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Review IJMDSA

A Review on Design Optimization of Automotive Conventional Differential System for Rear Wheel Drive

Ashwin Naik[1,*], Suryakant Kadam[2], Sachin More[3], Gopal Kate[4], Nilesh Raut[5]

Abstract

The following review paper provides a thorough explanation of the limitations of the automotive conventional differential system under various circumstances and suggests a viable solution for each constraint by enhancing the differential unit's design and construction. The conventional differential used in automotive (CAR, TRUCKS etc.) is the system which is used to transmit power from the engine to the rear wheels of the vehicle via the propeller shaft, hence we can say that the differential works on the principle of eliminating the tractional difference between the rear wheels of the vehicle. The main function of the differential system is to distribute equal power to the rear wheel when the vehicle is moving straight and to increase the speed of the outer wheel and decrease the speed of the inner wheel when the vehicle makes a turn (LEFT OR RIGHT) and vice versa, because the radius of turn of the outer wheel is greater than the radius of turn of the inner wheel. The main limitation of the conventional differential is that when the vehicle is stuck in a pit/mud there is loss of traction (in the rear wheels) as the differential unit ceases the power transmitted wheel. This paper describes the characteristics to be optimized of the conventional automotive differential system to improve vehicle stability and provide the necessary traction.

Keywords: Differential, Turning–Radius, Traction, Wheels, Torque

INTRODUCTION

Under actual driving conditions of the vehicle, movement requires the wheels to move at different speeds. This is due to the fact that the path traced by each/individual wheel is not the same. These inequalities in the wheels are accommodated/controlled through the use of an automotive differential mechanism. Hence, a differential mechanism can be defined as a power-distribution mechanism with a single input link with two output links [1].

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The differential mechanism has been used in the automotive industry since the middle of the eighteenth century, shortly after its first successful trial in the year 1827. Ideally, a differential mechanism is defined as a power distribution or torque control device to equalize the traction between the wheels under different conditions. Differential assembly avoids uneven torque distribution [2].

The automotive differential is an integral part that governs the performance of a vehicle. The construction of the differential unit assembly is an important characteristic or factor that determines the performance of the automobile or vehicle. The automotive differential mechanism is a Planetary Gear Train (PGT) transmission system (Figure 1). Since automotive differentials are employed to transmit power at a right angle, the PGT arrangement is the most efficient mechanism best suited for operating the differential unit.

The automotive differential consists of an input bevel (coupled to propeller shaft) connected to crown gear and sun gear coupled to the planet gears (2–4). The sun gear is free to rotate around its axis input bevel pinion (Figure 2) [3].

Drive Gear -> Driven Gear -> Differential House -> Differential Axle Spider -> Bevel Pinions -> Side Gears

The wheels of a vehicle rotate at different speeds, especially when turning corners. The differential driving the pair of wheels while letting them to rotate at varying speeds. In vehicles lacking a differential, such as karts, both driving wheels must rotate at the same speed, usually on a common axle driven by a simple chain-drive mechanism [31–40]. When cornering, the inner wheel must travel a shorter distance than the outer wheel; therefore, with no differential, the inner wheel spins and/or the outer wheel drags, resulting in difficult and unpredictable handling, tyre and road damage, and strain on (or possible failure of) the entire drivetrain (Figure 3).

Problem Statement

One problem with the convention differential used in automotive industry is that if one wheel is held stationary, the counterpart wheel turns at twice its normal speed. It can pose challenges when one wheel lacks sufficient traction, such as in snowy or muddy conditions. In such situations, the wheel lacking traction may spin without effectively providing grip, while the opposing wheel remains stationary, impeding the vehicle's movement.

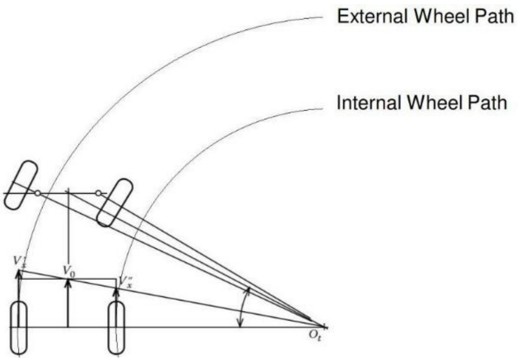

Figure 1. Path of differential wheels [01].

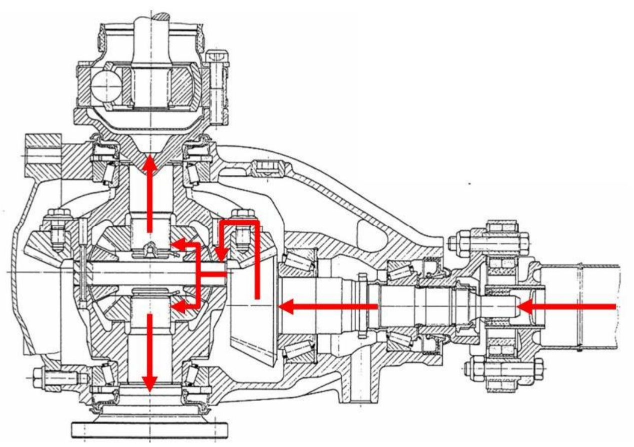

Figure 2. Power Path of differential wheels.

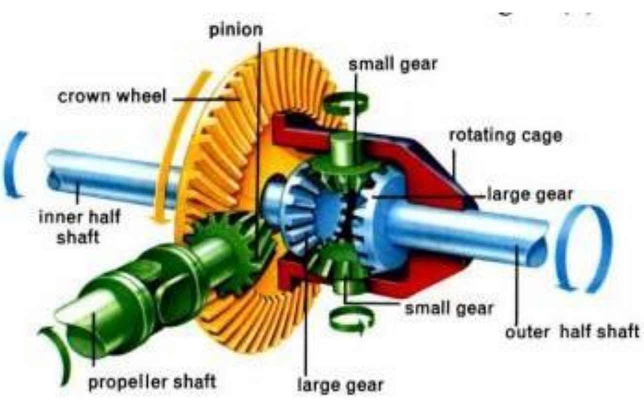

Figure 3. Components of differential [15].

To address this issue, Automotive Slip Differentials (LSD or SLIP LOCK) are employed. However, the implementation of these systems incurs significant costs, consequently driving up the overall expense of the vehicle (Figure 4).

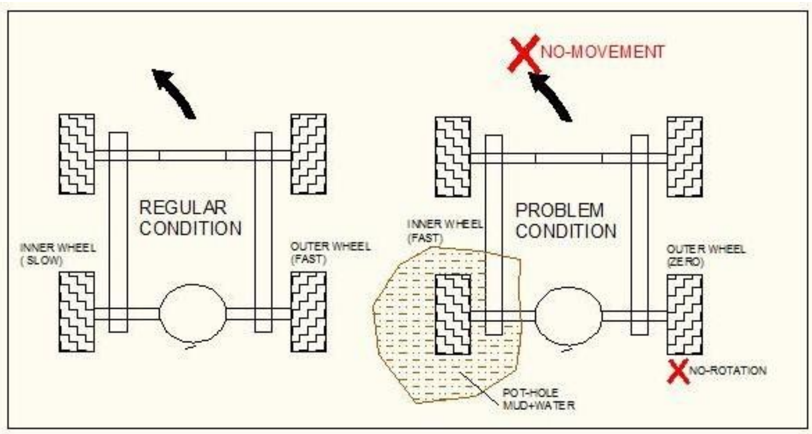

Figure 4. Differential working in slip–condition.

LITERATURE SURVEY

Hong-Sen Yan & Long-Chang Hsieh [3]

The authors of this article/paper, conducted an experimental analysis of the conceptual design of the automotive differential system. By comparing various kinematic graphs of combinations of PGT arrangements used in the differential gear assembly, the authors have explained in detail the design and performance characteristics of the Planetary Gear Train (PGT) used in the automotive differential assembly. The constructional layout of the differential unit is the primary factor that impacts the performance of the vehicle, therefore the PGT comprises of one Input Bevel Gear coupled to a Ring Bevel Gear, and two Bevel Sun Gears coupled to the Planetary Gears. Depending on how the differential unit is built, the number of planetary gears might range from 2 to 4.

Based on the results of the experiment, the paper concludes by terming automotive differential as a joint fractionated planetary gear train with 2 degrees-of- freedom. All potential design concepts have been developed for automotive differentials based on the properties of PGTs within the design constricts.

Giovani Publio Giordani, Celso Fratta [04]

The authors of this paper have described the properties of the Locking Differential System by demonstrating Light Commercial Vehicles equipped with the Detroit Locker/NoSpin Differential System. The Detroit Locker/NoSpin Concept technology was developed by Eaton Co. with a 100%

locking capability. The article provides detailed information about the Locking Differential Assembly used in the automotive industry (Figure 5).

Figure 5. Exploded view of detroit locker [04].

The Detroit Locker consists of consists of a mirror image design known as NoSpin assembly with side gears, spring retainers, spring, clutch and spider assembly. The NoSpin assembly is a Positive Locking Mechanism with left and right clutches with locking teeth that engage with mating teeth on the spider assembly. When the vehicle is moving in straight direction the drive components remain locked together, the split shafts act as a single shaft transmitting equal power to the left and right wheel. When the vehicle takes a turn the split axle of the outer wheel disengages from the spider assembly due to compression of the spring & the split axle of the inner wheel remains engaged to the spider assembly.

When the vehicle is stuck in a slippery surface the clutch ring is provided such that the spring expands and disengages from the spider assembly transmitting power from the propeller shaft directly to the unstuck wheel. Vehicles with different specifications were equipped with this differential unit and tested under various conditions. It was found that vehicles equipped with the Detroit Locker/NoSlip differential were found to have more traction control and improved stability as compared to the Open Differential Automotive System.

Hiroki Sasaki, Genpei Naitou, Yoshiyuki Eto, Jiro Okuda, Hirotaka Kusukawa & Shinichi Sekiguchi [5],

The authors of this paper discussed about the design and development an Electronically Controlled Limited Slip Differential(eLSD) to improve vehicle dynamics. A high-speed vehicle must be in control of the driver for safe journey/ride, for this reason an eLSD (also known as Active Limited Slip Differential A-LSD) is developed to provide required necessary traction and controlled distribution torque to the left and right wheels as per the driving conditions. The paper describes the functions of eLSD/A-LSD and its impact on vehicle dynamics and traction. An eLSD/A-LSD is used to split the slip-torque and eliminate the tractional difference in the left and right wheel and minimize the tractional loss (Figure 6).

The construction design of eLSD/A-LSD consists of three main units:

i. Sensing Unit
ii. Hydraulic Oil Unit
iii. Final Drive Unit
   1. Sensing Unit – Sensing Unit is used to detect the slip/loss of traction in wheels and control the ABS to adjust the split of the slip-torque to the left or right as per the conditions detected. The Sensing Unit is a grouping of speed sensors, G-sensors, throttle sensors, and a brake lamp switch connected to an integral sensor for mathematically rectifying slip-torque.
   II. Hydraulic Oil Unit – Hydraulic Unit is used to rectify the pressure at the point of supply as per the conditions detected by the sensing unit.

III. Final – Drive Unit – The Final-Drive Unit employs a wet multi-plate clutch to transform the hydraulic force of the oil into the gripping force of clutch.

Driving the car on a dry surface was used for the testing of the eLSD/A-LSD unit, and the results were assessed by accounting for the vehicle's change in yaw rate. The car was evaluated in three different eLSD/A- LSD modes: locked state, free state, and eLSD/ALSD Activated State. It was found that the vehicle understeered in the free condition and tended to oversteer in the differentially locked state. The vehicle's yaw rate fluctuated between understeer and oversteer at the eLSD/ALSD Activated State, improving vehicle stability and eliminating the tractional differential between the left and right wheels. The authors of this article came to a conclusion that the eLSD/A-LSD corrects yaw rate up to the split-torque limits of understeering and oversteering, giving the wheels enough split-torque for corners and slip conditioning.

Shan Shih & Ward Bowerman [6]

This paper focuses on evaluating the performance of the Torsen differential by calculating its torque bias and comparing it with that of variousautomotive differential systems. Torque Bias capacity of the differential is an important performance parameter which enhances the traction control and safety of the vehicle. The researchers of this article have done an experimental analysis to evaluate the performance of the Torsen Differential. Design of torque bias ratio is an important factor to calculate the friction rate, balance & slip/loss of traction in wheels and control the ABS to stability of vehicle. Torsion Spin & Durability test was carried out on an Torsen Differential & (Full Pack) Clutch Limited Slip Differential.

The test results revealed that the vehicle equipped with Torsen Differential System has a higher torque bias. It was also noted that both differential systems' power losses due to friction were within acceptable limits, but that the power losses in Torsen Differential Systems are higher than those of a high pack LSD. This study clearly shows that the created model is a useful design tool for design optimization. This article concludes that the vehicle equipped with the Torsen Differential has high rate of driving stability and optimum torque bias ratio & the bearing mounted in the system have minimized the losses due to friction (Table 1).

Table 1. Torsen Vs high pack lsd [06]

S.N.	Type	Needle Bearing Arrangement	Torque Bias	Power Loss (%)
01.	Torsen	i. Between two Side Gears & Between Side Gears & Differential Case	2.77	0.81
		ii. Between Side Gears only	6.09	1
		iii. No Bearings	16.8	1.38
02	LSD	i. No Bearings	2.0	1.1

Alexandre Rodrigues Phino & Cleber P. Franco [7]

The researchers have carried out a comparative study in order to find the most feasible option for the application based on the driver's comfort, vehicle performance, vehicle stability, and driving conditions. This article is developed by carrying out tests based on the hypotheses or speculations made by the researchers, i.e., a traction control system combined with an

Wet open/conventional differential gives similar results as an LSD with a torque bias ratio of 1.6 and losses due to friction that are within a controllable range. The results of the test show that the traction control system improves the performance of the open/conventional differentials. It was evident that the system used showed a similar response to the LSD. The authors concluded that it is feasible to equip the vehicle with an open/conventional Differential integrated with the Traction Control instead of using the expensive and heavier LSD.

Pavel Kučera & Václav Píštěk [8]

This paper explains the use of automotive mechatronics technology for developing differential locking systems for vehicles. The main advantage of the developed system is that it prevents vehicle jamming in slipper conditions. The system detects the condition and automatically engages and disengages the differential locker as per the condition signals received from the sensor unit. The researchers of this paper have developed an automotive control algorithm for various applications such as defence vehicles, snow trucks, fire extinguisher trucks, buses, or vehicles having a drive train configuration of 10 by 10. The sensors detect the condition, and the locker is controlled by actuators and clutch assemblies. The most crucial section of the article is the one on prototyping and installing it in a vehicle to assess its performance. The results of the tests and assessment showed that the developed system works efficiently.

Hirotaka Kaneko, Kenichi Tobita, Shinichi Sekiguchi, Akira Muroi & Yoshinori Hirano [9],

In this research paper is mainly focused on judder analysis of electronically controlled limited slip differential device, to improves the vehicle dynamics, reducing drivetrain judder and self-excited vibration. The process performing by judder analysis conducted on an electronically controlled limited slip differential (eLSD) system to identified several effective measures for dealing with the self-excited vibration, such as the adoption of a torsional damper and an appropriate development target for the p-v characteristic of the multiplate clutch.

John Park, Jeff Dutkiewicz & Ken Cooper [10]

The wheel with less grip spins quickly and loses traction when using conventional open differentials, and distribute input torque to two output shafts with equal torque levels. With limited slip differentials, a clutch is designed to lessen the difference in rotational speed and transmit more torque to the wheel with grip. Active limited slip differentials get over the drawback of passive limited slip differentials by using a controlled clutch system. The rear-wheel-drive car model was created using ADAMS Software, and the simulations results demonstrate how the active limited slip differential system, or e-Diff, enhances manoeuvrability and handling (Figure 6). The active limited slip differential can increase mobility without compromising handling, however it needs to be used in conjunction with the TCS (Traction Control Systems) or ESP to function well (Electronic Stability Programme).

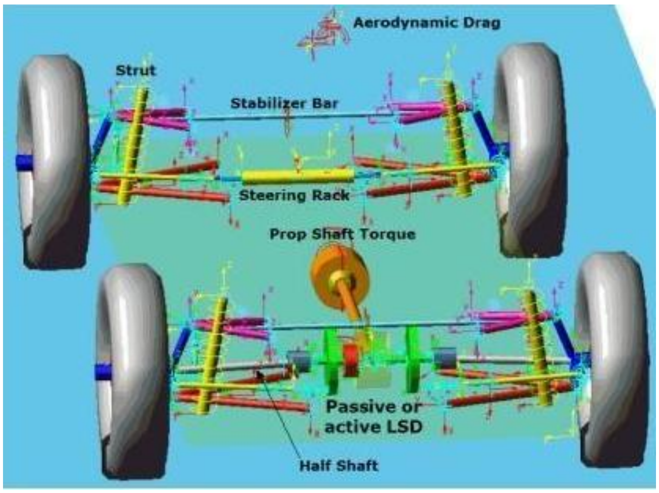

Figure 6. RWD vehicle configuration [10].

Craig S. Ross, Clinton E. Carey, Todd Schanz, Edmund. F. Gaffney III & Michael Catalano [11]

Electronically controlled limited-slip differentials are being introduced, which allow active differential control in all driving situations and can operate as an open differential, a fully locked differential, or at any point between these extremes. The system was tested in two front-wheel-drive General Motors vehicles, with a wet clutch connected to the differential carrier and right-side half-shaft of an all- wheel-drive capable transmission. The electronically limited slip differential is used in a multi-plate wet clutch, which is mounted in the same location as an all - wheel drive vehicle's power take-off unit, and hydraulic pressure applies the clutch to reduce the speed difference across the differential (Figure 7).

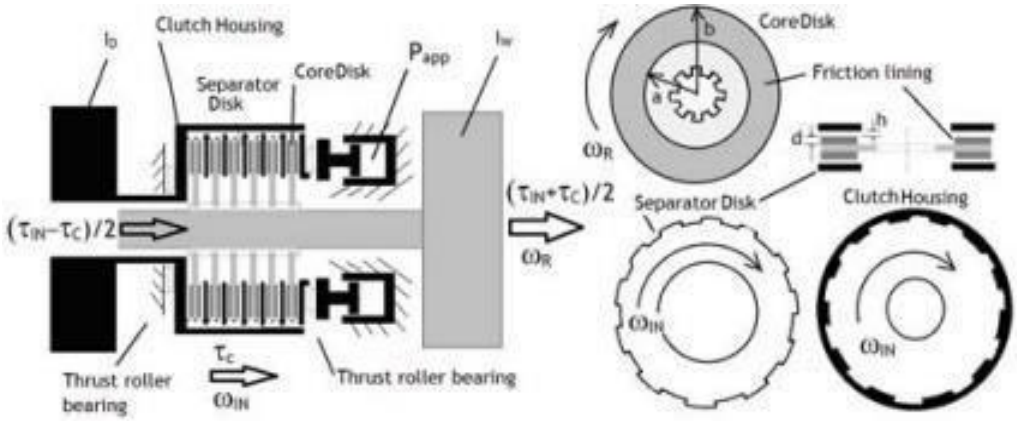

Figure 7. Schematic of wet clutch eLSD [27].

The electronically limited slip differential unit was installed in two vehicles, one with a multi-axis automatic transmission and the other with a manual transmission. And the ECU monitors the system, clutch pressure, and oil temperature, as well as controlling clutch pressure. The rapid prototype controller acted as a hub for communication between the system's controllers, allowing the electronically limited slip differential controller to request more line pressure from the transmission ECU. A step input test, a split-mu launch, and an acceleration-in-turn test were used to evaluate system performance [41–45].

Hideaki Ina, Hisashi Izumi, Tadao Itoh, Takehisa Yamada & Fumihiko Matsuura [12],

The structure is a cam-applied, simplified- structure LSD that uses a constant torque bias ratio to distribute input torque to two output shaft torques. The LSD's structure, principles, torque distribution characteristic, and experimental results are described in this paper.

Fuji Univance Corp., in collaboration with Automotive Products plc, developed a new limited slip differential with a simple structure and special cams. Regardless of the input torque, the limited slip differential has a constant torque bias ratio. This paper describes its structure, operation principle, design parameter analysis results on the torque bias ratio characteristic, and experimental results (Figure 8).

Figure 8. Exploded view of suretrac LSD [21].

Nonnwats Anantapal, [13]

The universal joint is a popular type of joint that limits the angle of the driving axle and the driven axle to not less than 160 degrees. This article presents the application concept of a universal joint at an angle lower than 160 degrees, such as a limited slip differential, a center differential, a viscous coupling, or a clutch. The limited slip differential, center differential, viscous coupling, and clutch, which are operated by friction, are known to wear gradually during operation and could distort the physical properties of the parts when heat increases. However, there are other types of limited slip differentials that have the ability to adjust slip rate by applying a pair of universal joints (new designs), which are used for transmission. The universal joint's application concept is determined by the angle between a driving axle and a driven axle. A high angle between the driver and the driven is preferred to lower the input load and stop the operation of the driver when the angle between them is at 90 degrees.

Ramanand R. Shetty, Lee B. Arnold & Alf Eriksen [14]

This paper discusses the design and development of a new limited-slip differential technology and its application in a high-performance race car. The primary requirements of racing applications—ultimate traction, improved handling, speed sensitivity, tuneability, high torque capacity, shock and impact resistance, and compact size—can be fulfilled by mechanical couplings. This paper is based on the actual implementation of the technology in a production race car. The hydro- mechanical differential operates in both torque and slip- sensitive modes, with the torque mode allowing power to be transmitted equally to the rear wheels when both wheels have equal traction [46–56].

Swe Zin Nyunt, Zarchi Thaung& Aung Hein Latt [15]

In this article, an automobile with a Bevel-Gear differential system is utilized to demonstrate to students in an automotive lab the design features of an automotive differential. The experiment is performed on a scaled 3D-printed prototype of the Toyota Hilux differential. A differential mechanism not necessarily a gear train can be applied to transfer energy to the intersecting shafts and get rid of the torsional difference in the wheels. A bevel gear train is employed as the differential system in this experiment to transfer power between two intersecting shafts at virtually any angle and at any speed depending on the operating circumstances of the vehicle.

The authors of this article ensured that a scaled 3D-printed prototype of the differential system had properties similar to those of the actual differential in order to simulate the behaviour of the actual differential and explain it to students. The paper concludes that the 3D printed prototype of the differential used in the experiment composed of the similar properties to that of the actual differential.

Patrick Hopkins & L. Daniel Metz [16]

This article explains the understeer & oversteer characteristics of a rear-wheel drive vehicle equipped with a differential locking mechanism. When a vehicle turns a corner, the inner must travel in a shorter arc than the outer wheel. As a result, the inside and outside wheel should ideally be allowed to rotate at different speeds. The differential locking system described here can be locked or unlocked automatically based on road surface conditions. The sensor-based system may be very sensitive and thus send signals to the system even if differential locking is not required. This system allows the differential to be locked only when the steering angle is less than a certain value and to be released when the steering angle exceeds that value. A differential is a device that allows the drive train to apply equivalent torque to driven wheels, eliminating the tractional difference in the driven wheels. Steering of vehicle takes place about the yaw axis of the vehicle. The roll couple must be adjusted in an open differential to control the moment about the yaw axis. The locking differential adjusts the vehicle's yaw between understeer and oversteer, making it more stable in corners.

Keller A.V., Gorelov V. A. & Anchukov V. V. [17]

Lockable power dividing modules are one of the most popular and efficient ways to improve a vehicle's off-road manoeuvrability. the developed mathematical model of all - terrain truck motion can be used to investigate vehicle dynamics in various exploitation modes. The driveline dynamic load at differential locking unit engagement was estimated using an imitation of a typical driving mode. The results of the experiment show the effects of transmission dynamic loads and stresses, which are required for future coupling unit design.

The control algorithm of transfer case active differential depending on different environmental conditions was developed using the mathematical model.

Andrey Efimov, Oleg Polushkin, Sergey Kireev & Marina Korchagian [18]
In this research paper they present mathematical model of an interaxle drive with a limited gear ratio to investigate the dynamics of changes in power and kinematic parameters of a car's movement. The efficiency of the differential is used as a single criterion for a wheeled vehicle's energy efficiency. The mathematical model allows for the calculation of dynamic loads influencing the locking mechanism, which is required for designing the locking mechanism's components. It should be used for vehicle transmission in each range of road conditions.

REVIEW

After carefully examining the literature, it is obvious that there are limited slip differentials and locking differentials; however, they are quite expensive and heavy. The solutions now on the market are either too archaic, requiring the driver to exit the vehicle before locking the differential, or they are extremely sophisticated, which is highly expensive to install in commercial vehicles [19–25].

A bevel gear train is used in the construction of a conventional automotive differential (PGT, or planetary gear train). The differential system can be optimised in this development by including a clutching mechanism to lock the differential (speed locking) that can be engaged or disengaged manually or automatically.

We can achieve the above results by adjusting the system. So, it is necessary to design and construct an automated self - locking differential locking system for a vehicle where both the locking mechanism and the differential drive would be hydraulically driven. Furthermore, there are numerous differential systems available that have individual benefits but cannot overcome all of the limitations.

Rather than using expensive and heavy LSDs and differential locks, it is feasible to optimise the design by making adjustments to achieve the required traction and improve vehicle stability [26–30].

RESULTS

Based on the literature study we have identified the performance parameters of the automotive convention differential that are need to optimized to prevailed the problems and to overcome the limitation by developing a low - cost solution for providing a locking mechanism by optimizing the design of the conventional differential and achieving similar performance of the developed prototype to that of the high-grade differentials available in the market (Table 2).

Table 2. Parameters to be optimesed.

S.N.	Parameter	Convention Design	Optimised Design	References 01
01.	Speed Locking	NO	Installing Speed Locker Mechanism	[4] - Light Commercial Vehicle with Locking Differential [8] Prototyping a System for Truck Differential Lock Control [16] Oversteer/Understeer Characteristics of a Locked Differential [29] Restrictive Differentials
02.	Torque–Bias Ratio	Understeered or Oversteered	Optimize Range between Understeer & Oversteer	[06] An Evaluation of Torque Bias and Efficiency of Torsen Differential [16] Oversteer/Understeer Characteristics of a Locked Differential

03.	Loss of Traction in Slip Condition	Maximum loss of traction due to tractional difference in wheels	Tractional Control using Torque bias	[4] Light Commercial Vehicle with Locking Differential [10] Simulation and Control of Dana's Active Limited - Slip Differential e-Diff [24] Development of a Limited Slip Differential [29] Restrictive Differentials
04.	Power Loss during Transmission	High Power Loss	Reduce Power Loss with speed locking	[6] An Evaluation of Torque Bias and Efficiency of Torsen Differential [30] Friction Characteristics of Controlled-Slip Differential Lubricants [32] Adjustable Racing Limited Slip Differentials Utilizing Gerodisc System [33] Frictional Power Loss Distribution of Automotive Axles-Experimental Evaluation and Analysis

CONCLUSION

i. Use of speed locking mechanism in differential gearbox as it improves the vehicle's stability and provides necessary traction in slip condition without any manual efforts. [4]
ii. Adjusting the torque biasing ratio of the Planetary Gear Train Differential provides improved traction at cornering or turning at high speed.[6]
iii. The combination of the sensor-based clutching mechanism and conventional differential instead of using the heavy and expensive eLSD or locking differential. [8]
iv. The use of sensor-based engagement & disengagement system provides tractive efforts in slip conditions.[10]
v. The inexpensive installation & low maintenance of the system as compared to 4X4 Traction Control Vehicle. [33]

Proposed Solutions to Problem Statement

Based on the above review we have proposed a solution to the problem statement i.e. is to have a sensor-based locking mechanism that can be activated automatically by sensing a difference in speed or stalling of one wheel to lock the differential and provide the same traction to the differentiated wheels.

Acknowledgment

We are profoundly grateful to Prof. N. N. Raut for his expert guidance and continuous encouragement throughout to see that this project reaches its target since its commencement to its completion.

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