

# Design, Analysis, and Development of a Custom Helical Limited Slip Differential for Formula Student Applications

Chopade Pranav Sunil | Ganacharya Deeksha Rajiv | Dumbre Anushka Abhijit | Dharmishtha Kishore Bharti | Dhotre Sanchit Babarao  
Department of Mechanical Engineering

**Abstract** - This study focuses on the design, analysis, and development of a custom helical limited-slip differential (LSD) for a Formula Student race car. In a standard open differential, torque is not distributed equally during high-torque or low-traction conditions, which leads to wheel slip and affects the vehicle's performance and control. To overcome this, the proposed design uses helical gears to automatically transfer more torque to the wheel with a better grip without using friction plates or viscous systems. The overall process includes the selection of the gear mechanism, calculation of the torque bias ratio, CAD modelling with three design iterations, selection of materials (7075-T6 aluminum for the casing and EN19/AISI 4140 steel for gears), and structural analysis using SolidWorks FEA. The results show that all components are within safe stress limits, where the casing shows a maximum von Mises stress of 376 MPa compared to a yield strength of 505 MPa (FOS = 3.7), and the pinion and side gears have factors of safety of 4.6 and 11, respectively. The calculated torque bias ratio of 2.09:1 confirms that the differential can effectively improve traction and handling under racing conditions.

**Keywords:** *Limited Slip Differential (LSD), Torque Bias Ratio, Helical Gears, Formula Student, Finite Element Analysis, Vehicle Traction, Drivetrain Design, EN19 Steel, 7075-T6 Aluminum*

## INTRODUCTION

In Formula Student racing, the performance of the drivetrain has a major impact on the vehicle handling, acceleration, and overall dynamic behavior. Among all the drivetrain components, the differential plays an important role, as it transmits power from the engine to the wheels while allowing them to rotate at different speeds. A conventional open differential is simple and cost-effective; however it has limitations in terms of traction, especially during sharp cornering or on low-grip surfaces. These situations are common in Formula Student events, such as skid pad, autocross, and endurance, where maintaining traction is critical.

To address these issues, the use of a custom Limited Slip Differential (LSD) is necessary to improve traction, ensure better torque distribution, and enhance vehicle stability. Commercially available differentials are usually expensive and may not directly fit the requirements of a Formula Student vehicle without modification. In contrast, a custom-designed LSD allows better control over performance, reduces the overall cost, and can be easily integrated into the existing drivetrain system of a car.

The main function of the LSD is to control the distribution of torque between the rear wheels and reduce excessive slip when one of the wheels loses traction. This helps transfer

more power to the wheel with a better grip, which improves acceleration while exiting corners and reduces unwanted wheel spin. It also helps drivers maintain better control of their vehicles. A properly designed LSD improves cornering by providing stability during the entry and effective power delivery during the exit.

This paper presents the design, analysis, and prototype development of a helical gear-type LSD designed specifically for a Formula Student car. The work includes concept selection, design calculations, CAD modelling through three iterations, material selection, structural analysis using FEA, and fabrication. The aim of the study was to develop a reliable, efficient, and cost-effective differential that meets the performance requirements of Formula Student racing.

## 2. GEOMETRIC MODELING AND COMPONENT DESCRIPTION

### 2.1 Components

The helical LSD assembly consists of nine main components, each of which plays an important structural and functional role in transmitting torque and controlling slip.

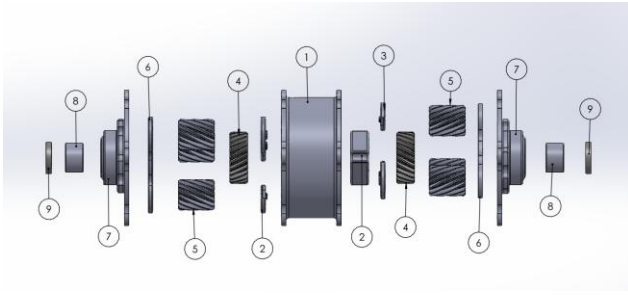


Fig 1: Exploded view of the differential.

### 1 Middle Casing

The middle casing acts as the main housing of the limited-slip differential. It contains an internal gear system and helps maintain proper alignment and load distribution. The casing was designed to handle high dynamic loads, transmit torque effectively, and provide support for mounting side casings. It also helps maintain structural strength and holds the lubricating oil required for smooth operation.

### 2 Gear Middle Guide

The middle guide of the gear is responsible for the proper positioning and controlled movement of the differential gears inside the housing. It supports correct gear engagement, maintains the required spacing between the pinion and side gears, and prevents axial movement during operations. This improves gear meshing, reduces wear, and ensures efficient torque transmission.

### 3 Pinion Guide

The pinion guide supports the pinion gears and ensures proper alignment during the differential operation. It restricts unwanted movements and helps maintain continuous engagement between the pinion and side gears. This improves torque biasing, ensures smooth rotation, and increases the overall reliability of the system.

### 4 Side Gears

The side gears are connected to the half shafts through tripod joints and are responsible for transmitting power to the wheels. In the LSD, these gears work with pinion gears to allow different wheel speeds while reducing slip. Their accurate design and material strength help in effective torque transmission and ensure durability under varying loads during the racing conditions.

### 5 Pinion Gears

Pinion gears, also called spider gears, are placed inside the differential casing and meshed with the side gears. They

enable differential action during turning and help distribute the torque between both wheels. In the LSD, these gears work with a helical design to control the slip, improving the traction and overall vehicle handling.

### 6 Gear and Pinion Guide

This component acts as a common support structure for both the side and pinion gears, ensuring proper alignment and meshing. It maintains the required spacing, controls the rotational movement, and prevents gear displacement under load. This helps ensure smooth operation and consistent torque transmission.

### 7 Side Casing

The side casing encloses the entire differential assembly and supports the tripod joints. Along with the middle casing, it forms a complete housing, protecting the internal components from dust and external elements. It also provides mounting surfaces and bearing support, ensuring proper alignment and structural integrity.

### 8 Bearings

Bearings support the rotating parts of the differential assembly and help reduce friction during operation. They carry both radial and axial loads that are generated during acceleration and cornering. The use of appropriate precision bearings improves the efficiency, stability, and overall durability of the drivetrain system.

### 9 Oil Seal

The oil seal prevents the leakage of lubricating oil from the differential housing and stops dirt or moisture from entering inside. It is fitted around the rotating shaft area, ensuring proper lubrication of the gears and bearings, which helps reduce wear and increase the overall life of the system.

### 2.2 Operating Principle



Fig 2: Front view of prototype



Fig 3: Side view of prototype

A Helical Limited Slip Differential (HLSD) is a mechanical device that automatically distributes torque between the drive wheels based on the available traction. Unlike clutch-type or viscous LSDs, it operates entirely through the interaction of helical gears and does not require friction plates or fluid systems. Therefore, the mechanism is simple, reliable, and provides smooth operation.

The HLSD mainly consists of a differential casing, side gears connected to the axle shafts, and multiple helical pinion gears placed between them. The inclined teeth of helical gears generate axial thrust forces while transmitting torque. During straight-line motion, both wheels have equal traction; therefore the differential behaves like an open differential, where all components rotate together and equal torque is delivered to both wheels without any internal gear movement.

A speed difference occurs between the wheels when the vehicle turns or when one wheel loses traction. This causes the helical pinion gears to rotate and move slightly in their slots. Owing to the helical shape of the gears, this movement generates an axial thrust that pushes the gears against the casing and creates friction. This friction resists the speed difference and transfers more torque to the wheel with a better grip. The entire process occurred smoothly without sudden locking or jerky motion.

The operation of the HLSD is based on the worm gear principle, where torque can be easily transmitted in one direction but is resisted in the reverse direction (from the faster rotating wheel). This results in automatic torque biasing towards the wheel with higher traction. The Torque Bias Ratio (TBR), which defines the amount of torque is transferred, depends on factors such as the helix angle and friction between the gear surfaces and casing. Typically, TBR the values range from 2:1 to 5:1.

### 2.3 Design Calculations

#### 1 Torque Bias Ratio Calculations

The torque bias ratio (TBR) characterizes the LSD's ability to transfer torque from the slipping wheel to the gripping wheel. The following parameters were used.

Table 1: Input Parameters for Torque Bias Ratio Calculation

Parameter	Symbol	Value	Unit
Applied Wheel Torque	$T_{wheel}$	215,000	N-mm
Friction Coefficient	$\mu$	0.61	-
Helix Angle	$\Phi$	30°	degrees
Pressure Angle	$\Theta$	20°	degrees
Planet (Pinion) Pitch Radius	$R_{planet}$	17	mm
Sun (Side Gear) Pitch Radius	$R_{sun}$	28.56	mm
Sprocket Radius	$R_{sprocket}$	106	mm

## 2 Gear Design Parameters

Table 2: Helical Gear Design Parameters

Parameter	Symbol	Pinion (Planet)	Side Gear (Sun)	Unit
Number of Teeth	Z	13	23	-
Normal Module	M <sub>n</sub>	2	2	mm
Normal Pressure Angle	Θ <sub>n</sub>	20°	20°	degrees
Helix Angle	Φ	30°	30°	degrees
Transverse Module	M <sub>t</sub>	2.3094	2.3094	mm
Pitch Diameter	D	30.02	53.12	mm
Face Width	b	36	24	mm
Addendum	h <sub>a</sub>	2	2	mm
Dedendum	h <sub>f</sub>	2.5	2.5	mm
Tangential Force	F <sub>t</sub>	14,322.73	8,095.46	N
Radial Force	F <sub>r</sub>	6,019.51	3,402.33	N
Axial Force	F <sub>a</sub>	8,269.23	4,673.91	N

### 3 FACTOR OF SAFETY FROM ANALYTICAL CALCULATIONS

Using the material properties of EN19/AISI 4140 ( $S_{ut} = 775$  MPa,  $S_{yt} = 555$  MPa), the analytical factors of safety were computed as follows:

$$FOS (Pinion) = S_{ut} / \sigma_p = 775 / 29.45 \approx 26.3$$

$$FOS (Side Gear) = S_{ut} / \sigma_g = 775 / 74.96 \approx 10.3$$

These high analytical FOS values confirm that the gear dimensions are conservatively safe, with the FEA providing more precise local stress concentration results.

### 4 Spline Calculations

Table 3: Spline Design Parameters

Parameter	Value	Unit
Major Diameter (D <sub>o</sub> )	24	mm
Minor Diameter (D <sub>i</sub> )	21.5	mm
Number of Teeth (Z)	22	-
Tooth Depth (d)	1.25	mm
Module (m)	1.19 (rounded: 1.25)	mm
Addendum (h <sub>k</sub> )	0.5625	mm
Dedendum (h <sub>f</sub> )	0.75	mm
Pitch Diameter (D <sub>p</sub> )	27.5	mm
Profile Shift (x)	±1.83	mm

### 2.4 Material Selection

Material selection is important to ensure the proper strength, durability, and lightweight performance of the system. The LSD assembly is subjected to high torque and dynamic loads during cornering, gear tooth forces, and repeated fatigue loading. Therefore, materials were selected by considering factors such as mechanical strength, weight limitations, wear resistance, ease of manufacturing, and overall cost.

#### 1 Casing Material - Selected: 7075-T6 Aluminum

7075-T6 aluminum was selected for the casing because of its high strength-to-weight ratio and good fatigue strength. This enables the design of a lighter and thinner casing without compromising structural performance. Although it requires corrosion protection, such as anodizing or coating, the casing is manufactured using machining and fasteners; therefore weldability is not an issue. Overall, 7075-T6 provides a good balance between weight, stiffness, and fatigue life, making it suitable for a compact and high-performance Formula Student differential design.

#### 2 Gear Material - Selected: EN19 / AISI 4140 Steel

EN19 (AISI 4140) was selected because it offers an excellent combination of strength, toughness, and machinability. After heat treatment, it provides high strength and good fatigue resistance, making it suitable for gear applications. Surface hardening methods, such as induction hardening or nitriding, can be used to improve wear resistance while maintaining a tough core. Although

EN24 or AISI 4340 offers higher strength, the improvement is not significant for Formula Student requirements and comes with higher cost and machining difficulty.

## 2.5 CAD Modeling - Three Design Iterations

### Iteration 1

The initial design used six teeth for the pinion and 18 teeth for the side gear, with a module of 1.5 mm, pressure angle of 20°, and helix angle of 23°. The aim was to keep the design compact while maintaining the required gear ratios. However, this setup caused undercutting in the pinion gear owing to the low number of teeth, which affected the tooth geometry and reduced the addendum circle. In addition, having an even number of teeth on both gears resulted in poor contact patterns and uneven load distribution.

### Iteration 2

To overcome the issues in Iteration 1, the design was updated to 13 (pinion) and 23 (side gear) teeth, with a module of 2 mm, pressure angle of 20°, and helix angle of 30°. The increase in the number of teeth and modules improved the strength of the gear teeth and provided a better contact ratio. A higher helix angle also aided in smoother power transmission and better load sharing, resulting in a stronger and more reliable gear set without the risk of undercutting.

### Iteration 3

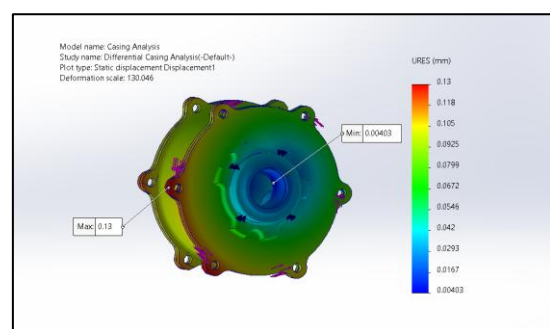
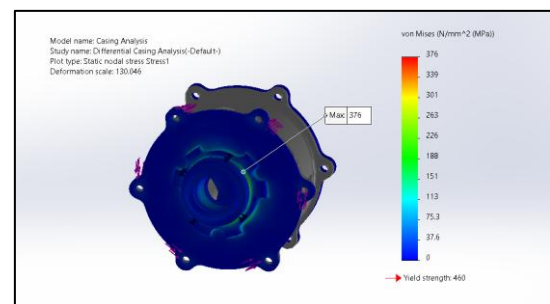
After improving the gear design in Iteration 2, the third iteration focused on strengthening the overall structure and making it suitable for real-world use. The casing was improved by optimizing the wall thickness and adding reinforcements at high-stress areas, which increased the rigidity and reduced the deformation. Proper mounting features were added to ensure secure installation in the vehicle. These changes improved the stability, ease of assembly, and durability, making the differential not only functionally effective but also practical for actual applications. The final iteration was physically validated using a 3D printed prototype assembly.



Fig 4: Isometric view of prototype

## 3. Results and Discussion

### Comparative Material Study - Casing (Iteration 3)



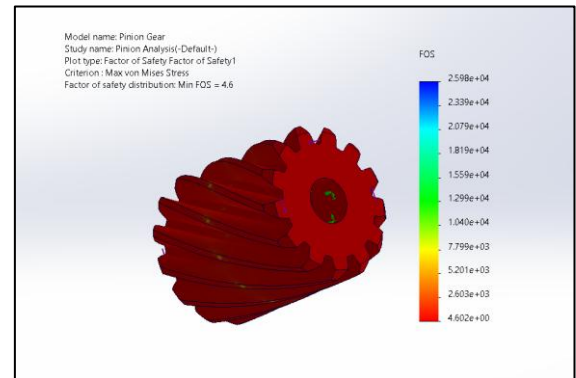
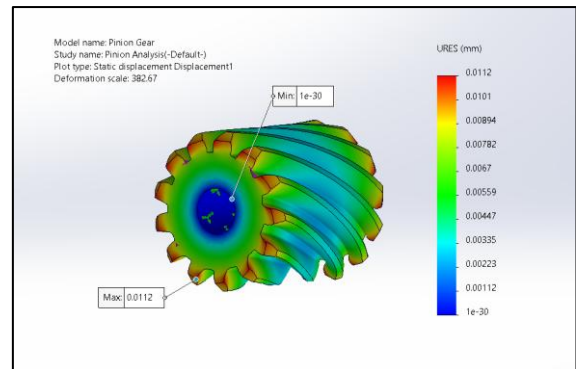
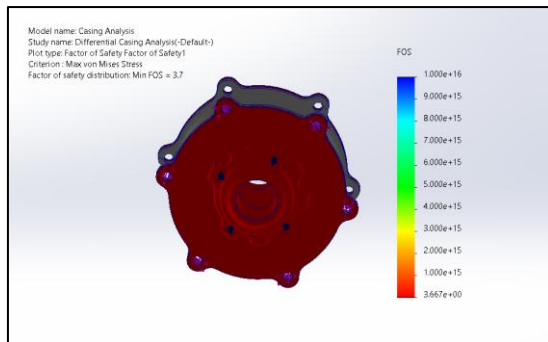


Table 4: Casing Material Analysis Results (Iteration 2 & 3 loading conditions)

Parameter	Al 7075-T6	Al 6063-T6	Al 6061-T6	Unit
Von Mises Stress	376	317	329	MPa
Displacement	0.13	0.082	0.087	mm
Strain	0.0.00436	0.00374	0.00392	-
Factor of Safety	3.7	2	2.5	-

**Note:** The above results are based on the initial design iterations with higher load assumptions and without complete geometric optimization. After the final optimization and inclusion of the bearing support, the casing exhibited a stress of 376 MPa, displacement of 0.13 mm, and a factor of safety of 3.7, which confirmed the improvement achieved in Iteration 3.

### Pinion Gear Material Comparison

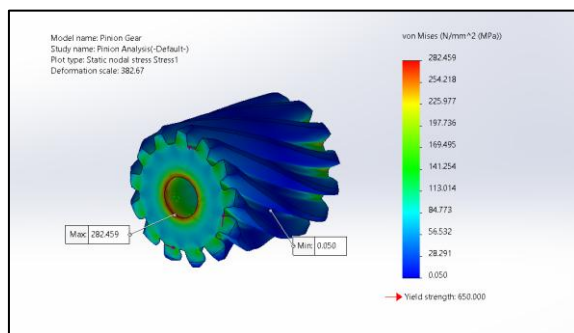


Table 5: Pinion Gear FEA Results by Material

Parameter	Mild Steel	EN8	EN19	EN24	Unit
Von Mises Stress	295.24	282.45	282.45	282.45	MPa
Displacement	0.0120	0.0112	0.0112	0.0112	mm
Strain	0.00095	0.00093	0.00093	0.00093	-
Factor of Safety	1.8	2.8	4.6	4.8	-

### Side Gear Material Comparison

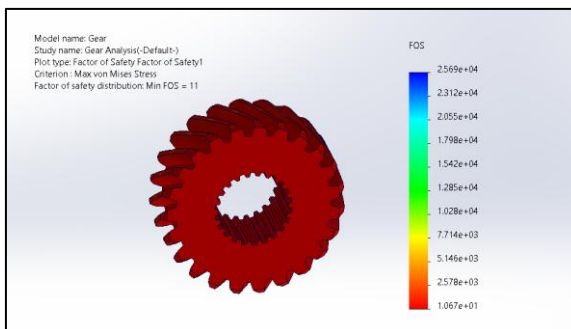
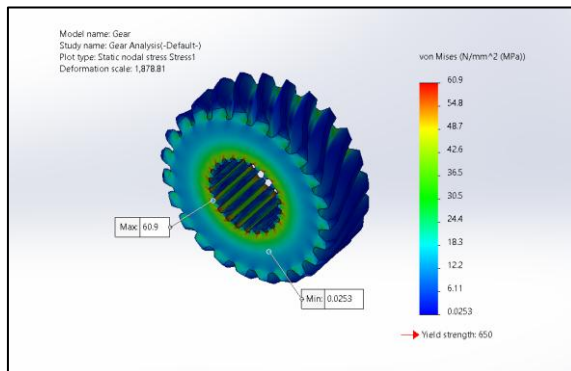
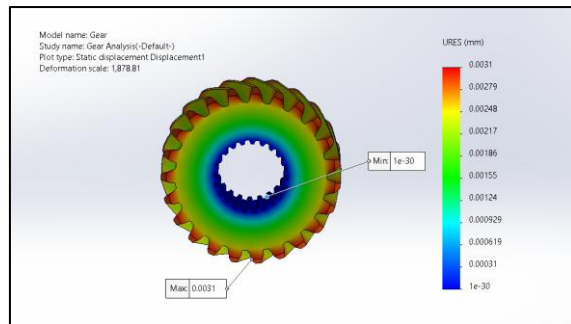


Table 6: Side Gear FEA Results by Material

Parameter	Mild Steel	EN8	EN19	EN24	Unit
Von Mises Stress	60.8	60.9	60.9	60.9	MPa
Displacement	0.00312	0.00310	0.00310	0.00310	mm
Strain	0.000204	0.000203	0.000203	0.000203	-
Factor Safety	of 4.1	6.6	11.0	11.0	-

## OVERALL DISCUSSION

A helical limited-slip differential was designed and evaluated based on the calculated input torque, gear forces, and axial thrust generated owing to the helix angle. From the theoretical analysis, it is clear that the differential can transmit the required torque without excessive slippage. The stresses developed in the gears and housing were within the allowable limits, indicating that the design was safe for the given loading conditions.

For material selection, 7075-T6 aluminum was preferred over 6061 and 6063 because of its higher strength, better fatigue resistance, and improved safety factor, making it suitable for dynamic automotive applications. EN19 steel was selected for the gears because of its high strength, toughness, good fatigue properties, and ease of machining.

The FEA results show that when both wheels have equal traction, the torque is distributed evenly. In the case of unequal traction, the helical gear arrangement transfers more torque to the wheel with a better grip in a smooth manner without sudden locking. Even at high torque values, the system operated smoothly without excessive stress or deformation. The differential also performs well when external conditions, such as road loads, braking, and cornering forces, are considered.

Overall, the developed helical LSD performed effectively under the calculated loads, simulation conditions, and practical operating scenarios. The design met the required objectives and was reliable, mechanically sound, and suitable for use in Formula Student vehicles.

Table 7: Summary of FEA Results for Final Design (EN19 Steel Gears, 7075-T6 Al Casing)

Component	Max Stress (MPa)	Yield Strength (MPa)	Max Displacement (mm)	Min FOS
Casing (7075-T6 Al)	376	505	0.130	3.7
Pinion Gear (EN19)	282.45	650	0.00559	4.6
Side Gear (EN19)	60.9	650	0.00310	11.0

## 6. FUTURE SCOPE

The current model is a 3D-printed prototype used to check the assembly, fitment, and working of the helical limited-

slip differential. In the future, the final differential will be manufactured using high-strength alloy steels, such as EN19 or EN24, through CNC machining and closed-die forging to achieve better strength and accuracy. Important components undergo heat treatment processes such as carburizing, quenching, and tempering to improve their hardness, wear resistance, and fatigue life. Surface finishing methods, such as grinding and shot peening, can also be used to increase durability.

After manufacturing, the differential was installed in a vehicle drivetrain and tested under real conditions, such as acceleration, cornering, and low traction. The performance was verified by comparing the experimental results with the FEA results to ensure proper operation and reliability. Further improvements can include adjustable preload, changes in the helix angle, and the use of advanced coatings to improve the torque bias ratio (TBR) control and the overall life of the components.

## 7. CONCLUSION

This paper presents the design, analysis, and prototype development of a custom helical limited-slip differential for Formula Student applications. The design achieved a Torque Bias Ratio of 2.09:1, improving traction and handling compared to an open differential. After three iterations, the gear geometry was finalized with a 13-tooth pinion and 23-tooth side gear, eliminating earlier issues such as undercutting.

7075-T6 aluminum was selected for the casing owing to its high strength-to-weight ratio, and EN19/AISI 4140 steel was used for the gears for better strength and machinability. The FEA results confirmed safe operation with safety factors of 3.7, 4.6, and 11 for the casing, pinion, and side gear, respectively, along with minimal deformation.

Overall, the developed helical LSD is a reliable and cost-effective solution suitable for Formula Student vehicles, with potential for further testing and in real-world applications.

## ACKNOWLEDGEMENTS

The authors express sincere gratitude to Prof. S. B. Dhotre for his continuous guidance and support throughout this project. Heartfelt thanks are also extended to Dr. A. P. Pandhare, Head of Department, and Principal Dr. S. D.

Lokhande, for their encouragement and institutional support. The authors also thank all staff members and fellow students for their valuable suggestions and assistance during this study.

## REFERENCES

- [1] S. H. Tarte et al., "Design and Analysis of Lightweight Helical Gear Limited Slip Differential (LSD) for Racing Car Applications," *FISITA World Congress*, 2020.
- [2] L. K. Chang et al., "Limited-Slip Differential Modelling and Control," *IEEE Transactions on Vehicular Technology*, 2022.
- [3] J. Dong and Y. Sun, "Theoretical Study on Limited Slip Principle of Differential," *IOP Conf. Series: Materials Science and Engineering*, 2021.
- [4] J. C. Pulicktharayil and P. S. Rao, "Structural Analysis and Performance Optimization of Helical Gears," *Int. Journal of Research Publication and Reviews*, vol. 6, no. 3, pp. 4071–4075, 2025.
- [5] S. Konar and V. Gautam, "Design and Analysis of an Open Differential," *IJAPIE*, 2019.
- [6] M. Gadola, D. Chindamo, and B. Lenzo, "On the Passive Limited Slip Differential for High Performance Vehicles," *SAE Technical Paper*, 2018.
- [7] J. W. H. Trout, "Analysis and Testing of the Quaife Torque-Biasing Differential," Master's Thesis, University of Texas at Arlington, 2018.
- [8] R. A. James, "Design of an Aluminum Differential Housing," MIT Thesis, 2004.
- [9] Shinde et al., "A Review on Types of Mechanical Differentials," *IRJMETs*, vol. 3, no. 1, 2021.
- [10] M. Gadola et al., "The Mechanical Limited-Slip Differential Revisited," *IJAER*, vol. 13, no. 2, pp. 1478–1495, 2018.
- [11] P. Xianlong et al., "Design and Research of Face Gear LSD," *Vehicle System Dynamics*, vol. 63, 2024.
- [12] Yusuf et al., "Design and Analysis of Helical Gear Using AGMA and ANSYS," *IJERA*, vol. 8, no. 9, 2014.
- [13] Sarkar et al., "Stress Analysis of Helical Gear Using FEM," *IJMERR*, vol. 2, no. 4, 2013.
- [14] Naushad et al., "Helical Gear Analysis Using FEA," *IJERA*, vol. 10, no. 6, 2020.
- [15] Bag et al., "Review on AISI 4340 Steel," vol. 12, no. 8, 2020.
- [16] Sunny et al., "Design of Automotive Differential," *IJRET*, vol. 8, 2014.
- [17] Vasiliev et al., "Preload Adjustment of Differential Bearings," 2020.
- [18] Kolluru et al., "Oil Seal Pressing Arrangement in Axle," 2016.
- [19] Babu et al., "Frequency Analysis of Bevel Gear," *IJERA*, vol. 13, no. 1, 2023.
- [20] Venkatesh et al., "High-Speed Composite Helical Gear Design," 2014.
- [21] "Processing Parameters Optimization in Hot Forging of AISI 4340," *JMR&T*, vol. 23, 2023.
- [22] Aravind et al., "Rear Axle Maintenance Tools," 2016.
- [23] Sankar et al., "Design and Analysis of Differential Gear System," 2022.
- [24] Rahman et al., "Performance Comparison of Torque-Biasing LSDs," 2023.
- [25] Mishra et al., "CFD Analysis of Lubrication Flow in Differential Systems," 2024.