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Automatic Toe Angle Adjustment of Vehicles: A Comprehensive Review

Pawan Rahane, Prof. Atul Bhimrao Wankhade, Prof. Umesh M. Mohod, Prof. J. A. Wakode

Department of Mechanical Engineering

Anuradha Engineering College, Chikhli, MH, India

Abstract*: The toe angle automatic adjustment system has shown up as a groundbreaking technology in automotive engineering to improve the performance, stability, and tire life of vehicles. This review integrates the advancements in dynamic toe mechanisms within modern suspension systems, autonomous vehicles, and electric platforms. Technologies that allow for real-time modification for optimal vehicle handling and fuel efficiency include sensor-based control, electromechanical actuators, and artificial intelligence. Applications include off-road systems, racing automobiles, and passenger cars. The advantages of these systems include improved cornering stability, reduced tire wear, and energy savings. Despite all these improvements, sensor calibration, cost of the system, and environmental durability are some of the persistent challenges. The paper reflects research trends such as the use of AI-driven predictive systems and adaptive controls for different terrains and highlights the gap in the study of long-term performance. Comparative analysis of the existing technologies indicates trade-offs between accuracy, cost, and implementation feasibility. A review of this nature is an insight into how automatic toe angle adjustment could be the answer to meeting the demands of modern automobiles*

Keywords: Dynamics of the vehicle, Real-time control, Sensor-based control, Toe Angle, Vehicle stability

I. INTRODUCTION

One critical thing that wheel alignment ensures is that safety and efficiency, as well as the way in which an automobile performs, would be taken care of. Toe angle, among the various alignment parameters, has the most profound impact on vehicle stability and tire wear. Toe angle pertains to how much the wheels are pointing inward (toe-in) or outward (toe-out) when seen from above. Ideal toe angle settings can help reduce tire wear, improve fuel economy, and offer precise control over the vehicle. Usually, dealing with the toe angle has been adjusted at intervals during routine maintenance earlier, but when these methods are used, they usually are not adequate for addressing dynamic driving behaviors or real-time vehicle adjustments.

With the advancement of automobile engineering, technological improvements have been made toward development of totally automatic systems of toe angle adjustment. These systems rely on real-time data acquisition, intelligent control algorithms, and a greater level of accuracy from the actuator mechanisms for the completion of wheel alignment process with respect to varying road and driving conditions. Automated toe adjustment enhances the vehicle's performance and handling, and it will improve safety through the dynamic interaction with tire-road interaction, lateral force and yaw stability.

This literature review serves as a comprehensive overview on the progress of the systems for toe angle adjustment over the period and presents an analysis of critical studies through methodologies such as failure investigation, tire force estimation, slip angle prediction, and active control strategies and real-time measurement for alignment. The presentation of the systems' development is in chronological order, along with emphasizing the methodologies, simulation/experimental approaches, and key findings. Another objective of this review is to propose future research directions by identifying existing research gaps through analyzing thoroughly in existing works.

II. BACKGROUND

The automotive industry has always been focused on making cars better in safety, handling, and performance-oriented attributes while upgrading their suspension and steering systems. Misaligned pairs of car wheels affect the most man parameters in vehicle dynamics-especially misbalance in fuel economy, performance, tire wear, and comfort. Thus perhaps one of the first considerations facing toe angle is, based on the tire-road and steering scenario, its beerish π (which describes the angle axis to the road-where the tires actually move) and then commonly limitations, as regards the more significant moves concerning camber/toe adjusters' realignment.

It has always been how toe angles were corrected by any workshop or service station in the past. The new fast-running vehicles at present and also a need for real-time adjustments under road conditions are catalysts. It is ensured that, even on the road surfaces, the troublesome speed of the vehicle and certain constraints for tire forces also have to be considered for real-time changes in the toe angle values so that the output corresponds to get better handling and thus stability and fuel efficiency.

Development of the previous studies written to engage itself with further researches after defect mechanical analysis, towards prior steering gear components, higher sensitive controllers, and later an automatic device of the toe-control solution was now in the article. It looks towards presenting extensive experience, up to that point as it has been documented in the literature, of what is important and also brings about an up-to-date knowledge of development in different areas and the challenges inherent and the insights on the way that might stimulate the forthcoming developments in vehicle dynamics and alignment systems.

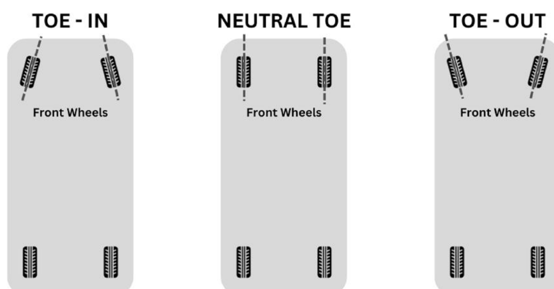

Fig. 1 Toe angle representation

II. LITERATURE REVIEW

Wheel alignment, suspension systems, and tire dynamics are all important factors that affect how a vehicle handles and stays stable. Although toe angle is crucial in defining a vehicle's accuracy in terms of safety and efficiency, current advancements in the automatic toe angle adjustment system were examined from a variety of research addressing various problems. These include dynamic control, system integration, and the estimation of force generated inside the tires.

An automotive steering system's tie rod end failure was investigated by Falah, et al. (2007). The basis of their study was the need to identify defects in steering parts that cause misalignment, leading to the inability of the vehicle to handle well. They established that structural weaknesses of tie rods and steering joints will lead to misalignment, and hence affect vehicle stability. Their findings are crucial for understanding how steering system failures can disrupt toe angle adjustments and the importance of durable materials in steering components.

Gadola, et al. (2014) came up with and tested a Kalman filter based model to estimate vehicle slip angles. Accurate estimation of tire slip angles, which are crucial for adjusting toe angles during dynamic vehicle maneuvers, was highlighted by the study. Errors of slip angle were reduced by employing Kalman filtering. This consequently enhanced the alignment and vehicle control accuracy in model-based predictions. Its use is valuable in real-time applications, especially with respect to accuracy in toe-angle adjustment for stabilization.

Rezaeian et al. (2015) presented a new approach to estimating tire forces that can be utilized in real-time vehicular applications. The authors emphasized the need for accurate measurement of tire forces to enable prediction and adjustment of wheel alignment. Their real-time estimation method couples tire models with vehicle dynamics to provide crucial information for automated systems that control toe angles. This paper argues for the integration of advanced tire force estimation methods to enhance the accuracy of toe angle adjustments and enhance vehicle handling.

Hsu et al. (2010) conducted research on evaluating tire slip angles and friction limits through the use of steering torque. The analysis of the relationship between steering torque and tire dynamics presents a technique for real-time identification of lateral force limits of the vehicle. This method has an advantage in automatic toe angle systems as it provides timely warnings for potential instability conditions, allowing the system to pre-emptively adjust alignment before losing control.

A detailed investigation on the structural performance of bus passenger tie rods was undertaken by Vithalkar and Gawande (2015). Their study examined the diverse failure modes of tie rods in bus suspension systems, which play a crucial role in both steering accuracy and wheel alignment. The study of tie rod failures is important for the design of automatic toe adjustment mechanisms that enhance the durability and safety of steering systems under various operating conditions.

An on-board strain-based system for intelligent tires was used by Yunta, et al. (2019) to analyze the impact of camber angle on tire tread behavior. The results show that camber and toe angles have a significant impact on tire wear, especially in high-performance and autonomous vehicles. This research contributes to understanding how dynamic adjustments of the toe angle can optimize tire life and improve vehicle handling.

Kavitha et al. (2019) proposed a method to activate the camber and toe of a double wishbone suspension system. Active control of both camber and toe angles is involved in their approach to enhance vehicle stability during cornering. This active control strategy is essential for automatic systems that adjust toe angles based on real-time driving conditions, contributing to improved performance in both safety and efficiency.

Kavitha et al. (2018) refined their research on adaptive suspension strategies that use camber and toe angle optimization. They emphasized that dynamic suspension control is key in optimizing vehicle handling when changing loads or driving conditions. Their research was foundational for the development of self-adjusting systems that both camber and toe angles could adjust to suit road conditions, providing smooth and safe driving experiences.

Kurebwa & Mushiri (2019) created and simulated an integrated steering system for SUVs that can be used for different purposes, using the Toyota model. An integrated steering and suspension system was demonstrated in the simulation to enhance vehicle handling and stability. It can further be extended to an automatic toe angle system where, in real-time, the steering is adjusted dynamically to align the wheels.

The impact of dynamic changes in wheel alignment parameters on the steering wheel's high-speed rocking vibrations was studied by Zhang and Su (2023). Their results revealed that even minute toe and camber angle misalignments have a considerable influence on driver comfort and control at higher speeds. The findings thus suggest that perfect alignment is not only essential for performance but also for safety. Hence, there is a strong requirement for automatic adjustments.

In 2024, Tzortzis et al. proposed a control method that utilizes yaw rate to adjust the camber angle of prototype vehicles. Their work can be used to understand how yaw rate feedback may be utilized for the automatic adjustment of wheel alignment in order to enhance vehicle stability. Yaw rate is particularly relevant to automatic toe adjustment systems that utilize real-time vehicle dynamics to optimize alignment during complex maneuvers.

The impact of active tire camber angle control on the vehicle's handling dynamics was investigated by Chen et al. (2024). Closed-loop driver-vehicle systems reveal that active control of both camber and toe angles can significantly improve vehicle handling and stability. This study explores the possibility of employing active camber and toe adjustment systems in future autonomous vehicles to enhance control during dynamic driving conditions.

In 2022, Xu et al. proposed an image-based wheel alignment system that would automatically measure camber and toe-in. Their method relies on precise cameras and image processing algorithms to calculate the measurements, ensuring accuracy, which qualifies it for integration with automated wheel alignment systems. This is a non-contact system whose measurements can be employed to track and make real-time adjustments to toe angles for better accuracy and ease in vehicle maintenance.

Sulaiman and his colleagues (2021) investigated how IoT can be used to monitor wheel alignment. In the study, the authors demonstrated the ways in which Internet of Things technologies can be leveraged to establish smart alignment systems that monitor toe and camber angles in real time. The systems can send real-time feedback to vehicle control systems, automatically making necessary adjustments to the toe angles as per the driving conditions at a given time.

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In 2013, Furferi and his team created and tested a machine vision system for automatic vehicle wheel alignment. The system is based on high-resolution cameras to detect and correct wheel misalignments, including toe angles, in different driving conditions. This research supports the development of automated systems that can perform real-time adjustments, improving vehicle safety and performance without requiring manual intervention.

Vashist et al. (2021) analyzed the suspension system of a car, with a specific emphasis on adjusting its toe angle. The study gave valuable insights into how suspension systems and wheel alignment interact, particularly when used off-road. This research has implications for developing automatic toe angle adjustment systems that maintain stability in diverse driving environments.

Online toe angle misalignment can be detected by Lee & Choi (2023), who have employed lateral tire force and alignment moments. They proved that monitoring tire forces in real-time can detect misalignments, which will activate self-adjustments of toe angle. This is especially important for stability in vehicles, particularly under heavy loads or on challenging road conditions.

Gohane et al. (2021) examined the tire wear characteristics of commercial vehicles and discovered that misalignment, specifically toe angles, causes uneven tire wear. The study results point out the necessity of automatic toe angle adjustment to extend the life of tires and reduce maintenance costs. This research focuses on the requirement for accurate alignment in vehicle fleets to optimize operational efficiency.

Wang (2022) scrutinized studies on the impact of caster angle on the steering and stability of vehicles. As per his findings, caster angle has a significant impact on steering response, but toe angle adjustments are essential for adjusting vehicle handling. This study highlights the necessity of incorporating toe angle control in vehicle dynamics systems to improve steering stability.

Kalpana (2019) explored a vehicle speed-reducing system using ultrasonic sensors to detect potholes and humps. Although the study is primarily focused on speed control, it illustrates the potential of using sensor-based systems to detect alignment issues, such as toe misalignment. This indicates the growing trend of integrating alignment systems with other vehicle control mechanisms to improve overall performance.

Lee et al. (2022) investigated a collision avoidance system for slippery road conditions. Their research demonstrated how real-time adjustments to vehicle alignment, including toe angle, can significantly improve collision avoidance in low-friction environments. In addition, online application vehicle dynamics models were proposed for Henning and Sawodny (2016) specifically related to synthesis and validation for control application. Those vehicle dynamics models established a starting point for their corresponding real-time application, where this would have automatically toe-adjusted angle settings due to reliable expressions of different dynamics.

Li et al. (2023) proposed a cooperative approach to sharing control systems in autonomous vehicles by involving the driver and automation. The research considered how the driver's inputs and automated systems could cooperate in optimizing vehicle handling, including adjustment of toe angles.

IV. METHODS USED

TABLE I: METHODS USED

	Appearance		
Reference	Methods Used	Key Focus	Key Findings
Falah et al. (2007)	Failure analysis of tie rod ends in automobile steering systems; load and stress evaluation through metallurgical analysis and finite element methods.	Analyzing the causes of failure in tie rods.	Identified stress-induced failures and design flaws affecting alignment stability.
Gadola et al. (2014)	Kalman filter-based model; vehicle dynamics simulation and slip angle estimation under dynamic conditions.	Vehicle slip angle estimation for better alignment control.	Improved accuracy in slip angle prediction, enhancing stability control.
Rezaeian et al. (2015)	Tire force estimation strategy; integration of real-time algorithms in	Real-time tire force estimation.	Highlighted the importance of accurate

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	vehicle applications.		tire force calculations in alignment systems.
Kavitha et al. (2019)	Active control strategy; adaptive camber and toe optimization for double-wishbone suspension systems.	Dynamic adjustment of toe and camber angles.	Enhanced vehicle stability and performance with active suspension strategies.
Xu et al. (2022)	Vision-based measurement system; image processing for camber and toe-in alignment monitoring.	Automated and accurate wheel alignment.	Achieved high precision in measuring camber and toe-in angles.
Sulaiman et al. (2021)	IoT-based wheel alignment system; real-time remote monitoring and diagnostics.	Intelligent monitoring of wheel alignment.	Enabled remote diagnostics and improved alignment management.
Zhang and Su (2023)	Dynamic analysis of wheel alignment parameters; high-speed steering wheel vibration study.	Impact of wheel alignment on vibrations.	Found direct correlations between misalignment and steering wheel instability.
Tzortzis et al. (2024)	Yaw rate-based control system for camber angle adjustments.	Dynamic control for prototype vehicles.	Improved vehicle handling and stability through active camber adjustments.
Lee and Choi (2023)	Online detection of misalignment using lateral tire force and aligning moment.	Real-time detection of toe misalignment.	Framework for real-time toe adjustment.

V. DISCUSSION

The outcomes of this literature review are presented in thematic categories according to the evolution and target of the research conducted in this area of automatic systems for toe angle adjustment. Each category represents the main results and contributions of the papers cited indicating level of technological innovations and their impact.

Structural Failures and Design Challenges

Initial research has focused on structural soundness of components in the context of toe angle adaptation, which have implications for component failures in tie rod assemblies. Falah et al. (2007) investigated tie rod failures in the steering systems of automobiles, and identified material fatigue and manufacture defects as the two main causes. This study emphasized the need for robust design and material selection to enhance durability and reliability.

Dynamic Estimation Techniques

A few authors have generated models and procedures for the estimation of dynamic vehicle parameters which are of concern to toe angle adaptation. Gadola et al. (2014) developed a Kalman filter-based vehicle slip angle estimation model to implement real-time, dynamic assessment of the alignment state. Rezaeian et al. (2015) presented a new approach to tire force estimation, where data is used in real time, which serves as a basis for predictive modeling of alignment systems. Hsu et al. (2010) described a method to estimate tire slip angles and friction thresholds in steering torque that exceptionally enhanced vehicle stability and safety under conditions that varied.

Active Control Mechanisms for Toe and Camber

The incorporation of active control systems represented a major breakthrough in alignment technologies, with an emphasis on dynamic adjustment modalities. Kavitha et al. (2019) has shown that both active toe and camber control strategies can be used to optimize a double wishbone suspension, creating better handling and ride quality in a vehicle.

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Chen et al. (2024) investigated active camber angle control in closed-loop systems, with an emphasis on its consequences on vehicle dynamics as well as driving-vehicle interaction.

Vision-Based and IoT Systems

Emerging vision and IoT technologies facilitated accurate tracking and control of the alignment parameters. Xu et al. (2022) proposed a vision-based system for camber and toe-in alignment measurement that has high accuracy and automatization. Sulaiman et al. (2021) presented an IoT based wheel alignment monitoring system that is able to measure and remotely view in real-time.

Dynamic Real-Time Adjustments

Dynamic real-time systems solved the issue of parameter tracking under vehicle conditions. Lee and Choi (2023) presented a method for online detection of toe misalignment based on lateral tire force and aligning moments, ensuring immediate correction for enhanced safety. Zhang and Su (2023) investigated time-varying wheel alignment parameter patterns and their impacts on high-speed steering vibratory ones and as such, made a case for adaptive alignment solutions.

Vehicle Stability Enhancements

Studies using advanced control and predictive modeling techniques for improving vehicle stability. Tzortzis et al. (2024) proposed a yaw rate-based control system, which can adjust the camber angle of prototype cars and showed better corner stability. Chen et al. (2024) with reference to the concept of active camber angle control emphasized its importance for the effective tuning of dynamic vehicle handling properties, especially in situations involving complex driving maneuvers.

Fully Automated Alignment Systems

The latest researches have been directed toward a fully automated approach with various technologies for automatic adaptation of the algorithm to be used. Xu et al. (2022) and Sulaiman et al. (2021) Visionic systems, Internet of things (IoT) systems, and on-the-fly analysis are combined to provide complete alignment tracking and control. Furferi et al. (2013) developed and evaluated machine vision systems for wheel alignment of vehicles, showing their real world application in automated work-shops.

Experimental and Simulation-Based Validation

Results of a number of studies combined experimental verification and simulation to guarantee the validity and practicality of proposed methods. Kurebwa and Mushiri (2019) have applied simulation to design and test integrated drive by drive steering systems for SUVs. Vashist et al. (2021) modeled suspension systems of all-terrain vehicles and investigated the alignment parameters, in extreme conditions.

Discussion Summary

The thematic analysis points to a chronological development of systems for toe angle adaptation, from the treatment of structural failures to the use of active control schemes, to the utilization of vision sensors in order to control systems, and towards purely automated alignment systems. These developments emphasize the need of real-time data acquisition, predictive modeling, and Internet of Things integration for improvement of vehicular stability, safety and performance. Future work should include economic viability of implementation, AI-enabled predictive algorithms, and large-scale experimental verification, in order to advance this field.

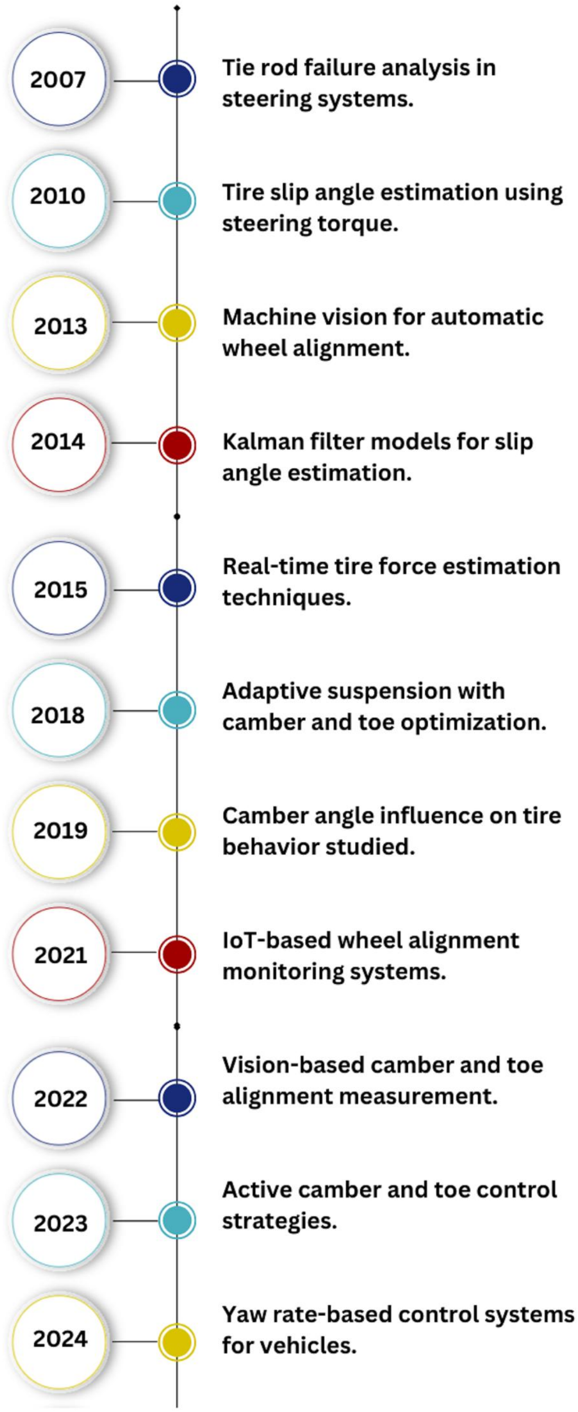

Fig. 2 Research in Chronological Order

VI. CONCLUSION

This review is about automatic toe angle adjustment systems that have improved throughout the history of this area from a mechanical diagnostic approach to a modern, sensor-driven control system mode. The through-line theme analysis indicates massive growth in diagnostics, estimation techniques, and active control strategies, with modern investigations exploiting IoT and machine learning. Though the latter achieves a high increase in its performance, the main obstacles, such as its high cost and specific environmental conditions, should be addressed to realizing their techno-logical promise.

VII. FUTURE SCOPE

Future studies should look into bringing together inexpensive, versatile solutions for everyday use cases. Design of the latest generations of AI models specifically for cars may also result in accurate systems. Studies of other mechanisms and materials involved in power steering might lead to solutions for the weaknesses of those parts. The collaboration of the academic and industrial sectors is the strongest bridge between abstract theoretical advances and the realities of building practical implementations is strictly followed.

REFERENCES

[1]. Falah, A. H., Alfares, M. A., & Elkholy, A. H. (2007), "Failure investigation of a tie rod end of an automobile steering system, Engineering Failure Analysis," 14(5), 895–902.

[2]. Gadola, M., Chindamo, D., Romano, M., & Padula, F. (2014), "Development and validation of a Kalman filter-based model for vehicle slip angle estimation, Vehicle System Dynamics," 52(1), 68–84.

[3]. Rezaeian, A., Zarringhalam, R., Fallah, S., Melek, W., Khajepour, A., Chen, S. K., Moshchuck, N., & Litkouhi, B. (2015), "Novel tire force estimation strategy for real-time implementation on vehicle applications, IEEE Transactions on Vehicular Technology," 64(6), 2231–2241.

[4]. Judy Hsu, Y. H., Laws, S. M., & Gerdes, J. C. (2010), "Estimation of tire slip angle and friction limits using steering torque, IEEE Transactions on Control Systems Technology," 18(4), 896–907.

[5]. Prashant R. Vithalkar, R. R. Gawande, "Study of analysis of bus passenger tie rod: a review," IJRET: International Journal of Research in Engineering and Technology, Volume: 04 Issue: 11 | Nov-2015.

[6]. Yunta, J., Garcia-Pozuelo, D., Diaz, V., & Olatunbosun, O. (2019), "Influence of camber angle on tire tread behavior by an on-board strain-based system for intelligent tires," Measurement: Journal of the International Measurement Confederation, 145, 631–639.

[7]. Kavitha, C., Shankar, S. A., Karthika, K., Ashok, B., & Ashok, S. D. (2019), "Active camber and toe control strategy for the double wishbone suspension system," Journal of King Saud University - Engineering Sciences, 31(4), 375–384.

[8]. Kavitha, C., Shankar, S. A., Ashok, B., Ashok, S. D., Ahmed, H., & Kaisan, M. U. (2018), "Adaptive suspension strategy for a double wishbone suspension through camber and toe optimization," Engineering Science and Technology, an International Journal, 21(1), 149–158.

[9]. Kurebwa, J., & Mushiri, T. (2019), "Design and simulation of an integrated steering system for all-purpose Sport Utility Vehicles (SUVs) - Case for Toyota," Procedia Manufacturing, 35, 56–74.

[10]. Zhang, B., & Su, X. (2023), "Influence analysis of dynamic changes of wheel alignment parameters on high-speed rocking vibration of steering wheel," Measurement: Journal of the International Measurement Confederation, 217.

[11]. Tzortzis, I. N., Papalamprou, G., & Katzourakis, D. (2024), "Introducing a Yaw Rate-Based Control System for Adjusting the Camber Angle of the Front Wheels on a Prototype Vehicle," 2024, 32nd Mediterranean Conference on Control and Automation, MED 2024, 340–345.

[12]. Chen, Z. L., Wang, W., & Raksincharoensak, P. (2024), "Investigation of Active Tire Camber Angle Control on Vehicle Handling Dynamics and Closed-Loop Driver-Vehicle System," IFAC-Papers OnLine, 58(29), 166–171.

[13]. Xu, G., He, W., Chen, F., Shen, H., & Li, X. (2022), "Automatic and Accurate Vision-Based Measurement of Camber and Toe-In Alignment of Vehicle Wheel," IEEE Transactions on Instrumentation and Measurement, 71.

[14]. Sulaiman, M. H., Sulaiman, S., & Saparon, A. (2021), "IoT for wheel alignment monitoring system," International Journal of Electrical and Computer Engineering, 11(5), 3809–3817.

IJARSCT
ISSN (Online) 2581-9429
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International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.67
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[15]. Furferi, R., Governi, L., Volpe, Y., & Carfagni, M. (2013), "Design and assessment of a machine vision system for automatic vehicle wheel alignment," International Journal of Advanced Robotic Systems, 10.

[16]. Vashist, A., Deepshikha, & Kumar, R. (2021), "Design and analysis of suspension system for an All-Terrain vehicle," Materials Today: Proceedings, 47, 3331–3339.

[17]. Hwangjae Lee, Seibum B. Choi, "Online detection of toe angle misalignment based on lateral tire force and tire aligning moment," International Journal of Automotive Technology, Volume 24, pages 623 – 632, (2023).

[18]. Gohane, G., Indurkar, A., Chimurkar, P., Patle, S., Nagina, S. K., Tirpude, S., & Bawane, U. (2021), "Study & Analysis of Tire Wear Characteristics of TATA LPO 1618," IOP Conference Series: Materials Science and Engineering, 1017(1).

[19]. Wang, Z. (2022), "Methods in Research about Effect of Caster Angle on Vehicle Steering and Stability," in Highlights in Science, Engineering and Technology MAME (Vol. 2022).

[20]. V. Kalpana, "Implementation of Vehicle Speed Reducing System at Speed Breaks by Detecting Patholes and Humps Using Ultrasonic Sensor," International Journal of Recent Technology and Engineering (IJRTE), Volume-7, Issue-5S3, February 2019.

[21]. Hwangjae Lee, Seibum Choi, Member, "Development of Collision Avoidance System in Slippery Road Conditions," IEEE Transactions on Intelligent Transportation Systems, Vol. 23, Issue 10, Oct. 2022.

[22]. Lee, E., Jung, H., & Choi, S. (2018), "Tire lateral force estimation using kalman filter," International Journal of Automotive Technology, 19(4), 669–676.

[23]. Judy Hsu, Y. H., Laws, S. M., & Gerdes, J. C. (2010), "Estimation of tire slip angle and friction limits using steering torque," IEEE Transactions on Control Systems Technology, 18(4), 896–907.

[24]. Henning, K. U., & Sawodny, O. (2016), Vehicle dynamics modelling and validation for online applications and controller synthesis, Mechatronics, 39, 113–126.

[25]. Li, X., Wang, Y., Su, C., Gong, X., Huang, J., Liu, X., Yuan, X., & Wang, S. (2023), "Driver and automation cooperation approach for share steering control system," Journal of the Franklin Institute, 360(11), 7269–7293.

[26]. https://thenounproject.com/icon/tyre-6839529/