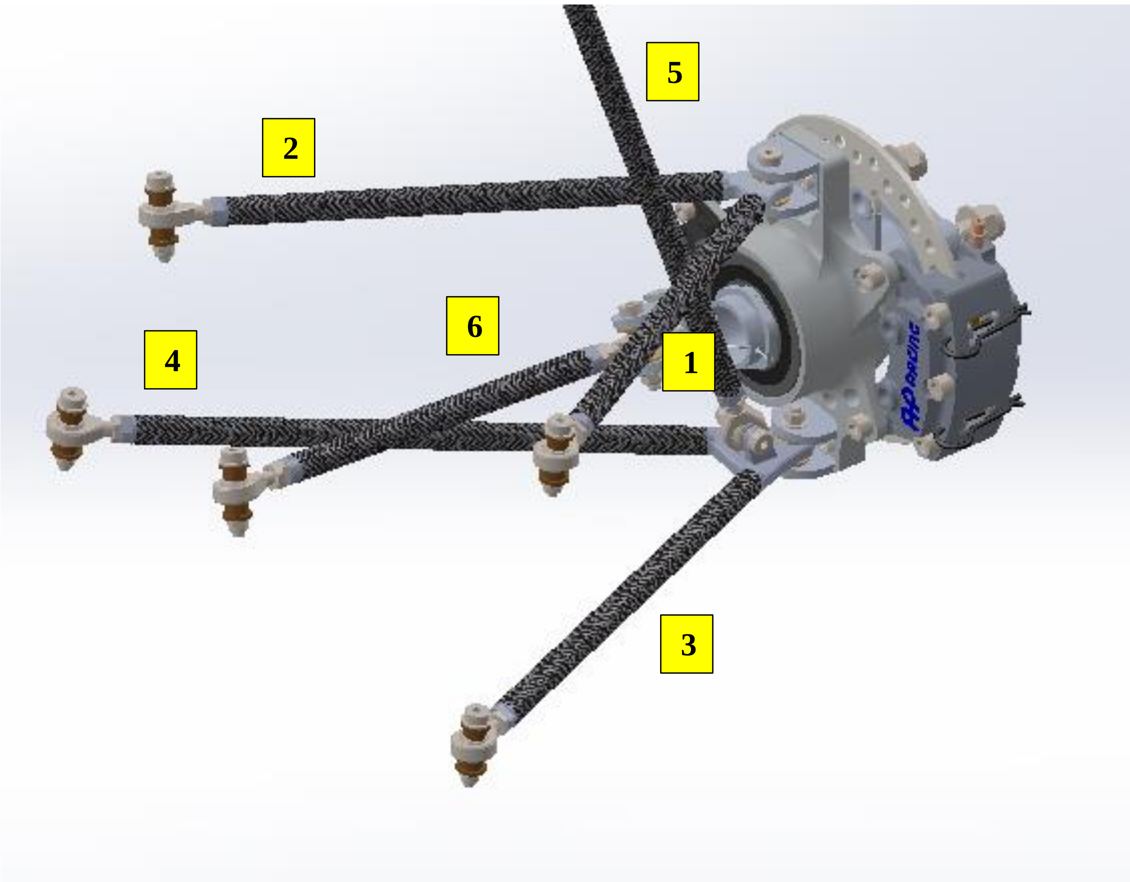

Figure 41: Suspension links

The analysis of the push/pull rod in suspension systems requires a more accurate method than simply assuming the vertical force at the tire contact patch is equal to the vertical component of the push/pull rod force. Using the component forces, similar triangles, or trigonometry to calculate the push/pull rod force alone can lead to significant underestimation, especially in pull-rod suspensions where the upper wishbone applies an additional vertical force.

To obtain more accurate results, a recommended method is the Static Free Body Diagram 6x6 Matrix Method. This method involves considering all six suspension tubes and their respective forces using a matrix equation, rather than isolating the push/pull rod alone. Numerous papers and online resources are available that explain this method in detail, providing a comprehensive understanding of the forces in the suspension system.

It is important to make certain assumptions when applying this method, such as considering the suspension tubes as two-force members and neglecting the acceleration of the wheel assembly for simplicity. Additionally, the calculation should account for inboard vs. outboard drive/brake setups, as the forces transmitted through the suspension members can vary depending on the configuration.

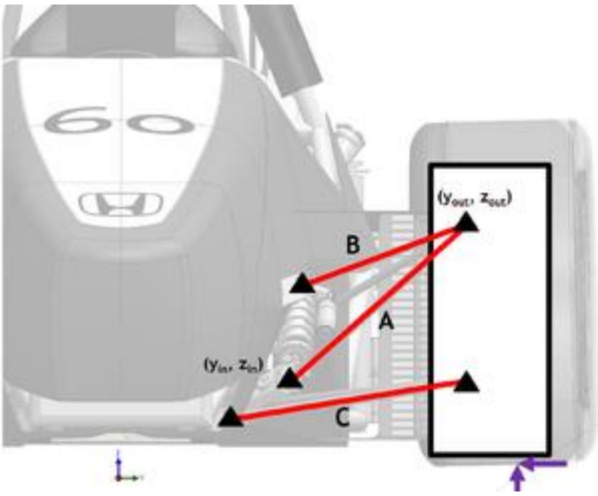

Figure 42: Diagram of the suspension links

By applying the principles of sum of forces and sum of moments to the wheel assembly and breaking down the suspension tube force vectors into their components, a solvable 6x6 linear system can be derived. This system can be solved using linear algebra techniques to determine the unknown magnitudes of the forces in each suspension tube.

To calculate the forces in each of the six suspension tubes, the first step is to determine the x, y, and z components of each tube's force vector. This can be done by multiplying the unit vectors of each tube by the magnitude of the force in each arm, which will be left as a variable since it is unknown.

$$\sum \mathrm{Fx} = \left(\frac{\Delta x_A}{L_A}\right) \cdot |F_A| + \left(\frac{\Delta x_B}{L_B}\right) \cdot |F_B| + \left(\frac{\Delta x_C}{L_C}\right) \cdot |F_C| + \left(\frac{\Delta x_D}{L_D}\right) \cdot |F_D| + \left(\frac{\Delta x_E}{L_E}\right) \cdot |F_E| + \left(\frac{\Delta x_F}{L_F}\right) \cdot |F_F| + Fx_{tire} = 0$$

$$\sum \mathrm{Fy} = \left(\frac{\Delta y_A}{L_A}\right) \cdot |F_A| + \left(\frac{\Delta y_B}{L_B}\right) \cdot |F_B| + \left(\frac{\Delta y_C}{L_C}\right) \cdot |F_C| + \left(\frac{\Delta y_D}{L_D}\right) \cdot |F_D| + \left(\frac{\Delta y_E}{L_E}\right) \cdot |F_E| + \left(\frac{\Delta y_F}{L_F}\right) \cdot |F_F| + Fy_{tire} = 0$$

$$\sum \mathrm{Fz} = \left(\frac{\Delta z_A}{L_A}\right) \cdot |F_A| + \left(\frac{\Delta z_B}{L_B}\right) \cdot |F_B| + \left(\frac{\Delta z_C}{L_C}\right) \cdot |F_C| + \left(\frac{\Delta z_D}{L_D}\right) \cdot |F_D| + \left(\frac{\Delta z_E}{L_E}\right) \cdot |F_E| + \left(\frac{\Delta z_F}{L_F}\right) \cdot |F_F| + Fz_{tire} = 0$$

(3)

Calculating the moments from each tube is best done in vector form using the cross product of the moment arm vector and the force vector. This will yield a moment vector with components Mx, My, and Mz, which can be inserted into their respective ∑Mx=0, ∑My=0, and ∑Mz=0 equations. [12]

The resulting six equations can be rearranged into a matrix equation of the form A*X=b, where A represents the coefficient matrix, X represents the vector of unknowns (forces in the suspension tubes), and b represents the vector of known values (forces and moments). Solving this matrix equation using linear algebra techniques will yield the solution for the unknown forces in each suspension tube.

$$\begin{bmatrix} \begin{bmatrix} \square \\ \hat{a} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ \hat{b} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ \hat{c} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ \hat{d} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ \hat{e} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ \hat{f} \\ \square \end{bmatrix} \\ \begin{bmatrix} \square \\ r_a \times \hat{a} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ r_b \times \hat{b} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ r_c \times \hat{c} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ r_d \times \hat{d} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ r_a \times \hat{e} \\ \square \end{bmatrix} & \begin{bmatrix} \square \\ r_a \times \hat{f} \\ \square \end{bmatrix} \end{bmatrix} \cdot \begin{bmatrix} F_A \\ F_B \\ F_C \\ F_D \\ F_E \\ F_F \end{bmatrix} = \begin{bmatrix} -Fx_{tire} \\ -Fy_{tire} \\ -Fz_{tire} \\ -Mx_{tire} \\ -My_{tire} \\ -Mz_{tire} \end{bmatrix}$$

(4)

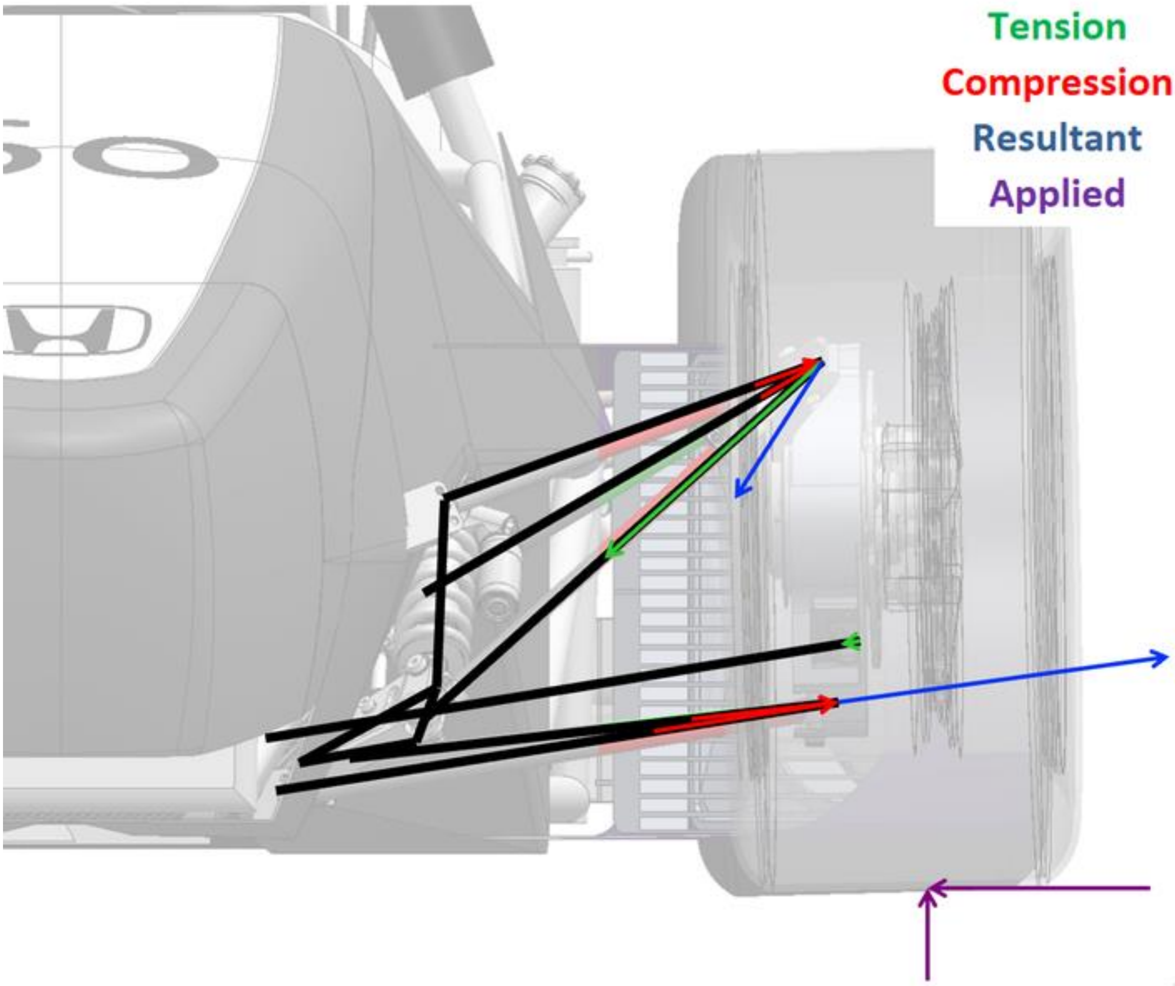

Figure 43: Resulting forces on a suspension

The forces on the tires are calculated using the load transfer formulas from vehicle dynamics, considering the lateral and longitudinal accelerations of the vehicle. These formulas allow us to determine how the forces are distributed among the tires during different manoeuvres, such as acceleration, braking, and cornering.

Load transfer occurs due to the vehicle's inertia and the distribution of weight over the axles. During acceleration, for example, the load is transferred to the rear of the vehicle, resulting in a higher load on the rear tires and a lower load on the front tires. This generates traction forces on the rear tires that propel the vehicle forward. Similarly, during braking, the load is transferred to the front of the vehicle, increasing the load on the front tires, and reducing the load on the rear tires. This allows for greater braking capacity on the front wheels.

During cornering, lateral forces act on the tires and generate load transfer towards the outside of the curve. This results in a higher load on the outer tires and a lower load on the inner tires. [2]

$$WT_{lat} = \frac{m_{car} \cdot a_{lat} \cdot h_{cdg}}{Track} \tag{5}$$

$$WT_{long} = \frac{m_{car} \cdot a_{long} \cdot h_{cdg}}{Wheelbase} \tag{6}$$

$$Fz_{tire} = \frac{m_{car} \cdot g}{4} + \frac{WT_{lat} + WT_{long}}{2} \tag{7}$$

$$Fz_{\%} = \frac{Fz_{tire}}{m_{car} \cdot g} \tag{8}$$

$$Fx_{tire} = Fz_{\%} \cdot m_{car} \cdot a_{long} \tag{9}$$

$$Fy_{tire} = Fz_{\%} \cdot m_{car} \cdot a_{lat} \tag{10}$$

All the geometrical and physical data of the car, including the mass of the car, the center of gravity height, the track width, the wheelbase, and the loaded radius of the tire, are known values because they are design parameters.

Inputs		
m_carPlusDriver	310	kg
h_centerOfGravity	0.30	m
Track	1.20	m
Wheelbase	1.57	m
r_tireLoaded	0.20	m

Table 8: Inputs

To accurately calculate the accelerations, it is required additional information regarding the tire data and characteristics. The maximum lateral and longitudinal acceleration that the vehicle can safely achieve depends on the tire's maximum grip or adherence, in our case, the Hoosier R20 Formula Student tires.

While the specific adherence coefficient of our tires is unknown since they haven't been extensively studied, we can make use of typical values for grip observed in race cars. These values provide a reasonable estimation of the tire's capability to generate lateral and longitudinal forces during various manoeuvres.

The adherence of the tire in different conditions is determined with the adherence ellipse. It is a graphical representation of the tire's traction limits or the maximum forces it can generate in different directions. It illustrates the relationship between the lateral and longitudinal forces that a tire can produce while maintaining traction.

The adherence ellipse is typically displayed on a coordinate plane, with the lateral force plotted on the x-axis and the longitudinal force on the y-axis. The shape of the ellipse is determined by the tire's characteristics, including its grip level, cornering stiffness, and longitudinal traction.

The size and orientation of the adherence ellipse depend on various factors, such as tire compound, tread pattern, inflation pressure, and road surface conditions. A larger ellipse represents higher grip and the ability to generate larger forces, while a smaller ellipse indicates lower grip and limited force generation. [13]

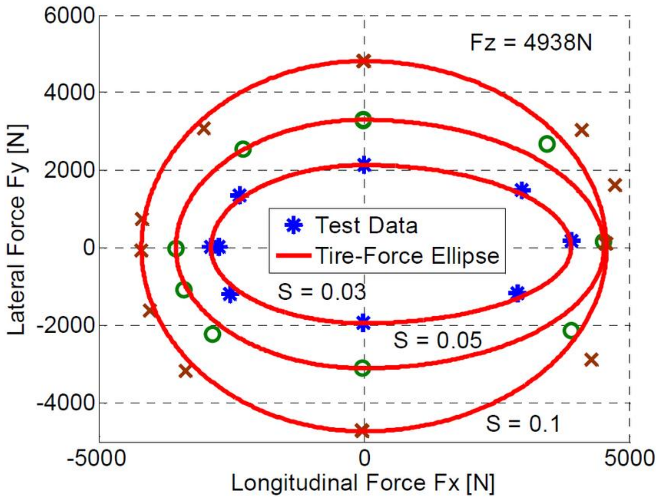

Figure 44: Adherence ellipse example

In general, tires have higher longitudinal grip compared to lateral grip due to their construction and design. The tire's tread pattern, compound, and other factors contribute to its ability to generate traction in the forward and backward direction. This allows the tire to provide better acceleration and braking performance.

In combined situations where both longitudinal and lateral forces are applied simultaneously, such as during cornering or aggressive manoeuvres, the maximum adherence is a combination of both types of grip. The tire must effectively balance and distribute the available grip between lateral and longitudinal forces to maintain traction and provide optimal performance.

The typical value of the adherence coefficient for a regular utility car is generally around 1. However, Formula Student tires are designed to have higher levels of grip, and under optimal tire conditions, they can achieve adherence coefficients of up to 2.5. It is important to note that the maximum longitudinal and lateral accelerations of the car are limited by the maximum adherence coefficient of the tires. Therefore, the vehicle's performance in terms of acceleration and cornering is directly influenced by the tire's grip capabilities. The higher the adherence coefficient, the greater the potential for the car to achieve higher levels of acceleration and cornering forces.

$$F_{long} = m_{car} \cdot a_{long} = m_{car} \cdot g \cdot \mu_{long} \tag{11}$$

$$F_{lat} = m_{car} \cdot a_{lat} = m_{car} \cdot g \cdot \mu_{lat} \tag{12}$$

$$a_{long} = \mu_{long}$$

$$a_{lat} = \mu_{lat}$$

Nevertheless, to ensure the safety and structural integrity of the car, the maximum accelerations are typically limited by applying a safety factor. This safety factor accounts for various uncertainties and factors such as variations in tire conditions, road surfaces, and other dynamic loads. By incorporating a safety factor of 1.2, the design of the car is more robust and capable of withstanding higher loads than what is expected under normal operating conditions. This approach ensures that the car remains reliable and stable during intense driving manoeuvres, providing an added margin of safety for the driver and the vehicle.

Taking all of these factors into consideration, the table below provides the maximum accelerations of the car, with several cases to analyse.

Loadcase Name	Failure Mode	Long G + for accel	Lat G +for outside	Velocity	WT_lateral	WT_long	Fz_%	Fx_car	Fy_car	Fx	Fy	Fz	Fx-Added Driveshafts
Static	Fatigue				0	0	25.00%	0	0	0	0	760	0
Max Braking	Fatigue	-2.00	0.00		0	-1162	6%	-6082	0	-358	0	179	0
Max Turn	Fatigue	0.00	2.00		1521	0	50%	0	6082	0	3041	1521	0
Max Speed	Fatigue	0.00	0.00		0	0	25%	0	0	0	0	760	0
Max Accel	Fatigue	2.00	0.00		0	1162	44%	6082	0	2683	0	1341	0
Combined 1	**Fatigue**	**-1.75**	**1.75**		**1330**	**-1017**	**30%**	**-5322**	**5322**	**-1605**	**1605**	**917**	**0**
Combined 2	Fatigue	1.75	1.75		1330	1017	64%	5322	5322	3384	3384	1934	0
Combined 3	Fatigue	-1.75	-1.75		-1330	-1017	-14%	-5322	-5322	724	724	-413	0
Combined 4	Fatigue	1.75	-1.75		-1330	1017	20%	5322	-5322	1056	-1056	603	0
	Fatigue				0	0	25%	0	0	0	0	760	0
Max Braking	Yield/Buckle	-3.00	0.00		0	-1743	-4%	-9123	0	334	0	-111	0
Max Turn	Yield/Buckle	0.00	3.00		2281	0	63%	0	9123	0	5702	1901	0
Max Speed	Yield/Buckle	0.00	0.00		0	0	25%	0	0	0	0	760	0
Max Accel	Yield/Buckle	2.40	0.00		0	1395	48%	7299	0	3498	0	1458	0
Combined 1	Yield/Buckle	2.25	2.25		1711	1307	75%	6842	6842	5106	5106	2269	0
Combined 2	Yield/Buckle	-2.25	2.25		1711	-1307	32%	-6842	6842	-2164	2164	962	0
Max Bump	Yield/Buckle	0.00	0.00		0	0	75%	0	0	0	0	2281	0
Combined 3	Yield/Buckle	2.25	-2.25		-1711	1307	18%	6842	-6842	1257	-1257	559	0
Combined 4	Yield/Buckle	-2.25	-2.25		-1711	-1307	-25%	-6842	-6842	1685	1685	-749	1
Rev. Braking	Yield/Buckle	1.75	0.00		0	0	25%	5322	0	1330	0	760	0

Table 9: Load cases front suspension

Loadcase Name	Failure Mode	Long G + for accel	Lat G +for outside	Velocity	WT_lateral	WT_long	Fz_%	Fx_car	Fy_car	Fx	Fy	Fz	Fx-Added Driveshafts
Static	Fatigue				0	0	25.00%	0	0	0	0	760	0
Max Braking	Fatigue	-2.00	0.00		0	-1162	6%	-6082	0	-358	0	179	0
Max Turn	Fatigue	0.00	2.00		1521	0	50%	0	6082	0	3041	1521	0
Max Speed	Fatigue	0.00	0.00		0	0	25%	0	0	0	0	760	0
Max Accel	Fatigue	2.00	0.00		0	1162	44%	6082	0	2683	0	1341	0
Combined 1	**Fatigue**	**-1.75**	**1.75**		**1330**	**-1017**	**30%**	**-5322**	**5322**	**-1605**	**1605**	**917**	**0**
Combined 2	Fatigue	1.75	1.75		1330	1017	64%	5322	5322	3384	3384	1934	0
Combined 3	Fatigue	-1.75	-1.75		-1330	-1017	-14%	-5322	-5322	724	724	-413	0
Combined 4	Fatigue	1.75	-1.75		-1330	1017	20%	5322	-5322	1056	-1056	603	0
	Fatigue				0	0	25%	0	0	0	0	760	0
Max Braking	Yield/Buckle	-2.50	0.00		0	-1453	1%	-7603	0	-85	0	34	0
Max Turn	Yield/Buckle	0.00	3.00		2281	0	63%	0	9123	0	5702	1901	0
Max Speed	Yield/Buckle	0.00	0.00		0	0	25%	0	0	0	0	760	0
Max Accel	Yield/Buckle	2.50	0.00		0	1453	49%	7603	0	3717	0	1487	0
Combined 1	Yield/Buckle	2.25	2.25		1711	1307	75%	6842	6842	5106	5106	2269	0
Combined 2	Yield/Buckle	-2.25	2.25		1711	-1307	32%	-6842	6842	-2164	2164	962	0
Max Bump	Yield/Buckle	0.00	0.00		0	0	75%	0	0	0	0	2281	0
Combined 3	Yield/Buckle	2.25	-2.25		-1711	1307	18%	6842	-6842	1257	-1257	559	0
Combined 4	Yield/Buckle	-2.25	-2.25		-1711	-1307	-25%	-6842	-6842	1685	1685	-749	1
Rev. Braking	Yield/Buckle	1.75	0.00		0	0	25%	5322	0	1330	0	760	0

Table 10: Load cases rear suspension

Note that there are different load cases to consider. The first set of cases represents normal operating conditions of the car, where the main concern is fatigue failure due to continuous exposure to significant forces, although not reaching the maximum tire adherence values. These cases include acceleration, braking, turning, and their combinations.

On the other hand, we also evaluate the maximum loads that occur under specific and rare conditions. These cases involve extreme and unusual situations such as maximum acceleration, braking, turning, and their combinations. Although infrequent, the suspension must be able to withstand these loads.

Additionally, there is a specific case for tire forces during a bump, which corresponds to a coefficient of 3 times the vertical load on the tire at that moment. It is important to consider this scenario as it represents a unique and demanding situation that the suspension design must be capable of handling.

Once all the necessary inputs for the equation (4) have been accurately calculated, we are equipped to determine the forces acting on each element of the suspension. This comprehensive analysis enables us to assess the load distribution and understand how the various components of the suspension system are affected under different operating conditions.

The calculated force values provide us with the necessary information to design each component of the suspension system with confidence, knowing that they will be able to withstand the applied forces. Armed with this knowledge, we can proceed to design the various elements of the suspension, such as control arms, uprights, springs, dampers, and other components, ensuring they are properly sized and constructed to handle the anticipated loads.

Ultimately, by leveraging the knowledge obtained from force calculations, we can confidently design a suspension system that delivers optimal performance, handling, and durability, ensuring a safe and enjoyable driving experience for the driver.

	Long G	Lat G	Up-Fore	Up-Aft	Low-Fore	Low-Aft	Push/Pull	Tie/Toe	
None			0	0	0	0	0	0	
Static			280	154	-469	-235	847	-104	
Max Braking	-2.00	0.00	-165	323	622	-705	237	-205	
Max Turn	0.00	2.00	2'090	1'721	-3'865	-2'599	1'780	-1'297	
Max Speed	0.00	0.00	280	154	-469	-235	847	-104	
Max Accel	2.00	0.00	2'226	-1'874	-6'313	4'445	1'215	1'171	
Combined 1	**-1.75**	**1.75**	110	2'215	1'171	-4'314	1'234	-1'510	
Combined 2	1.75	1.75	4'600	-742	-11'370	3'163	1'899	232	
Combined 3	-1.75	-1.75	678	-326	-1'921	932	-515	162	
Combined 4	1.75	-1.75	373	-1'213	-1'515	2'466	532	829	
			280	154	-469	-235	847	-104	
			280	154	-469	-235	847	-104	
Max Braking	-3.00	0.00	175	-290	-614	640	-159	184	
Max Turn	0.00	3.00	3'569	3'035	-6'661	-4'580	2'279	-2'302	
Max Speed	0.00	0.00	280	154	-469	-235	847	-104	
Max Accel	2.40	0.00	2'795	-2'503	-8'051	5'886	1'260	1'566	
Combined 1	2.25	2.25	6'701	-1'251	-16'754	4'973	2'142	438	
Combined 2	-2.25	2.25	46	2'931	1'748	-5'733	1'358	-1'998	
Max Bump	0.00	0.00	841	461	-1'407	-705	2'541	-311	
Combined 3	2.25	-2.25	385	-1'477	-1'705	2'984	456	1'008	
Combined 4	-2.25	-2.25	1'659	-715	-4'604	2'104	-961	349	
Reverse Braking	1.75	0.00	1'139	-910	-3'189	2'175	709	568	
			Highest Operating Force front						
		Fatigue (tension)	-165	-1874	-11370	-4314	-515	-1510	N
		Buckling	6701	3035	1748	5886	2541	1566	N
		Comp	6701	3035	1748	5886	2541	1566	N
		Tens	-165	-2503	-16754	-5733	-961	-2302	N

Table 11: Loads of each front suspension arm

	Long G	**Lat G**	**Up-Fore**	**Up-Aft**	**Low-Fore**	**Low-Aft**	**Push/Pull**	**Tie/Toe**	
None			**0**	**0**	**0**	**0**	**0**	**0**	
Static			**160**	**91**	**281**	**-1'382**	**1'187**	**96**	
Max Braking	-2.00	0.00	**-218**	**264**	**1'057**	**-864**	**232**	**-236**	
Max Turn	0.00	2.00	**1'595**	**1'616**	**-89**	**-7'735**	**2'614**	**211**	
Max Speed	0.00	0.00	**160**	**91**	**281**	**-1'382**	**1'187**	**96**	
Max Accel	2.00	0.00	**2'197**	**-1'659**	**-6'925**	**1'590**	**2'455**	**2'105**	
Combined 1	**-1.75**	**1.75**	**-279**	**1'955**	**4'434**	**-6'699**	**1'343**	**-1'032**	
Combined 2	1.75	1.75	**4'241**	**-468**	**-9'371**	**-3'966**	**3'741**	**2'708**	
Combined 3	-1.75	-1.75	**732**	**-199**	**-2'309**	**655**	**-492**	**475**	
Combined 4	1.75	-1.75	**438**	**-1'142**	**-2'473**	**2'215**	**1'001**	**831**	
			160	**91**	**281**	**-1'382**	**1'187**	**96**	
			160	**91**	**281**	**-1'382**	**1'187**	**96**	
Max Braking	-2.50	0.00	**-53**	**62**	**247**	**-189**	**42**	**-57**	
Max Turn	0.00	3.00	**2'790**	**2'916**	**-517**	**-12'776**	**3'418**	**276**	
Max Speed	0.00	0.00	**160**	**91**	**281**	**-1'382**	**1'187**	**96**	
Max Accel	2.50	0.00	**2'966**	**-2'343**	**-9'731**	**2'878**	**2'821**	**2'869**	
Combined 1	2.25	2.25	**6'262**	**-783**	**-14'377**	**-4'806**	**4'632**	**4'003**	
Combined 2	-2.25	2.25	**-435**	**2'603**	**5'878**	**-8'535**	**1'382**	**-1'427**	
Max Bump	0.00	0.00	**481**	**273**	**842**	**-4'145**	**3'562**	**287**	
Combined 3	2.25	-2.25	**488**	**-1'378**	**-3'002**	**2'927**	**942**	**970**	
Combined 4	-2.25	-2.25	**1'750**	**-438**	**-5'297**	**1'136**	**-811**	**1'132**	
Reverse Braking	1.75	0.00	**1'110**	**-811**	**-3'399**	**616**	**1'366**	**1'056**	
			Highest Operating Force rear						
		Fatigue (tension)	-279	-1659	-9371	-7735	-492	-1032	N
		Buckling	6262	2916	5878	2927	4632	4003	N
		Comp	6262	2916	5878	2927	4632	4003	N
		Tens	-435	-2343	-14377	-12776	-811	-1427	N

Table 12: Loads of each rear suspension arm

3.3 *DESIGN OF THE CONTROL ARMS*

The control arm assembly consists of carbon fiber tubes that are bonded with aluminium inserts. These inserts contain the rod ends, allowing the mechanism to rotate through them. The design of the tubes and adhesive takes into account the previously calculated loads in order to ensure proper strength and control the stress distribution in the carbon fiber tubes and adhesive joints. This design approach ensures that the control arms can effectively handle the forces and loads experienced during vehicle operation.

Figure 45: Exploded view of a wishbone

The carbon fiber data sheet and structural adhesive properties provided by the manufacturer serve as the basis for the design of the wishbone's structural and adhesive components. These properties include information such as the tensile strength, modulus of elasticity, and adhesive bonding strength. The wishbone can be designed using these data to withstand the anticipated forces and loads, ensuring its structural integrity and reliability.

3.3.1 STRUCTURAL ANALYSIS

For the structural analysis of the wishbone, initial calculations are performed by hand to determine the minimum required tube area and moment of inertia to withstand the anticipated loads. These calculations involve evaluating the safety factor acting on the wishbone under different load conditions. The material properties of the carbon fiber tube, such as their tensile strength and modulus of elasticity, are known values given by the manufacturer Clip Carbono. [14]

Carbon fiber properties		
Tension Yield	612	MPa
Compression Yield	456	MPa
Fatigue	459	MPa
Young modulus E	70	Gpa

Table 13: Carbon fiber properties

The structural analysis of the wishbone will involve three key failure modes: tension, compression, and fatigue.

In the tension analysis, the maximum tensile stresses experienced by the wishbone will be evaluated to ensure that the material's tensile strength is not exceeded. This is important as tension can lead to structural failure and compromise the integrity of the wishbone.

Similarly, in the compression analysis, the maximum compressive stresses will be examined to verify that the material can withstand the compressive forces without buckling or deformation.

Furthermore, the fatigue analysis will focus on assessing the cyclic loading conditions that the wishbone may encounter during its operational lifespan. By considering the expected number of load cycles and the material's fatigue strength, the design will be evaluated to ensure it can withstand these repeated loadings without experiencing fatigue failure.

Through these failure case analyses, the structural integrity and durability of the wishbone will be assessed, allowing for the identification of potential design improvements or the need for material adjustments to ensure optimal performance and reliability.

3.3.1.1 Tension

In the tension analysis for the tube, we will focus on evaluating the maximum tensile stresses caused by normal forces acting on the component.

To calculate the tensile stress, we use the formula: [14]

$$\sigma = Force \;/\; Area \tag{13}$$

The area of the circular ring section of the tube is just the area contained between the inner and outer diameter. Then, we will compare the tension in the tube with the maximum tensile force, taking into account the allowable stress of the material and ensuring a minimum safety factor of 1.2.

$$n = \frac{\sigma_{max}}{\sigma} = \frac{\sigma_{max}}{F_{max} \;/\; \pi \cdot (r_o^2 - r_i^2)} \geq 1.2 \tag{14}$$

3.3.1.2 Fatigue

For the fatigue analysis, the same formulas will be used, but considering a reduced allowable stress of the material by 25%. The analysis will consider the typical force cases that the suspension experiences during operation. These cases include acceleration, braking, turning, and their combinations. The goal is to determine if the suspension arm can withstand the cyclic loading and avoid fatigue failure over its intended lifespan.

3.3.1.3 Compression (Buckling)

In the analysis of buckling compression, formulas are used that consider the effective length of the structural element and the material properties. One of the commonly used formulas is Euler's buckling formula, which states that the critical buckling load is proportional to the modulus of elasticity of the material, the moment of inertia of the cross-section, and inversely proportional to the square of the effective length [4]. This can be expressed as:

$$P_{critical} = \frac{(\pi^2 \cdot E \cdot I)}{(K \cdot L_{eff})^2} \tag{15}$$

Where $P_{critical}$ is the critical buckling load, E is the modulus of elasticity, I is the moment of inertia of the cross-section, K is the effective length factor (dependent on the boundary conditions), and L_{eff} is the effective length of the element. In the case of the suspension system, the effective length is the same as the length of the tube because it is an articulated union.

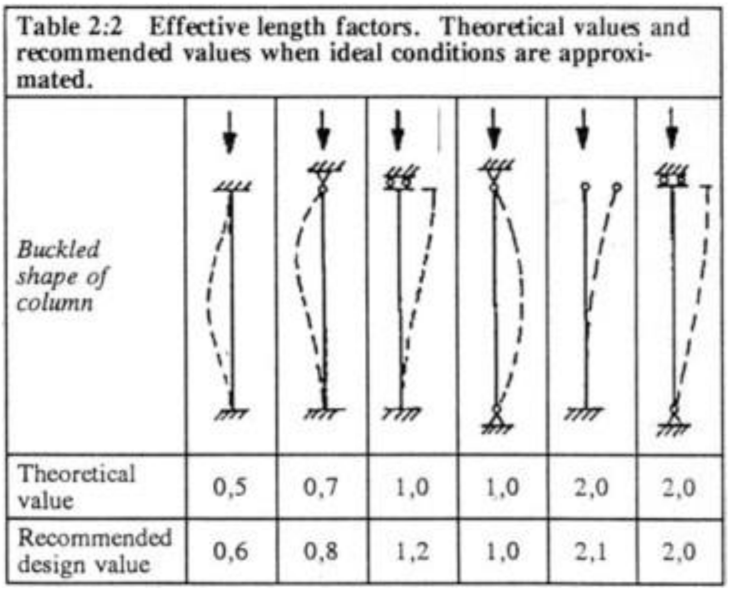
Table 2:2 Effective length factors. Theoretical values and recommended values when ideal conditions are approximated.

Buckled shape of column						
Theoretical value	0,5	0,7	1,0	1,0	2,0	2,0
Recommended design value	0,6	0,8	1,2	1,0	2,1	2,0

Figure 46: Buckling considerations

The safety factor in buckling compression is calculated as the ratio of the critical buckling load to the maximum compressive force applied to the structural element. It is important to ensure that the safety factor is higher than 1.2 to provide a margin of safety against buckling failure. The safety factor can be calculated as:

$$n = \frac{\mathrm{P_{critical}}}{F_{max}} \geq 1.2 \tag{16}$$

If the safety factor is less than 1.2, it indicates that the compressive load is approaching the critical buckling load and there is a higher risk of buckling failure. Therefore, it is necessary to increase the size, strength, or stiffness of the structural element to improve its resistance to buckling under compression and ensure a higher safety factor.

3.3.2 ADHESIVE DESIGN

The adhesive manufacturer provides us with a specifications sheet that includes important information, such as the Tension Yield value. This value indicates the maximum tensile stress that the adhesive can withstand before experiencing deformation or failure. The selected adhesive is the structural 3M™ Scotch-Weld™ EC-9323-2 B/A, special for critical composite structures. Maximum shear strength is obtained with 0.10 – 0.20 mm bond line thickness [15], so the inserts will keep that distance to the carbon fiber tube wall. This parameter is very critical and will be controlled by centering the insert directly in the tube with an overlap the size of the inner tube. [5]

Adhesive properties		
Tension Yield	30	Mpa
comp yield	30	Mpa
Fatigue	22.5	Mpa

Table 14: Adhesive properties

The adhesive design for the joint area involves considering both tension and fatigue cases. Compression is omitted as adhesive work very well in such conditions. In tension, the adhesive must be able to withstand the maximum tensile load applied to the joint. The design should ensure that the adhesive's tensile strength exceeds the maximum tensile load, considering the critical problems that can arise if the adhesion is not perfect. It is used a safety factor of at least 5 for adhesive design in the suspension to avoid problems. This higher safety factor provides an additional margin of safety to account for any uncertainties or potential weaknesses in the adhesive bond.

In the fatigue case, the adhesive must be able to withstand cyclic loading without experiencing adhesive failure. This involves considering the number of cycles and the stress amplitude applied to the joint. The design should ensure that the adhesive has sufficient fatigue resistance to withstand the expected number of cycles without failure. To do so, a reduction of the adhesive maximum stress of 25% will be considered.

$$n = \frac{\sigma_{max}}{\sigma} = \frac{\sigma_{max}}{F_{max} \,/\, 2 \cdot \pi \cdot r \cdot L} \geq 5 \tag{17}$$

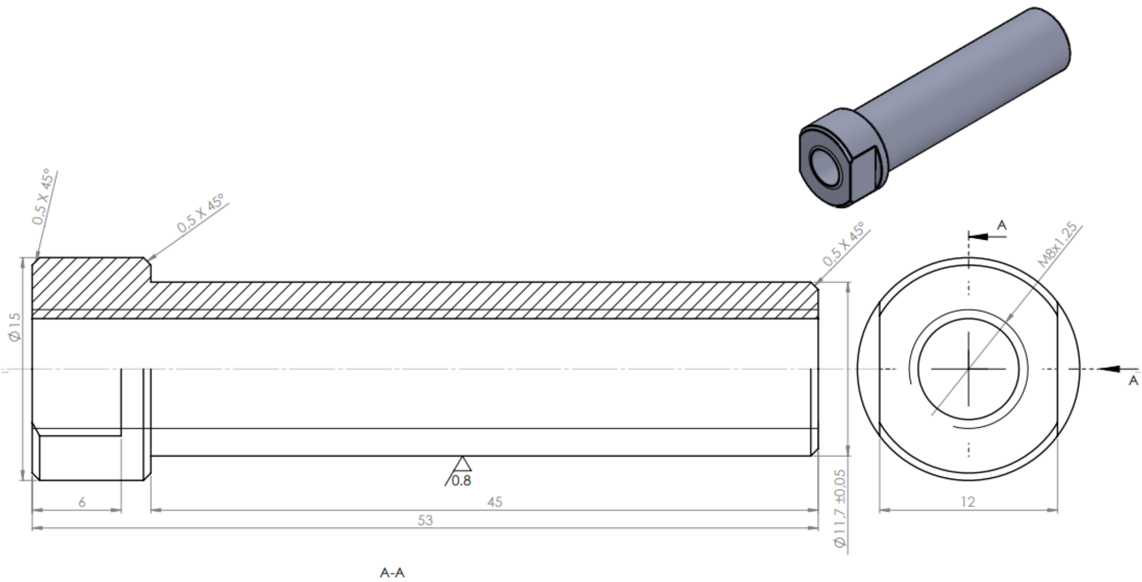

Figure 47: Drawing of the insert

Proper surface preparation is essential to ensure effective adhesion between the materials. Before applying the adhesive, it is crucial to thoroughly clean and prepare the surface to remove any contaminants, such as dirt, grease, or oxidation, that may hinder the bonding process. This can be achieved through various methods, including solvent cleaning, abrasion, or chemical treatments.

Firstly, solvent cleaning involves using appropriate solvents to remove any surface contaminants. This ensures a clean and pristine surface for optimal adhesion. Secondly, abrasion techniques, such as sanding or roughening the surface, create a textured surface that promotes better bonding by increasing the surface area available for adhesion. This is particularly important for smooth or non-porous materials that may have lower surface energy.

Additionally, chemical treatments can be applied to enhance adhesion by creating chemical bonds between the adhesive and the substrate. These treatments often involve the use of primers or adhesion promoters that are specifically formulated to improve the bonding properties of the surfaces. [17]

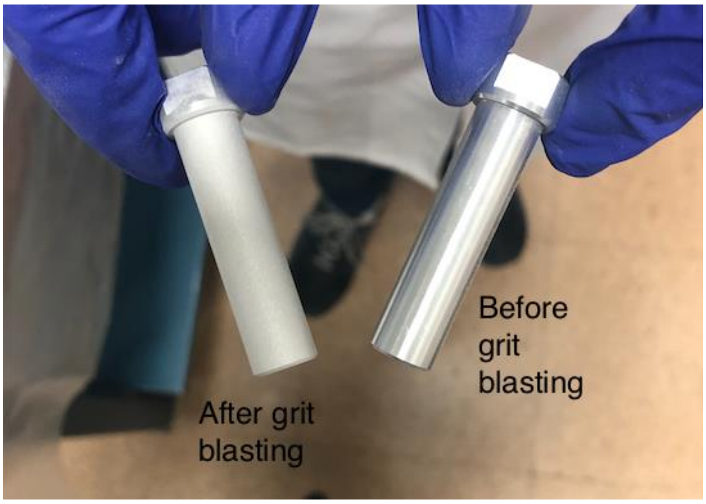

Table 15: Surface preparation of the inserts

3.3.3 RESULTS

The final dimensions of the tube and adhesive are obtained through an iterative process, adjusting the tube diameter, wall thickness, and insert length until an optimal design that meets all the imposed safety conditions.

The iteration begins by selecting initial values for the tube diameter, wall thickness, and insert length based on engineering judgment and previous design considerations. These initial values are then used to calculate the forces and stresses in the suspension components using the load cases and analysis methods discussed earlier with an excel sheet.

Next, the calculated forces and stresses are compared against the allowable limits and safety factors determined for each component. If the initial dimensions do not meet the safety requirements, the values are adjusted, and the calculations are repeated. This iterative process continues until a set of dimensions is found that satisfies all the safety conditions and design constraints.

Throughout the iteration, it is crucial to consider other design factors, such as weight, packaging constraints, and manufacturability. These factors may influence the final dimensions and material selection to ensure an optimal balance between performance, strength, and practicality.

The selected carbon fiber tubes have an outer diameter of 15mm and a wall thickness of 1.5mm, which meet the imposed safety factor of 1.2. These dimensions were determined through the iterative design process, considering the calculated forces and stresses in the suspension components. The chosen tube dimensions provide sufficient strength and reliability to withstand the applied loads while ensuring a margin of safety.

Carbon fiber tubes front							
OD	**15**	**15**	**15**	**15**	**15**	**15**	mm
Wall	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	mm
Area	63.61725	63.6172512	63.61725	63.61725	63.61725	63.61725	mm2
Inertia	1467.173	1467.17286	1467.173	1467.173	1467.173	1467.173	mm4
Lenght	307.0516	316.428396	347.7154	377.3841	568.5749	270.7065	mm
k	1	1	1	1	1	1	
Pcr	10751.18	10123.4413	8383.611	7117.244	3135.478	13831.89	N
Tension Yield	612	612	612	612	612	612	MPa
Comp Yield	456	456	456	456	456	456	MPa
Fatigue	459	459	459	459	459	459	MPa
σ Tension	-2.59705	-39.337537	-263.357	-90.1101	-15.1092	-36.179	Mpa
σ Compression	105.328	47.7021767	27.47888	92.521	39.93525	24.62214	Mpa
σ Fatigue	-2.59705	-29.456907	-178.732	-67.8122	-8.09719	-23.731	Mpa
n tension	235.6518	15.5576594	2.323841	6.791695	40.50505	16.91587	
n compression	1.604492	3.33591573	4.795757	1.209196	1.234163	8.830411	
n fatigue	176.7389	15.5820843	2.568084	6.768693	56.68635	19.34177	

Table 16: Carbon fiber tubes design front

Carbon fiber tubes rear							
OD	**15**	**15**	**15**	**15**	**15**	**15**	mm
Wall	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	mm
Area	63.61725	63.6172512	63.61725	63.61725	63.61725	63.61725	mm2
Inertia	1467.173	1467.17286	1467.173	1467.173	1467.173	1467.173	mm4
Lenght	348.096	325.861934	372.5921	311.0884	361.1996	311.0884	mm
k	1	1	1	1	1	1	
Pcr	8365.291	9545.7885	7301.494	10473.97	7769.346	10473.97	N
Tension Yield	612	612	612	612	612	612	MPa
Comp Yield	456	456	456	456	456	456	MPa
Fatigue	459	459	459	459	459	459	MPa
σ Tension	-6.83351	-36.822811	-225.992	-200.82	-12.742	-22.4275	Mpa
σ Compression	98.42973	45.8390252	92.40293	46.00789	72.80381	62.92599	Mpa
σ Fatigue	-4.39198	-26.074908	-147.303	-121.583	-7.72743	-16.2276	Mpa
n tension	89.55862	16.6201326	2.70806	3.047508	48.02998	27.2879	
n compression	1.335918	3.27341851	1.242084	3.578526	1.677473	2.616414	
n fatigue	104.5087	17.6031302	3.116032	3.775201	59.39876	28.28521	

Table 17: Carbon fiber tubes design rear

For the adhesive design, an optimal adhesive thickness of 0.15mm is considered, and the length of the insert is iterated to achieve a bonding area that meets the safety factor of 5 in all cases.

Adhesive front							
OD	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	mm
Length	**30**	**30**	**45**	**45**	**30**	**30**	mm
Area	1102.699	1102.69902	1654.049	1654.049	1102.699	1102.699	mm2
Tension Yield	30	30	30	30	30	30	Mpa
comp yield	30	30	30	30	30	30	Mpa
Fatigue	22.5	22.5	22.5	22.5	22.5	22.5	Mpa
σ Tension	-0.14983	-2.2694733	-10.1291	-3.46577	-0.87169	-2.08725	Mpa
σ comp	6.076614	2.75204866	1.05688	3.5585	2.303957	1.420508	Mpa
σ fatigue	-0.14983	-1.6994369	-6.87433	-2.60816	-0.46715	-1.3691	Mpa
n tension	200.227	13.2189263	2.961758	8.656082	34.41605	14.37296	
n comp	4.93696	10.9009701	28.38543	8.430519	13.02108	21.11921	
n fatigue	150.1703	13.2396795	3.273049	8.626766	48.16487	16.43418	

Table 18: Adhesive design front

Adhesive rear							
OD	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	**11.7**	mm
Length	**45**	**45**	**45**	**45**	**45**	**45**	mm
Area	1654.049	1654.04853	1654.049	1654.049	1654.049	1654.049	mm2
Tension Yield	30	30	30	30	30	30	Mpa
comp yield	30	30	30	30	30	30	Mpa
Fatigue	22.5	22.5	22.5	22.5	22.5	22.5	Mpa
σ Tension	-0.26283	-1.416262	-8.692	-7.72384	-0.49008	-0.8626	Mpa
σ comp	3.785759	1.76303943	3.553959	1.769534	2.800147	2.42023	Mpa
σ fatigue	-0.16892	-1.0028811	-5.66549	-4.67627	-0.29721	-0.62414	Mpa
n tension	114.1433	21.1825219	3.451449	3.884078	61.21467	34.7787	
n comp	7.924435	17.0160687	8.441291	16.95361	10.71372	12.39551	
n fatigue	133.1973	22.435362	3.971413	4.81153	75.70431	36.04977	

Table 19: Adhesive design rear

3.3.4 ANSYS VALIDATION

To validate the results, simulations are conducted using ANSYS to analyse the carbon fiber tubes, aiming to compare their outcomes for similarity. The Composite module within ANSYS is employed to simulate the behaviour of the carbon fiber tube. This involves creating a finite element model of the composite material, which consists in this case of the fiber components. The material properties of the fiber are inputted, along with the fiber orientation and stacking sequence, given by the carbon fiber manufacturer.

Bidirectional carbon fiber properties		
Tension Yield	612	MPa
Compression Yield	456	MPa
Tensile ultimate Strength	720	MPa
Compressive ultimate Strength	570	MPa
Density	1.6	g/cm^3
Young's Modulus X	70	Gpa
Young's Modulus Y	70	Gpa
Young's Modulus Z	7	Gpa
Poisson's Ratio XY	0.1	
Poisson's Ratio YZ	0.08	
Poisson's Ratio XZ	0.08	
Shear Modulus XY	5	Gpa
Shear Modulus YZ	5	Gpa
Shear Modulus XZ	5	Gpa

Table 20: Bidirectional carbon fiber properties

The simulation involves subjecting the composite tube to tension and compression scenarios for each suspension arm of the car under their most loaded configurations. The Composite module takes into account the anisotropic nature of composite materials, which exhibit different mechanical properties in different directions due to the fiber orientation.

To facilitate the calculation of each individual suspension arm, a parametric model will be generated using Ansys Workbench. This approach involves defining variables and parameters that can be easily adjusted, allowing for efficient exploration of various design configurations. With this parametric model, it becomes possible to systematically study the effects of different input parameters on the performance of the composite tubes under tension and compression scenarios. This streamlined process not only enhances accuracy in assessing the structural response but also expedites the evaluation of design changes, ultimately aiding in the validation process and contributing to the overall optimization of the suspension system. The input parameters of the model will be the maximum and the length of load of each tube, since the outer and inner diameter are the same for all suspension arms.

The initial step involves creating the geometry by constructing a surface with a diameter of 12mm and subsequently adding a thickness of 1.5mm to form the composite tube. Following this, the tube is meshed, with particular emphasis on refining the mesh at the tube ends to prevent any potential discontinuities.

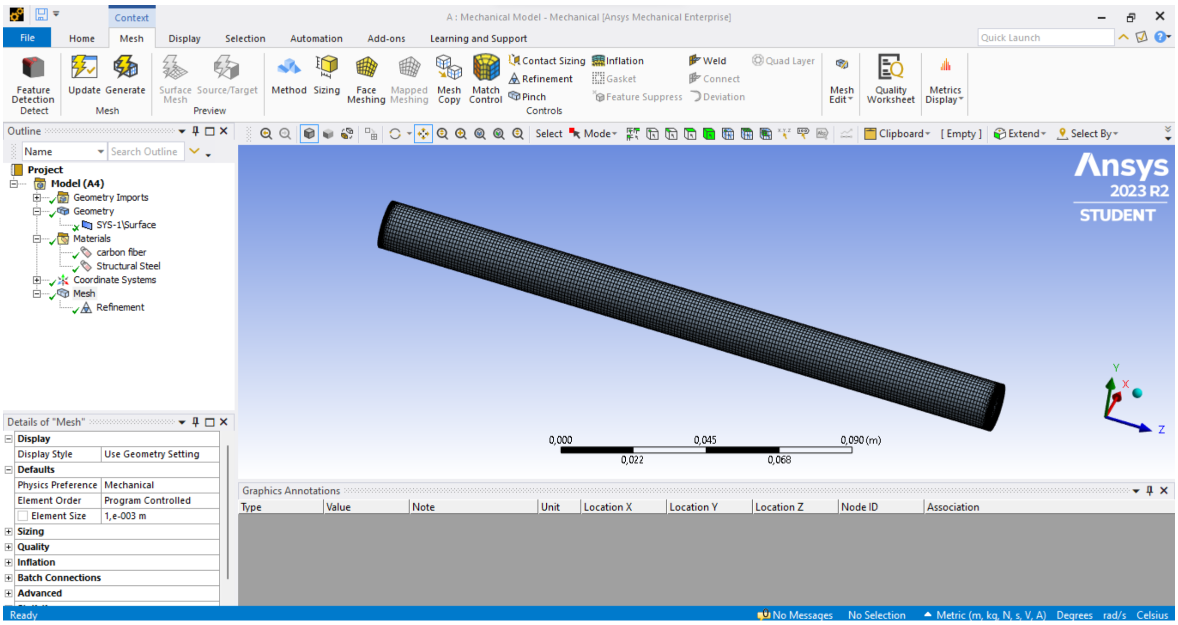

Figure 48: Geometry and mesh

The subsequent step involves creating the carbon fiber composite and applying different layers to the tube using the ACP (Advanced Composite Pre) module. This module facilitates the process of defining the composite material properties, such as fiber orientation, stacking sequence, and ply thickness, allowing for the accurate representation of the real-world composite behaviour. The carbon fiber is already designed as bidirectional in the material properties, so the fibres are disposed in the tube following the principal axis and defined as three layers of 0.5mm thick, evolving the tube. [18]

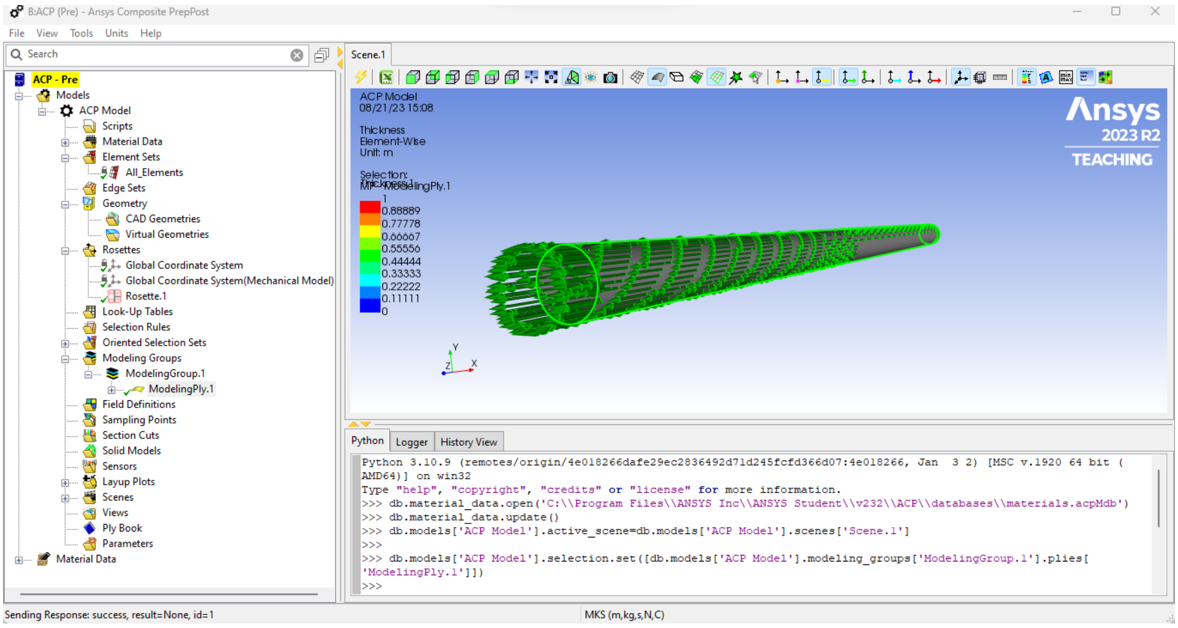

Figure 49: Composite layers of the carbon fiber tube in ANSYS ACP

Once the carbon fiber tube is created, it is exported to the Static Structural module for simulation. Tension and compression normal stresses are simulated by fixing one end of the tube and applying a force to the opposite end. The results obtained include the equivalent von Mises stress and the average displacement of the tube. This scenario is simulated for all tubes lengths and maximum forces.

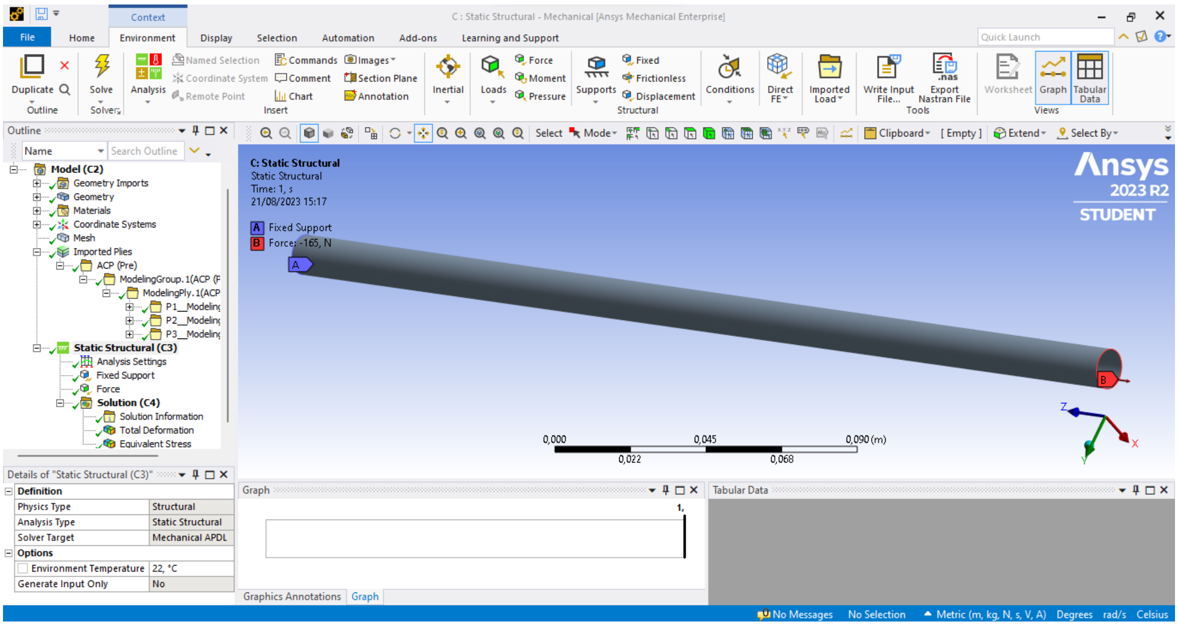

Figure 50: ANSYS Mechanical model

With all these steps completed, the results from the ANSYS simulation are as follows, compared to the previous structural study.

The comparison between the tension results reveals a notable similarity, albeit with slightly lower safety coefficients in the ANSYS simulation. However, significant disparities emerge in the compression analysis. This variance can be attributed to the differential inclusion of buckling effects in the previous calculations, contrasting with ANSYS's exclusive focus on compression failure. Additionally, the calculated tube displacements indicate an exceptionally minimal extent due to the inherent robustness of the fiber material. This promising outcome suggests that the suspension's overall stiffness will experience negligible impact. Thus, the validity of assuming the tubes as nearly infinitely rigid is substantiated.

Name	P1 - Lenght	P4 - Force Magnitude	P2 - Equivalent Stress Average	P3 - Total Deformation Average	n ANSYS	n first study
Units	mm	N	Mpa	mm		
DP 0	307.05	-165	2.98	0.01	205.13	235.65
DP 1	316.42	-2503	45.23	0.10	13.53	15.56
DP 2	347.71	-16754	302.29	0.74	2.02	2.32
DP 3	377.38	-5733	103.30	0.27	5.92	6.79
DP 4	568.57	-961	17.22	0.07	35.54	40.51
DP 5	270.7	-2302	41.72	0.08	14.67	16.92
DP 6	348.09	-435	7.85	0.02	77.98	89.56
DP 7	325.86	-2343	42.32	0.10	14.46	16.62
DP 8	372.59	-14377	259.11	0.68	2.36	2.71
DP 9	311.08	-12776	230.96	0.51	2.65	3.05
DP 10	361.19	-811	14.62	0.04	41.85	48.03
DP 11	311.08	-1427	25.80	0.06	23.72	27.29
DP 12	307.05	6701	121.17	0.26	3.76	1.60
DP 13	316.42	3035	54.85	0.12	8.31	3.34
DP 14	347.71	1748	31.54	0.08	14.46	4.80
DP 15	377.38	5886	106.06	0.28	4.30	1.21
DP 16	568.57	2541	45.54	0.18	10.01	1.23
DP 17	270.7	1566	28.38	0.05	16.07	8.83
DP 18	348.09	6262	112.98	0.28	4.04	1.34
DP 19	325.86	2916	52.67	0.12	8.66	3.27
DP 20	372.59	5878	105.94	0.28	4.30	1.24
DP 21	311.08	2927	52.91	0.12	8.62	3.58
DP 22	361.19	4632	83.52	0.21	5.46	1.68
DP 23	311.08	4003	72.37	0.16	6.30	2.62

Table 21: ANSYS results

Chapter 4. CONCLUSION AND FUTURE WORK

4.1 CONCLUSIONS

In conclusion, the design and development of the IFS05 suspension system for the Formula Student car have been successfully executed. Through a thorough analysis of previous versions and rigorous studies and validations, significant improvements have been made to enhance the performance and handling of the vehicle.

The modifications made to the IFS05 suspension were driven by the development requirements identified during track testing. The aim was to address the issues encountered in the previous IFS03 and IFS04 versions while improving the overall performance of the car and advancing the department's knowledge. Several significant changes were implemented in the suspension geometry:

- **Antidive and antisquat geometry**: The inclusion of these features helps to control excessive pitch during braking and acceleration, respectively, aiming for a 30% reduction.
- **Wheelbase reduction**: The wheelbase was shortened from 1730mm to 1570mm, which contributes to improved manoeuvrability and responsiveness of the car.
- **Track equalization**: The track width of both the front and rear axles was adjusted to 1200mm, promoting better stability and handling characteristics.
- **Motion ratio optimization**: The motion ratio was fine-tuned to a value of 1.2, ensuring the suspension operates optimally and in line with the desired performance targets.
- **Enhanced suspension rod layout and design**: The arrangement and design of the suspension rods were optimized to enhance structural integrity, reduce weight, and improve overall suspension performance.

- **Improved camber gain and static targets**: The suspension was fine-tuned to achieve better control over camber gain and meet the desired static camber targets, enhancing tire contact and traction during cornering.
- **Roll center definition**: The roll centers were accurately defined to maintain stability and minimize roll forces during vehicle dynamics.
- **Optimized steering geometry**: The steering geometry was carefully designed to achieve 100% Ackermann with maximum steer travel, improving the car's cornering ability and reducing tire slip when turning.
- **Reduced steering forces**: Trail was reduced by 22% to minimize steering forces, resulting in improved steering response and driver feedback.
- **Caster and kingpin angle adjustments**: The caster and kingpin angles were modified to control steering forces and camber gain during steering manoeuvres, further enhancing the car's handling characteristics.

These changes collectively contribute to the overall performance, handling, and stability of the IFS05 suspension, providing a more refined and efficient setup for the Formula Student car.

Significant progress has also been made in the mechanical design of the car, particularly in the calculation of suspension stresses and the design and dimensioning of suspension components. Through the analysis of the forces and loads acting on the suspension system during various load cases, we have been able to determine the critical areas where structural integrity and strength are paramount with:

- **Load Calculation**: Analysis of the forces and loads acting on the suspension system has been conducted. Considering various load cases, such as acceleration, braking, turning, combined cases, and bumps, we have been able to accurately determine the magnitude and direction of the forces exerted on the suspension components. This has enabled us to identify the critical areas where structural integrity and strength are crucial.

- **Suspension Arms Design**: A meticulous design process has been undertaken to optimize the performance, weight, and durability of the suspension arms. Factors such as material selection, stress distribution, and safety factors have been carefully considered. The aim has been to develop suspension arms that can effectively transmit forces, withstand the anticipated loads, and provide controlled motion. Through iterative design iterations, we have achieved a balance between weight reduction and structural robustness, ensuring the reliability and longevity of the suspension system with the carbon fiber tubes and the adhesive.

Overall, the IFS05 suspension design represents a significant step forward in terms of performance, safety, and sustainability for the Formula Student car. The successful implementation of these improvements opens up opportunities for further advancements in future iterations and underscores the importance of continuous innovation in the field of automotive engineering.

4.2 FUTURE WORK

In terms of future work, there are several key areas that the department should focus on regarding the suspension geometry and rear uprights. These include:

- **Rear Axis**: The caster and kingpin inclination play a crucial role in the overall handling and stability of the vehicle. Further analysis and optimization of these parameters specifically for the rear axis will help fine-tune the suspension geometry and improve the vehicle's performance. New uprights may be designed to follow up the new design of the front ones and optimize the rear suspension parameters.

- **New Rear Upright**: To achieve the desired requirements and accommodate the changes in the suspension geometry, it is necessary to design and manufacture a new rear upright. This can be achieved by modifying the UCA (Upper Control Arm) attachment point in the uprights to ensure proper alignment and functionality. The new upright is modular. Following this design, we are able to change easily the suspension geometry.
- **Optimize the Design of the Uprights**: The design of the uprights can be further optimized to achieve weight and volume reduction while maintaining structural integrity. Exploring innovative design approaches, such as topologic optimization and additive manufacturing.
- **Study and Improve Bearing Performance**: While not directly related to the suspension geometry, it is important to address any existing free play between the upright and the wheel hub. Studying the bearings and implementing measures to reduce or eliminate this free play will enhance the overall performance and reliability of the suspension system.
- **Car simulation**: In order to test and measure all the changes in the car, we should be able to simulate the full vehicle performance on the track to ensure that the modifications are based in real data instead of recommendations.
- **Manufacturing process**: The suspension soldering in the chassis was deficient. We must find a way to precisely manufacture the suspension attachments to ensure that the designed geometry is the one that is mounted in the car.

By focusing on these future lines of work, the department can continue to advance the design and development of the suspension system, further improving the vehicle's performance. These efforts will contribute to the ongoing pursuit of excellence and innovation in the field of automotive engineering and improving the ISC Formula Student Racing Team.

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ANNEX I – ALIGNMENT OF PROJECT WITH SDGS

Alignment with the Sustainable Development Goals (SDGs) is a relevant aspect to consider in any master's thesis and future professional projects. Here are some SDGs that are related to this project:

- **SDG 9: Industry, Innovation, and Infrastructure**: The design and optimization of a Formula Student suspension system involve innovation in the field of automotive engineering, contributing to the development of more efficient and advanced technologies in the industry.

- **SDG 11: Sustainable Cities and Communities**: Studying the suspension system of a high-performance vehicle can have applications in designing safer and more efficient suspension systems for automobiles in general, contributing to the creation of safer and sustainable communities in terms of mobility.

- **SDG 12: Responsible Consumption and Production**: By optimizing the vehicle's suspension system, the aim is to improve efficiency and reduce resource consumption, such as fuel and materials used in the manufacturing of suspension components.

- **SDG 13: Climate Action**: By enhancing the efficiency and performance of the vehicle through a well-designed suspension system, it is possible to reduce the environmental impact related to greenhouse gas emissions and fuel consumption. Moreover, working with a 100% electric vehicle contributes to the research and development of electric mobility, with zero emissions throughout its lifecycle.

- **SDG 17: Partnerships for the Goals**: Conducting a master's thesis in collaboration with a Formula Student team can foster partnerships between academia and industry, promoting knowledge transfer and collaboration to achieve common objectives related to sustainable mobility and technological innovation.

These are just a few examples of how research on a Formula Student suspension system can contribute to the SDGs. It is important to specifically identify and analyse how the project addresses and relates to the goals and targets set in the United Nations' 2030 Agenda.

Figure 51: SDGs of the master's thesis

ANNEX II – FINAL RESULTS

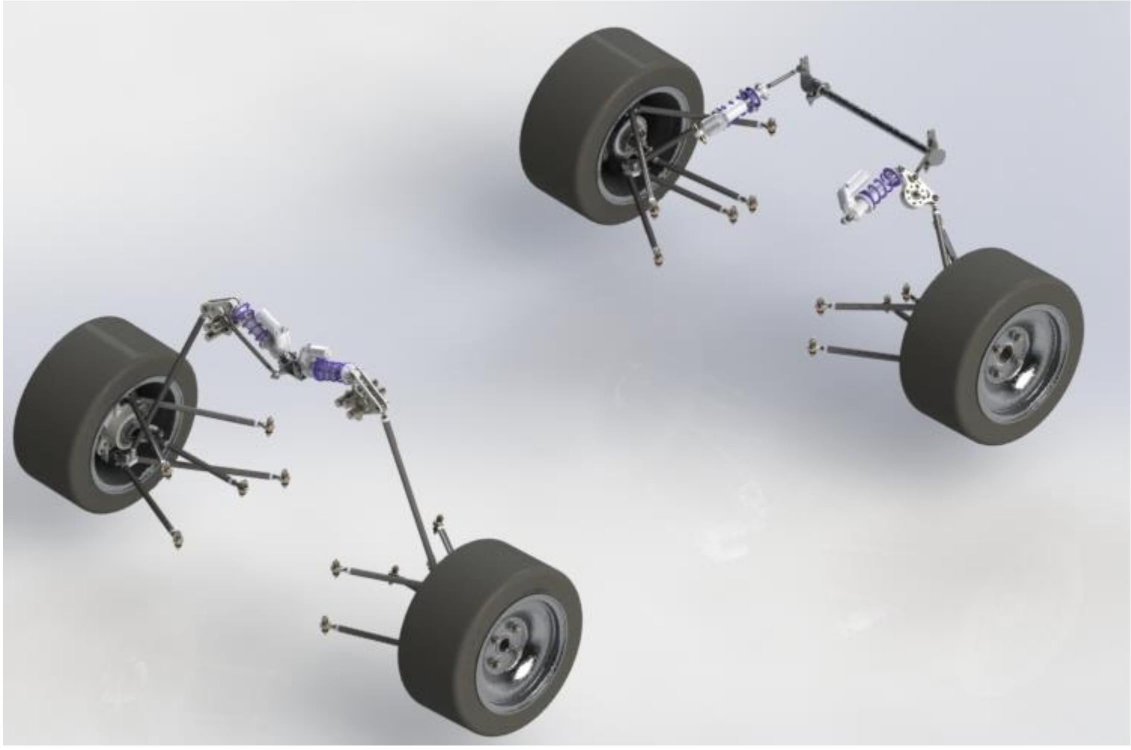

Figure 52: Suspension render

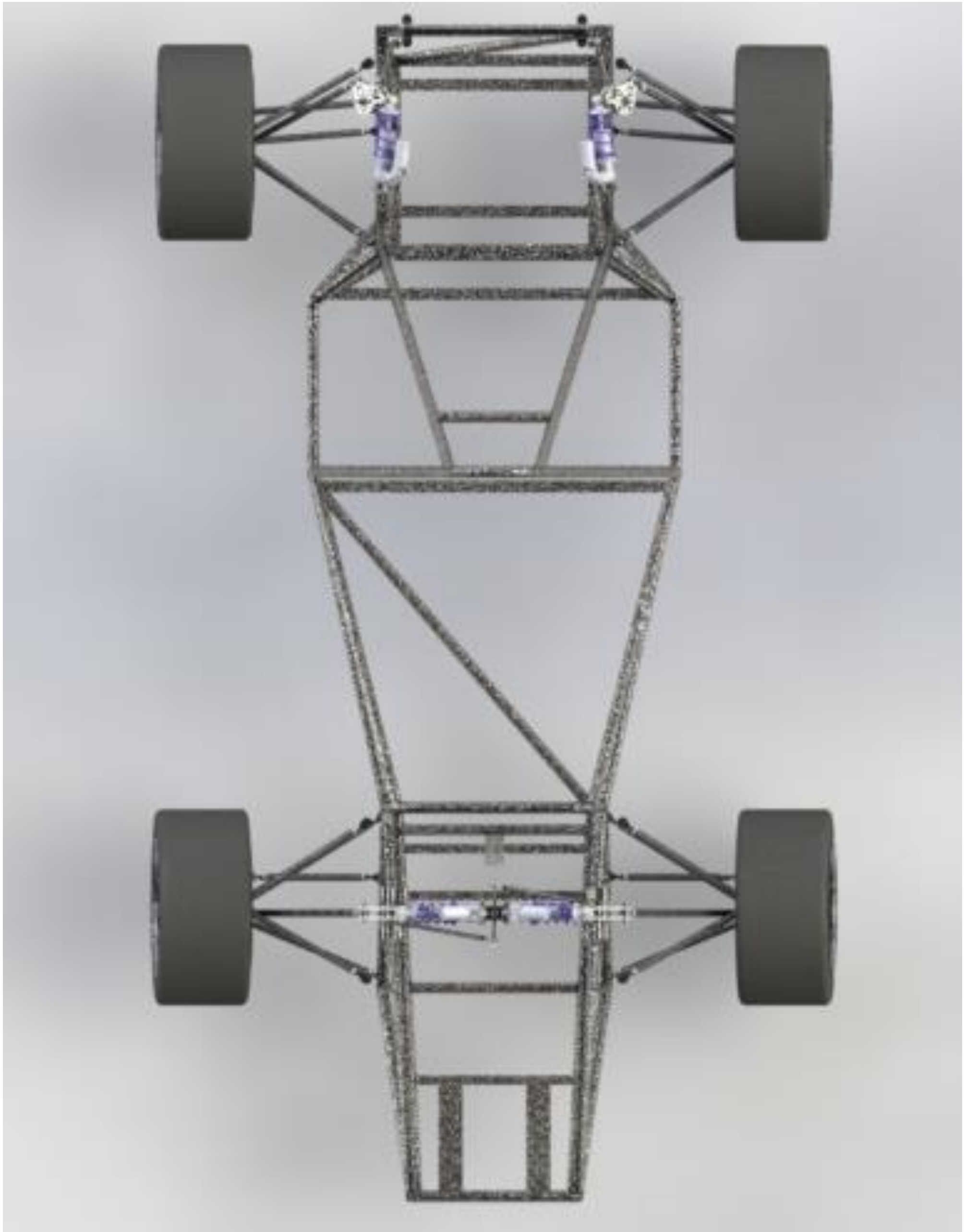

Figure 53: Suspension top view

Figure 55: Front suspension front view

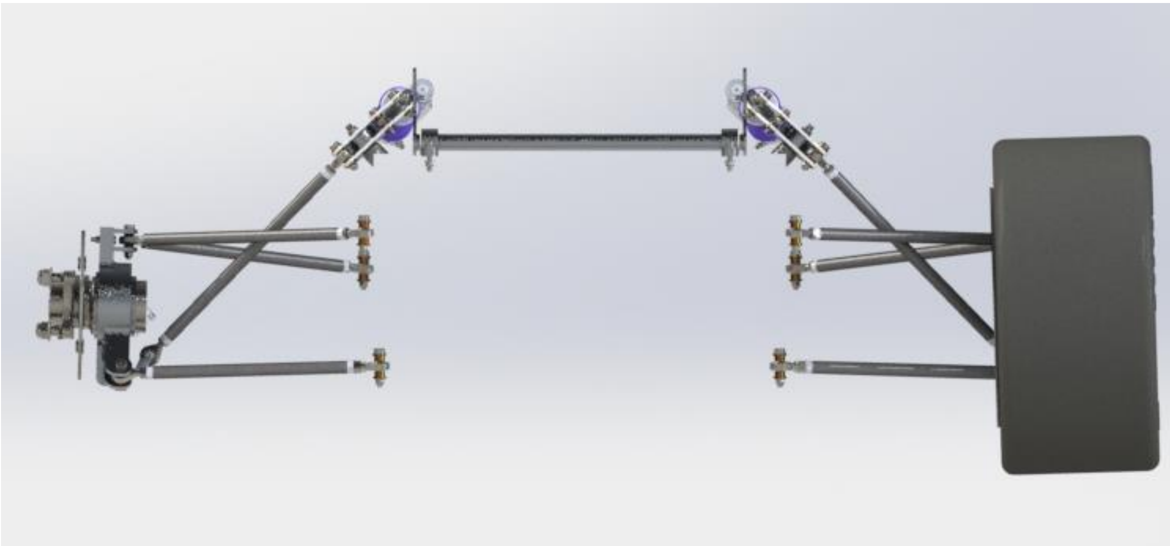

Figure 54: Rear suspension front view

Figure 56: Suspension soldering

Figure 57: rear suspension soldering

Figure 58: Suspension final assembly