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K. N. Toosi University
of Technology

Faculty of Mechanical Engineering

Final Project of Chassis Systems

Machine Learning Assisted Optimization of McPherson Suspension Kinematics Using Neural Networks and Quasi-Newton Methods

By
Amirhossein Mohammadi

Supervisor
Dr. Shahram Azadi

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Abstract

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1. Introduction

Vehicle dynamics is the study of forces and motions governing the behavior of the vehicle. It bridges mechanics, control theory, and design to optimize and encompass several key domains. Some of the most important fundamental areas are as follows.

- Longitudinal Dynamics focuses on acceleration and braking performance, involving engine torque, aerodynamic drag, tire-road friction, and weight transfer during speed changes.
- Lateral Dynamics governs cornering behavior, handling stability, maneuvering, and steering response, influenced by suspension geometry, roll stiffness, and tire slip angles during turns.
- Tire Dynamics defines the interaction between tires and the road, determining grip, slip behavior, and force generation under braking, acceleration, and cornering.
- Vertical Dynamics deals with suspension performance, ride comfort, handling performance, and wheel control over uneven surfaces, optimizing spring-damper systems and kinematics like camber/toe curves.

Each domain interacts longitudinal forces affect tire grip, lateral motion depends on suspension tuning, and vertical dynamics influence tire contact making integrated optimization essential for balanced performance.

This report presents a comprehensive vehicle dynamics analysis in two parts. First, full vehicle handling simulations are conducted for an AWD sedan, evaluating performance through standardized Single Lane Change and J-Turn maneuvers. The second part focuses on front suspension system optimization, where the McPherson strut geometry is systematically refined in order to meet target performance specifications while maintaining packaging constraints.

1.1. Different Types of Suspension Systems

Modern vehicles employ three fundamental suspension types of dependent, independent (rigid), and semi-independent each offering distinct trade-offs between cost, comfort, and performance.

- Dependent (rigid) suspension systems, feature a solid axle that connects both wheels, causing them to move in unison exemplified by live axles with leaf springs as shown in Figure 1.1 or torque tubes (e.g., classic trucks). This design prioritizes durability and load-bearing capacity but compromises ride comfort and handling precision.

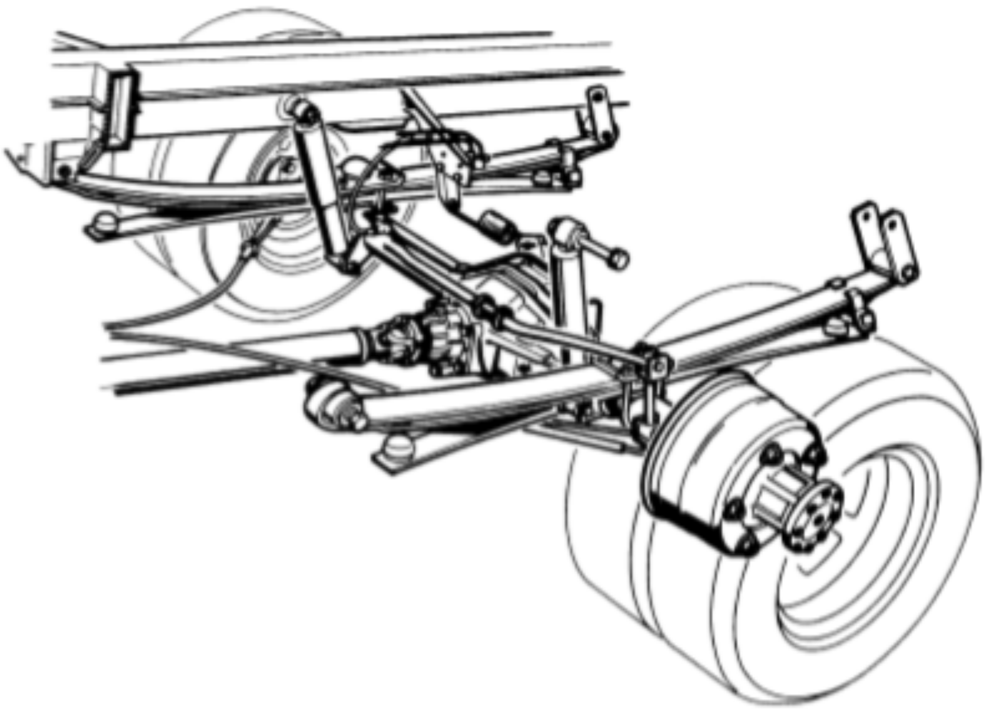

Figure 1.1. Rear Solid Axle of the VW LT Light Commercial Vehicle (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001, Fig. 1.20)

- Independent suspension systems as shown in Figure 1.2 allow wheels to move separately via mechanisms like McPherson struts, double wishbones, or multi-link arrangements, offering superior handling and traction at higher cost.

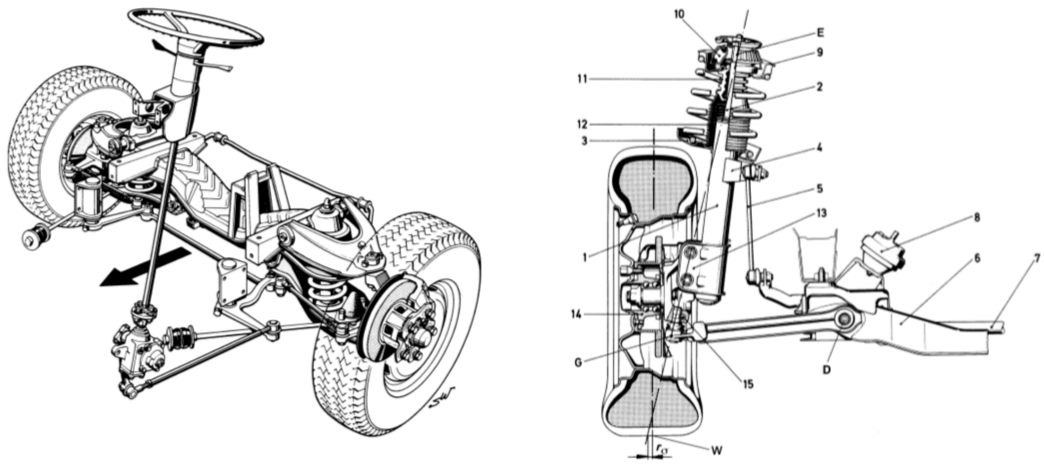

Figure 1.2. Double Wishbone Front Axle on the VW Light Commercial Vehicle and Rear View of the Left-Hand Side of the McPherson Front Axle on the Opel Omega (1999) (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001, Fig. 1.7 and Fig. 1.8)

- Semi-independent suspensions bridge the gap with designs like torsion beams or twist axles (Figure 1.3), where a flexible cross-member permits limited independent movement, balancing affordability with adequate comfort. From heavy-duty solid axles to performance-tuned multi-link setups, each architecture serves distinct needs, reflecting trade-offs in cost, complexity, and dynamic performance.

Figure 1.3. Twist-beam suspension of the VW Golf IV (1997), VW Bora (1999) and Audi A3 (1996) (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001, Fig. 1.7 and Fig. 1.8)

1.2. Kinematics and Elastokinematics of a Suspension System

Kinematics refers to the motion of the wheels during vertical suspension travel and steering, often termed wheel or suspension geometry in standards such as DIN. In contrast, elastokinematics describes shifts in wheel position caused by forces and moments acting between the tires and the road, as well as longitudinal wheel displacement relative to suspension mounting points. These variations arise due to elastic deformation in suspension components, which helps manage compliance while maintaining kinematic integrity.

Design of a suspension system is mainly done through configuration and alteration of the design parameters affecting kinematics and elastokinematics. The performance specifications (design criteria) of a suspension system are quantified through kinematic and compliance curves, which describe the relationship between wheel travel and critical alignment parameters. The primary objective of this project is to optimize the hardpoint geometry (key joint coordinates) of a McPherson strut suspension system to satisfy three essential performance targets mentioned as follows.

Camber angle variation refers to the change in the vertical tilt of the wheel (inward or outward) as the suspension moves through its travel range. During cornering, optimal camber behavior is critical - engineers typically design for progressive negative camber gain (wheels tilting inward) as the suspension compresses (bump) which can be seen in Figure 1.4. This design maximizes the tire contact patch when cornering forces are highest, improving grip. The camber curve is primarily determined by the strut top mount position (both vertically and laterally) and the geometry of the lower control arm. Performance vehicles often show more aggressive camber gain compared to comfort-oriented vehicles, demonstrating the tuning flexibility of these hardpoints.

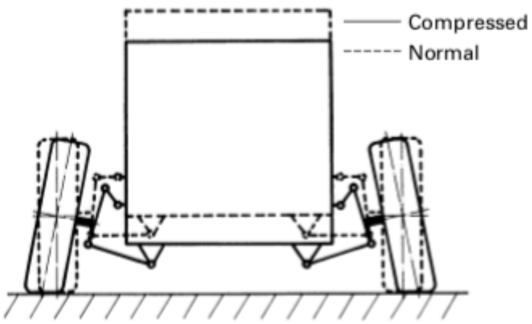

Figure 1.4. Negative Camber in Bump (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001, Fig. 3.47)

Toe angle progression describes how the wheel steering alignment (toe-in or toe-out) changes during suspension movement. Ideal designs maintain minimal toe variation during normal travel (less than ±10 degrees) to ensure straight-line stability, while sometimes incorporating slight dynamic toe-in during braking for enhanced stability. The tie-rod linkage plays a crucial role - its length and attachment point on the steering knuckle significantly affect toe behavior. Additionally, the lateral compliance of control arm bushings influences how much toe change occurs under load. This parameter requires careful balancing, as excessive toe variation can lead to nervous handling or accelerated tire wear.

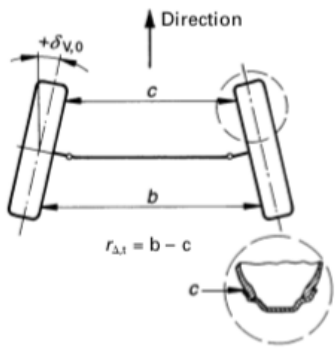

Figure 1.5. Toe-in Configuration (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001, Fig. 3.58)

Track width alteration measures the lateral displacement of wheels during suspension articulation. Excessive track width change causes tire scrub, reducing efficiency and causing uneven wear. This parameter is governed by the wheel center movement arc, which depends on control arm length and angle relative to the chassis. The suspension chassis mounting points are equally critical and their strategic placement ensures the wheel moves vertically with minimal side-to-side deviation. Proper control of track width alteration contributes significantly to predictable handling and consistent tire contact with the road surface.

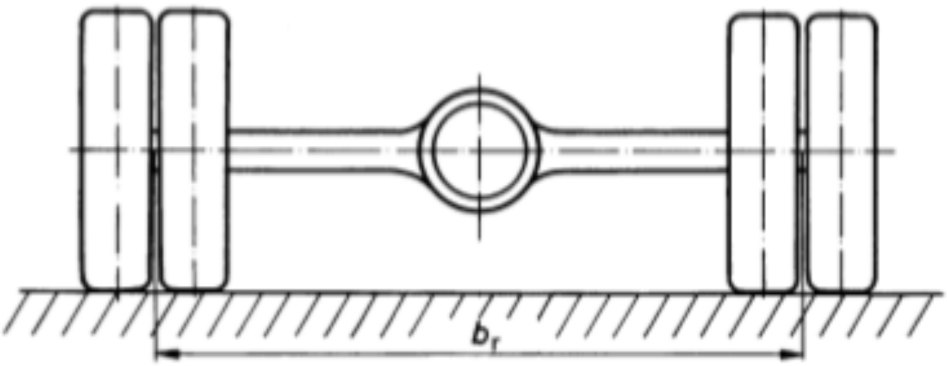

Figure 1.6. The Track Specification b_r Relates to The Mean Distance (Source: Jornsen Reimpell, Helmut Stoll, Jurgen W. Betzler, "The Automotive Chassis: Engineering Principles", Butterworth-Heinemann, 2001, Fig. 3.4)

1.3. Machine Learning: Basic Definitions

Machine Learning (ML) is a transformative branch of Artificial Intelligence (AI) that focuses on developing self-improving algorithms and statistical models capable of performing complex tasks without being explicitly programmed. At its core, ML systems autonomously extract patterns from data, build mathematical representations of real-world processes, and make data-driven decisions that improve with experience. This adaptive learning capability distinguishes ML from traditional programming and makes it indispensable for modern applications ranging from computer vision and natural language processing to predictive maintenance and autonomous decision-making systems.

Fundamentally, machine learning provides a methodological framework for creating intelligent systems that learn directly from data. Data scientists and ML engineers employ these techniques to construct models that not only analyze and interpret complex datasets but also generate actionable predictions. The discipline sits at the intersection of computer science, statistics, and domain-specific knowledge, requiring careful consideration of both algorithmic theory and practical implementation.

2. Full Vehicle Maneuvering Simulations

As mentioned in the previous chapter, full vehicle handling simulations are conducted for an AWD sedan in MSC ADMAS software, evaluating performance through standardized Single Lane Change and J-Turn maneuvers.

Single Lane Change is a standardized maneuver where a vehicle quickly shifts to an adjacent lane at constant speed (typically 80-100 km/h) to test lateral stability (yaw rate/roll angle), steering response and path tracking accuracy.

J-Turn on the other hand is an aggressive 90° turn at high speed (e.g., 60 km/h) to evaluate transient handling during rapid direction change, weight transfer effects and electronic stability control (ESC) performance.

Both of these tests are ISO/SAE standardized tests for vehicle dynamics validation. The lane change assesses stability, while the J-turn stresses extreme handling limits.

The first phase of the project requires assembling a full AWD Sedan vehicle model in ADAMS software. As shown in Figure 2.1, all subsystems are properly defined. The suspension system includes an anti-roll bar in the front axle of the full vehicle model.

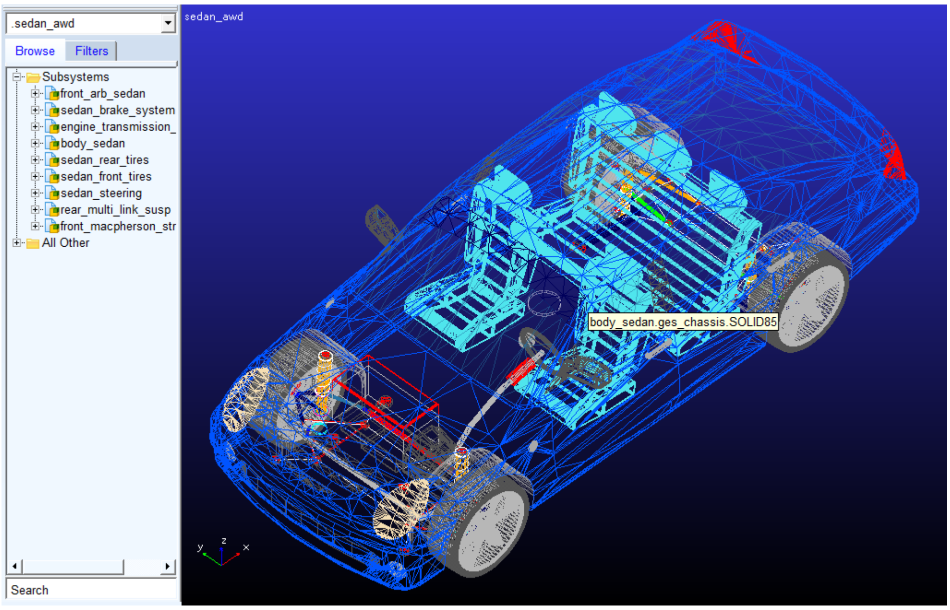

Figure 2.1. Full AWD Sedan Model and its Subsystems

Additionally, the tie rod components are being flexible and meshed (material: steel) to enable finite element analysis (FEA) as shown in Figure 2.2. This setup allow for structural and dynamic simulations in subsequent analysis stages.

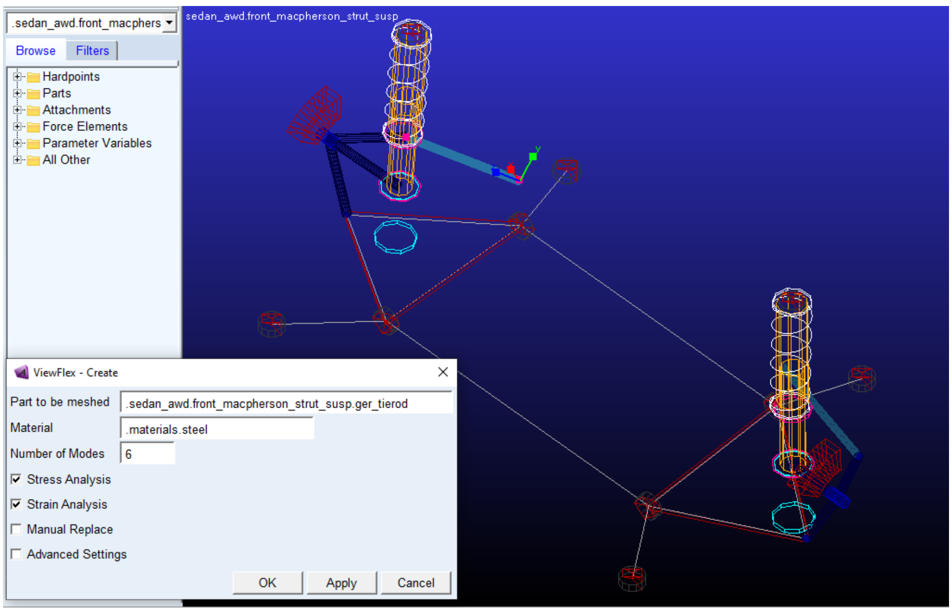

Figure 2.2. Full AWD Sedan Model and its Subsystems

In the next step and after meshing and replacing the tie rod components with the generated MNF files, the following dynamic analyses (Single Lane Change and J-Turn) on the complete AWD Sedan model are performed. Table 2.1 shows key parameter values used in the simulations.

Table 2.1. Handling Simulations Parameters

Parameter	**Single Lane Change**	**J-Turn**
Duration (s)	10	5
Number of steps	1000	500
Velocity (km/h)	80	80
Gear Position	4	4
Angle (Degree)	Max Steering Wheel Angle = 150	Steer Angle = 90

The maximum stress applied to the flexible tie rod component during simulations and testing is calculated while also a Von Mises stress contour plot is generated in ADAMS' Postprocessor to visualize stress distribution as shown in Figures 2.3 and 2.4.

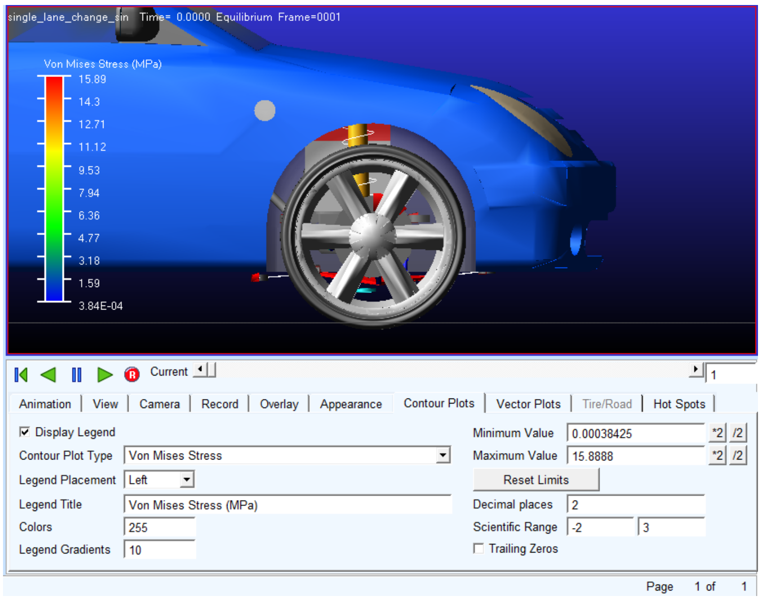

Figure 2.3. Von Mises Stress Contour Plot for Right Tie Rod During Single Lane Change

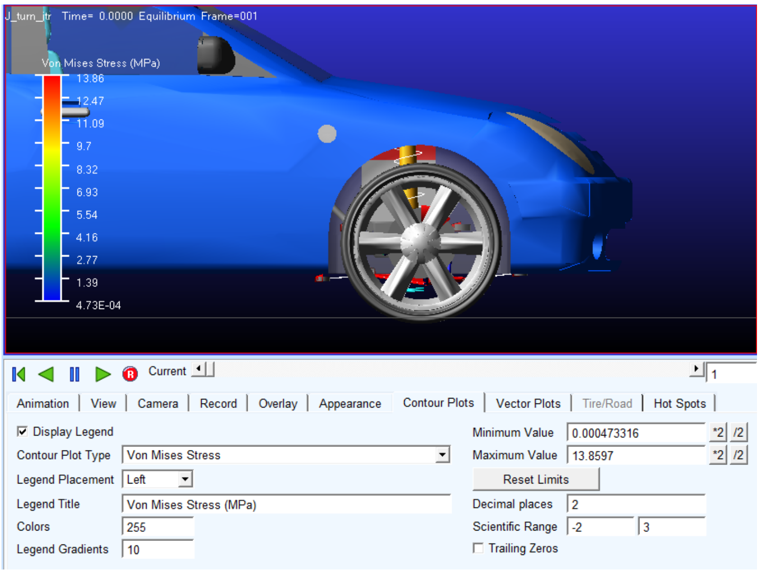

Figure 2.4. Von Mises Stress Contour Plot for Right Tie Rod During J-Turn Maneuvering

This analysis identifies peak stress concentrations and critical load zones in the tie rod under dynamic conditions, verifying whether stresses remain within the yield strength limits of the material. The results enable structural integrity validation and inform potential design refinements if stress levels approach or exceed safe thresholds, ensuring the component meets durability requirements under extreme maneuvering loads. More details are stated in Table 2.2.

Table 2.2. Maximum Stress Values on Tie Rod

Tie Rod	Node ID	Single Lane Change Maximum Stress (MPa)	J-Turn Maximum Stress (MPa)
Right	118	15.89	13.86
Left	57	8.27	6.88

To fully evaluate the lateral dynamic behavior, the simulation must extract and analyze key handling characteristic curves including lateral velocity, roll angle, yaw rate, lateral acceleration and side slip angle. These parameters provide critical insights into the transient response of the vehicle during maneuvers, allowing engineers to assess stability, cornering performance, and overall dynamic control.

The lateral velocity and acceleration curves reveal how quickly the vehicle responds to steering inputs, while the roll angle indicates body lean during turns.

Yaw rate measurements show the rotational response about the vertical axis, and side slip angle data helps evaluate tire grip limits and stability at the limits of handling.

Together, these metrics form a comprehensive picture of the vehicle's dynamic performance, enabling validation against design targets and identification of potential areas for suspension or chassis refinement. The analysis of these interrelated parameters is essential for optimizing both safety and performance characteristics in the vehicle development process.

Conclusion

References

[1] Jornsen Reimpell, Helmut Stoll and Jurgen W. Betzler, “The Automotive Chassis: Engineering Principles”, Butterworth-Heinemann, 2001.

[2] N. Ikhsan, R. Ramli and A. Alias, “Suspension Optimization Using Design of Experiment (DOE) Method on MSC/ADAMS-INSIGHT”, *Jurnal Teknologi*, August 2015.

[3] Lijun Qian and Qin Shi, “Optimization of Wheel Positioning Parameters of Automotive Front Suspension Based on ADAMS”, School of Mechanical and Automotive Engineering, HeFei University of Technology, China.

[4] Du Canyi, Zhu Baochai, Wang Hengbo, Mai Xingye and Qin Taixing, “Design and Optimization of Front Suspension of FSAE based on ADAMS Simulation”, 4th International Conference on Sensors, Mechatronics and Automation, 2016.

[5] Sayyad Nasiri, Naser Sina and Abolqasem Eslami, “Multi-objective Optimisation of McPherson Strut Suspension Mechanism Kinematics using Random Search Method”, *Indian Journal of Science and Technology*, July 2015.