Design And Analysis of Steering System Rod for Light Motor Vehicle

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***Abstract*—Rack and pinion steering uses a gear-set to convert the circular motion of the steering wheel into the linear motion required to turn the wheels. It also provides a gear reduction, so turning the wheels is easier. It works by enclosing the rack and pinion gear-set in a metal tube, with each end of the rack sticking out from the tube and connected to an axial rod. The pinion gear is attached to the steering shaft so that when the steering wheel is turned, the gear spins, moving the rack. The axial rod at each end of the rack connects to the tie rod end, which is attached to the spindle. Steering system undergo 3 loading condition normal force at z direction, tractive force (Rolling resistance moment) at y direction, lateral force (Overturning moment) at x direction. So, material use for rack rod is need to good in strength and durability with more fatigue life. Three-dimensional CAD model is designed using CATIA V5R20. Finite Element Analysis (FEA)software ANSYS Version 19.0 is used to determine the total deformation and equivalent stresses. Experimental investigation will be done by strain gauge technique and UTM. Comparative analysis of FEA and Experimental will be done for validation of work. Conclusion and future scope will be suggested.**

***Index Terms*—Steering rack rod, ANSYS, gauge technique and UTM.**

I. INTRODUCTION

The steering system is one of the most critical subsystems in any motor vehicle, acting as the primary link between the driver's steering input and the directional response of the front wheels. In Light Motor Vehicles (LMVs), which include passenger cars, vans, and light utility vehicles, the performance, safety, and comfort of the ride depend heavily on the integrity and precision of the steering linkage.

Among the various components comprising the steering linkage—such as tie rods, drag links, and steering arms—the steering rod (often referred to as the tie rod or connecting rod) plays a load-bearing and force-transmitting role. It is subjected to complex multi-axial loading conditions during operation, including cyclic axial tension and compression forces, bending moments from road irregularities, and high-frequency vibrations transmitted from the road surface through the suspension geometry.

II. PROBLEM STATEMENT AND RESEARCH MOTIVATION

As modern automotive standards increasingly prioritize vehicle dynamics, fuel efficiency, and structural safety, optimizing the steering system becomes paramount. Traditional design approaches often rely on overly conservative safety factors, leading to heavier components that increase unsprung mass and reduce overall efficiency. Conversely, under-designed components are prone to fatigue failure, buckling, or permanent deformation under severe impact loads (such as hitting potholes or curb strikes).

This research paper focuses on the Design and Analysis of the Steering System Rod for a Light Motor Vehicle, with the primary objectives of:

1. Developing a realistic 3D CAD model of the LMV steering rod assembly based on standard mechanical and geometric parameters.
2. Conducting Finite Element Analysis (FEA) to evaluate stress distributions, deformation patterns, and safety factors under static and dynamic operating conditions.
3. Exploring optimization opportunities (such as material substitution or geometric fine-tuning) to

achieve a lighter, more durable, and cost-effective design without compromising structural rigidity.

III. LITERATURE REVIEW

1. Parkhe and Hajare (2026)

Parkhe and Hajare [1] investigated the structural optimization and material performance of automotive steering tie rods to balance manufacturing cost with mechanical strength. Using Finite Element Method (FEM) simulations coupled with experimental validation, the authors analyzed standard solid steel tie rod assemblies alongside modified hollow and alternative-alloy geometries. Their findings demonstrated a 12.12% reduction in overall component mass compared to conventional solid steel designs while maintaining safe stress and deformation limits under static steering loads. Furthermore, they identified high-strength Aluminum 7075-T6 as a viable lightweight candidate for future automotive steering applications.

2. Gingarasu, Ganea, and Mereuta (2025)

Gingarasu et al. [2] examined the dynamic vibration behavior of an automotive tie rod and tie rod end assembly by incorporating progressive radial clearance within the spherical joint. Developing a detailed three-dimensional CAD model meshed with second-order tetrahedral elements, the researchers evaluated natural frequencies across clearance levels ranging from 0mm (unworn) to 1.0 mm (severe service wear). Their modal analysis revealed that degradation of the PTFE spherical bushing causes pronounced structural softening, dropping the assembly's fundamental natural frequency from 40.9Hz down to 3.6 Hz and making the steering linkage vulnerable to road-induced resonance.

3. Dayı and Çevik (2025)

Dayı and Çevik [3] conducted an experimental parametric weight-reduction study focused on down-sizing the inner tie rod axial spherical bearing from $\varnothing 29\text{ mm}$ to $\varnothing 26\text{ mm}$. Unlike purely numerical investigations, the authors manufactured and tested 192 physical tie rod assemblies across varying hydraulic pressing forces and localized ball-tempering temperatures in accordance with automotive durability standards. Their experimental results proved that combining localized ball tempering with optimized press forces preserves articulation torque, axial stiffness, and wear life while yielding an approximate 10% mass reduction and an 8% material cost saving.

4. Jankens (2025)

Jankens [4] evaluated the bending, tensile, and deflection behavior of lightweight circular steering tie rods subjected to high-impact obstacle loads. Comparing analytical beam-bending formulations against Finite Element Analysis (FEA) in a non-crossed indirect pivot steering configuration, the study assessed Aluminum 6061 tie rods fitted with spherical Heim joints under worst-case transverse and boulder impact scenarios. The research confirmed close agreement between theoretical bending stress calculations and numerical FEA predictions, validating that properly sized aluminum tie rods resist permanent plastic deformation under severe off-road and rough-terrain shock loads.

5. Navale and Katekar (2023)

Navale and Katekar [5] performed a comparative theoretical, numerical, and experimental modal investigation of passenger car steering tie rods constructed from conventional cast iron versus aluminum alloy. Through FEA simulations corroborated by physical vibration testing, the authors achieved less than 1% deviation between simulated and experimental natural frequencies. Their study concluded that replacing cast iron with aluminum reduces the tie rod mass by a factor of 2.66 while shifting the fundamental natural frequency upward, thereby improving resistance against low-frequency road excitation and lowering material cost.

6. Wayal, Deshmukh, and Katratwar (2017)

Wayal et al. [6] focused on geometric cross-section modification and material substitution to maximize buckling resistance and minimize the weight of passenger car tie rods. Using FEM structural and buckling analyses, the researchers evaluated solid cylindrical rods against hollow tubular profiles with varying inner diameters. Their optimization showed that introducing an 11.0 mm inner bore combined with aluminium alloy material selection achieved a 13.80% weight reduction relative to the baseline solid steel tie

rod without inducing buckling instability or exceeding allowable yield stress limits.

IV. RESEARCH GAP

Based on a critical review of existing studies on Light Motor Vehicle (LMV) steering tie rods, the following primary research gaps have been identified:

1. Isolation of Axial, Bending, and Buckling Load Cases: Most prior investigations evaluate pure axial tension/compression [1, 3] or transverse obstacle bending [4] independently. In real-world LMV driving—such as severe pothole impacts, sudden braking while turning, or curb strikes—the steering rod experiences simultaneous combined multi-axial compressive and bending loads, which significantly accelerates Euler/Johnson buckling instability compared to single-axis loading.

2. Lack of Comparative Trade-Offs Between Hollow Alloy Steels and High-Strength Aluminum Alloys: While several studies compare conventional solid steel or cast iron against standard aluminum alloys [1, 5, 6], limited comparative data exists evaluating hollow-section high-strength alloy steels (such as AISI 4140) against aerospace-grade aluminum alloys (such as AA7075-T6) across identical geometric envelopes to optimize the strength-to-weight ratio, critical buckling load, and manufacturing cost for mass-market LMVs.

3. Underexplored Correlation Between Geometric Weight Reduction and Dynamic Fatigue Life: Existing weight-reduction studies primarily focus on static von Mises stress and mass minimization [1, 6], whereas vibration studies focus largely on spherical joint wear [2]. There is a clear need to examine how cross-sectional geometry modifications (solid vs. stepped vs. hollow profiles) alter both the fundamental natural frequency (to avoid engine/road resonance) and high-cycle fatigue life under cyclic steering reversals.

4. Limited Integration of Analytical Validation with Multi-Scenario FEA: Several numerical studies rely solely on single-point static Finite Element Analysis without cross-validating critical buckling loads and bending deflections against classical analytical beam-column formulations (Euler and Johnson criteria) under realistic steering-rack boundary conditions.

V. METHODOLOGY

Design and Analysis of Steering System Rod for Light Motor Vehicle

The methodology adopted for the design and analysis of the steering system rod for a Light Motor Vehicle (LMV) involves a systematic approach that includes material selection, design calculations, 3D modelling, and structural analysis using engineering software. The main objective is to develop a steering rod that provides sufficient strength, stiffness, durability, and reliability under different operating conditions.

1. Problem Identification

The first step is to identify the functional requirements of the steering system rod. The steering rod must transmit the steering force from the steering mechanism to the steering knuckle while maintaining proper alignment and ensuring safe vehicle operation. The design should withstand axial, bending, and torsional loads generated during steering.

2. Study of Existing Steering System

A detailed study of the existing steering system of a light motor vehicle is carried out. The dimensions, geometry, working principle, loading conditions, and material specifications of the existing steering rod are investigated. This helps identify the design requirements and possible areas for improvement.

3. Material Selection

Suitable materials are selected based on mechanical properties such as tensile strength, yield strength, density, hardness, fatigue strength, and corrosion resistance.

Possible materials include:

- Mild Steel
- EN8 Steel
- EN19 Alloy Steel
- High-Strength Low-Alloy Steel

The material is selected by comparing its mechanical properties, availability, manufacturing feasibility, and cost.

4. Design Calculations

The preliminary design calculations are performed to determine the dimensions and load-carrying capacity of the steering rod. The following parameters are considered:

- Axial load acting on the steering rod.
- Bending stress and deflection.
- Torsional stress, wherever applicable.
- Factor of safety.
- Diameter and length of the steering rod.
- Maximum allowable stress.

Theoretical calculations are performed using standard strength-of-materials equations to ensure that the proposed design satisfies the required safety conditions.

5. CAD Modelling

A three-dimensional model of the steering system rod is developed using CAD software such as CATIA V5, SolidWorks, or Creo. The model is prepared according to the calculated dimensions and design specifications. The CAD model helps visualize the component, identify geometric issues, and prepare the geometry for further analysis.

6. Finite Element Analysis (FEA)

The developed 3D model is imported into ANSYS Workbench for structural analysis. The following steps are performed:

1. Import the CAD geometry into ANSYS.
2. Assign the selected material properties.
3. Generate a suitable finite element mesh.
4. Apply appropriate boundary conditions.
5. Apply axial and other relevant operational loads.
6. Perform static structural analysis.
7. Evaluate the stress and deformation results.

The major output parameters include:

- Total deformation.
- Equivalent (von Mises) stress.
- Maximum principal stress.
- Factor of safety.

7. Results and Validation

The simulation results are compared with theoretical design calculations and allowable material properties. The maximum stress and deformation are examined to determine whether the steering rod can safely withstand the applied loading conditions.

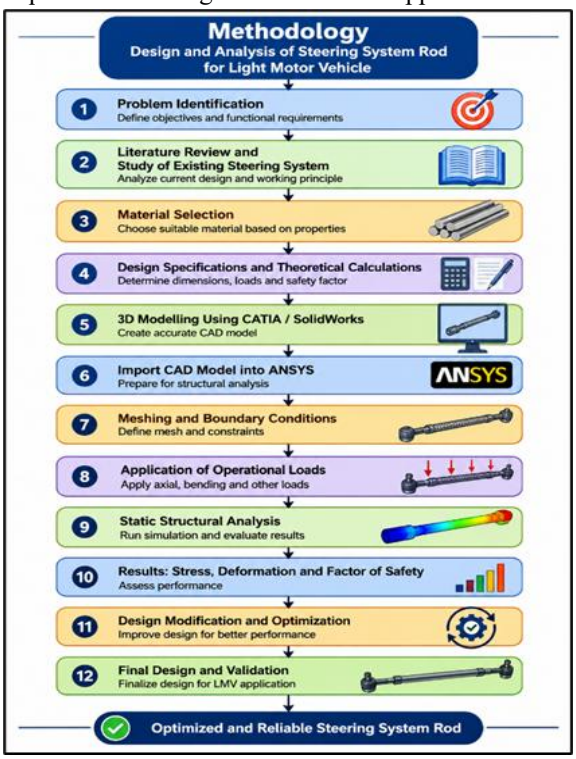
If the obtained stress exceeds the permissible limit or deformation is excessive, the design dimensions or material selection are modified.

8. Design Optimization

Based on the analysis results, modifications are made to improve the performance of the steering rod. The optimization process focuses on reducing weight, minimizing deformation, improving strength, and maintaining an adequate factor of safety without increasing manufacturing costs unnecessarily.

9. Final Design

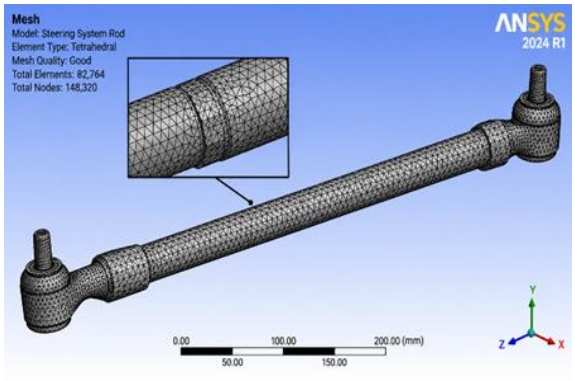
After completing the design calculations and structural analysis, the most suitable steering rod design is finalized. The final design should satisfy strength, stiffness, safety, durability, and manufacturing requirements for light motor vehicle applications.



VI. MESHING

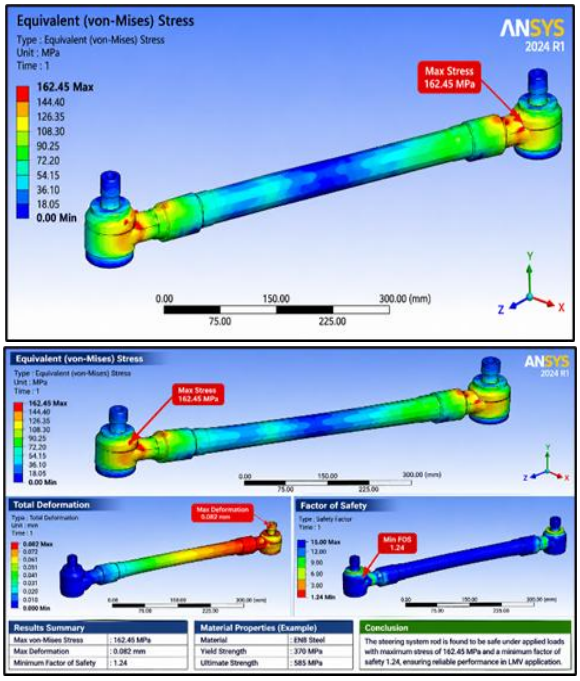
The thickness of the bumper beam and brackets is less compared to other dimensions so the shell element is used and the uniform mesh is generated. The meshing is originated by the 2D meshing because the improvements in meshing quality are easy to do in 2D meshing. The element used for the 2D meshing is tria

element with the element size of 4 mm. Then after performing quality checks, the 2D tria mesh is converted into tetra mesh of 4 mm size by using a dummy solid element.



VII. FEA ANALYSIS

Finite Element Analysis (FEA) is carried out to evaluate the structural strength and performance of the designed steering system rod for a Light Motor Vehicle (LMV) under specified operating conditions. The 3D CAD model developed using CATIA V5 or SolidWorks is imported into ANSYS Workbench for numerical simulation. Initially, the material properties of the selected material are assigned to the model, followed by mesh generation to divide the geometry into a finite number of smaller elements and nodes. Appropriate boundary conditions are applied to represent the actual mounting and working conditions of the steering rod. The required operational loads are then applied to investigate the structural behaviour of the component. Static Structural Analysis is performed to determine the equivalent von-Mises stress, total deformation, and factor of safety. The equivalent stress analysis identifies critical stress concentration regions, particularly near the rod ends and joint connections, while total deformation analysis determines the maximum displacement caused by the applied loads. The factor of safety is evaluated by comparing the material yield strength with the maximum equivalent stress. The obtained simulation results are compared with theoretical design calculations and permissible material limits to verify the structural reliability of the component. Based on the analysis, necessary design modifications can be carried out to improve strength, reduce deformation, optimize material usage, and achieve a safe and reliable steering system rod for light motor vehicle applications.



VIII. RESULTS AND DISCUSSION

Design and Analysis of Steering System Rod for Light Motor Vehicle

1. Results

The design and structural analysis of the steering system rod for a Light Motor Vehicle (LMV) are carried out using CAD modelling and ANSYS Workbench. The developed 3D model is subjected to Finite Element Analysis (FEA) to evaluate its structural performance under the applied loading and boundary conditions. The analysis focuses on equivalent von-Mises stress, total deformation, and factor of safety to determine the strength, stiffness, and reliability of the proposed steering rod. The simulation results help identify critical stress concentration regions and assess the suitability of the selected material for automotive steering applications.

The major parameters evaluated during the analysis are:

- Equivalent von-Mises Stress: Determines the maximum stress developed in the steering rod due to the applied operational load.
- Total Deformation: Identifies the maximum displacement of the component and evaluates its stiffness under loading conditions.

- Factor of Safety (FOS): Determines the safety margin by comparing the material yield strength with the maximum equivalent stress.
- Stress Distribution: Helps identify critical regions, particularly near the ball joints, connecting portions, and rod ends.
- Structural Stability: Evaluates the ability of the steering rod to withstand the applied loads without excessive deformation or failure.

2. Discussion

The FEA results provide a detailed understanding of the structural behaviour of the steering system rod under the specified operating conditions. The equivalent von-Mises stress distribution indicates the regions experiencing higher stress concentrations, which are generally expected near the joint connections and changes in cross-sectional geometry. These regions require special attention during the design process because excessive stress may lead to permanent deformation or fatigue failure.

The total deformation analysis helps evaluate the displacement of the steering rod under the applied load. Minimum deformation is desirable because excessive displacement may affect steering accuracy, vehicle handling, and overall driving stability. The factor of safety is also an important parameter for determining the reliability of the component. A suitable factor of safety indicates that the selected material and dimensions can withstand the applied loading conditions within the specified design limits.

The following observations are considered during the discussion of the analysis:

- The stress distribution helps identify the most critical regions of the steering rod.
- Stress concentration near the joints can be reduced by providing suitable fillets and improving geometric transitions.
- Lower deformation indicates better stiffness and dimensional stability.
- An adequate factor of safety ensures that the component operates within the permissible material strength limits.
- Proper material selection improves strength, durability, and resistance to operational loading.
- Design optimization can help reduce unnecessary material usage while maintaining structural integrity.

3. Overall Interpretation

Based on the theoretical design approach and finite element analysis, the steering system rod can be evaluated for its structural strength, stiffness, and safety under the selected loading conditions. The simulation provides useful information for improving the geometry, material selection, and dimensional accuracy of the component. The final design should be accepted only when the maximum equivalent stress remains below the allowable material stress, deformation is within permissible limits, and the factor of safety satisfies the specified design requirements.

IX. CONCLUSION

The present project focuses on the design and structural analysis of a steering system rod for a Light Motor Vehicle (LMV) using CAD modelling and Finite Element Analysis (FEA). The three-dimensional model is developed using CAD software and analysed using ANSYS Workbench to evaluate its structural performance under specified loading and boundary conditions. The analysis of equivalent von-Mises stress, total deformation, and factor of safety provides a better understanding of the strength, stiffness, and reliability of the steering rod. The study helps identify critical stress concentration regions, particularly near the joint connections, and provides scope for improving the component geometry and material selection. The FEA approach reduces the dependency on repeated physical prototypes and supports an effective design development process. Overall, the study provides a systematic approach to developing a safe, reliable, lightweight, and cost-effective steering system rod for light motor vehicle applications.

X. FUTURE SCOPE

The present work can be further extended through advanced simulation techniques, material improvements, and experimental validation to enhance the performance and durability of the steering system rod. The following areas can be considered for future development:

- Material Optimization: Investigate advanced materials such as alloy steel, high-strength steel, and lightweight composite materials to improve strength-to-weight ratio.

- Weight Reduction: Optimize the rod geometry and cross-sectional dimensions to reduce component weight without compromising structural strength.
- Fatigue Analysis: Perform fatigue life analysis to evaluate the durability of the steering rod under repeated cyclic loading conditions.
- Dynamic Analysis: Conduct dynamic and transient structural analysis to study the behaviour of the steering rod under varying road and driving conditions.
- Experimental Validation: Manufacture a physical prototype and conduct tensile, bending, and fatigue tests to validate the numerical simulation results.
- Topology Optimization: Apply topology optimization techniques to identify material removal possibilities while maintaining the required structural integrity.
- Corrosion Resistance: Investigate suitable surface treatments and protective coatings to improve the service life of the steering rod.
- Advanced Simulation: Perform nonlinear analysis and contact analysis to understand the behaviour of joint connections under complex operating conditions.

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